INTEGRATED CLIMATE RESILIENT MODELLING OF RENEWABLE ENERGY TRANSITION IN NEPAL

A Thesis submitted by

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ABSTRACT

There is a global consensus on the need for accelerating renewable energy transition. Developing countries have plentiful untapped feasible renewable energy which could be extremely valuable for the future. This study analyses the transition in a South Asian developing country, Nepal, by encompassing systematic literature review, quantification of energy security, policy analysis, use of machine learning on primary data to assess household energy behaviour, energy planning modelling in LEAP, and climate change analysis using hydrological modelling in HEC-HMS, through bottom-up methods. Moreover, this study develops an integrated multi-layered renewable energy transition modelling framework considering technical, socio-economic and people's perceptions aspects. Nepal faces a 'pseudo energy secure' condition due to massive reliance on traditional fuels, suppressed demand, import-dominated energy systems, and marginal growth of domestic renewables. Although the energy policies development trajectory of Nepal is progressive, they remain insufficient to support the transition fully. International donations and government subsidies have often failed in the past due to the lack of a sustainable 'energy ecosystem' development. Socio-economy significantly influences household energy behaviour: 68% of rural and 67% of semi-urban residents resist energy changes, while 73% of urban residents are open to change but prefer fuel-stacking. An integrated demand management scenario shows that up to 300 Mtoe of energy can be saved by 2050 in Nepal, with the residential sector potentially saving 53%. Energy-related emissions can be reduced from 66.6 MtCO_2e (baseline) to 10.5 MtCO_2e by 2050. Hydrological simulations indicate varied impacts of climate change on hydropower generation. Many run-of-river hydropower projects in the central and western regions of Nepal are likely to meet only 70% of their energy targets due to climate change. It emphasizes the need for a project evaluation framework to identify and prioritize climate-resilient hydropower schemes. It is essential that Nepal focuses on setting realistic energy targets, considering sectoral demands and resource availability, and adopts high-discharge hydropower projects for resilience to climatic variations. In addition, constructing storage-type hydropower projects at strategic locations, extending the national electricity grid to rural areas, and implementing community-awareness initiatives are vital. The comprehensive renewable energy transition modelling framework is a contribution to the global renewable energy sector addressing three UN SDGs: 7 (affordable and clean energy), 13 (climate action) and 11 (sustainable cities and communities). Additionally, development of the *Energy Security Composite Index of Nepal (ESCOIN)* and insights of climate change impacts on hydropower offer specific benefits to Nepal and the Himalayan region.

CERTIFICATION OF THESIS

I, Utsav Bhattarai, declare that the PhD Thesis entitled *Integrated Climate Resilient Modelling of Renewable Energy Transition in Nepal* is not more than 100,000 words in length including quotes and exclusive of tables, figures, appendices, bibliography, references, and footnotes.

This Thesis is the work of Utsav Bhattarai except where otherwise acknowledged, with the majority of the contribution to the papers presented as a Thesis by Publication undertaken by the student. The work is original and has not previously been submitted for any other award, except where acknowledged.

Date: 13th November 2024

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STATEMENT OF CONTRIBUTION

From my PhD research, I produced eight peer reviewed journal papers, all published or currently under review in the top decile (D1) journals. I co-authored 12 additional peer reviewed journal papers and one conference paper during my PhD period (2021-2024).

Peer reviewed papers from my PhD research

1. **Bhattarai, U.**, Maraseni, T. and Apan, A. 2022. Assay of renewable energy transition: A systematic literature review. *Science of The Total Environment*, 833, 155159. https://doi.org/10.1016/j.scitotenv.2022.155159
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   (Student contributed 80% to this paper. Collectively, T. Maraseni and A. Apan contributed the remainder).

2. **Bhattarai, U.**, Maraseni, T., Devkota, L.P. and Apan, A., 2024. A Composite Indicator-based Method to Assess the Energy Security of Nepal and prospects of Cross-border Electricity Sharing in South Asia. *Environmental Development*, 51:101002. https://doi.org/10.1016/j.envdev.2024.101002
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3. **Bhattarai, U.**, Maraseni, T., Devkota, L.P. and Apan, A., 2024. Evaluating Four Decades of Energy Policy Evolution of a South Asian Country – Nepal: A Comprehensive Review. *Sustainable Development*, 1-29. https://doi.org/10.1002/sd.3053
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4. **Bhattarai, U.**, Maraseni, T., Apan, A. and Devkota, L.P. 2023. Rationalizing donations and subsidies: Energy ecosystem development for sustainable renewable energy transition in Nepal. *Energy Policy*, 177. https://doi.org/10.1016/j.enpol.2023.113570

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5. **Bhattarai, U.**, Maraseni, T., Devkota, L.P. and Apan, A., 2023. Application of machine learning to assess people's perception of household energy in the developing world: A case of Nepal. *Energy and AI*, 14, 100303. https://doi.org/10.1016/j.egyai.2023.100303
Decile: D1, Impact Factor: 9.6, SNIP: 2.291, Publisher: Elsevier
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6. **Bhattarai, U.**, Maraseni, T., Devkota, L.P. and Apan, A. 2024. Learning from the Past and Planning for Nepal's Sustainable Energy Future: Bottom-up modelling in LEAP. *Journal of Cleaner Production* (under fifth round of review) [Manuscript ID: CLEPRO-D-23-34745R4].
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7. **Bhattarai, U.**, Maraseni, T., Devkota, L.P. and Apan, A., 2024. Facilitating sustainable energy transition of Nepal: A best-fit model to prioritize influential socio-economic and climate perception factors on household energy behaviour. *Energy for Sustainable Development*, 101505. https://doi.org/10.1016/j.esd.2024.101505
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8. **Bhattarai, U.**, Maraseni, T., Devkota, L.P. and Apan, A. 2024. Hydropower and climate resilience of Nepal Himalaya: A bottom-up hydrological approach. Submitted to *Earth Systems and Environment* [Accepted; In Press].
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Additional peer reviewed papers co-authored during my PhD period (2021-2024)

9. Awal, A., **Bhattarai, U.**, Pandey, V.P. and Bhattarai, P.K., 2024. Downstream impacts of dam breach using HEC-RAS: A case of Budhigandaki concrete arch dam in central Nepal. *Environmental Systems Research*, 13(1), 37. https://doi.org/10.1186/s40068-024-00358-3

10. Devkota, L.P., **Bhattarai, U.**, Devkota, R., Maraseni, T. and Marahatta, S. 2024. Questioning the use of ensembles versus individual climate model generated flows in future flood predictions: Plausibility and implications. *Journal of Flood Risk Management*, e12978. https://doi.org/10.1111/jfr3.12978

11. **Bhattarai, U.**, Devkota, R., Maraseni, T., Devkota, L. and Marahatta, S. 2023. Attaining multiple sustainable development goals through storage hydropower development amidst community vulnerabilities. *Sustainable Development*, 1-27. https://doi.org/10.1002/sd.2634

12. Baniya, R., Talchabhadel, R., Panthi, J., Ghimire, G.R., Sharma, S., Khadka, P.D., Shin, S., Pokhrel, Y., **Bhattarai, U.**, Prajapati, R. and Thapa, B.R. 2023. Nepal Himalaya offers considerable potential for pumped storage hydropower. *Sustainable Energy Technologies and Assessments*, 60:103423. https://doi.org/10.1016/j.seta.2023.103423

13. **Bhattarai, U.**, Devkota, L.P. and Maraseni, T. 2023. How Effective Is Inter-Basin Transfer to Manage Temporal Variation Of “Too Much” And “Too Little” Water Conditions for Irrigation in a Himalayan Basin? *SCITECH Nepal Journal of Scientific and Technical Studies*. https://doi.org/10.3126/scitech.v17i1.60466

14. **Bhattarai, U.**, Devkota, L.P., Marahatta, S., Shrestha, D. and Maraseni, T. 2022. How will hydro-energy generation of the Nepalese Himalaya vary in the future? A climate change perspective. *Environmental Research* 214(1), 113746. https://doi.org/10.1016/j.envres.2022.113746

15. Bhattarai, R., **Bhattarai, U.**, Pandey, V.P. and Bhattarai, P.K. 2022. An artificial neural network-hydrodynamic coupled modelling approach to assess the impacts of floods under changing climate in the East Rapti Watershed, Nepal. *Journal of Flood Risk Management*, e12852. https://doi.org/10.1111/jfr3.12852

16. Dhakal, S., **Bhattarai, U.**, Marahatta, S. and Devkota, P. 2022. . Impact of climate change on the full spectrum of low flows of Budhigandaki River Basin in Nepal using Gumbel distribution. *International Journal of Energy and Water Resources*. https://doi.org/10.1007/s42108-022-00214-z

17. Devkota, L.P., **Bhattarai, U.**, Khatri, P., Marahatta, S. and Shrestha, D. 2022. Resilience of Hydropower Plants to Flow Variation through the Concept of Flow Elasticity of Power: Theoretical Development. *Renewable Energy*, 184: 920-932. https://doi.org/10.1016/j.renene.2021.11.051

18. Marahatta, S., **Bhattarai, U.**, Devkota, L.P. and Aryal, D. 2022. Unravelling the water-energy-economic-continuum of hydroelectricity in the face of climate change. *International Journal of Energy and Water Resources*. https://doi.org/10.1007/s42108-021-00174-w

19. Marahatta, S., Aryal, D., Devkota, L.P., **Bhattarai, U.** and Shrestha, D. 2021. Application of SWAT in Hydrological Simulation of Complex Mountainous River Basin (Part II: Climate Change Impact Assessment). *Water*, 13(11), 1548. https://doi.org/10.3390/w13111548

20. Sapkota, S., Pandey, V.P., **Bhattarai, U.**, Panday, S., Shrestha, S.R. and Maharjan, S.B. 2021. Groundwater potential assessment using an integrated AHP-driven geospatial and field exploration approach applied to a hard-rock aquifer Himalayan watershed. *Journal of Hydrology: Regional Studies*, 37, 100914. https://doi.org/10.1016/j.ejrh.2021.100914

Conference paper

21. Bhattarai, A., **Bhattarai, U.**, Maharjan, K.R. and Devkota, L.P. 2024. Assessing the characteristics of extreme floods in Nepal. Post-conference publication in Special Issue: *International Conference on Mountain Hydrology and Cryosphere*, 9-10 November, Kathmandu, Nepal. International Association of Hydrological Sciences (IAHS), Copernicus Publications.

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Utsav

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ABBREVIATIONS

AC	Alternating Current
ADB	Asian Development Bank
AEPC	Alternative Energy Promotion Centre
AESPI	Aggregated Energy Security Performance Indicator
AGT	Azerbaijan-Georgia-Turkey
AHP	Analytical Hierarchy Process
AR6	Sixth Assessment Report
ARMA	Autoregressive Moving Average Method
ASEAN	Association of Southeast Asian Nations
BBIN	Bangladesh, Bhutan, India, Nepal
BIMSTEC	Bay of Bengal Initiative for Multi-Sectoral Technical and Economic Cooperation
BOOT	Build-Own-Operate-Transfer
BP	British Petroleum
BRIC	Brazil, Russia, India and China
BU-NEP	Bottom-Up Nepal Model
CBS	Central Bureau of Statistics
CCAFS	Climate Change Agriculture and Food Security
CCP-model	Climate Change Perception Model
CIDA	Canadian International Development Agency
COM	Commercial Sector Improvement Scenario
COP	Conference of the Parties
CREF	Central Rural Energy Fund
CV	Coefficient of Variance
DANIDA	Danish International Development Agency
DC	Direct Current
DHM	Department of Hydrology and Meteorology

diff	Difference
DoC	Department of Customs
DoED	Department of Energy Development
DOM	Domestic Sector Improvement Scenario
DoR	Department of Roads
DSM	Composite Demand Side Management Scenario
EC	European Commission
EFOM	Energy Flow Optimization Model
EI	Energy Institute
EIA	Energy Information Administration
EJ	Exa Joules
EPA	Environmental Planning Associates
EPDC	Electric Power Development Company Limited
EROI	Energy Return on Energy Invested
ES	Energy Security
ESCOIN	Energy Security Composite Index of Nepal
ESI	Energy Security Index
ESIOP	Energy Security Index of Pakistan
ETC	Extra Trees Classifier
EU	European Union
FDC	Flow Duration Curve
FN	False Negative
FP	False Positive
FY	Fiscal Year
G2G	Government-to-government
GCC	Gulf Cooperative Council
GCM	General Circulation Model
GDP	Gross Domestic Product
GESRI	Geopolitical Energy Supply Risk Index
GGI	Global Green Growth Institute, Korea

GHG	Greenhouse Gas
GIS	Geographic Information System
GIZ/GTZ	Deutsche Gesellschaft für Internationale Zusammenarbeit / German Technical Cooperation
GJ	Giga Joules
GMS	Greater Mekong Subregion
GoN	Government of Nepal
GtCO$_2$e	Giga Tonnes of Carbon Dioxide Equivalent
GW	Giga Watt
GWh	Giga Watt-hour
HBV	Hydrologiska Byråns Vattenbalansavdelning
HDM	Hierarchical Decision Model
HEC-HMS	Hydrologic Engineering Center Hydrologic Modeling System
HH	Household
HHI	Herfindhal-Hirschman Index
HMG	His Majesty's Government of Nepal
HP	Hydropower
HREC	Human Research Ethics Committee
HRU	Hydrologic Response Unit
HSPF	Hydrologic Simulation Program FORTRAN
HTR	Hausman Taylor Regression
HYD	Hydropower-dominated Generation Scenario
ICIMOD	International Centre for Integrated Mountain Development
ICT	Information and Communication Technology
IEA	International Energy Agency
IFC	International Finance Corporation
IHA	International Hydropower Association
IND	Industrial Sector Improvement Scenario
INGO	International Non-governmental Organization
IPCC	Intergovernmental Panel on Climate Change

IRADe	Integrated Research and Action for Development
IRENA	International Renewable Energy Agency
JICA	Japan International Cooperation Agency
KNN	K-Nearest Neighbors
KVDA	Kathmandu Valley Development Authority
kW	Kilo Watt
LEAP	Low Emissions Analysis Platform
LED	Light Emitting Diode
LPG	Liquified Petroleum Gas
LUT	Lappeenranta University of Technology
MARKAL	MAED-MARKet Allocation
MARO	Multistage Adaptive Robust Optimization framework
ML	Machine Learning
MLP	Multi-Layer Perceptron
MME	Multi-model ensemble
MoEn	Ministry of Energy
MoE	Ministry of Environment
MoEWRI	Ministry of Energy, Water Resources and Irrigation
MoF	Ministry of Finance
MoF&SC	Ministry of Forests and Soil Conservation
MoFA&GM	Ministry of Federal Affairs and General Administration
MoFA&LD	Ministry of Federal Affairs and Local Development
MoFE	Ministry of Forests and Environment
MoICS	Ministry of Industry, Commerce and Supplies
MoITC	Ministry of Industry Trade and Commerce
MoPE	Ministry of Population and Environment
MoPIT	Ministry of Physical Infrastructure and Transport
MoPPW	Ministry of Physical Planning and Works
MoSTE	Ministry of Science, Technology and Environment
MoWR	Ministry of Water Resources

MR-P	Multinomial Regression – Probit
MR-L	Multinomial Regression – Logit
$MtCO_2e$	Million Tonnes of Carbon Dioxide Equivalent
MW	Mega Watt
NAST	Nepal Academy of Science and Technology
NDC	Nationally Determined Contributions
NEA	Nepal Electricity Authority
NED	Nepal Electricity Department
NEO22	Nepal Energy Outlook 2022
NGO	Non-governmental Organization
NISP	Nepal Irrigation Sector Project
NISS	Nepal Investment Summit Secretariat
NOC	Nepal Oil Corporation
NORAD	Norwegian Agency for Development Cooperation
NPC	National Planning Commission
NREF	National Renewable Energy Framework
NREP	Nepal Renewable Energy Programme
NSE	Nash-Sutcliffe Efficiency
O&M	Operation and Maintenance
OAPEC	Organization of Arab Petroleum Exporting Countries
OECD	Organization for Economic Cooperation and Development
PARDL	Panel AutoRegressive Distributed Lag Model
PBIAS	Percentage Volume Bias
PCA	Principal Component Analysis
PIB	Press Information Bureau, India
PMG-ARDS	Pooled Mean Group-AutoRegressive Distributed Lag Model
PRI	Policy Research Institute
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analysis Framework
PSTR	Panel Smooth Transition Regression

PV	Photovoltaics
Q40	40% Exceedance Flow Value
R&D	Research and Development
R2	Coefficient of Determination
RC	Ridge Classifier
RCM	Regional Climate Model
RCP	Representative Concentration Pathway
RE	Renewable Energy
REF	Rural Energy Fund
REN21	Renewable 2021 Global Status Report
RESI	Renewable Energy Security Index
RET	Renewable energy transition
RF	Random Forest
ROR	Run-of-River
SAARC	South Asian Association for Regional Cooperation
SAFIR	South Asia Forum for Infrastructure Regulation
SAFTA	South Asian Free Trade Area
SAPP	Southern African Power Pool
SARI/EI	South Asia Regional Initiative for Energy Integration
SCE-model	Socio-economic Model
SD	Standard Deviation
SDG	Sustainable Development Goal
SDIP	Sustainable Development Investment Portfolio
SEI	Stockholm Environment Institute
SES	Sustainable Energy Security Index
SESI	Singapore Energy Security Index
SMEC	Snowy Mountain Engineering Corporation
SNV	Stichting Nederlandse Vrijwilligers (”Foundation of Netherlands Volunteers”)
SRES	Special Report on Emission Scenarios

SSP	Shared Socioeconomic Pathway
STAR	Smooth Transition Auto Regressive Model
SWAT	Soil and Water Assessment Tool
SWI	Shannon-Wiener Index
TIMES	The Integrated MARKAL-EFOM System
TN	True Negative
toe	Tons of Oil Equivalent
TP	True Positive
TPE	Third Pole Environment
TRA	Transportation Sector Improvement Scenario
TWh	Terra Watt-hour
UK	United Kingdom
UNCRD	United Nations Center for Regional Development
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
USA	United States of America
USD/US$	United Stated Dollar
WAPP	West Africa Power Pool
WB	World Bank
WEC	World Energy Council
WECS	Water and Energy Commission Secretariat
WIOD	World Input-Output Database
WIS	“Wish-for” Scenario
WMO	World Meteorological Organization

CHAPTER 1: INTRODUCTION

1.1 Background

Energy is a building block for development. As a result, there is a global competition among countries to maximize energy generation and improve its efficient use. This competition is especially pronounced in the global north, which has historically generated substantial quantity of energy to support its development activities. The 2022 global energy supply amounted to 632 EJ (1 Exajoule, EJ = 10^{18} J), 80% relying on fossil-fuels and the remaining supported by renewables, traditional biomass and nuclear energy (IEA, 2023b). Asia Pacific is the largest energy generating region (281 EJ) followed by North America (115 EJ). The largest energy producing country is China (160 EJ, 25% of the world total and 57% of the Asia Pacific total) while the United States (94 EJ, 15% of the world total) ranks second (IEA, 2023b). The total renewable energy supply in 2022 was 75.5 EJ, out of which the contribution of China was 15 EJ (about 20%). Coal had the largest share (about 45%) in the electricity and heat sectors (total of 247 EJ) while renewables contributed about 17% (41 EJ) to these sectors. Among renewables, hydropower had the largest contribution (16 EJ, 40%) (IEA, 2023b). Furthermore, the total world electricity generation was 29,033 TWh; fossil fuels and modern renewables contributed 61% and 30%, respectively (IEA, 2023b). China generated a third (8,912 TWh) of the world's total electricity in 2022 which is almost equal to that generated by the US and Europe combined (IEA, 2023b). The total renewable energy capacity of the world was 3,391 GW in 2022, out of which 1,630 GW (48%) was contributed by Asia (IRENA, 2024). The total hydropower installed capacity of the world was 1,394 GW in 2022 with the largest contributor (413 GW) being China (IRENA, 2024).

Moreover, energy is also a yardstick of development. Increased energy use across different sectors of the economy and their direct or indirect implications on the lives and livelihood of the people gauge the overall prosperity of a nation. The total final energy consumption of the world amounted to 442 EJ globally in 2022, out of which industrial, transport and building sectors consumed 167 (38%), 117 (26%) and 133 EJ (30%), respectively. China is the largest energy consuming country in the world (107 EJ) having a consumption almost double the amount of the US (66 EJ). Asia Pacific is the largest energy consuming region with a final consumption of 191 EJ (IEA, 2023b). Qatar, United Arab Emirates and Singapore are the top three countries in terms of energy consumption per capita consuming 700, 535 and 530 GJ/capita in 2023 (EI, 2023).

With energy consumption in such large magnitudes, global energy-related emissions have also intensified considerably from 32.2 in 2012 to 34.4 $GtCO_2e$ in 2022 (EI, 2023). Corresponding to the energy consumption, Asia Pacific is the largest emitting region (52%), with China alone accounting for 59% of the total energy-related emissions of this region (EI, 2023). The total energy-related emissions of North America and Europe amounted to 5,851 and 3,770 $MtCO_2e$, respectively (EI, 2023). Moreover, studies have reported high emissions in the last two decades mainly due to the humungous energy demands and consumption of the Organization for Economic Cooperation and Development (OECD) member countries and emerging economies such as China, India, Brazil and South Africa (Lin and Omoju, 2017). Globally, the US has the largest per capita emissions (13.3 tCO_2e) in 2023, China ranks second (8.9 tCO_2e) while Japan ranks third (8.0 tCO_2e) (IEA, 2023a).

The current fossil-fuel dominated energy systems are highly problematic. Finite quantity, alarming rates of depletion, and uneven spatial distribution of fossil fuel reserves in nature are major challenges to the sustainability of such systems. Moreover, they contribute to environmental degradation and suffer from issues of growing demand accentuated by volatility of oil prices (Furlong, 2020; Solaun and Cerda, 2019). The last century has witnessed energy-intensive development all over the world (Best, 2017; York and Bell, 2019). However, the disparity in energy generation, access, and usage between developed and developing countries, and among different socioeconomic groups within countries, has become more pronounced over time (Feng et al., 2023; Nie et al, 2024; Yawale et al, 2023). Climate change has further stressed natural resources availability (Amin et al., 2024; Khan and Hassan, 2024) and impacted the energy sector globally (Coleman et al., 2023; Jones et al, 2023). Further, the Intergovernmental Panel on Climate Change (IPCC) has emphasized the urgent need for immediate steps to reduce energy consumption impacts and combat climate change (Masson-Delmotte et al., 2019). These concerns have underscored the necessity of intensifying the efforts of renewable energy transition for a cleaner, safer and better future.

Gasser (2020) recalls that renewable energy transition stemmed from the oil embargo imposed by the members of the Organization of Arab Petroleum Exporting Countries (OAPEC) in Europe during the 1970s. Coming down half a century, the transition has gained substantial momentum because of global discourses and unified efforts. Creation of the International Energy Agency (IEA) in 1974, IPCC by the UN World meteorological Organization (WMO) and United Nations Environment Program (UNEP) in 1988 are some key milestones. The climate and energy framework adopted by the European Commission (EC) targeting 27% share of renewables by 2030 is an important commitment (EC, 2015). Development in line with Sustainable Development Goal (SDG 7: affordable and clean energy), European Green Deal, Agenda 2030 and other global efforts have provided impetus to renewable energy transition (Borozan, 2022). Furthermore, ratification of the Kyoto Protocol in COP 3 (1997), Doha Amendment (2012), Paris Agreement (COP 21: 2015), COP 27 (2022) until the recent Dubai COP28 have driven the global emission reduction efforts, with developing countries leading the way (Bigerna et al., 2021). At COP28, 130 countries joined hands to pledge to triple the world's renewable energy capacity and double the energy efficiency improvements by 2030 (REN21, 2024). Moreover, expanding and modernizing energy systems in the global south has been the focus of the SDG-7 (UN, 2015).

Energy transition and the economy are intrinsically associated, largely guided by the resource-supply-demand dynamics (Sharma and Balachandra, 2019). Research has shown that current attempts of transitioning to cleaner energy alternatives and reduction of energy-related emissions are sluggish across all economic sectors globally (Johnstone et al., 2020; Venegas Cantarero, 2020). Bigerna et al. (2021) indicates towards likely large cross-country differences persisting for renewables particularly in electricity generation in the long run requiring more supportive policy interventions at the national level. Interestingly, York and Bell (2019) argue that the diffusion of renewables in the energy mix is more of an addition to the conventional energy systems rather than transiting from it. Efforts to capacitate climate resilience and provide support to the most vulnerable are not able to cope with the urgency of climate change challenge, energy security, mitigation of environmental impacts and attainment of the SDGs (Bogdanov et al., 2021). Despite global commitments, there is an acute need for speeding up the transition from fossil fuels to renewables worldwide.

The developed world is leading current research and development on the transition, while developing countries are lagging far behind (Bhattarai et al., 2022b; Liao et al., 2021; McGreevy et al., 2021). Studies have emphasized that technology, expertise, financial capabilities, public awareness and adaptive capacity significantly influence the willingness, and sustainability of renewable energy transition (Franco and Taeighagh, 2024; Weko and Goldthau, 2022). Collaborations between developed and developing countries could harness untapped renewable energy potential and accelerate the global shift to clean energy (Vanegas Cantarero, 2020; Xu et al., 2023). People tend to switch to modern and efficient technologies as well as increase the energy consumption as they climb up the energy ladder (Dominguez et al., 2021) and renewable sources become more desirable (Shahzadi et al., 2022). Furthermore, studies highlight the potential of developing Asian economies in mitigating greenhouse gas emissions and minimizing climate change impacts through effective public awareness and adoption of renewable technologies (Mohsin et al., 2021). Considerable efforts are being made by the resourceful developed countries in expanding access to renewable energy in the developing countries through technology transfers and financial support (Ram et al., 2022). Planning efficient future energy pathways by examining the impacts of policy options, economic instruments and social preferences accentuated by changing climate is made possible through modeling frameworks (Solé et al., 2020; Su and Urban, 2021).

There has been considerable progress recently in the development and application of numerical models globally for comprehending renewable energy transition. Economic/econometric models such as Panel Smooth Transition Regression (PSTR); general economic equilibrium models (e.g., Hybrid Dynamic Computable General Equilibrium Model) and energy market models (e.g., LUT Energy Systems Transition Model) are generally used (Guo et al., 2020; Jiang et al., 2021; Li et al., 2021). Decision support systems such as Energy PLAN model are also popular for modelling energy transitions (Hvelplund and Djørup, 2017; Marczinkowski and Barros, 2020). More comprehensive techno-econometric energy systems such as Low Emissions Analysis Platform (LEAP; originally the Long-range Energy Alternatives Planning system) and *pymedeas* have been used in the renewable energy transition domain (Solé et al., 2020; Su and Urban, 2021). Moreover, most of these models are based on a top-down approach which are suitable at the global or regional scales. But they find limited applications at the national and sub-national levels where local specificities significantly drive the energy transition process (Hunt et al., 2021; Israel and Jehling, 2019; Jiang et al., 2021). Even the models that consider local variables and societal factors impacting the transition mostly focus on an isolated sector such as energy (Koengkan and Fuinhas, 2020), economics (Aniello et al., 2019), and environment (Liu et al., 2020; Usman et al., 2024), among others. This has the possibility of overlooking the inter-disciplinary impacts of the transition across different sectors (Usman et al., 2024). Moreover, limited possibilities of climate change assessment in these models are additional constraints for a holistic analysis.

This study aims to address these research gaps by developing a comprehensive multi-layered modelling framework integrating technical, socio-economic and people's perceptions and climate change influencing the renewable energy transition. The methodological framework developed and applied in several published journal articles from this research makes a valuable contribution by demonstrating how energy research can be effectively conducted in the resource-constrained global south. Additionally, this research aims to support Nepal's renewable energy transition, leveraging its significant potential for renewables to achieve sustainable energy security.

1.2 Problem statement

As the renewable energy transition is driven by several interconnected aspects of the society, a holistic approach to planning is required (Gasser, 2020; Usman et al., 2024). Developing countries are massively reliant on traditional/conventional (mostly fossil and biomass) fuels in their generation mix while using energy inefficient appliances. The energy choices people are provided by the state are limited. Moreover, people's voices are not adequately incorporated in policy making, planning, and implementation in these regions. Therefore, chances of transitioning to cleaner and more efficient energy technologies are rather lean despite willingness and efforts. Hence, this research addresses three pertinent issues related to renewable energy transition which are explained subsequently.

a. Limited number of studies on renewable energy transition in the developing world: Studies have shown large global north-south disparities in the renewable energy transition research and development. Furthermore, large numbers of untapped feasible renewable energy sources are located in the developing countries which can be extremely important for the future (Xu et al., 2023; Carrosio and Scotti, 2019; Murshed, 2021). As a result, optimum utilization of these precious resources is of utmost importance for an energy secure future. Cases have demonstrated that the transitions, although claimed to be efficient, economical, environment-friendly, politically just and equitable, are not devoid of controversies and conflicts (Hunt et al., 2021; Martinez and Komendantova, 2020; Proka et al., 2018). Hence, there is a need to concentrate more on the developing world to evaluate the existing energy status, identify factors influencing end-users' behaviour, role and effectiveness of policy interventions and the functioning of the overall energy ecosystem. Thus, developing a renewable energy transition framework focused on the developing world is a significant contribution of this research. I demonstrate its application in a developing country, Nepal, as a case.

b. Need for a comprehensive renewable energy transition modelling framework: A holistic resource accounting and planning modelling framework considering the different components of society is extremely important for properly guiding the renewable transition process. Recent studies have mostly centered on technological advancement with the aim of discovering new types and increasing the efficiency of existing renewable energy sources/fuels and storage (Diezmartinez, 2021; Zhang et al., 2024). Furthermore, studies have revealed that in addition to technology, stable and comprehensive policies, well-coordinated inter-sectoral cooperation and state-industry co-relations along with capacity building and community acceptance are key factors contributing to effective clean energy transition (Bell, 2020; Carrington and Stephenson, 2018; Mohsin et al., 2021). Models considering societal factors impacting the transition have been developed. However, rather than considering these aspects in totality, most are focused on an isolated sector such as energy (Koengkan and Fuinhas, 2020; Raza et al., 2022), economics (Aniello et al., 2019), environment (Liu et al., 2020; Usman et al., 2024), market policy (McGreevy et al., 2021), and uncertainties of investment decision in the energy sector (Yunzhao, 2022; Zhao and You, 2021), among others. This leads to possible missing out on the inter-disciplinary impacts of the transition across different sectors (Usman et al., 2024). Moreover, the models/frameworks need to have the capability to test 'in-priori' the likely impacts of technological changes, economic decisions, and policies on the transition through scenario analysis considering local variables. This research has attempted to address this gap.

c. Bottom-up assessment of the impacts of climate change on renewable energy transition: Studies focused on the impacts of climate change on renewable energy transition are rather limited, compared to other aspects of energy (Bhattarai et al., 2022b). Moreover, climate change analysis has mostly been carried out using a top-down approach with global climatic datasets and boundary conditions (Bahn et al., 2019; Bointner et al., 2016; Creutzig et al., 2014; Millot et al., 2020; Sharma and Balachandra, 2019; Solaun and Cerdá, 2019). Although such assessments might be suitable for a larger geographical domain, there are high chances of bypassing local climatic conditions and associated impacts on the transition. This leads to the need for the application of a bottom-up approach for climate change impact studies, based on contextual climate information, how they are stressed, and possible adaptation and mitigation measures with societal acceptance to avoid future unwanted consequences. Even locally conducted studies, such as WECS/GoN (2013b), for example in Nepal, did not explicitly consider the impacts of climate change on energy systems nor did they carry out scenario analyses founded on social preferences.

Hence, taking the case of Nepal, this study contributes to the energy research in developing contexts in the face of climate change, using inclusive bottom-up methods.

1.3 Objectives and research significance

The focal question which orients this research is how an integrated methodological framework to model the renewable energy transition can be developed which is customizable to the local context and apply it to test plausible future transition scenarios. This leads to the requirement of a bottom-up approach in formulating the model. This framework is developed based on the findings of a global review whereas it has been applied to a developing country Nepal with a significant interplay between the different governing factors of renewable energy transition within the society which generic models cannot simulate adequately. In order to meet this overarching objective, the specific objectives of this study are:

1. To assess the baseline energy condition of Nepal considering its energy security and policy development

2. To apply the comprehensive modelling framework to Nepal and evaluate its energy supply- and demand-side scenarios until the mid of this century

3. To quantify the likely impact of climate change on the hydropower sector of Nepal

4. To recommend appropriate policy prescriptions for a sustainable renewable

energy transition of Nepal leading to long-term energy security

Paper #1 from this research is on global literature review providing the necessary background information for the development of the integrated methodological framework. Paper #2, Paper #3 and Paper #4 address objective 1. Consequently, Paper #5 and Paper #6 attends to objective 2 while Paper #7 and Paper #8 address the third objective of this research. Recommendations pertaininig to objective 4 is drawn from the findings of all the previous papers cumulatively.

1.4 Thesis structure

This thesis is organized in such a way that Chapter 1 sets the background of the research, articulates the problem statement, and establishes the objectives and significance of the study. Chapter 2 follows with a literature review pertinent to the research topics and also provides a brief description of the study area and the methodological overview of the research. Chapter 3 presents a published systematic literature review paper on the global renewable energy transition (Paper #1). Chapter 4 discusses about a composite indicator-based method developed to assess the energy security of Nepal (Paper #2). Chapter 5 is on the evolution of energy policy in Nepal (Paper #3), while Chapter 6 evaluates the historical impacts of donations and subsidies on Nepal's energy sector (Paper #4). Chapter 7 discusses how socio-economic factors influence the household energy behaviour in Nepal (Paper #5). Chapter 8 presents a comprehensive modelling of Nepal's energy sector considering both supply- and demand-sides using an energy planning model developed in LEAP (Paper #6). Chapter 9 explores the socio-economic and climate perception factors that affect household energy preferences of the country (Paper #7) while Chapter 10 quantifies the potential impacts of future climate change on Nepal's hydropower (Paper #8). Finally, Chapter 11 provides the overall research summary, highlights its contributions and acknowledges the limitations. This chapter also presents policy recommendations for a sustainable energy future of Nepal and suggests avenues for extension of this research. The report ends with a list of references.

CHAPTER 2: LITERATURE REVIEW

This chapter discusses the findings from contemporary literature on various aspects related to energy and renewable energy transition. In addition, I have separately published a systematic literature review paper, which is presented in Chapter 3. I have published seven additional papers included as chapters (Chapter 4 to Chapter 10) in this thesis which contain detailed literature review of the respective topics of research. Hence, this chapter is focused on providing an overarching literature review related to my research objectives.

2.1 General

It is an established fact now that renewable energy transition will not occur spontaneously – at local, regional, national or international levels (Johnstone et al., 2020). The diffusion of renewables has been identified as a fundamental action at global policy levels for sustainable development, which is in line with SDG 7 (affordable and clean energy). Although the magnitude of total energy consumption has increased between 2009 and 2019, the share of fossil fuels has remained almost in the same proportion (at about 75 to 80%) (REN21, 2024). Notably, Dietzenbacher et al. (2020) showed that renewable energy use has been found to increase by a rate of about 2.3% per year from 2000 to 2014 globally, the transition having a positive impact in Europe, USA and East Africa. Unfortunately, scholars warn that the current development in renewable energy technologies and existing efforts are not sufficient to considerably reduce the energy related emissions from fossil fuels and the consequent impacts (Nijsse et al., 2023; Murshed, 2021). Several factors can be attributed to influence the willingness and successful implementation of such an energy transition.

2.2 Factors affecting renewable energy transition

Studies have primarily identified technology, investment capacity, market, environment, government and institutional roles, policy instruments and regulatory frameworks, and social acceptance as the primary factors driving the renewable energy transition of a country or a region (Bhattarai et al., 2022b; Hurlbert et al., 2020; Mohsin et al., 2021). I have briefly discussed them in the subsequent sections.

2.2.1 Socio-economic setting

The energy sector impacts multiple disciplines and operates at various scales, ranging from households to national and regional levels (Mohsin et al., 2021; Nie et al, 2024). Distinct north-south disparities can be seen in the global energy landscape, primarily governed by variations in people's socio-economic conditions and energy behaviour (Ahmad et al., 2023; Bashir et al., 2024). For instance, Conradie et al. (2023) examined people's behaviour regarding space heating in Europe while Braito et al. (2017) assessed photovoltaic investment in Austria and Italy and concluded likewise. Similarly, adoption of renewable energy technologies at the household scale in Germany was studied by Jacksohn et al. (2019) and six Mediterranean countries by Strazzera and Statzu (2017). Tekler et al. (2022) presented a case study of acceptance of better energy technologies in the workplace in Singapore.

Such studies are clear indications that developed regions are better off economically and technologically with large investments being made in research and development in the energy sector (Shahzadi et al., 2021). The level of awareness is greater among the general public (Hussain et al., 2023), and they have convenient access to and can afford efficient energy appliances (Salari et al, 2021). Contrarily, developing countries suffer from poverty (Azhgaliyeva and Mishra, 2022), low levels of literacy and awareness (Cantarero, 2020), corruption (Bhattarai et al., 2023a) and limited energy choices from the state (Sanjel and Baral, 2021). That is why, these nations are massively reliant on traditional/conventional (mostly fossil and biomass) fuels in their generation mix while using energy inefficient appliances (Mukelabai et al., 2023). Hence, transitioning to cleaner and more efficient energy technologies are rather lean despite willingness and efforts (Hunt et al., 2021; Israel and Jehling, 2029; Maennel and Kim, 2018). As a result, developing countries are falling behind in their economic progression in the absence of sufficient energy supply and efficient usage (Gebreslassie et al., 2022).

2.2.2 Policy context

It is the primary role of the government to drive the renewable energy transition at the national level. Hence, setting achievable targets, developing the necessary infrastructure, carrying out institutional reforms, local capacity strengthening, awareness raising and implementing regulatory mechanisms are the major activities that the government needs to focus on (Mohsin et al., 2021; Lin and Omoju, 2017). And the starting point for providing impetus to the transition is the formulation of suitable policies to create a conducive environment for all the stakeholders. Studies in Europe share success stories of collaboration between government, industry and society through supportive policies (Adesanya et al., 2020; Pons-Seres de Brauwer and Cohen, 2020; Child et al., 2019). Likewise, Bayulgen (2020), Gottschamer and Zhang (2020) and Cantarero (2020) provide examples of efficient government -society synergy and institutional capacity building in the developing countries. However, scholars also warn against the existing policies that foster the use of fossil fuels which is further intensified by regional geo-politics and social poverty, particularly in the developing contexts (Gulagi et al., 2020; Müller et al., 2021).

Policies are guided by public demands. Although the implementation of policies follows a top-down approach, their formulation and regular revisions ideally require bottom-up trajectories to achieve the desired targets (Aryal et al., 2021; Wu, 2020). In the global north, the general public are usually involved in policy making (Hill and Connelly, 2018; Johnstone et al., 2020; Borozan, 2022). However, the case is different for the global south, in which the policy making process is typically dominated by influential groups, consisting mostly of politicians and elites, senior bureaucrats, supported by active involvement of non-government organizations and donors with little or no say of the general people (Aryal et al., 2021; Lohani et al., 2022). Involvement of civil societies, the private sector and general public to an extent of persuasion is rather theoretical (Liao et al., 2021), although legitimacy of the policies comes through the parliament (Aryal et al., 2022). This could significantly delay the development activities, which in turn could increase the disparity among the rich and poor, further limiting people's voice in policy making: leading to a vicious cycle (Hashemi, 2021, Sovacool et al., 2020). Moreover, Wittmayer et al. (2022) emphasizes the need for valuing the general public in policy making instead of only sectoral experts, state and international interventions.

Interestingly, policies might not always be as effective as they are desired to be. For instance, Tsvetanov (2019) shows that inappropriate policies might actually hinder solar PV penetration rather than encouraging it, taking the case of US. Likewise, taking the case of several developed countries, Pi et al. (2024) not only showed that energy efficiency has a leading role in attaining environmental sustainability but also highlighted the importance of green energy policies to ensure sustainable development. Additionally, studies underscore the roles of awareness, information dissemination (Matavel et al., 2023), and policy reforms (Ko, 2023) in promoting sustainable energy practices. Hence, identifying key actors in the policy development process and timely incorporating changes in the national level policies concurrent with the global and regional development allows for assessing and reacting to the contemporary needs for national benefits (Bhattarai et al., 2024b; Chen et al., 2023a). Thus, reviewing policy progression, acknowledging the achievements, and learning from the past to plan for future is a rational pathway of development.

2.2.3 Societal perceptions, preferences and energy behaviour

Studies have assessed the influence of human and social capital governed by societal factors in the energy transition (Liao et al., 2021; Roberts, 2020). Europe, particularly Germany, has made exemplary progress in civic participation in the energy system changes and decentralization with the concept of 'prosumers' (Bryant et al., 2019; Ahrens, 2017). In developing countries, shift towards community-ownership of renewable energy systems have been proven to be beneficial in the implementation of clean energy technologies (Bayulgen, 2020; Munro, 2019). However, scholars also highlight that social concerns such as equity and equality generally get overlooked in international technology transfers and donations from the developed to the developing world (Barbir, 2009). Moreover, newer energy technologies are definitely not the cheapest and might not be as efficient as they are claimed to be (Alonso-Fradejas, 2021; Hunt et al., 2021). These risk the transition efforts being compromised, particularly in the developing world. Additionally, points of friction could arise between the incumbent energy system regime, existing jobs and market, and the energy transition initiatives (Proka et al., 2018). Furthermore, scholars have recommended against 'assuming' social behaviour, particularly related to perception and adoption of new technologies, because of the highly dynamic interplay between different dimensions of the society (Martinez and Komendantova, 2020; Windemer, 2023). Hence, adequately incorporating societal perceptions, people's preferences of the energy transition and likely changes in the end-user energy behaviour across all economic sectors is a pressing need (Kim et al., 2018; Winkler et al., 2018). Therefore, testing of plausible future energy scenarios specific to the local context and making informed decisions are possible through the development and application of appropriate planning models.

2.3 Supply- and demand-side management with energy planning models

Scholars have recommended integrated analysis of supply- and demand-sides for effective energy planning (Butchers et al., 2020; Kurniawan et al., 2023; Shakya et al., 2023). Global practices show that diversifying the energy mix is the most logical approach to energy transition (Aryal and Dhakal, 2022; Bhattarai et al., 2022b). Studies have advised promoting hybrid technologies to tackle climate related challenges and variable load issues (Parag and Ainspan, 2019). On the demand side, increasing the access of the end-users to multiple clean energy technologies as well as increasing the efficiency of energy use across all sectors have been recommended (Shakya et al., 2023). Moreover, Sovacool et al. (2018) points out that the social dimension of energy has not got the necessary attention compared to the other hard disciplines such as science and engineering in energy research.

Different types of energy planning models have been used in various parts of the world to efficiently plan the energy transition. Increase in the development of models has been primarily attributed to multiple factors such as convenient access to numerous global energy databases (e.g., IRENA, EIA Outlook, BP Energy Outlook and WIOD), refined expertise and technology, and advancement of the computing capabilities in terms of hardware and software over time (Solé et al., 2020; Zhao and You, 2021). These models vary in their applicability depending upon the data availability, spatial disaggregation of the supply and demand entities, top-down/bottom-up approaches, and other factors. Many top-down approaches, such as computable general equilibrium and econometric models consider exogenous inputs from macroeconomic variables to calculate the energy demands (Indra Al Irsyad et al., 2017). On the other hand, bottom-up models such as Energy Flow Optimization Model (EFOM), Low Emissions Analysis Platform (LEAP) (McPherson and Karney, 2014), MAED-MARKet Allocation (MARKAL) (Nakarmi et al., 2016), and The Integrated MARKAL-EFOM System (TIMES) (Aryal and Dhakal, 2022), consider endogenous inputs.

Energy planning models can be broadly categorized into five types based on their theoretical consideration and structure: Regressive transition models, General economic analysis models, Energy market models, Energy system models, and Decision-making models and frameworks (Ali Raza et al., 2020; Jiang et al., 2021). They differ in multiple aspects such as parameterization of the real-world variables, assumptions and limitations, modular structure, modelling procedures, input/output data types and formats, and visualization capabilities (Solé, et al., 2020). Machine learning models have also become popular in recent times in the energy modelling domain (Mukelabai et al., 2023; Yao et al., 2023).

One such popular comprehensive model is the Low Emissions Analysis Platform

(LEAP; originally the Long-range Energy Alternatives Planning system) developed by the Stockholm Environment Institute (SEI), USA. LEAP is an integrated, scenario-based modelling tool that can be used to track energy consumption, production and resource extraction as well as GHG emissions in all sectors of an economy (Shakya et al., 2023). It has been used to model the techno-economic energy systems in different parts of the world (Amo-Aidoo et al., 2022; Liya and Jianfeng, 2018; Mirjat et al., 2018; Su and Urban, 2021). LEAP has been applied for energy planning in more than 190 countries, out of which 37 have used it to help develop their NDCs (SEI, 2022).

In the case of Nepal, MARKAL energy systems modeling framework was used by the Government of Nepal to generate a long-term energy plan until 2050 (WECS/GoN, 2013b). Likewise, Aryal and Dhakal (2022) applied the TIMES modelling system to examine the end-use electrification and regional electricity sharing prospects for Nepal. Such models are based on techno-economic analyses for scenarios development and simulation. However, the model lacks dedicated social and climate change analysis components.

The *pymedeas* model (Solé et al., 2020) is another recent addition to the energy modelling domain. It has capabilities of identifying the key physical variables for the energy transition and their relationships with other sectoral-indicators and environmental impacts. It also allows testing of scenarios representing technological changes, finance and the environment (Solé et al., 2018). The model has been developed for Europe, but has provisions for customization at the country or world level. It is an open-source system and builds on the WIOD database. Studies using this modelling framework generally use top-down approach for simulating climate change impacts on the energy transition based on the Shared Socioeconomic Pathways (SSPs) of IPCC (Masson-Delmotte et al., 2019; Solé et al., 2020).

A vast majority of past model-based studies are either focused on a particular energy sector (Dhaubanjar et al., 2019; Pokhrel et al., 2021; Shrestha et al., 2017) or find global and regional applications (Jiang et al., 2021; Koengkan and Fuinhas, 2020; Mohsin et al., 2021). Additionally, most are based on a top-down approach and make use of global datasets and international boundary conditions making them less suitable for local application. Only some models have the capability of analyzing impacts of climate change on the energy transition but again, using global climate data. Therefore, this study aims to address these issues in the developed modelling framework.

2.4 Energy-related emissions, climate change and the transition

Global energy-related carbon emissions amounted to a new record high of 37.4Gt CO_2e, coal contributing to more than 65% of the increase in 2023 (IEA, 2023a). Studies have indicated that energy-related emissions are the largest contributor to environmental degradation, including climate change (IPCC, 2021).

Climate change has been seen as an overarching problem exacerbating the stress on all sectors, including energy (Ali Raza et al., 2020; Jiang et al., 2021). The Himalayan region is more prone to the impacts of changing climate (Chauhan et al., 2023; Lutz et al., 2022), including Nepal (Bhattarai et al., 2022a; Kaini et al., 2020; Marahatta et al., 2022; Shrestha et al., 2021). Changing temperature, alteration in precipitation patterns and other climatic parameters will most likely have a direct impact on the sources of energy in the future. Further, rise in temperature leads to an increased energy demand for cooling systems and decrease in the efficiency of thermoelectric plants (Marczinkowski and Barros, 2020; Ringkjøb et al., 2020). Also, irrigation and domestic water demands will rise requiring additional energy to meet these increases (McEwan, 2017). Quantifying these anticipated impacts and identifying evidence-based remedial measures are important to attain the SDG 13: climate action (UN, 2020). Moreover, the 2015 Paris COP 21, a global consensus, proposed that the average global warming be kept below 1.5 to 2°C to avoid the irreversible threat to environmental, economic, social and political challenges by climate change for years and decades to come. Further, the sixth assessment report by IPCC (AR6) has recommended limiting global warming to 1.5°C in order to significantly reduce the risks and impacts of climate change (Masson-Delmotte et al., 2019).

Energy and climate studies usually generate plausible scenarios based on predefined global boundary conditions for simulating the impacts of climate change on different sectors (Alimi et al., 2017; Dhaubanjar et al., 2020; Pandey et al., 2021; Solé et al., 2020). Broadly, two approaches of climate change assessment are common in literature: top-down and bottom-up. The top-down approach follows an 'ex ante' method (Ray and Brown, 2015) and uses general circulation models (GCMs) / regional climate models (RCMs) to predict future climate and make assessments comparing these predictions with a historical baseline. However, due to the coarse resolution of GCMs/RCMs, downscaling for smaller specific areas of interest with bias-correction is needed (Adachi and Tomita, 2020; Tapiador et al., 2020). Moreover, these models and data demand large computational power. With the increase in (hardware and software) computational capabilities and development of complex physically-distributed and data-driven models, use of the top-down approach has gained popularity in recent times (Brown et al., 2019; Ray et al., 2018b). Artificial neural networks, smooth support vector machines, adaptable random forests and other machine learning methods have now found application in bias correction of climate data recently (Keller et al., 2022). However, a major drawback this method faces is that for the same area, different GCMs/RCMs predict completely different climate futures, with limited certainty on the likelihoods of their occurrences. Moreover, this approach may be satisfactory at the regional level, but the identification of short-term and long-term impacts and provisioning their mitigation measures pertaining to the local context of the energy transition are less impactful.

On the other hand, the bottom-up approach follows an 'ex post scenario development' method (Ray and Brown, 2015). This method follows the notion that climate change is a global phenomenon, but the impacts are highly local in nature. In this approach, future climatic variability range of a study area is first ascertained using observed historical data, primarily based on the recommendations of past climate change studies. Climatic data is then generated using an appropriate algorithm; stochastic weather generators are mostly used (Steinschneider et al., 2019). Stochastic weather generators are computationally efficient for investigating climate stress and their sectoral impacts (Steinschneider and Brown, 2013; Shrestha and Basnyat, 2019). These models are parameterized based on existing meteorological records which are then used to generate large ensembles of weather records that are similar to but not bound by variability in past observations (Brown et al., 2019; Ray and Brown, 2015). Such generated data is then used in other energy planning models to assess the impact of climate change on the overall energy systems.

In the case of Nepal, short-, medium- and long-term national energy visions were the outcomes of a study in the beginning of the last decade considering low, medium and high economic growth scenarios combined with policy mixes (WECS/GoN, 2013a; 2013b). The National Climate Change Policy of Nepal has encouraged research on climate change focused studies having cross cutting impacts (GoN, 2019). A study by the Department of Hydrology and Meteorology (DHM), Nepal (DHM/GoN, 2017) estimated a historical increase (1975-2014) in the annual maximum temperature at the rate of 0.056°C/year. It also shows that the minimum temperature trend is increasing at the rate of 0.02°C/year. The National Adaption Plan was prepared by the Government of Nepal in 2019 to help safeguard all the sectors most likely to be impacted by climate change (MoFE/GoN, 2019). It was based on simulation results using IPCC CMIP5 GCM datasets for two RCPs (4.5 and 8.5). The altered climatic conditions in the future are expected to impact different developmental sectors, such as water, energy, disaster management, biodiversity, agriculture, health, urban planning and livelihoods. However, it also mentions that the predictions have a large amount of uncertainty.

"Decision Tree" is an emerging concept of bottom-up approach in climate studies mostly related to the water resources sector (Brown et al., 2019; Ray et al., 2018a, 2018b) with encouraging results. It finds its application in selected hydropower projects of Nepal (WB, 2015) using local weather generators such as that developed by Shrestha and Basnyat,(2019). However, this method has limited application in renewable energy transition and planning at the national level. This pioneer study aims to contribute to this research gap by modelling the renewable energy transition process of Nepal using a comprehensive bottom-up modelling framework with multi-disciplinary components.

2.5 Study Area: Nepal

This study has been carried out in Nepal. Specific details of the study area are discussed in the individual papers (Chapter 4 to Chapter 10). An overarching overview is provided in this section.

Nepal is a mountainous country situated in the central Himalayan region land-locked between India and China, with an area of 147,516 km^2 and a population of about 30.4 million (CBS, 2021) (Figure 2.1). Nepal can be broadly categorized into four distinct physiographic regions: mountains, high hills, mid hills, and the Terai plains. However, there is almost no human habitat in the mountain region (around above 3,000 meters above sea level, masl) largely owing to its rugged terrain and harsh climatic conditions. Regions above 4,000 masl have permanent snowline where the temperature is below freezing throughout the year, making it almost impossible for human settlements. Moreover, access to these areas is extremely difficult. Nepal has a complex terrain with many glaciers, rivers, valleys, and lakes (Mool et al., 2001). The country's high topographic gradient is demonstrated by the variation in elevation from 60 to 8,848 masl (Mt. Everest) within an average aerial distance of less than 200 km in north-south direction (Baniya et al., 2023). There is a large climatic variation in Nepal: from sub-tropical in the southern Terai plains to alpine in the northern mountainous region (DHM/CCAFS, 2013).

With a GDP of 41.39 billion USD (in the fiscal year, FY 2022/23), Nepal has a very small economy that makes up only 1% of South Asian and 0.04% of the global economy (WB, 2024). In the FY 2022/2023, Nepal's total energy consumption was 14.943 million tons of oil equivalent (toe) (WECS/GoN, 2023). The energy mix included traditional sources (firewood, agricultural residue, and dry dung for direct combustion, 64.2%), commercial sources (petroleum, coal, and grid electricity, 33.3%), and other off-grid renewable sources (micro-hydro, solar, and biogas, 2.5%) (WECS/GoN, 2023). Fossil fuel imports largely outnumber domestic energy gener-

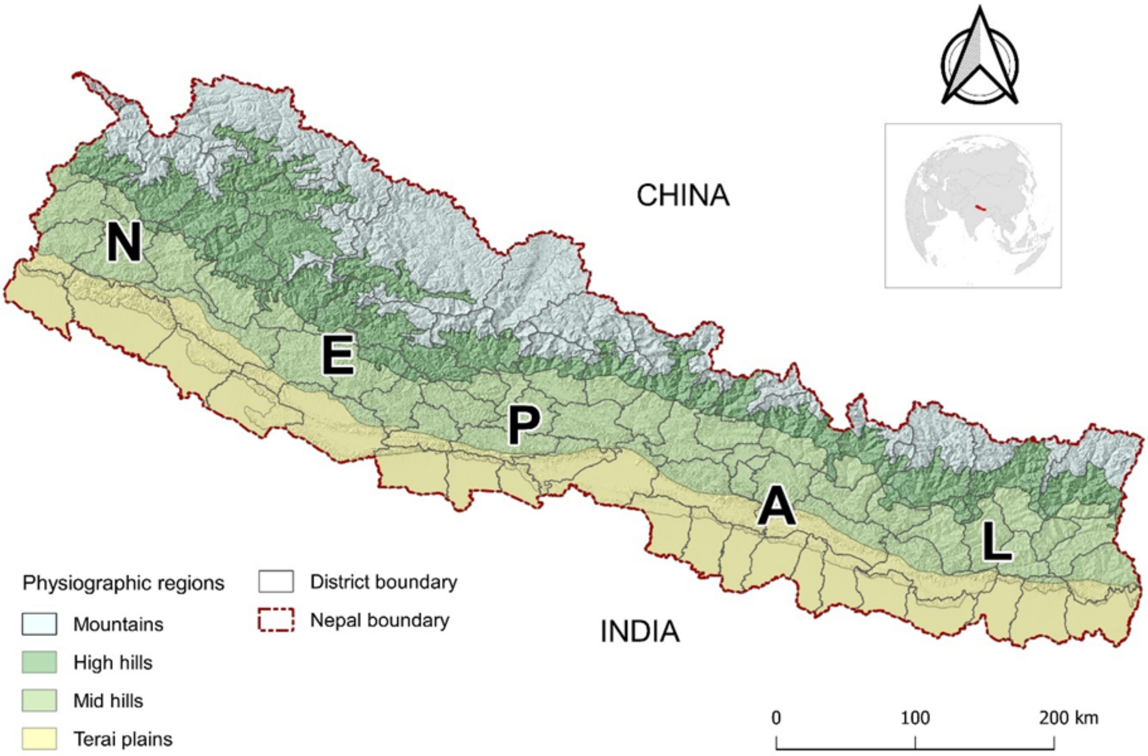

Figure 2.1: Geographical setting of Nepal

ation of Nepal. It imported about US$ 2.46 billion worth of fossil fuels (17.3% of the country's total import) from India in 2021/22, the largest amount being spent on diesel (DoC/GoN, 2023). This amounts to more than 6% of the country's annual GDP with Nepal's share of imports accounting for 91% of total trade (DoC/GoN, 2023). Furthermore, annual electricity consumption of the country was 6,789 GWh with a peak demand of 1,870 MW in the FY 2022/23 (MoF/GoN, 2023; NEA/GoN, 2023). The total national installed power capacity was 2,666 MW, with contributions from large hydropower projects (2,499 MW), solar (75 MW), thermal (53.4 MW), smaller renewables (82 MW), and co-generation from sugar mills (6 MW) (MoF/GoN, 2023). Nepal imported 1,855 GWh from India throughout the year and exported 1,333 GWh (about 72% of imports) also to India from June to October (NEA/GoN, 2023).

2.6 Methodological overview

This study develops a comprehensive multi-layered modelling framework integrating technical, socio-economic and people's perceptions influencing the renewable energy transition in the face of climate change. The overall research methodology adopted in this study is presented in Figure 2.2. Individual methodologies of each chapter (3 to 10; paper# 1 to 8) are given in the respective chapters while an overview is presented here.

The overarching research methodology applied for the development of an integrated framework consists of several intertwined components comprising of: global review of literature, policy review, energy security assessment, social perceptions through primary data collection and machine learning, energy modelling, hydrological modelling, hydropower generation and climate change impact assessments using a bottom-up method. An extensive global review of literature was carried out in the first part of the study to assess problems associated with the existing energy generation mix and the need for accelerated renewable energy transition. Additionally, historical evolution of renewable energy transition was also examined. Drivers of change, extent of their impact, obstacles to the transition and the global attempts to overcome the difficulties were explored. The findings were published in Paper #1 (Chapter 3) of this research. The renewable energy transition framework was then developed based on the findings of the review. It incorporates the dynamics between the different technical, social, economic and geo-political components that define the energy transition of a country. This framework has a wider general applicability. However, in this study, it has been applied to examine the past and current status of the energy sector of Nepal and also to evaluate likely future changes in its supply and demand sides including the impacts of climate change.

The next step consisted of establishing the baseline of the current energy status of Nepal. An *Energy Security Composite Index of Nepal (ESCOIN)* was developed to assess the energy security of the country. Additionally, Nepal's energy policies from the last forty years were reviewed with an aim to assess the policy development

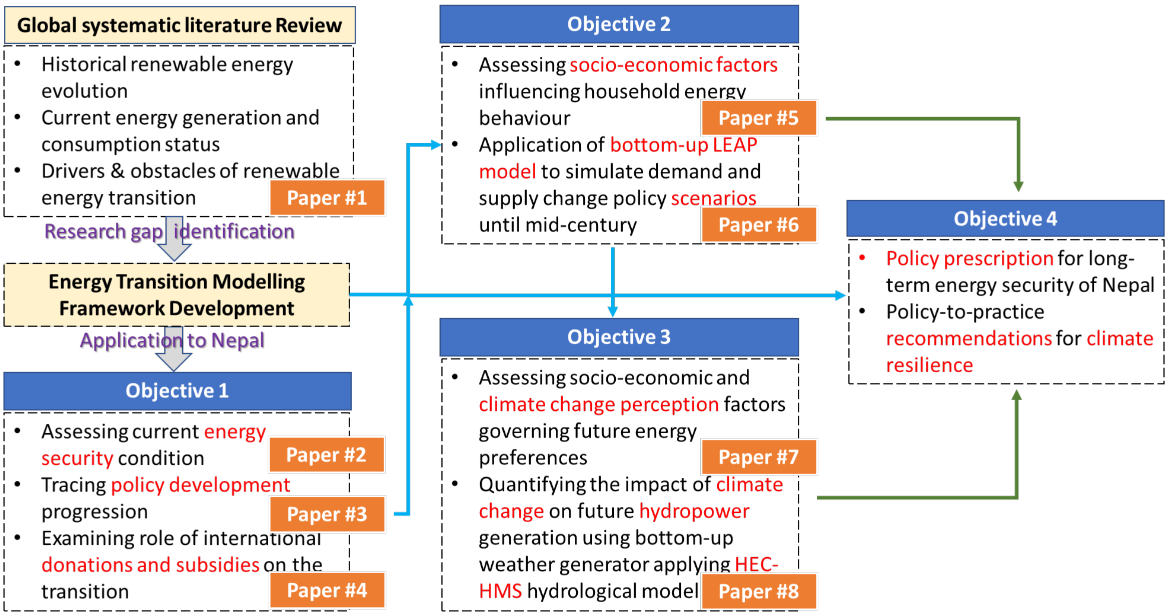

Figure 2.2: Flowchart of the overall research methodology adopted in this study

trajectory including its achievements and shortcomings. This was followed by examining the roles of international donations and government subsidies in the renewable energy transition of Nepal. This marked the achievement of the first objective of the research leading to the publication of three papers (Paper# 2, Paper# 3 and Paper# 4).

The subsequent step consisted of understanding the socio-economic factors across different locations and social strata influencing their energy perceptions at the household level through the application of machine learning on primary data from across Nepal. This information was helpful in setting up the energy planning model for Nepal in LEAP by meticulously including the supply- and demand-side conditions, energy-related emission estimates and incorporating public perceptions and opinions in energy planning. This model was simulated for multiple future scenarios envisioned by energy policies of Nepal and the changing socio-economic contexts. This marked the completion of the second objective of the research leading to two papers (Paper# 5 and Paper# 6 – under fifth round of review).

Identifying the influential socio-economic and climate change perception factors on future energy preferences at the household level was the next step in the workflow.

This information was useful in understanding the generation- as well as demand-side concerns of the residential energy sector. Hydrological modelling of Nepal was then carried out in the Hydrologic Engineering Center Hydrologic Modeling System (HEC-HMS) model to evaluate how the water availability is likely to be altered for hydropower production under future climatic conditions. These activities marked the completion of the third objective with the publication of two research papers (Paper# 7 and Paper#8 – under second round of review). Finally, the fourth objective was achieved by providing comprehensive policy recommendations on the renewable energy transition for Nepal based on the findings of the entire research cumulatively.

2.7 Assumptions and Limitations

This study inherently possesses certain limitations characteristic of a PhD research. Specifically, the available research resources, including (primary and secondary) data and the duration allocated for the study, as well as the academic requirements attached to the PhD, impose certain constraints. Additionally, several assumptions underpin this research, particularly regarding the data, methods and analysis. Each chapter (paper) of this thesis explicitly lists the assumptions and limitations pertinent to the respective study. Moreover, the concluding chapter of this report (Chapter 11) outlines the overall limitations and presents technical, policy, and future research recommendations aimed at addressing and potentially overcoming the limitations and challenges identified in this research.

CHAPTER 3: PAPER 1 – ASSAY OF RENEWABLE ENERGY TRANSITION: A SYSTEMATIC LITERATURE REVIEW

3.1 Introduction

This paper (Paper #1) explores the overall global knowledge-stock on renewable energy transition using a Systematic Literature Review method. In this paper, I have provided a comprehensive perspective on the factors that encourage and hinder the transition globally and how the disparities across the global north and south impact it differently.

3.2 Published paper

3.3 Links and implications

From this paper, I find that the developed countries are leading the renewable energy transition research while the developing world is far behind. I show that transitioning to renewables effectively and sustainably demands participatory bottom-up approaches, promoting local technologies, devising and implementing robust policy mixes and giving due consideration to the local specificities. Furthermore, I find the need of a strong global north-south collaboration to minimize the risk of the transition being compromised at the local, national, regional and global levels. Moreover, accurate estimations and projections of energy demands, energy generation resources accounting and proper infrastructure development, from the activity levels to the national level, guided by supportive policies is key to a successful transition. These aspects hold even more importance in developing countries, such as Nepal.

CHAPTER 4: PAPER 2 – A COMPOSITE INDICATOR-BASED METHOD TO ASSESS THE ENERGY SECURITY OF NEPAL AND PROSPECTS OF CROSS-BORDER ELECTRICITY SHARING IN SOUTH ASIA

4.1 Introduction

This paper (Paper #2) sets the baseline for understanding the current energy status of Nepal. To make a quantitative assessment of the energy sector of Nepal, I developed a new *Energy Security Composite Index of Nepal (ESCOIN)* applying a comprehensive indicator-based approach and considering multiple influential factors sourced through literature review which were customized based on the local context of the country. This paper directly contributes to the first objective of my research.

4.2 Published paper

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A composite indicator-based method to assess the energy security of Nepal and prospects of cross-border electricity sharing in South Asia

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ABSTRACT

Scholars recommend country (or region) specific energy security indices capable of adequately considering local specificities in the absence of a 'universal' index. Such an index is not available for Nepal. Hence, this study is the first to develop the *Energy Security Composite Index of Nepal (ESCOIN)*, applying a comprehensive indicator-based approach to quantify energy security (ES) of Nepal. We build upon the notion that a country is able to trade energy when it is energy secure. We quantify Nepal's energy security and qualitatively assess the prospect for regional power trade in South Asia. A long list of 77 indicators is compiled from an extensive review of international literature. Based on the context, applicability to Nepal, data availability and conditions of multicollinearity, this list of indicators is narrowed down to 21. Principal Component Analysis is then applied to evaluate the importance of the components for *ESCOIN*. Our results show that Nepal has consistently held a boundary position between "moderate" to "high" classes of ES in the last decade. We identify key reasons for this. First, the country's domestic sector is over-reliant on traditional fuels (dry-dung, firewood and agricultural residues). Second, Nepal faces a problem of suppressed demand in the absence of energy-intensive development activities in all productive sectors of the economy. Third, the growth in the energy demand is met only marginally by domestic hydropower and other renewables, and largely by increasing imports. Hence, we surmise a 'pseudo energy secure' state for Nepal. Although efforts are underway, electricity trade with China, Bangladesh and other South Asian Association for Regional Cooperation (SAARC) countries is economically difficult and technically challenging. Hence, cross-border electricity trading, particularly with India, can be seen as an opportunity for Nepal provided considerable infrastructural development occurs, institutional capacity is strengthened, and genuine political commitment and trust are sustained. Moreover, Nepal should focus on achieving self-sufficiency in energy through domestic hydropower and renewable sources and aim to stabilize energy consumption rather than being overly ambitious of exports, at least in the near future.

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1. Introduction

1.1. Background

This paper is focussed on the quantification of energy security (ES). We build upon the notion that a country/region is able to trade its surplus energy when it is energy secure (Huda and Ali, 2018; SARI/EI, 2020). Researchers have explored a variety of energy-related topics, including its security (Gasser 2020; Le et al., 2019; Radovanović et al., 2017), in response to Sustainable Development Goal 7 of the United Nations, which is to "ensure access to affordable, reliable, sustainable, and modern energy for all" (UN, 2020). Moreover, Global North-South disparities are prevalent in the energy sector with regards to their economic conditions, research capabilities, implementation of advanced technologies and sustainability (Bhattarai et al., 2022b; Dominguez et al., 2021; Weko and Goldthau, 2022), ultimately impacting ES.

To tackle the issue of rising global energy (in)security, recent studies have emphasized the necessity of fair cooperation between developed (donor) and developing (recipient) countries by sharing the unevenly distributed resources for a sustainable energy future (Bhattarai et al., 2023b,c; Pandey et al., 2022; SARI/EI, 2021). The Association of Southeast Asian Nations (ASEAN) Power Grid (Aris and Jørgensen, 2020; Li et al., 2020), Southern African Power Pool (SAPP) (SAPP, 2021), Greater Mekong Subregion (GMS) (ADB, 2009), Gulf Cooperative Council (GCC) countries (Reiche, 2010), West Africa Power Pool (WAPP) (WAPP, 2021), Azerbaijan-Georgia-Turkey (AGT) Power Bridge Project (USEA, 2012) are some prominent examples globally.

1.2. Quantification of energy security

Energy security (ES) has been defined in different ways. For instance, the International Energy Agency (IEA) describes ES as "uninterrupted availability of energy sources at an affordable price" (IEA, 2021). The World Bank's definition is "ensuring that countries can produce and use energy sustainably at reasonable costs" (WB, 2013). Likewise, the World Energy Council (WEC) defines it as "a nation's capacity to meet current and future energy demand reliably, withstand and bounce back quickly from system shocks with minimal disruption to supplies" (WEC, 2021). In our study, we consider ES to provide a measure of how well a geographic region (country or group of countries) is able to meet the energy demands in a sustainable way without compromising on other socio-economic, geo-political and environmental sectors.

Indicator-based methods are popular in quantifying ES at various geographical domains, including the global level (Jewell et al., 2014), the EU (Radovanović et al., 2017), Asia (Le et al., 2019), the Baltic region (Zeng et al., 2017), and China (Gong et al., 2021), among others. The general methodology of these approaches entails the identification of an extensive list of indicators (usually through literature review), assignment of appropriate weights/scores, and bottom-up aggregation of those indicators into a composite index. Additionally, depending on particulars of the study area, researchers have named these indices differently, such as Energy Security Index of Pakistan (ESIOP) by Abdullah et al. (2021), Singapore Energy Security Index (SESI) by Ang et al. (2015a), Aggregated Energy Security Performance Indicator (AESPI) by Martchamadol and Kumar (2014), Energy Insecurity Index for Asia by Le et al. (2019), and Geopolitical Energy Supply Risk Index (GESRI) by Muñoz et al. (2015), among others. They all essentially quantify the energy situation of a geographic area although they may vary in their choice of the governing indicators and weights. Drawing on an extensive review of these methods (Appendix Table A1), the details of the variables and indices applied in each case are summarized in Table 1.

1.3. Regional power trading in South Asia

Asia is largely dependent on fossil fuels with very little chance of a significant change in the foreseeable future (IEA, 2021). The world's fastest-growing region, South Asia, is also one of the least integrated (Tripathi, 2020). Fig. 1 provides an annual energy snapshot of South Asia to set the context of our study. This study is on Nepal - a developing country in South Asia surrounded by two energy super-powers, China and India. China is the largest energy consuming nation (43,791 Tera-Watt-hours, TWh annually), followed by India (9841 TWh) (Fig. 1) while Nepal compares very low (44 TWh) among others in this region (Ritchie et al., 2023; World Bank, 2024). Fossil fuels accounted for 28% of Nepal's total energy consumption, whereas they accounted for 70% or more in all the other nations except Bhutan (18%) in 2021. China and Bhutan had comparable per capita energy consumption rates of 30,711 kWh and 29,171 kWh, respectively while that of Nepal was 1608 kWh in 2021 (Ritchie et al., 2023); current electricity consumption of Nepal is 305 kWh per capita (WECS/GoN, 2023). Afghanistan and the Maldives respectively have the highest (11,781 current US$) and lowest (355.8 current US$) per capita GDPs in this region (Ritchie et al., 2023; World Bank, 2024). The 2022 per capita GDP of Nepal was 1336.5 (current US$) which is equivalent to nearly ten percent of the per capita GDP of China and half of India (World Bank, 2024).

Interestingly, a recent study shows that two-thirds of the untapped global hydropower potential is in the Himalayas (Xu et al., 2023) among which Nepal has a significant potential contribution (Baniya et al., 2023; Gyanwali et al., 2020; Zou et al., 2022). South Asia's total hydroelectricity potential is estimated to be around 350 GW (SARI/EI, 2017). The economically feasible hydroelectricity potential of Nepal and Bhutan is enormous: 43,000 MW (Sharma and Awal, 2013) and 32,000 MW (Tripathi, 2020), respectively. Therefore, India's interest in generating and importing electricity from these two neighbours is logical (Tripathi, 2020). Efforts of regional cooperation have been initiated in the past. The Bay of Bengal Initiative for Multi-Sectoral Technical and Economic Cooperation (BIMSTEC), South Asian Free Trade Area (SAFTA), South Asia Forum for Infrastructure Regulation (SAFIR), Bangladesh, Bhutan, India, Nepal (BBIN), and other regional initiatives have promising and ambitious roles in cross-border energy sharing

Table 1
Long list of indicators for the quantification of energy security of Nepal (Abdullah et al., 2021; Ang et al., 2015a; Bompard et al., 2017; Erahman et al., 2016; Gong et al., 2021; Huang et al., 2021; Iyke et al., 2021; Le et al., 2019; Li et al., 2016; Martchamadol and Kumar, 2013; Martchamadol and Kumar, 2014; Nag, 2021; Narula and Reddy, 2016; Narula et al., 2015; Podbregar et al., 2020; Radovanović et al., 2017; Radovanović et al., 2018; Ren and Sovacool, 2014; Sharifuddin, 2014; Šimić et al., 2021; Sovacool and Mukherjee, 2011; Sovacool, 2013; Vivoda, 2010; Wang and Zhou, 2017; Xu and Ni, 2017; Zeng et al., 2017).

S.N	Indicators	Abdullah et al. (2021)	Ang et al. (2015a)	Bompard et al. (2017)	Erahman et al. (2016)	Gong et al. (2021)	Huang et al. (2021)	Iyke et al. (2021)	Le et al. (2019)	Li et al. (2016)	Matchamadol and Kumar (2013)	Matchamadol and Kumar (2014)	Nag (2021)	Narula and Reddy (2016)	Narula et al. (2017)	Podbregar et al. (2020)	Radovanović et al. (2017)	Radovanović et al. (2018)	Ren and Sovacool (2014)	Sharifuddin (2014)	Šimić et al. (2021)	Sovacool and Mukherjee (2011)	Sovacool (2013)	Vivoda (2010)	Wang and Zhou (2017)	Xu and Ni (2017)	Zeng et al. (2017)	**Applicable to Nepal**	**Data Availability**
	A. Availability																												
1	Total primary energy supply per capita	✓			✓	✓	✓	✓			✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓			
2	Total energy consumption per capita	✓			✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		*	#
3	Share of the total population with access to basic energy												✓		✓					✓		✓		✓					
4	Electricity consumption per capita	✓	✓	✓		✓					✓	✓			✓			✓		✓		✓		✓	✓	✓		*	#
5	Electricity consumption per household	✓									✓	✓							✓	✓		✓		✓	✓			*	#
6	Share of the total population with access to electricity (ratio)				✓						✓	✓	✓		✓				✓	✓		✓	✓	✓	✓			*	#
7	Ratio of total energy reserve to production	✓			✓		✓				✓	✓		✓		✓				✓		✓	✓	✓	✓				
8	Ratio of reserve to production of oil	✓			✓		✓				✓	✓		✓		✓				✓		✓	✓	✓	✓				
9	Ratio of reserve to production of gas	✓			✓		✓				✓	✓		✓		✓				✓		✓	✓	✓	✓				
10	Ratio of reserve to production of coal										✓	✓		✓		✓				✓		✓	✓	✓	✓				
11	Share of renewable energy in total energy consumption	✓						✓	✓		✓	✓	✓	✓			✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	*	#
12	Total unmet energy demand as a ratio of the total energy consumption	✓						✓						✓								✓		✓		✓		*	#
	B. Sectoral Consumption																												
13	Share of transportation energy in total energy consumption	✓											✓							✓		✓		✓				*	#

14	Energy consumption in transportation sector per capita	✓	✓																	✓		✓		✓				*	#
15	Energy consumption in the domestic sector per capita	✓																		✓		✓		✓				*	#
16	Energy consumption in the domestic sector per household	✓									✓	✓								✓		✓		✓				*	#
17	Share of oil use in transportation of the total oil consumption	✓											✓									✓		✓				*	
	C. Economics																												
18	Gross domestic product (GDP) per capita	✓				✓	✓						✓				✓	✓			✓	✓		✓	✓	✓		*	#
19	Energy intensity (total energy per GDP)		✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	*	#
20	Net Energy Import Dependency (NEID)	✓	✓								✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	*	#
21	Share of energy import in the total energy consumption	✓		✓			✓	✓	✓	✓			✓		✓		✓	✓	✓	✓		✓	✓	✓	✓		✓	*	#
22	Gasoline price per litre	✓	✓		✓	✓							✓	✓		✓			✓	✓		✓	✓	✓	✓	✓		*	#
23	Diesel price per litre	✓	✓		✓	✓							✓	✓		✓			✓	✓		✓	✓	✓	✓	✓		*	#
24	Natural gas price		✓		✓								✓	✓		✓			✓	✓		✓	✓	✓	✓	✓		*	#
25	Electricity price per kWh		✓		✓	✓							✓	✓		✓		✓	✓	✓		✓	✓	✓	✓	✓		*	#
26	Transportation sector energy intensity										✓	✓	✓		✓					✓		✓		✓				*	#
27	Industrial sector energy intensity										✓	✓	✓		✓					✓		✓		✓				*	#
28	Commercial sector energy intensity	✓									✓	✓	✓		✓					✓		✓		✓				*	#
29	Agricultural sector energy intensity	✓									✓	✓	✓		✓					✓		✓		✓				*	#
30	Share of national income towards energy						✓				✓	✓	✓			✓						✓		✓		✓		*	
31	Investment in energy with private partnership						✓															✓				✓		*	
32	Energy cost as a percentage of manufacturing and operating cost		✓			✓	✓						✓									✓		✓		✓		*	
33	Ores and metal exports												✓									✓							
34	Energy exports	✓		✓			✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓			*	
	D. Technology																												
35	Share of electricity in total energy consumption									✓	✓	✓	✓						✓	✓		✓	✓	✓	✓			*	#
36	Transportation and distribution losses in electricity	✓			✓				✓	✓	✓	✓	✓	✓								✓	✓	✓				*	#
37	System Average Interruption Duration Index (SAIDI)		✓																			✓						*	
38	System Average Interruption Frequency Index (SAIFI)		✓																			✓						*	
39	Electricity generation efficiency		✓										✓	✓	✓				✓			✓	✓	✓	✓			*	
40	Electricity load factor		✓																			✓							
41	Total losses in the total energy supply	✓		✓	✓						✓	✓			✓				✓			✓	✓	✓	✓			*	
42	Average age of infrastructure																		✓			✓						*	
43	Reliability of electricity supply												✓						✓			✓		✓				*	
44	Potential of renewable energy generation	✓									✓	✓	✓	✓								✓						*	#
45	Share of indigenous energy in total energy consumption				✓					✓			✓						✓			✓	✓	✓				*	#
46	Share of oil consumption met locally						✓						✓									✓		✓					
47	Share of oil consumption met by imports						✓						✓									✓		✓				*	#
48	Share of gas consumption met locally						✓						✓									✓		✓					
49	Share of gas consumption met by imports						✓						✓									✓		✓				*	#
50	Share of hydropower in total electricity generation	✓					✓															✓		✓				*	#
51	Share of non-hydro renewables in total electricity generation						✓						✓									✓		✓				*	#
52	Share of nuclear energy in total electricity generation						✓						✓				✓	✓				✓	✓	✓					
53	Total thermal efficiency of electricity and heat plants						✓			✓												✓		✓				*	
54	Share of local generation in total energy consumption				✓	✓	✓															✓		✓				*	
55	Percentage of clean fuels in the total energy consumption		✓				✓	✓	✓	✓	✓	✓	✓									✓		✓				*	#
56	Oil and well exploration	✓											✓									✓							
	E. Governance																												
57	Political stability																		✓			✓		✓	✓			*	
58	Corruption ranking of the country	✓																	✓			✓			✓			*	
59	Government effectiveness index	✓																	✓			✓	✓		✓			*	
60	Regulatory quality and rule of law																		✓			✓		✓	✓			*	

61	Sovereign Credit Rating																✓	✓			✓							*	
62	Time required to obtain permanent connection to electricity														✓							✓			✓			*	
63	Oil rent as a share of GDP	✓																				✓						*	
64	Gas rent as a share of GDP																					✓						*	
65	Total natural resources rent as a share of GDP																					✓						*	
66	Stock of oil as a percentage of total oil consumption	✓											✓							✓		✓	✓	✓				*	
67	Stock of oil as a percentage of total energy import												✓							✓		✓	✓	✓				*	
68	Net fuel reserve as a share of total energy consumption	✓	✓										✓							✓		✓	✓	✓				*	
	F. Environment																												
69	Total carbon emission from the total primary energy consumption		✓		✓	✓	✓	✓						✓					✓	✓		✓		✓		✓		*	#
70	Carbon emission per capita	✓				✓			✓		✓	✓	✓		✓					✓		✓	✓	✓		✓		*	#
71	Carbon footprint of electricity generation								✓													✓	✓	✓				*	#
72	Carbon emission per household												✓		✓							✓		✓			✓	*	#
73	Carbon emission per GDP		✓						✓	✓	✓	✓	✓									✓		✓			✓	*	#
74	Carbon intensity					✓			✓				✓	✓	✓		✓	✓				✓		✓	✓	✓	✓	*	#
75	Energy-related carbon emission per capita		✓			✓	✓	✓	✓						✓					✓		✓	✓	✓				*	
76	Other GHGs emission per capita													✓					✓			✓	✓	✓				*	
77	Forest area as a share of the total land area	✓																				✓	✓					*	#

Note: ✓ denotes the exact same or similar indicators that have been considered by the respective study; * mark the list of indicators that are applicable to the context of Nepal; 'Data availability' refers to the availability of continuous timeseries quality data for Nepal from authentic sources for our period of analysis (2011-2020); # denote the indicators which have been considered in this study.

(SARI/EI-IRADe, 2021; SARI/EI/IRADe, 2021). In addition to hydropower, recent studies have reported a large potential for solar energy in Nepal (Gautam et al., 2015; Lohani and Blakers, 2021). It is important to note here that both hydropower and solar power are clean, low carbon and renewable energy technologies. The huge energy (mostly electricity) generation potential from these clean sources is well beyond what Nepal will be able to consume domestically (ADB, 2007; WECS/GoN, 2013). Hence, cross-border energy/electricity trade has been identified as a rational effort to secure the economic prosperity of Nepal as well as contributing to fulfill the demands of the voracious neighbouring energy users, primarily India and China. However, without being able to evaluate the condition of domestic ES, cross-border energy trade cannot be realized effectively. We aim to address this challenge for Nepal.

1.4. Research significance and contribution

The potential for regional electricity sharing in South Asia has been studied in the past, as seen in studies like SARI/EI (2021), SARI/EI-IRADe (2021), SARI/EI/IRADe (2021) and SARI/EI-IRADe (2018). They have primarily modelled energy demand and supply scenarios across the participating beneficiary nations. Several scholars have used econometric models to analyze the interactions between Nepal's economic outputs and the availability of electricity, including Nepal and Musibau (2021) and Parajuli et al. (2014). However, these studies lack a comprehensive qualitative analysis of the ES condition of Nepal. Some earlier studies concentrated on quantifying ES. For instance, Nag (2021) views energy sufficiency as synonymous to ES, while others such as Chalvatzis and Ioannidis (2017) assess very few aspects of the socio-economic construct which have pronounced impacts on ES (Kilinç-Pala, 2021). Hence, a comprehensive assessment of the factors affecting the ES is necessary for Nepal.

Scholars recommend country (or region) specific ES indices which can incorporate the local specificities in contrast to 'one size fits all' standard indices (Chalvatzis and Ioannidis, 2017; (Gong et al., 2021); Le et al., 2019; Radovanović et al., 2017). In this study, we have adopted a well-established method of indicator selection, weighting, and aggregation that has proven successful in other countries. However, we claim our contribution to be the first to develop a comprehensive index for Nepal (which we have termed *Energy Security Composite Index of Nepal, ESCOIN*). We further explore Nepal's prospects of regional energy/electricity sharing with the neighbouring countries, particularly India and China under energy secure conditions. Therefore, the specific objectives of this study are:

i) To quantify the energy security of Nepal by developing and applying a multidisciplinary composite index
ii) To qualitatively analyze Nepal's prospects for electricity trading in South Asia based on the conditions of ES

This paper is a significant addition to energy scholarship of South Asia, in general and Nepal, in particular. This study will provide better insights of how various indicators affect Nepal's ES in the absence of a 'universal' index. Moreover, the evidence-based information from our findings will be beneficial to the South Asian countries in devising their cross-border energy sharing plans for national and regional prosperity.

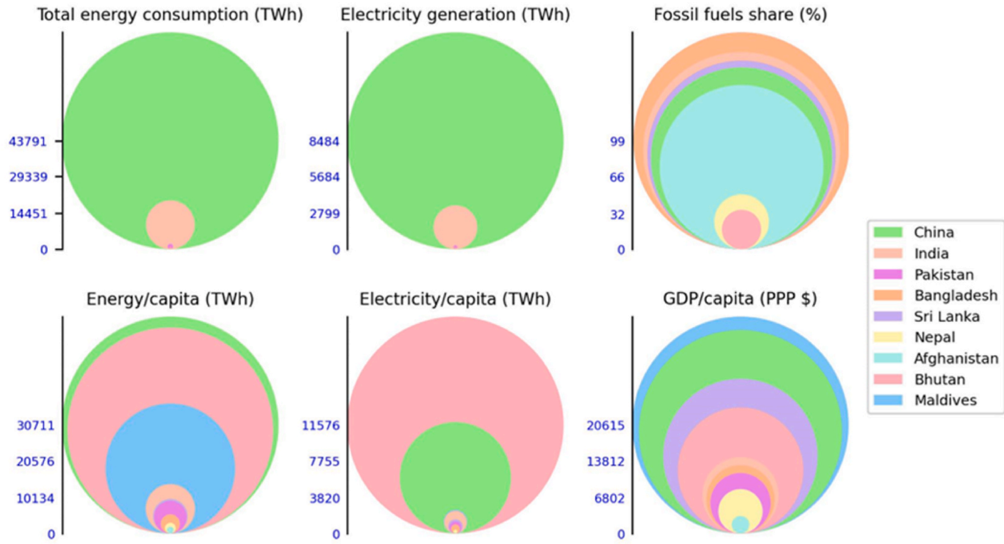

Fig. 1. Comparison of energy related indicators (total primary energy consumption in Tera-Watt-hours, TWh; total electricity generation in TWh; share of fossil fuels on the total energy (%), energy consumption per capita (TWh); electricity generation per capita (TWh); and GDP per capita in current US$) among SAARC countries and China for the year 2021. Radii of the circles are equal to the respective values. [Data source: Ritchie et al. (2023); WECS/GoN (2023); World Bank (2024)].

2. Study area: Nepal

Nepal is a mountainous country located between the two fastest-growing economies in the world, China and India (Fig. 2). A unique combination of abundant water resources (about 250 billion cubic meters per year) (WECS/GoN, 2011) and high head because of the mountainous terrain, makes Nepal extremely favourable for generation of hydroelectricity (Marahatta et al., 2022; Sharma and Awal, 2013). However, only about 3 percent of its feasible hydro-electricity potential has been realized till date due to political incompetence, poor economy, construction-related challenges, climate-related risks, environmental implications, and frequent natural disasters (Bhattarai et al., 2023a,c; Devkota et al., 2022; Devkota et al., 2020; NEA/GoN, 2023).

With a GDP of 41.39 billion USD (in the FY, 2022/23), Nepal has a very small economy that makes up only 1% of South Asian and 0.04% of the global economy (World Bank, 2024). Nepal's annual energy consumption was 640 million GJ during 2021/2022 (WECS/GoN, 2023). Three categories of energy sources, namely, traditional (firewood, agriculture residue and dry dung for direct combustion; 64.2%), commercial (petroleum, coal and grid electricity; 33.3%) and other renewables (2.5%) constituted the energy generation mix of the country in the fiscal year 2021/2022 (Fig. 3) (WECS/GoN, 2023). Furthermore, Nepal's total annual electricity consumption was 6789 GWh, having a peak demand of 1870 MW in 2022/2023 (MoF/GoN, 2023). The residential sector consumed the most electricity, accounting for 36.6% (2485 GWh) of the total consumption, followed by the industrial sector (30.7%) (NEA/GoN, 2023). Total electricity capacity connected to the national grid of Nepal was 2666 MW until the end of 2022/23, out of which, hydropower, solar, thermal, other smaller renewable technologies and co-generation from sugar mills contributed 2449 MW, 75 MW, 53.4 MW, 82 MW and 6 MW, respectively (MoF/GoN, 2023).

3. Methodology

Due to the significant heterogeneity in the geographic, economic, technological and political conditions of a nation/region, researchers have concluded that it is nearly impossible to develop a universal index for the quantification of ES. We provide an extensive review of international literature carried out at different spatial scales (Table 1 and Appendix Table A1). The vast majority of these studies have recommended that the application of such indicators and/or composite indices be limited to a particular country/region. Therefore, this study uses a well-established methodology (Fig. 4) based on indicators to create a composite index specifically for evaluating the ES situation of Nepal. Subsequently, a potential role for Nepal in regional electricity sharing in South Asia is also discussed qualitatively based on the ES conditions. The steps are explained subsequently.

3.1. Compilation of long list of indicators

Firstly, a long list of indicators was compiled based on literature review. We conducted a thorough analysis of recent literature with the goal of quantifying ES using various methods (Table 1 and Appendix Table A1). The multi-dimensional energy supply and demand dynamics are typically modelled using indicator-based methods using a variety of variables as proxies. The indicators should, as Jewell

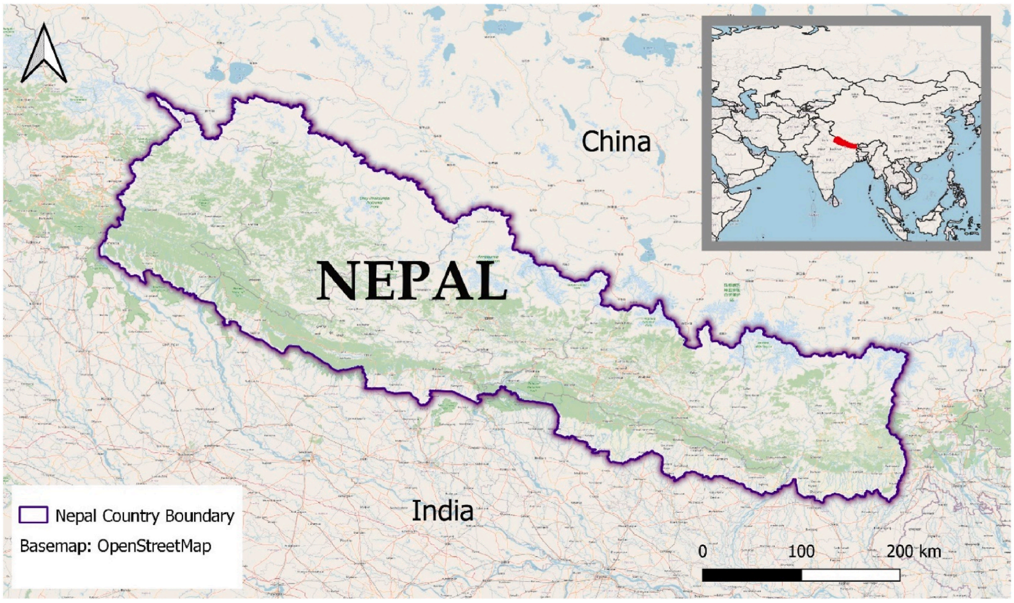

Fig. 2. Geographical setting of Nepal.

et al. (2014) correctly notes, be quantifiable using the data that is currently available, applicable to different future energy scenarios, and be able to identify important policy trade-offs and vulnerabilities for future energy planning. Additionally, Šimić et al. (2021) lists the 11 currently popular approaches for evaluating ES, which are mainly differentiated into two groups: based on security of supply and based on aggregation of indicators.

Pioneer studies in this area such as Vivoda (2010) and Sovacool and Mukherjee (2011), provided a comprehensive "wish list" of the criteria needed to evaluate ES. However, it is incredibly difficult to gather temporal (and/or spatial) data for all these indicators, particularly in data scarce developing nations such as Nepal. Because of this, most later studies limited their list of indicators to include fewer items for which data was available (Table 1). For instance, Abdullah et al. (2021) used 34 indicators, Sovacool (2013) evaluated 31, Podbregar et al. (2020) assessed 14, Huang et al. (2021) made use of 26 and Ang et al. (2015a) evaluated 22 indicators. Moreover, some studies directly used the indicators to generate an ES index, while others used composite metrics like the Shannon-Weiner Index (SWI) and Herfindhal-Hirschman Index (HHI) to assess the diversity within the indicators (Chalvatzis and Ioannidis, 2017; Chung et al., 2017; Matsumoto et al., 2018; Papież et al., 2018).

Literature contains a variety of indicator selection techniques. Some include subjective expert judgment, listing based on discussions and interviews, and literature reviews. To provide a balance between the index's stability and sensitivity, researchers frequently use a representative set of ten to 25 thorough indicators (Le et al., 2019). However, there is no "silver bullet" prescription to the choice of indicators. The precise number is ultimately decided based on the availability and quality of the data, though this rule of thumb could serve as a starting point. Further, Narula and Reddy (2015) emphasizes that no set of indicators can be final and unchangeable; rather, they must change over time to better reflect the dynamic state of a region. A long list of 77 indicators corresponding to the different socio-economic dimensions were initially identified in our case after considering all of these factors (Table 1).

3.2. Shortlisting of indicators

Three steps were adopted in the preliminary screening of the indicators. The first level screening was done by subjectively judging the indicators' applicability and relevance in the context of Nepal. For example, 'Ratio of reserve to production of oil/gas', 'Ores and metal exports', 'Share of oil consumption met locally' and 'Share of nuclear energy in total electricity generation', among others are not applicable to Nepal because it does not produce oil/gas, there are no commercially feasible metal ores or nuclear power plants (WECS/GoN, 2010, WECS/GoN, 2023). Hence, such indicators were discarded. The first level screening in this way retained 65 indicators (second last column of Table 1 marked with *). The second level screening was based on the availability of data. We chose the last decade (2011–2020) as our analysis time window primarily for two reasons. Firstly, Nepal is a data scarce country and hence the possibility of obtaining comprehensive data from different socio-economic sectors of the distant past is almost negligible. Secondly, changes in the socio-political and economic conditions of the recent decade are significantly different from that of the distant past, and hence, is more relevant for our analysis. Hence, indicators such as 'Average age of infrastructure', 'Total thermal efficiency of electricity and heat plants', 'Political stability' and 'Time required to obtain permanent connection to electricity', among others for which continuous timeseries data was not available for Nepal were excluded. Thus, the number of indicators was limited to 38 at this stage (the last column of Table 1 marked with #). These data were gathered on an annual basis for the years 2011 through 2020 from various

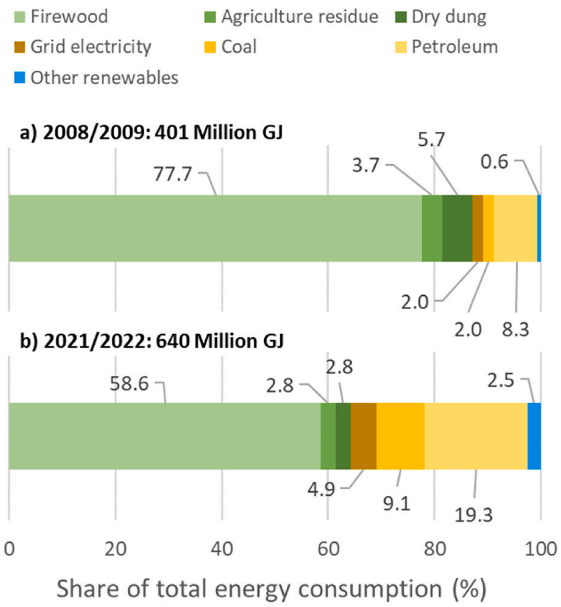

Fig. 3. Energy consumption of Nepal by fuel type for: a) 2008/2009 and b) 2021/2022; green, brown and blue shades indicate traditional, commercial and other small renewable sources respectively; magnitudes shown in bold at the top are the total annual energy consumptions in million GJ [Data source: WECS/GoN (2023); WECS/GoN (2010)]. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

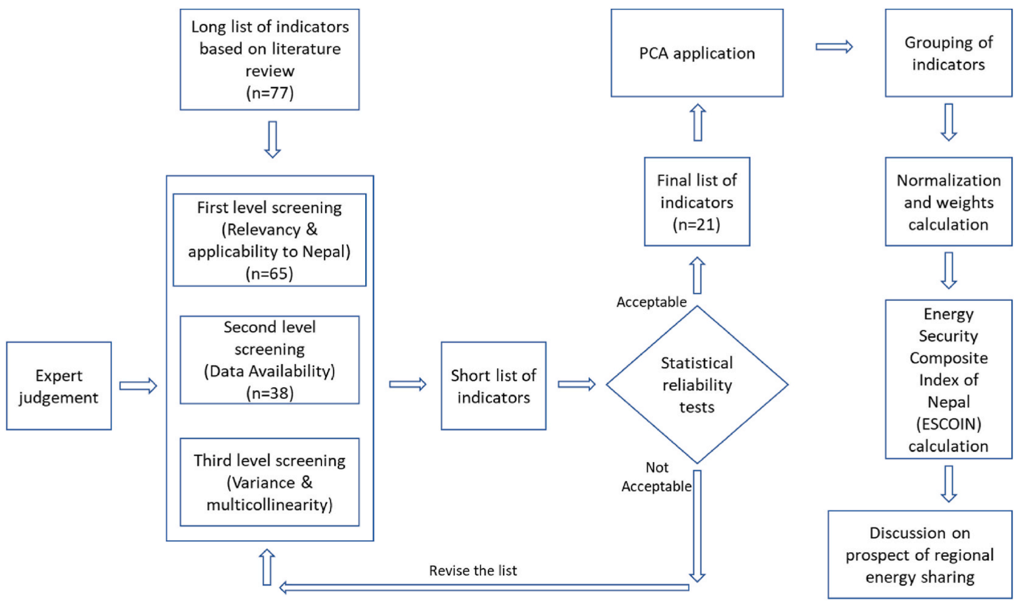

Fig. 4. Overall methodology adopted in this study.

national (reports from the Government of Nepal, GoN) and international published sources. The third step involved evaluating the indicators based on the variation in historical data and multicollinearity. The coefficient of variance (CV) was calculated using Equation (1).

$$CV_i = \frac{SD_i}{M_i} \tag{1}$$

Table 2
Coefficient of variance of the shortlisted 21 indicators.

Indicators Code	SD	Mean	CV	Indicators Code	SD	Mean	CV
I1	46.623	432.149	0.108	I12	0.134	0.890	0.150
I2	8.386	83.950	0.100	I13	0.094	0.893	0.105
I3	0.643	2.007	0.320	I14	0.001	0.009	0.146
I4	8.712	22.450	0.388	I15	0.000	0.003	0.131
I5	6.004	74.600	**0.080**	I16	0.000	0.002	0.218
I6	8.101	27.013	0.300	I17	0.134	0.890	0.150
I7	0.000	0.000	0.318	I18	2.514	29.900	**0.084**
I8	345.360	3082.852	0.112	I19	0.262	0.810	0.323
I9	0.004	0.140	**0.028**	I20	0.356	1.735	0.205
I10	3.588	14.718	0.244	I21	0.392	44.735	**0.009**
I11	0.204	1.128	0.181				

Note – SD: standard deviation; CV: coefficient of variance; values with CV less than 0.1 are bold-faced.

Table 3
Total variance explained.

Component	Initial Eigenvalues			Extraction Sums of Squared Loadings			Rotation Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	14.999	71.426	71.426	14.999	71.426	71.426	9.794	46.640	46.640
2	1.934	9.209	80.635	1.934	9.209	80.635	3.791	18.054	64.694
3	1.442	6.864	87.499	1.442	6.864	87.499	3.360	15.999	80.693
4	0.993	4.730	92.229	0.993	4.730	92.229	1.700	8.097	88.790
5	0.784	3.733	95.961	0.784	3.733	95.961	1.506	7.171	95.961

where CV_i is the coefficient of variance, SD_i is the standard deviation and M_i is the mean of the i^{th} indicator.

Scholars have highlighted that it is extremely difficult to obtain truly uncorrelated data or identify mutually exclusive indicators in such socio-economic data (Yong and Pearce, 2013; Ha and Thanh, 2022; Williams et al., 2010) as all of them have cumulative effects on cross-cutting sectors such as energy. Therefore, we chose to adopt a threshold cut-off correlation coefficient value of 0.95 in both positive and negative directions to filter out highly correlated indicators in our dataset. In addition, casual expert consultations were carried out to discuss and obtain an informal approval of our methods and the choice of indicators. This led to the retention of 21 indicators (Table 2). This number seems reasonable as recommended by previous studies (Le et al., 2019; Narula and Reddy, 2015).

3.3. Reliability testing

Cronbach's reliability test was then applied to the selected indicators as a final step. In order to determine whether a data set is suitable for statistical analysis (such as factor analysis), Cronbach's Alpha, a mathematical function (Equation (2)), measures the internal consistency or reliability of the data set. Cronbach's Alpha must be above 0.7 to be generally considered acceptable.

$$\alpha = \frac{N\bar{c}}{\bar{v} + (N-1)\bar{c}} \tag{2}$$

Where, N is the number of variables, $\bar{c}$ is the average covariance between the variables and $\bar{v}$ is the average variance.

Next, using Equation (3), Bartlett's test of sphericity was run to see whether factor analysis could be carried out for the dataset under consideration. By looking for small p-values that show the correlation matrix is significantly different from the matrix of zero correlation, the Bartlett test determines how much the data matrix deviates from an identity matrix.

$$\chi^2 = -\left(n - 1 - \left(\frac{2N+5}{6}\right) ln|R|\right) \tag{3}$$

Where, χ^2 is the chi-square value, n is the number of observations (rows), N is the number of variables (columns) and R is the determinant of the correlation matrix.

3.4. Principal Component Analysis (PCA)

Literature shows a variety of weighting and scoring systems for the identified indicators. Ang et al. (2015b) has discussed six of these popular techniques: equal weights, import/fuel share, principal component analysis (PCA), analytical hierarchy process (AHP), data envelopment analysis, and subjective weight allocation. These strategies each have advantages and disadvantages. Notwithstanding, there is still disagreement over which approach is superior and more general across scholars (Huang et al., 2021; Le et al., 2019).

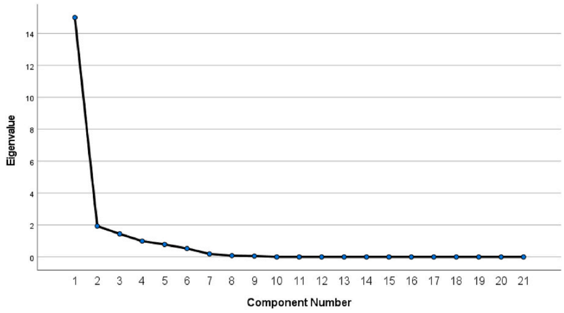

Fig. 5. Scree plot of the eigen values versus component number of PCA.

Table 4
Rotated component matrix of PCA.

Variables	Component				
	1	2	3	4	5
I17	−0.932				
I4	0.918				
I16	0.912				
I15	0.872				
I10	0.850				
I19	0.842				
I18	0.834				
I1	0.808				
I8	0.806				
I5	−0.795				
I14	0.744				
I20	0.733				
I3		0.904			
I13		−0.767			
I21		0.695			
I2		0.676			
I12			−0.917		
I11			−0.743		
I6			0.631		
I7				0.808	
I9					−0.969

Extraction Method: Principal Component Analysis; Rotation Method: Varimax with Kaiser Normalization.

Table 5
Component-wise weights.

Component	Weight	Value
1	w1	0.486
2	w2	0.188
3	w3	0.166
4	w4	0.084
5	w5	0.074

One of the inter-dependency statistical techniques that is most frequently used to achieve parsimony in the interpretation of observed data in unsupervised machine learning is factor analysis (Yong and Pearce, 2013; Storm et al., 2020). The possible unobserved variables are combined linearly (called factors) including an error term to model the observed variables. A variable's factor loading quantifies how closely connected to a particular factor the variable is. In this study, we have used Principal Component Analysis (PCA) method of factor analysis. PCA is typically used to avoid making arbitrary decisions about weighting an indicator within a dimension (Storm et al., 2020). Rotated component matrix provides the loadings' value. Varimax rotation of the loadings was used to maximize the variance of the squared loadings of a factor (column) on all the variables (rows) in a factor matrix, which has the effect of differentiating the original variables by the extracted factors. The indicators were put together into a desirable number of groups (called components) based on the variance explained and the Scree plot. Equation (4) was used to calculate the weighting factor of each component index.

$$w_k = \frac{V_k}{\sum V_k} \quad (4)$$

Where, w_k is the weighting factor of the k^{th} component; V_k is the percentage variance of the k^{th} component and $\sum V_k$ is the total variance.

It is to be noted here the indicators could have direct or inverse influencing impacts on the final index. In order to include this effect mathematically, each indicator (y_{ij}) was considered depending on the logic given in Equation (5).

If y_{ij} has an inverse influence,

$$y_{ij} = \frac{1}{y_{ij}} \text{ Else } y_{ij} = y_{ij} \quad (5)$$

Where, y_{ij} is the value corresponding to the i^{th} indicator and the j^{th} record.

The indicators within each component were normalized on a 1–5 scale using the minimum-maximum approach for better readability and convenience in comparison as shown by Equation (6).

$$Y_{ij} = \frac{5y_{ij}}{\max\left(y_{ij}\right)} \quad (6)$$

Where Y_{ij} is the normalized value of y_{ij} and $\max\left(y_{ij}\right)$ denotes the maximum value within the component.

In order to calculate the component index (C_{pj}), the root mean square value of the indices were considered using Equation (7).

$$C_{pj} = \sqrt{\sum \frac{y_{ij}^2}{c_p}} \quad (7)$$

Where, C_{pj} is the component index and c_p is the number of indicators in the p^{th} component.

3.5. Energy Security Composite Index of Nepal (ESCOIN) development

The *Energy Security Composite Index of Nepal (ESCOIN)* was calculated at annual timesteps using Equation (8) by multiplying the weights and adding the scores for each indicator within a component identified from PCA. Since these indices were created using both qualitative and quantitative data, it is challenging to interpret them using 'standard' rules. As a result, literature frequently uses subjective classification (Abdullah et al., 2021; Ang et al., 2015a; Bompard et al., 2017; Gong et al., 2021; Li et al., 2016). A similar classification of *ESCOIN* was adopted for this study. It is to be noted here that the scores given by Equation (6) are normalized on a 1–5 scale. Hence, it is logical to categorize the possible *ESCOIN* values derived from the weights and scores into five categories: 1–2 is considered "very poor", 2–3 "poor", 3–4 "moderate" and 4–5 "high". SPSS, MS Excel and *python* were used for the analysis and presentation.

$$ESCOIN = \frac{\sum \left(w_k C_{pj}\right)}{\sum w_k} \quad (8)$$

Where, *ESCOIN* is the *Energy Security Composite Index of Nepal.*

4. Results

4.1. Coefficient of variance

Table 2 lists the coefficients of variance (CV) of the shortlisted 21 indicators. Studies generally recommend discarding variables with values of CV less than 0.1 from further analysis (Abdullah et al., 2021; Le et al., 2019; Radovanović et al., 2018). This statistical technique for dimension reduction is used when there are many variables to be evaluated and large datasets. Nevertheless, relying solely on statistics without considering the physical significance of the parameters to a specific domain can result in the exclusion of the important variables that are likely to have an impact on the dependent variable. As a result, the number of variables was maintained at 21 in our case due to the implications on the energy sector under the country's shifting socio-geopolitical conditions, although a few values can be seen to have low coefficient of variances (Table 2).

4.2. Statistical reliability tests

4.2.1. Cronbach's test

The Cronbach alpha value was calculated to be 0.801 for the considered dataset indicating their reliability. This led to the indicators being used for the next step of standardization and aggregation.

Table 6
Component-wise weights, scores and the final values of *ESCOIN* for the study decade (2011–2020).

Year	C1w1	C2w2	C3w3	C4w4	C5w5	*ESCOIN*
2011	2.452	0.479	0.594	0.119	0.340	3.98
2012	2.527	0.520	0.589	0.122	0.350	4.10
2013	2.425	0.521	0.601	0.108	0.374	4.02
2014	2.356	0.571	0.662	0.096	0.352	4.03
2015	2.322	0.570	0.776	0.114	0.343	4.10
2016	2.233	0.594	0.933	0.081	0.358	4.19
2017	2.182	0.572	0.926	0.084	0.355	4.11
2018	2.141	0.595	0.955	0.081	0.365	4.13
2019	2.144	0.570	0.963	0.070	0.358	4.10
2020	2.126	0.581	0.717	0.073	0.348	3.84

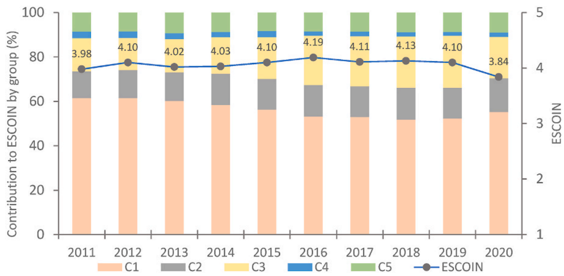

Fig. 6. Contribution of the respective components (C) on the *Energy Security Composite Index of Nepal (ESCOIN)* and its temporal trend during 2011–2020; contributions in % are plotted on the primary y-axis (left) while *ESCOIN* values (dimensionless) are plotted on the secondary y-axis (right).

4.2.2. *Bartlett's test*

Results of the Bartlett's test showed that the approximate Chi-Square value was 396.135 with a significance level (p-value) of 0.000. This confirms that factor analysis can be carried out for the considered dataset.

4.3. *PCA results*

The total variance explained by PCA is presented in Table 3. It is evident that this statistical model has been able to effectively account for almost 96% of the dataset's overall variance with five components. Additionally, scree plot of the eigen value versus the component number (Fig. 5) demonstrates that five components can satisfactorily retain the information of the variance of the dataset. Therefore, five principal components from the list of considered indicators were selected for further analysis. The rotated component matrix and component-indicator weighting values are given in Table 4. It is seen that Component 1 encompasses 12 indicators, Component 2 includes four, Component 3 comprises three while Components 4 and 5 each contain one indicator. Furthermore, the Component-wise weights are shown in Table 5. Component 1 has the highest weight of 0.486 followed by Component 2 of 0.188 and so on indicating their respective influences on *ESCOIN*.

4.4. *Energy Security Composite Index of Nepal (ESCOIN)*

Table 6 lists the annual values of *ESCOIN* with contributions of the five components (C1 to C5) while the annual trends are shown in Fig. 6. Since Component 1 has the greatest influence, it corresponds to the largest value in the "C1w1" column (ranging from 2.12 to 2.52) compared to the others. Component 4, on the other hand, has the least impact on *ESCOIN*, depicted by the values of "C4w4" ranging from 0.07 to 0.122. The values of *ESCOIN* vary between 3.84 (2020) to 4.19 (2016).

5. Discussion

5.1. *Methodological aspects*

Indicators and index-based methods provide quantitative information, but they may not be truly objective or unbiased (Narula et al., 2015). There is a large heterogeneity in the considered indicators, composite indices and the calculation methods across literature. Moreover, absolute values of an aggregated index carry no direct physical meaning. As mentioned in Narula and Reddy (2016), including more indicators does not necessarily lead to better tools. This is even more pronounced when the variables are very closely related. For example, 'Renewables in total energy consumption' and 'Hydropower in total energy consumption' are highly correlated in the Nepalese context because hydropower has always been the largest contributor to renewable energy. Similarly, 'Hydropower in total energy consumption' and 'Traditional fuels in total energy consumption' have a direct negative correlation. It should be noted that even though there is a strong correlation between the variables, it does not imply causation (Iyke et al., 2021). Thus, every effort should be made to avoid excessive decomposition and double counting of variables/indicators in order to develop a meaningful ES index that can be interpreted unambiguously.

Dimension reduction techniques, like PCA, are unsupervised learning methods frequently used in machine learning and artificial intelligence (Khan et al., 2020; Li et al., 2021; Storm et al., 2020; Wang et al., 2022). However, these methods perceive the input variables as having less of an impact on the outcome when they do not vary significantly over time, which may not be the case in reality. Four variables from our dataset (I5, I9, I18, and I21) are flagged less important applying the 0.1 CV threshold (Table 2). Such an exclusion does not seem correct when one considers how important these variables are to the energy domain. For instance, I5 is the share of traditional fuels in the total energy consumption. This did not vary significantly during the last decade (low CV of 0.080). But in the future, more effective energy technologies, better policies, and wider access to electricity will undoubtedly cause a steady decrease, which will have a positive effect on the values of *ESCOIN*. Moreover, a large number of the indicators occur in Component 1, and so the impact of the individual indicators cannot be straightforwardly evaluated because of the structure of PCA.

Some studies, such as Abdullah et al. (2021), combine historical and future (forecasted) datasets to derive an ES index. However, how the values of the considered variables change in the future is largely governed by the geo-political contexts, policy changes and other socio-economic alterations which are extremely difficult to predict and are largely prone to subjective bias. This leads to high chances of over-/under-estimation of the final index values. Thus, we limit our scope to quantification of *ESCOIN* for the historical case only using the available observed data. Several studies (e.g. Le et al., 2019) have reported differences in the final results with the implementation of PCA variants. Moreover, there are other methods, such as AHP and equal weights, which are more subjective in selecting parameters and defining their weights (Narula and Reddy, 2016; Sapkota et al., 2021; Sharifuddin, 2014). However, the high degree of subjectivity associated with such methods prevents it from being considered a generic method; PCA is much better in this regard (Storm et al., 2020). Furthermore, there is always room for improvement in the choice of variables, indicators short listing, and weighting and aggregation techniques (Narula and Reddy, 2015).

5.2. ESCOIN and its interpretation

The big question is – how can the *ESCOIN* values be interpreted? Referring to Fig. 6, the *ESCOIN* values indicate ES is consistently at the boundary of "moderate" to "high" conditions during the last decade based on the categorization scheme explained in Section 3.5. Three important observations can be made in this regard.

Firstly, Component 1 is composed of 12 indicators (namely, I17, I4, I16, I15, I10, I19, I18, I1, I8, I5, I14 and I20, in order of decreasing influence, Table A2) out of the considered 21. Thus, this component is expected to obviously have a large influence on the *ESCOIN* values. For instance, the electricity transmission and distribution losses (indicator I17) has only decreased slightly over the last decade. Share of fossil fuels in total energy consumption (I4) are on the rise. Additionally, conventional (agriculture-based) fuels (I5) account for a large share of the total energy consumption which decreased gradually from 86.27% in 2011 to 72.62% in 2020 (MoF/GoN, 2021). Commercial and agricultural energy intensity (I16 and I15) with respect to GDP has been decreasing. Despite changes in magnitude, alteration in the contribution of the different sources to the country's current mix of energy consumption is not impressive. In 2021/2022, traditional fuels made up 19 percent less of the total energy mix than they did in 2008/2009, but at the expense of 18% increase in petroleum and coal (WECS/GoN, 2023; WECS/GoN, 2010). Grid electricity has expanded from 2 to 4.9% while the share of other renewables has increased from 0.6% to 2.5% during this time (Fig. 3). Therefore, the influence of fluctuations in indicators of other components (C2 to C5) on the ES is alleviated by the largely stagnant contribution of Component 1 constituent variables.

Second, Nepal's energy imports and its share in the total energy consumption (quantified by indicator I10) have grown almost in parallel with demand over the last ten years, with around 18% of the total energy consumption supplied as imports in 2020 (MoF/GoN, 2021). This trend is most prominent in the transportation sector. In addition, the development of domestic hydropower and other renewable energy sources is not able to catch up with the increasing demand. Therefore, the differential impact on *ESCOIN*, especially from the sectoral indicators such as SC2, is very low.

Third, Nepal faces a situation of "suppressed energy demand" throughout our analysis time window. As seen from Fig. 1, Nepal's annual per capita energy and electricity consumption are among the lowest in South Asia and also globally. Demand is less while energy imports are increasing giving a false impression of energy sufficiency. Moreover, the domestic sector, which is largely dependent on traditional fuels, is the major energy consuming sector of Nepal. But it seems disconnected with the economic conditions of the country because domestic sector energy is mostly consumed for cooking which is directly linked to subsistence. Industrial and commercial sectors are still the minor energy consumers. Had there been a massive energy demand due to the rapid growth of the industrial and commercial sectors, Nepal would not have been able to meet them domestically and import would be further stressed. This would have been reflected in the *ESCOIN* values. Hence, due to the absence of an unmet energy demand situation, the *ESCOIN* values showing "moderate" to "high" conditions seems reasonable. For the very same reason, the value of *ESCOIN* did not show much variation during the Great Earthquake of 2015, India's economic blockade of Nepal in 2016, and COVID-19 in 2020, despite huge losses in the economic sector. Hence, we term this situation a "pseudo-energy secure" state for Nepal which can be expected to continue through the immediate future in the absence of paradigm shifts in the overall energy sector.

It is important to note that this is the first national ES study for Nepal using a comprehensive number of indicators. As the response variable of PCA in our analysis does not have any observed value (unsupervised), direct validation of our results against other 'observed' or 'published' values of the this variable is not possible. Such limitations of PCA have been highlighted by Deisenroth et al. (2020), Shaik et al. (2022) and Storm et al. (2020). Moreover, direct comparison with prior research in Nepal also cannot be made. We are also aware that direct comparisons with studies of a similar nature conducted in various geographic locations is against the advice of previous scholarship (Ang et al., 2015a; Augutis et al., 2017; Erahman et al., 2016; Narula and Reddy, 2015). That is why, we have resorted to indirect comparison of our results with similar other studies in the South Asian region for the sake of getting an indicative picture of our evaluation. For instance, Nag (2021) demonstrated that, when compared to the other SAARC nations from 2001 to 2010, Nepal consistently holds a strong position in terms of energy sufficiency. Additionally, Le et al. (2019) reported a very gradual rate of improvement in Nepal's ES condition. These findings are somewhat consistent with ours. Of course, the magnitudes differ between studies due to the use of different methods and variables. In addition, studies of Southeast Asia (Sharifuddin, 2014), Singapore (Ang et al., 2015a), Indonesia (Erahman et al., 2016), Thailand (Martchamadol and Kumar, 2014), and Pakistan (Abdullah et al., 2021) demonstrate that such indicator-based methods evaluated annually do not typically result in a very drastic change in the ES values over a period of one or two decades. But the length of the analysis time window and finer temporal resolution of analysis are, in turn, constrained by problems of data availability, particularly in developing nations such as Nepal.

5.3. Regional energy sharing prospect

With "pseudo-energy secure" conditions, what implications does it have in the electricity sharing prospects of Nepal in South Asia?

Besides hydropower and some renewables such as solar and biogas (Lohani and Blakers, 2021; Sanjel and Baral, 2019), other commercially viable energy sources such as coal, petroleum or gas, have not been identified in Nepal (WECS/GoN, 2011; WECS/GoN, 2023). As a result, Nepal is currently importing large amounts of (fossil) fuel and (dirty) electricity (generated from coal) from India to meet its growing demands. This is well-reflected in Fig. 6 which shows that the contribution of the third component (C3) of the rotated matrix on *ESCOIN* is steadily increasing with time, except for the anomaly observed in 2020 (attributable to the impacts of the COVID-19 pandemic). This component comprises of variables pertaining to the price of imported petrol and diesel along with share of electricity import in total electricity consumption. On the other hand, components C4 (representing domestic sector energy per capita) and C5 (energy intensity) exhibit minimal variation and contribute modestly to *ESCOIN*. The influence of C2 (encompassing the share of renewables in the total energy, access to electricity and the price of LPG) on *ESCOIN* remains relatively constant throughout the past decade. These are clear indications of growing India-Nepal cross border energy (including electricity) trade, though this trend leans unfavourably towards Nepal due to increased reliance on energy imports. Consequently, a reduction in the contribution of C3 and an increase in contributions from C2, C4 and C5 would be beneficial to Nepal's energy sector. Referring to the weights of the components given in Table 5, we observe that the share of C1 is nearly equal to the combined weights of the other four components because C1 consists of many variables ($n = 12$). As a result, it becomes challenging to isolate the specific impacts of each variable on *ESCOIN*. Furthermore, Nepal's limited electricity export to India during the monsoon is valued considerably low compared to its heavy year-round imports, primarily because of disproportionate rates (Bhattarai et al., 2022a; Marahatta et al., 2022; NEA/GoN, 2023). As a result, electricity export from Nepal has not been able to considerably alleviate national trade deficits. Moreover, environmental benefits have been compromised in an attempt to attain energy security (Shakya et al., 2023). Therefore, increasing the contributions of C2, C4 and C5 on *ESCOIN* (representing the overall energy security of the country) would be possible if Nepal were to have surplus energy (after meeting all the domestic demands) and could export it to neighbouring countries. And, under current conditions, this can only be achieved through aggressive hydroelectricity generation supplemented by other renewables feasible for Nepal.

Nepal's two energy-hungry neighbours, China and India, have positioned themselves as upcoming superpowers in terms of energy generation and consumption. Cross-border trade in electricity currently takes place between India and Bhutan, India and Nepal and India and Bangladesh, through bilateral government-to-government (G2G) agreements negotiated on a case-by-case basis (SARI/EI, 2021). India's own hydroelectricity potential is estimated at about 145 GW while the electricity demand of Nepal is about 0.5% of India. In 2006, India and Bhutan signed a pact to develop 10,000 MW by 2020 implementing an inter-governmental model, the surplus electricity being purchased by India. Bhutan currently exports about 75% of the electricity it produces to India, while Nepal lags far behind. In the FY 2022/2023, Nepal purchased 1855 GWh year-round from India and exported 1333 GWh (~72% of imported electricity) during June to October (NEA/GoN, 2023). With increasing demands, electricity import is not likely to change if run-of-river and storage projects are not constructed in strategic locations (Bhattarai et al., 2023a; Pokharel and Regmi, 2024). Nepal and China recently entered into a formal agreement in 2017 to jointly conduct gas and oil feasibility studies and build hydropower projects and transmission lines in Nepal (ET, 2017) to promote its technological and economic development. Nepal and Bangladesh have lately collaborated on cross-border electricity trade, given that India provides access to its land and infrastructure for which it was reluctant in the past (Chaudhary, 2023; Shrestha, 2023).

Dating back to the 1920s, cross-border electricity cooperation between India and Nepal has developed over time. There are currently four types of interconnected transmission lines (148 km at 400 kV capacity; 1101 km at 220 kV; 3979 km at 132 kV; and 514 km at 66 kV) in Nepal which are currently being used for electricity trade (NEA/GoN, 2023; SARI/EI, 2021). The current Nepal-India electricity transmission line is designed for low-power trade. Moreover, Nepal's economy is completely dependent on India because of large imports, a significant portion of which is fossil fuel. SARI/EI (2021) optimistically sees the collaboration between India and Nepal on energy sharing as a win-win scenario for trade between big and small countries. Although India had nominated the Power Trading Corporation as the focal agency for dealing with matters related to power trade with its counterpart Nepal Electricity Authority in 2001 (ADB, 2007), Nepal has not been able to reap benefits as expected from this collaboration (Bhattarai et al., 2024). The India-Bhutan (SARI/EI, 2021; 2021) and Thailand-Laos (ADB, 2009; Hecht et al., 2019) models of cross-border trade may be advantageous for both parties because the economically stronger nation invests in the projects and gains the majority of the rewards while the less wealthy nation also benefits.

Nepal has a large potential for hydropower development (Amjath-Babu et al., 2019; Bhattarai et al., 2023a,c; Marahatta et al., 2021; Sharma and Awal, 2013). The Hydropower Development Policy of Nepal, 2001) recognized hydropower as an exportable commodity. Additionally, Nepal's Energy Sector Vision 2050 identifies hydropower as the "lead" energy technology to meet both long-term and short-term energy needs (WECS/GoN, 2013). The Asian Development Bank (ADB) has also recognized Nepal's efforts to accelerate sustainable hydropower development in order improve the ES condition (ADB, 2017). The Whitepaper on Energy, Water and Irrigation: Present Situation and Future Prospect 2018 has ambitious targets of hydropower development and envisions promoting cross-border power transfer with integrated development of transmission lines and road. The economic value addition of products using cheap electricity can have a high profit margin in regional markets. Furthermore, once domestic needs are met, surplus electricity can be exported at favourable prices to neighbouring countries, primarily India. However, careful attention is to be given to the difference between the industrial sector average value addition (~0.86 US$ in 2002) and average cost of export per unit of electricity (~0.09 US$ in 2002) (USAID-SARI, 2003).

Recent studies, such as Gyanwali et al. (2023), warn of the possible reduction in hydropower generation and cross-border electricity export as a result of climate change in the future and also recommends diversified generation mix. Pandey et al. (2023) demonstrate how climate induced reduction in water availability and mechanical failures of hydropower projects due to lack of regular maintenance are taking a toll on Nepal's electricity sector. Contrarily, Bhattarai et al. (2023a) and Marahatta et al. (2022) demonstrate how storage type hydropower development in Nepal, including its pumped variants (Baniya et al., 2023), can be beneficial to multiple sustainable development goals as well as for climate resiliency. Unfortunately, it has not been able to utilize more than 3% of its economically viable hydropower potential (NEA/GoN, 2023) despite the development of Nepal's first hydroelectric project in 1911 (Sharma and Awal, 2013) (). Nepal's peak electricity demand was 1870 MW while the installed capacity reached 2666 MW in the FY 2022/2023, with plenty more addition to the national grid in the near future (MoF/GoN, 2023). Nepal will have a large surplus of electricity, which, if not exported, is likely to go to waste unless there is a significant increase in domestic demand for electricity in the industrial, commercial, and transportation sectors. Sanjel et al. (2019) highlights the possibilities of optimized electricity expansion in Nepal which could have considerable impacts on cross-border electricity trade. In addition, Sharma and Shrestha (2023) have explored additional energy generation pathways that Nepal needs to adopt to reduce its reliance on petroleum in the short- and long-runs.

On a positive note, the governments of Nepal and India signed a power sharing agreement recently. Under this agreement, India agreed to buy electricity exclusively from hydropower projects in Nepal financed or built by India (e.g., 679 MW Arun-4, 900 MW Arun-3, 750 MW West Seti, 900 MW Upper Karnali, among others with a total capacity of about 7000 MW), which is again disproportionate (Qazi, 2022). Nepal bears the environmental and social consequences of these projects while gaining a relatively small amount of electricity for domestic use whereas India enjoys larger benefits from the clean electricity. Moreover, studies such as Shakya et al. (2022a) highlight the influencing role of energy equity on energy intensity at the national level. Additionally, India's recently constructed 63 km long cross-border Motihari (India) to Amlekhgunj (Nepal) petroleum pipeline, with a capacity of two million metric tonnes per year, clearly demonstrates its motivation to keep Nepal dependent on India for importing fossil fuels (PIB/GoI, 2019). Nepal imported about US$ 2.46 billion worth of fossil fuels (17.3% of the country's total import) from India in 2021/22, the largest amount being spent on diesel import (DoC/GoN, 2023). This amounts to more than 6% of the country's annual GDP with Nepal's share of imports accounting for 91.1% of total trade (DoC/GoN, 2023). We acknowledge that maintaining fossil fuel reserves is necessary for sustaining the economic activities of a nation. This is even more significant in the case of Nepal, where (mainly fossil) fuel imports largely outnumber domestic energy generation. However, Nepal's policy of encouraging the implementation of activities such as construction of petroleum pipeline is unquestionably not in its best interests, economically, environmentally and geopolitically, particularly for its feat to attain net zero emissions in the near future.

It is evident that Nepal needs to make substantial progress in both energy supply and demand sides and concentrate on gaining self-sufficiency in domestic energy/electricity rather than fantasy of exports, at least in the near future. India is the nearest and the largest electricity market for Nepal. Regional hydroelectricity trade presents an opportunity for Nepal. However, it relies heavily on sincere political commitment and trust in the actions of participating countries. Unfortunately, these factors have often been compromised due to shifting political interests in the past (Bhattarai et al., 2023c). Due to reasons of proximity and rugged terrain, electricity trade with Bangladesh and China is both economically and technically challenging. Cross-border electricity trade with other South Asian Association for Regional Cooperation (SAARC) nations faces similar challenges. Moreover, large investment in technology and infrastructure, institutional capacity building and harmonization of standards and regulations are mandatory for a successful cross-border energy trading model (SARI/EI, 2021). Hence, Nepal has the potential to contribute to the increasing energy needs of South Asia in the long run, in spite of its relatively small generation capacity compared to the large demands, especially of India and China. However, this requires supportive policies and their effective implementation.

We acknowledge some limitations in this study. The focus of our study was on the quantitative estimation of Nepal's energy security followed by a qualitative examination of its cross-border energy sharing potential. Detailed quantification of cross-border energy trade possibilities within South Asia under current and future geopolitical contexts and the contribution potentials of Nepal was beyond the scope of this paper. Incorporating additional relevant indicators in the analysis, as more data becomes available, as well as carrying out such an evaluation using long-term panel data and scenarios analysis with validation against observed data could be an excellent continuation of this research.

6. Conclusion

Economic activities and the corresponding energy demand in South Asia are burgeoning. The energy hungry countries, particularly

China and India, are moving towards rapid development and exploring options to meet their energy needs. Strategically located between these two superpowers, Nepal has a very good hydropower potential. However, difficult terrain, resource constraints and political incompetence has restricted its hydropower development. This study evaluated the state of energy security of Nepal by applying an indicator-based methodology to develop an index which we termed the *Energy Security Composite Index of Nepal (ESCOIN)*. The study further qualitatively assessed Nepal's potential for regional power sharing in South Asia based on the condition of energy security. We adopted 21 highly relevant indicators applicable to Nepal derived from a long list derived from extensive literature review. The impact of these indicators on *ESCOIN* was assessed using Principal Component Analysis (PCA).

Our results show that Nepal has consistently held a boundary position between "moderate" to "high" classes of ES in the last decade. We identify key reasons for this. First, *ESCOIN* is significantly influenced by the presence of a steady and weighty dependence on traditional (agriculture based) fuels primarily in the domestic sector. Second, Nepal has been facing a condition of suppressed energy demand due to the absence of large industrial and commercial users resulting in reduced consumption in the last decade. Third, import of energy (mostly petroleum products) has increased almost in parallel to the growing demand due to the sluggish development of domestic hydropower and other renewable technologies. Hence, we surmise a 'pseudo energy secure' state for Nepal. Moreover, we infer that without immediate and intensive pragmatic interventions to address current energy-related issues, Nepal's state of energy security is likely remain constant in the near future.

Regional power-sharing, particularly to India, can be seen as an opportunity for Nepal, provided considerable infrastructural development occurs, institutional capacity is strengthened, and genuine political commitment and trust are sustained. Both countries need to learn from their past mistakes which led to frequent violations of cross-border trading agreements largely due to conflicting political interests. Moreover, careful comparison is to be made in the best interest of Nepal between the value addition to industrial products and cost of electricity export. Additionally, Nepal's policy of promoting counter-development activities (such as construction of petroleum pipelines) is certainly not in the best interests of the nation. It is also to be realized that disproportionate and unfair bilateral trade agreements can lead to unsustainable cooperation. Although efforts are underway, electricity trade with China, Bangladesh and other SAARC countries is economically difficult and technically challenging, predominantly due to reasons of proximity and rugged terrain. In addition, Nepal needs to significantly reduce dependence on traditional and fossil fuels, rely more on clean and renewable energy led by hydropower, and achieve self-sufficiency. Finally, Nepal should focus on achieving self-sufficiency in energy through domestic hydropower and renewable sources and aim to stabilize energy consumption rather than being overly ambitious of exports, at least in the near future. Moreover, a quantitative assessment of the cross-border energy (mainly electricity) trade from Nepal to its neighbours through scenarios analysis could be a plausible avenue for future research.

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CRediT authorship contribution statement

Utsav Bhattarai: Conceptualization, Data curation, Methodology, Software, Writing – original draft. **Tek Maraseni:** Conceptualization, Supervision, Writing – review & editing. **Laxmi Devkota:** Supervision, Writing – review & editing. **Armando Apan:** Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix

Table A1
Review of selected studies (in alphabetical order) at different geographical scales on energy security indices

S. N	Source	Name of Index	Country/region studied	Timeframe of analysis	Number of dimensions	Number of indicators/ metrics/ attributes	Method of Assessment
1	Abdullah et al. (2021)	Energy Security Index of Pakistan (ESIOP)	Pakistan	1991–2040	5	39	Composite index by PCA
2	Ang et al. (2015a)	Singapore Energy Security Index (SESI)	Singapore	1990–2010	3	22	Composite index by subjective weight allocation
3	Augutis et al. (2017)	Energy security level	Lithuania	2007–2030	3	68 (2 composite indicators)	Energy systems modelling
4	Bompard et al. (2017)	National energy security assessment	Italy	2014	2	24	Composite index
5	Chalvatzis and Ioannidis (2017)	Energy supply security	EU 28 countries	1990–2013		2 composite indicators	Composite index using SWI and HHI
6	Chung et al. (2017)	Diversity Reliability Index & Co-vary diversity reliability index	Taiwan	1996–2011	5	*NM*	Composite index using SWI and HHI
7	Chung et al. (2017)	Energy Security (ES) index	South Korea	2001–2014	4	6	HHI and weighting
8	Erahman et al. (2016)	Energy Security Index	71 countries	2008–2013	5	14	Composite index by PCA
9	Franki and Višković (2015)	Energy Security Index (ESI)	Croatia	2015	3	24	Composite index by weight allocation
10	García-Gusano et al. (2017)	Renewable Energy Security Index (RESI)	Spain & Norway	2014–2050	2	16	Energy systems modelling
11	Gong et al. (2021)	Energy Security Level	China	2004–2017	4	13	Composite index using entropy weight method
12	Huang et al. (2021)	Energy security performance	China	2008–2017	4	11	Fuzzy Best-Worst method, DEA & Assurance Regions
13	Iyke et al. (2021)	Energy security measure	USA	1989–2019	5	10	Individual assessment
14	Jewell et al. (2014)	Energy security assessment framework	Global	2000–2100	3	19	Integrated assessment model
15	Le et al. (2019)	Energy Insecurity Index for Asia	24 Asian countries	1990–2014	3	12	Composite index by PCA
16	Li et al. (2016)	Energy Security Index (ESI)	Japan, Korea, Singapore & Taiwan	1990–2012	3	9	Composite index by PCA
17	Martchamadol and Kumar (2013)	Aggregated Energy Security Performance Indicator (AESPI)	*NM*	*NM*	3	25	Composite index by PCA
18	Martchamadol and Kumar (2014)	Aggregated Energy Security Performance Indicator (AESPI)	Thailand	1986–2030	3	25	Composite index by PCA
19	Matsumoto and Shiraki (2018)	Energy security performance	Japan	2005–2050	2	35 (3 composite indicators)	Low Carbon Navigator tool
20	Matsumoto et al. (2018)	Energy security performance indicator	EU countries	1978–2014	2	3 composite indicators	SWI & Hierarchical cluster analysis
21	Mohsin et al. (2018)	Oil supply risk index	South Asia	2001–2015	NM	5 composite indicators	DEA & MCDA
22	Muñoz et al. (2015)	Geopolitical Energy Supply Risk Index (GESRI)	122 countries	2000–2010	4	47	Composite index by PCA
23	Nag (2021)	Energy Security Index (ESI)	South Asia	2000–2010	12	45	Composite index by factor analysis
24	Narula and Reddy (2016)	Sustainable Energy Security (SES) Index	Developing countries	*NM*	4	27	Hierarchical aggregation by weights and scores & AHP
25	Narula et al. (2015)	Sustainable Energy Security (SES) Index	India	2002–2012	4	23	Hierarchical aggregation and subjective weighting
26	Papież et al. (2018)	*NM*	26 EU countries	1995 & 2014	3	15	SWI, HHI & HHIE & PCA

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Table A1 (*continued*)

S. N	Source	Name of Index	Country/region studied	Timeframe of analysis	Number of dimensions	Number of indicators/ metrics/ attributes	Method of Assessment
27	Podbregar et al. (2020)	International Energy Security Risk Index	26 OECD countries	1980–2016	8	29	Composite index by PCA
28	Radovanović et al. (2017)	Energy Security Index	28 EU countries	1990–2012	NM	6	Composite index by PCA
29	Radovanović et al. (2018)	Geo-economic Index of Energy Security	EU countries	2004–2013	NM	9	Composite index by PCA
30	Ren and Sovacool (2014)	*NM*	China	*NM*	4	24	Fuzzy Decision-making Trial and Evaluation Laboratory Methodology
31	Sharifuddin (2014)	Energy Security Index (ESI)	Malaysia & Southeast Asian countries	2002–2008	5	35	Composite index by subjective weight allocation
32	Šimić et al. (2021)	Enery Security (ES) index	28 EU countries	2008–2017	*NM*	4	Fuzzy logic approach
33	Sovacool and Mukherjee (2011)	*NM*	*NM*	*NM*	5	320	Individual assessment and aggregation
34	Sovacool (2011)	*NM*	Asia Pacific	*NM*	20	200	*NM*
35	Sovacool (2013)	Energy Security Index (ESI)	18 countries	1990–2010	5	20	Empirical and relative scoring and weighting
36	Vivoda (2010)	Energy Security Assessment Instrument	10 Asia-Pacific countries	2009	11	30	*NM*
37	Wang and Zhou (2017)	Energy Security Index (ESI)	Global	*NM*	3	27	Composite index by PCA & subjective and objective weight allocation
38	Zeng et al. (2017)	Integrated energy security indicator	Baltic states (Estonia, Lativa & Lithuania)	2008–2012	3	18	MCDA, DEA and objective weighting

Note - PCA: Principal Component Analysis; SWI: Shannon-Weiner Index; HHI: Herfindhal-Hirschman Index; DEA: Data Envelopment Approach; MCDA: Multi-Criteria Decision Approach; HHIE: Herfindhal-Hirschman Index in Electricity; FDA: Functional Data Analysis; *NM*: not mentioned explicitly.

Table A2
Indicators shortlisted and adopted in this study (Please refer to Table 1 for a long list of the indicators)

S. N	Code	Indicator	Unit	Definition adopted in this study
1	I1	Energy consumption per capita	kgoe	Total final energy consumption from all sectors as a ratio of the total population
2	I2	Access to electricity	%	Percentage of the total population with connection to grid electricity
3	I3	Renewables in total energy consumption	%	Contribution of renewable energy sources (excluding hydropower) in the total energy consumption
4	I4	Fossil fuels in total energy consumption	%	Contribution of fossil fuels (petroleum, coal and LPG) in the total energy consumption
5	I5	Traditional fuels in total energy consumption	%	Contribution of traditional fuels (firewood, agriculture residue and dry dung) in the total energy consumption
6	I6	Electricity import in total electricity consumption	%	Share of imported electricity on the total electricity consumption
7	I7	Domestic sector energy per capita	kgoe	Energy consumption in the domestic sector as a ratio of the total population
8	I8	GDP per capita	US$	Gross domestic product as a ratio of the total population
9	I9	Energy intensity	1000 kgoe/US$	Ratio between the total energy consumption and the GDP (considered base year 2015) calculated annually
10	I10	Energy import in total energy consumption	%	Ratio of the total energy imported to total energy consumption
11	I11	Gasoline price per litre	US$	Retail price of gasoline per litre
12	I12	Diesel price per litre	US$	Retail price of diesel per litre
13	I13	LPG price per kg	US$	Retail price of liquified petroleum gas per kilogram
14	I14	Industrial sector energy intensity	1000 kgoe/US$	Ratio between the total energy consumption in the industrial sector and the GDP (considered base year 2015)
15	I15	Commercial sector energy intensity	1000 kgoe/US$	Ratio between the total energy consumption in the commercial sector and the GDP (considered base year 2015)
16	I16	Agricultural sector energy intensity	1000 kgoe/US$	Ratio between the total energy consumption in the agricultural sector and the GDP (considered base year 2015)
17	I17	Transmission and distribution losses in electricity	%	Share of transmission and distribution losses in the total electricity consumption
18	I18	Corruption ranking of the country	dimensionless	

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Table A2 (*continued*)

S. N	Code	Indicator	Unit	Definition adopted in this study
19	I19	Total carbon emission from the total primary energy consumption	million tons/ Mtoe	Ratio of the total carbon emission to the total energy consumption
20	I20	Carbon intensity of electricity	tons/kWh	Carbon emission per unit generation of electricity
21	I21	Forest area as a share of the total land area	%	Share of forests to the total land area of the country

Appendix B. Supplementary data

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References

Abdullah, F. Bin, Iqbal, R., Jawaid, M., Memon, I., Mughal, S., Memon, F.S., Ali Rizvi, S.S., 2021. Energy security index of Pakistan (ESIOP). Energy Strategy Rev. https://doi.org/10.1016/j.esr.2021.100710.

ADB, 2007. Hydropower Development in India: A Sector Assessment. Asian Development Bank, Manila.

ADB, 2009. Building A Sustainable Energy Future: the Greater Mekong Subregion. Asian Development Bank, Manila.

ADB, 2017. Nepal Energy Sector Assessment, Strategy, and Roadmap. https://doi.org/10.22617/TCS178936-2. Manila, Philippines.

Amjath-Babu, T.S., Sharma, B., Brouwer, R., Rasul, G., Wahid, S.M., Neupane, N., Bhattarai, U., Sieber, S., 2019. Integrated modelling of the impacts of hydropower projects on the water-food-energy nexus in a transboundary Himalayan river basin. Appl. Energy 239, 494–503. https://doi.org/10.1016/j.apenergy.2019.01.147.

Ang, B.W., Choong, W.L., Ng, T.S., 2015a. A framework for evaluating Singapore's energy security. Appl. Energy 148, 314–325. https://doi.org/10.1016/j.apenergy.2015.03.088.

Ang, B.W., Choong, W.L., Ng, T.S., 2015b. Energy security: definitions, dimensions and indexes. Renew. Sustain. Energy Rev. https://doi.org/10.1016/j.rser.2014.10.064.

Aris, H., Jørgensen, B.N., 2020. ASEAN power grid 20 years after: an overview of its progress and achievements. In: IOP Conference Series: Earth and Environmental Science. Institute of Physics Publishing. https://doi.org/10.1088/1755-1315/463/1/012055.

Augutis, J., Krikštolaitis, R., Martišauskas, L., Pečiulytė, S., Žutautaitė, I., 2017. Integrated energy security assessment. Energy 138, 890–901. https://doi.org/10.1016/j.energy.2017.07.113.

Baniya, R., Talchabhadel, R., Panthi, J., Ghimire, G.R., Sharma, S., Khadka, P.D., Shin, S., Pokhrel, Y., Bhattarai, U., Prajapati, R., Thapa, B.R., 2023. Nepal Himalaya offers considerable potential for pumped storage hydropower. Sustain. Energy Technol. Assessments 60, 103423. https://doi.org/10.1016/j.seta.2023.103423.

Bhattarai, U., Devkota, L.P., Marahatta, S., Shrestha, D., Maraseni, T., 2022a. How will hydro-energy generation of the Nepalese Himalaya vary in the future? A climate change perspective. Environ. Res. 214, 113746 https://doi.org/10.1016/j.envres.2022.113746.

Bhattarai, U., Maraseni, T., Apan, A., 2022b. Assay of renewable energy transition: a systematic literature review. Sci. Total Environ. 833, 155159 https://doi.org/10.1016/j.scitotenv.2022.155159.

Bhattarai, U., Devkota, R., Maraseni, T., Devkota, L., Marahatta, S., 2023a. Attaining multiple sustainable development goals through storage hydropower development amidst community vulnerabilities. Sustain. Dev. https://doi.org/10.1002/sd.2634.

Bhattarai, U., Maraseni, T., Devkota, L.P., Apan, A., 2023b. Application of machine learning to assess people's perception of household energy in the developing world: a case of Nepal. Energy and AI 14, 100303. https://doi.org/10.1016/j.egyai.2023.100303.

Bhattarai, U., Maraseni, T., Apan, A., Devkota, L.P., 2023c. Rationalizing donations and subsidies: energy ecosystem development for sustainable renewable energy transition in Nepal. Energy Pol. 177, 113570 https://doi.org/10.1016/j.enpol.2023.113570.

Bhattarai, U., Maraseni, T., Devkota, L.P., Apan, A., 2024. Evaluating four decades of energy policy evolution of a South Asian country – Nepal: a comprehensive review. Sustain. Dev. (In Production). https://doi.org/10.1002/sd.3053.

Bompard, E., Carpignano, A., Erriquez, M., Grosso, D., Pession, M., Profumo, F., 2017. National energy security assessment in a geopolitical perspective. Energy 130, 144–154. https://doi.org/10.1016/j.energy.2017.04.108.

Chalvatzis, K.J., Ioannidis, A., 2017. Energy supply security in the EU: benchmarking diversity and dependence of primary energy. Appl. Energy 207, 465–476. https://doi.org/10.1016/j.apenergy.2017.07.010.

Chaudhary, D.R., 2023. Nepal-Bangladesh May Be Allowed to Trade Power through Indian Corridor [WWW Document]. The Economic Times. URL. https://economictimes.indiatimes.com/news/international/world-news/nepal-bangladesh-may-be-allowed-to-trade-power-through-indian-corridor/articleshow/97207571.cms?from=mdr, 1.22.23.

Chung, W.S., Kim, S.S., Moon, K.H., Lim, C.Y., Yun, S.W., 2017. A conceptual framework for energy security evaluation of power sources in South Korea. Energy 137, 1066–1074. https://doi.org/10.1016/j.energy.2017.03.108.

Deisenroth, M.P., Faisal, A.A., Ong, C., Soon, 2020. Mathematics for Machine Learning, first ed., Vol. 1. Cambridge University Press. https://mml-book.com.

Devkota, R., Bhattarai, U., Devkota, L., Maraseni, T.N., 2020. Assessing the past and adapting to future floods: a hydro-social analysis. Clim. Change 163, 1065–1082. https://doi.org/10.1007/s10584-020-02909-w.

Devkota, L.P., Bhattarai, U., Khatri, P., Marahatta, S., Shrestha, D., 2022. Resilience of hydropower plants to flow variation through the concept of flow elasticity of power: theoretical development. Renew. Energy 184, 920–932. https://doi.org/10.1016/j.renene.2021.11.051.

DoC/GoN, 2023. Nepal Foreign Trade Statistics Fiscal Year 2022/23 (2079/80). Department of Customs, Government, of Nepal.

Dominguez, C., Orehounig, K., Carmeliet, J., 2021. Understanding the path towards a clean energy transition and post-electrification patterns of rural households. Energy for Sustainable Development 61, 46–64. https://doi.org/10.1016/j.esd.2021.01.002.

Erahman, Q.F., Purwanto, W.W., Sudibandriyo, M., Hidayatno, A., 2016. An assessment of Indonesia's energy security index and comparison with seventy countries. Energy 111, 364–376. https://doi.org/10.1016/j.energy.2016.05.100.

ET, 2017. Nepal, China sign three pacts to boost energy, economic ties [WWW Document]. URL. https://economictimes.indiatimes.com/news/international/world-news/nepal-china-sign-three-pacts-to-boost-energy-economic-ties/articleshow/60075580.cms. (Accessed 8 April 2022).

Franki, V., Višković, A., 2015. Energy security, policy and technology in South East Europe: presenting and applying an energy security index to Croatia. Energy 90, 494–507. https://doi.org/10.1016/j.energy.2015.07.087.

García-Gusano, D., Iribarren, D., Garraín, D., 2017. Prospective analysis of energy security: a practical life-cycle approach focused on renewable power generation and oriented towards policy-makers. Appl. Energy 190, 891–901. https://doi.org/10.1016/j.apenergy.2017.01.011.

Gasser, P., 2020. A review on energy security indices to compare country performances. Energy Pol. https://doi.org/10.1016/j.enpol.2020.111339.

Gautam, B.R., Li, F., Ru, G., 2015. Assessment of urban roof top solar photovoltaic potential to solve power shortage problem in Nepal. Energy Build. 86, 735–744. https://doi.org/10.1016/j.enbuild.2014.10.038.

Gong, X., Wang, Y., Lin, B., 2021. Assessing dynamic China's energy security: based on functional data analysis. Energy 217. https://doi.org/10.1016/j.energy.2020.119324.
Gyanwali, K., Komiyama, R., Fujii, Y., 2020. Representing hydropower in the dynamic power sector model and assessing clean energy deployment in the power generation mix of Nepal. Energy 202. https://doi.org/10.1016/j.energy.2020.117795.
Gyanwali, K., Adhikari, P., Khanal, S., Bhattarai, N., Bajracharya, T.R., Komiyama, R., Fujii, Y., 2023. Integrating glacio-hydrological and power grid models to assess the climate-resiliency of high mountain hydropower in Nepal. Renew. Sustain. Energy Rev. 183, 113433.
Ha, L.T., Thanh, T.T., 2022. Global value chains and energy security: evidence from global sample. Energy Strategy Rev. 42 https://doi.org/10.1016/j.esr.2022.100870.
Hecht, J.S., Lacombe, G., Arias, M.E., Dang, T.D., Piman, T., 2019. Hydropower dams of the Mekong River basin: a review of their hydrological impacts. J. Hydrol. (Amst.). https://doi.org/10.1016/j.jhydrol.2018.10.045.
Huang, B., Zhang, L., Ma, L., Bai, W., Ren, J., 2021. Multi-criteria decision analysis of China's energy security from 2008 to 2017 based on Fuzzy BWM-DEA-AR model and Malmquist Productivity Index. Energy 228. https://doi.org/10.1016/j.energy.2021.120481.
Huda, M.S., Ali, S.H., 2018. Environmental peacebuilding in South Asia: establishing consensus on hydroelectric projects in the ganges-brahmaputra-meghna (GBM) basin. Geoforum 96, 160–171. https://doi.org/10.1016/j.geoforum.2018.08.015.
IEA, 2021. World Energy Model Documentation.
Iyke, B.N., Tran, V.T., Narayan, P.K., 2021. Can energy security predict energy stock returns? Energy Econ. 94 https://doi.org/10.1016/j.eneco.2020.105052.
Jewell, J., Cherp, A., Riahi, K., 2014. Energy security under de-carbonization scenarios: an assessment framework and evaluation under different technology and policy choices. Energy Pol. 65, 743–760. https://doi.org/10.1016/j.enpol.2013.10.051.
Khan, M.A.H., Thomson, B., Debnath, R., Motayed, A., Rao, M.v., 2020. Nanowire-based sensor array for detection of cross-sensitive gases using PCA and machine learning algorithms. IEEE Sensor. J. 20, 6020–6028. https://doi.org/10.1109/JSEN.2020.2972542.
Kilinç-Pala, P.B., 2021. Approaches in energy exclusive security: theories of energy security and the dominance of realism. Polit. Pol. 49, 771–794. https://doi.org/10.1111/polp.12411.
Le, T.H., Chang, Y., Taghizadeh-Hesary, F., Yoshino, N., 2019. Energy insecurity in Asia: a multi-dimensional analysis. Econ. Modell. 83, 84–95. https://doi.org/10.1016/j.econmod.2019.09.036.
Li, Y., Shi, X., Yao, L., 2016. Evaluating energy security of resource-poor economies: a modified principle component analysis approach. Energy Econ. 58, 211–221. https://doi.org/10.1016/j.eneco.2016.07.001.
Li, B., Nian, V., Shi, X., Li, H., Boey, A., 2020. Perspectives of energy transitions in east and Southeast Asia. Wiley Interdiscip Rev Energy Environ 9. https://doi.org/10.1002/wene.364.
Li, M., Wibowo, S., Li, W., Li, L.D., 2021. Quantitative spectral data analysis using extreme learning machines algorithm incorporated with pca. Algorithms 14. https://doi.org/10.3390/a14010018.
Lohani, S.P., Blakers, A., 2021. 100% renewable energy with pumped-hydro-energy storage in Nepal. Clean Energy. https://doi.org/10.1093/ce/zkab011.
Marahatta, S., Aryal, D., Devkota, L.P., Bhattarai, U., Shrestha, D., 2021. Application of Swat in Hydrological Simulation of Complex Mountainous River Basin (Part Ii: Climate Change Impact Assessment), vol. 13. https://doi.org/10.3390/w13111548. Water (Switzerland).
Marahatta, S., Bhattarai, U., Devkota, L.P., Aryal, D., 2022. Unravelling the water-energy-economics-continuum of hydroelectricity in the face of climate change. International Journal of Energy and Water Resources. https://doi.org/10.1007/s42108-021-00174-w.
Martchamadol, J., Kumar, S., 2013. An aggregated energy security performance indicator. Appl. Energy 103, 653–670. https://doi.org/10.1016/j.apenergy.2012.10.027.
Martchamadol, J., Kumar, S., 2014. The aggregated energy security performance indicator (AESPI) at national and provincial level. Appl. Energy 127, 219–238. https://doi.org/10.1016/j.apenergy.2014.04.045.
Matsumoto, K., Shiraki, H., 2018. Energy security performance in Japan under different socioeconomic and energy conditions. In: Renewable and Sustainable Energy Reviews, vol. 90. Elsevier Ltd, pp. 391–401. https://doi.org/10.1016/j.rser.2018.03.070.
Matsumoto, K., Doumpos, M., Andriosopoulos, K., 2018. Historical energy security performance in EU countries. Renew. Sustain. Energy Rev. https://doi.org/10.1016/j.rser.2017.06.058.
MoF/GoN, 2021. Economic Survey 2020/21. Ministry of Finance. Government of Nepal, Kathmandu, Nepal.
MoF/GoN, 2023. Economic Survey 2022/23. Ministry of Finance. Government of Nepal, Singh Durbar, Kathmandu, Nepal.
Mohsin, M., Zhou, P., Iqbal, N., Shah, S.A.A., 2018. Assessing oil supply security of South Asia. Energy 155, 438–447. https://doi.org/10.1016/j.energy.2018.04.116.
Muñoz, B., García-Verdugo, J., San-Martín, E., 2015. Quantifying the geopolitical dimension of energy risks: a tool for energy modelling and planning. Energy 82, 479–500. https://doi.org/10.1016/j.energy.2015.01.058.
Nag, T., 2021. Barriers to cross-border energy cooperation and implications on energy security: an Indian perspective with reference to energy trade in South Asia. Global Bus. Rev. 22, 1530–1552. https://doi.org/10.1177/0972150919826380.
Narula, K., Reddy, B.S., 2015. Three blind men and an elephant: the case of energy indices to measure energy security and energy sustainability. Energy 80, 148–158. https://doi.org/10.1016/j.energy.2014.11.055.
Narula, K., Reddy, B.S., 2016. A SES (sustainable energy security) index for developing countries. Energy 94, 326–343. https://doi.org/10.1016/j.energy.2015.10.106.
Narula, K., Sudhakara Reddy, B., Pachauri, S., 2015. Sustainable Energy Security for India: an assessment of energy demand sub-system. Appl. Energy 186, 126–139. https://doi.org/10.1016/j.apenergy.2016.02.142.
NEA/GoN, 2023. A Year in Review Fiscal Year 2022/23. Nepal Electricity Authority, Government of Nepal.
Nepal, R., Musibau, H.O., 2021. Energy security, renewable, non-renewable energy and economic growth in asean economies: new insights. Singapore Econ. Rev. 66, 457–488. https://doi.org/10.1142/S0217590819430045.
Pandey, N., de Coninck, H., Sagar, A.D., 2022. Beyond technology transfer: innovation cooperation to advance sustainable development in developing countries. Wiley Interdiscip Rev Energy Environ. https://doi.org/10.1002/wene.422.
Pandey, R., Shrestha, R., Bhattarai, N., Dhakal, R., 2023. Problems identification and performance analysis in small hydropower plants in Nepal. Int. J. Low Carbon Technol. 18, 561–569.
Papież, M., Śmiech, S., Frodyma, K., 2018. Determinants of renewable energy development in the EU countries. A 20-year perspective. Renew. Sustain. Energy Rev. https://doi.org/10.1016/j.rser.2018.04.075.
Parajuli, R., Østergaard, P.A., Dalgaard, T., Pokharel, G.R., 2014. Energy consumption projection of Nepal: an econometric approach. Renew. Energy 63, 432–444. https://doi.org/10.1016/j.renene.2013.09.048.
PIB/GoI, 2019. Inauguration of Motihari-Amlekhganj (Nepal) Pipeline by PM and PM Oli of Nepal [WWW Document]. Press Information Bureau. Government of India. URL. https://pib.gov.in/PressReleseDetail.aspx?PRID=1584627, 6.10.21.
Podbregar, I., Šimić, G., Radovanović, M., Filipović, S., Šprajc, P., 2020. International energy security risk index-analysis of the methodological settings. Energies 13. https://doi.org/10.3390/en13123234.
Pokharel, P., Regmi, R.K., 2024. Climate change and hydropower resilience in Nepal: an integrated modeling approach in the Madi River Basin. H2Open Journal 7 (2), 199–221.
Qazi, S., 2022. China out, India in. How power project diplomacy plays out in Nepal [WWW Document]. URL. https://www.trtworld.com/magazine/china-out-india-in-how-power-project-diplomacy-plays-out-in-nepal-60102, 8.28.22.
Radovanović, M., Filipović, S., Pavlović, D., 2017. Energy security measurement – a sustainable approach. Renew. Sustain. Energy Rev. https://doi.org/10.1016/j.rser.2016.02.010.
Radovanović, M., Filipović, S., Golušin, V., 2018. Geo-economic approach to energy security measurement – principal component analysis. Renew. Sustain. Energy Rev. https://doi.org/10.1016/j.rser.2017.06.072.

Reiche, D., 2010. Energy Policies of Gulf Cooperation Council (GCC) countries-possibilities and limitations of ecological modernization in rentier states. Energy Pol. 38, 2395–2403. https://doi.org/10.1016/j.enpol.2009.12.031.

Ren, J., Sovacool, B.K., 2014. Quantifying, measuring, and strategizing energy security: determining the most meaningful dimensions and metrics. Energy 76, 838–849. https://doi.org/10.1016/j.energy.2014.08.083.

Ritchie, H., Rosado, P., Roser, M., 2023. Energy [WWW Document]. URL https://ourworldindata.org/energy. (Accessed 4 May 2024).

Sanjel, N., Baral, B., 2019. A Review of Renewable Energy Sector of Nepal. International (SAARC) Youth Scientific Conference (IYSC) 2019, Conference Proceedings (Peer Reviewed), pp. 115–120.

Sanjel, N., Baral, B., Acharya, M., Gautam, S., 2019. Analytical modelling for optimized selection between renewable energy systems and the conventional grid expansion. J. Phys. Conf. 1266 (1), 012014. IOP Publishing.

Sapkota, S., Pandey, V.P., Bhattarai, U., Panday, S., Shrestha, S.R., Maharjan, S.B., 2021. Groundwater potential assessment using an integrated AHP-driven geospatial and field exploration approach applied to a hard-rock aquifer Himalayan watershed. J. Hydrol. Reg. Stud. 37 https://doi.org/10.1016/j.ejrh.2021.100914.

SAPP, 2021. Southern African Power Pool Energising the SADC Region for Economic Development 2021 Annual Report.

SARI/EI, 2017. Economic Benefits from Nepal-India Electricity Trade Analytical Study.

SARI/EI, 2020. Prospects of Regional Energy Cooperation and Cross Border Energy Trade in the BIMSTEC Region.

SARI/EI, 2021. Prospects for Sustainable Energy Infrastructure Development and Role of Cross Border Energy Trade in South Asia Challenges, Opportunities and Way Forward.

SARI/EI-IRADe, 2018. Gains from Multilateral Electricity Trade Among BBIN Countries Modelling Study.

SARI/EI-IRADe, 2021. Strategy Paper for Creation of South Asia Forum for Electricity Market (SAFEM).

SARI/EI/IRADe, 2021. SAFIR Working Group Study Report on Regulatory Interventions for Grid Discipline and Grid Reliability in the South Asian Region (SAR).

Shaik, T., Tao, X., Higgins, N., Gururajan, R., Li, Y., Zhou, X., Acharya, U.R., 2022. FedStack: personalized activity monitoring using stacked federated learning. Knowl. Base Syst. 257, 109929.

Shakya, S.R., Adhikari, R., Poudel, S., Rupakheti, M., 2022. Energy equity as a major driver of energy intensity in South Asia. Renew. Sustain. Energy Rev. 170 https://doi.org/10.1016/j.rser.2022.112994.

Shakya, S.R., Nakarmi, A.M., Prajapati, A., Pradhan, B.B., Rajbhandari, U.S., Rupakheti, M., Lawrence, M.G., 2023. Environmental, energy security, and energy equity (3E) benefits of net-zero emission strategy in a developing country: a case study of Nepal. Energy Rep. 9, 2359–2371.

Sharifuddin, S., 2014. Methodology for quantitatively assessing the energy security of Malaysia and other southeast asian countries. Energy Pol. 65, 574–582. https://doi.org/10.1016/j.enpol.2013.09.065.

Sharma, R.H., Awal, R., 2013. Hydropower development in Nepal. Renew. Sustain. Energy Rev. 21, 684–693. https://doi.org/10.1016/j.rser.2013.01.013.

Sharma, B., Shrestha, A., 2023. Petroleum dependence in developing countries with an emphasis on Nepal and potential keys. Energy Strategy Rev. 45, 101053.

Shrestha, P.M., 2023. Nepal and Bangladesh lobby India for corridor to trade electricity [WWW Document]. The Kathmandu Post. URL https://kathmandupost.com/national/2023/01/12/nepal-and-bangladesh-lobby-india-for-corridor-to-trade-electricity, 3.10.23.

Šimić, G., Radovanović, M., Filipović, S., Mirković Isaeva, O., 2021. Fuzzy logic approach in energy security decision-making: "ESecFuzzy" software application. Soft Comput. 25, 10813–10828. https://doi.org/10.1007/s00500-021-05976-y.

Sovacool, B.K., 2011. Evaluating energy security in the Asia pacific: towards a more comprehensive approach. Energy Pol. 39 (11), 7472–7479. https://doi.org/10.1016/j.enpol.2010.10.008.

Sovacool, B.K., 2013. An international assessment of energy security performance. Ecol. Econ. 88, 148–158. https://doi.org/10.1016/j.ecolecon.2013.01.019.

Sovacool, B.K., Mukherjee, I., 2011. Conceptualizing and measuring energy security: a synthesized approach. Energy 36 (8), 5343–5355. https://doi.org/10.1016/j.energy.2011.06.043.

Storm, H., Baylis, K., Heckelei, T., 2020. Machine learning in agricultural and applied economics. Eur. Rev. Agric. Econ. 47, 849–892. https://doi.org/10.1093/erae/jbz033.

Tripathi, D., 2020. Re-imagining Border Studies in South Asia, First. Routledge.

UN, 2020. The Sustainable Development Goals Report. New York.

USAID-SARI, 2003. Economic Impact of Poor Power Quality on Industry Nepal Economic Impact of Poor Power Quality on Industry Nepal.

USEA, 2012. Azerbaijan-Georgia-Turkey AGT Power Bridge Project Working Group Phase II Final Report Study of the Technical Potential for Trade of Electricity between the Countries of Azerbaijan, Georgia and Turkey. Washington DC.

Vivoda, V., 2010. Evaluating energy security in the Asia-Pacific region: a novel methodological approach. Energy Pol. 38, 5258–5263. https://doi.org/10.1016/j.enpol.2010.05.028.

Wang, Q., Zhou, K., 2017. A framework for evaluating global national energy security. Appl. Energy 188, 19–31. https://doi.org/10.1016/j.apenergy.2016.11.116.

Wang, J., Mohammed, A.S., Macioszek, E., Ali, M., Ulrikh, D.V., Fang, Q., 2022. A novel combination of PCA and machine learning techniques to select the most important factors for predicting tunnel construction performance. Buildings 12, 919. https://doi.org/10.3390/buildings12070919.

WAPP, 2021. Annual Report 2021 West African Power Pool.

WB, 2013. Toward a Sustainable Energy Future for All. The World Bank.

WEC, 2021. World Energy Trilemma Index 2021. World Energy Council. Wales.

WECS/GoN, 2010. Energy sector synopsis report. In: Water and Energy Commission Secretariat, Government of Nepal, Singha Durbar, Kathmandu, Nepal.

WECS/GoN, 2011. Water resources of Nepal in the context of climate change. Water and Energy Commission Secretariat, Government of Nepal, Singha Durbar, Kathmandu, Nepal.

WECS/GoN, 2013. Nepal's Energy Sector Vision 2050 A.D. Water and Energy Commission Secretariat. Government of Nepal, Singha Durbar, Kathmandu, Nepal.

WECS/GoN, 2023. Nepal Energy Sector Synopsis Report-2023. Water and Energy Commission Secretariat, Government of Nepal, Singhadurbar, Kathmandu, Nepal.

Weko, S., Goldthau, A., 2022. Bridging the low-carbon technology gap? Assessing energy initiatives for the Global South. Energy Pol. 169 https://doi.org/10.1016/j.enpol.2022.113192.

Williams, B., Onsman, A., Brown, T., Andrys Onsman, P., Ted Brown, P., 2010. Exploratory factor analysis: a five-step guide for novices. Journal of Emergency Primary Health Care (JEPHC) 8, 990399.

World Bank, 2024. World Bank National Accounts Data, and OECD National Accounts Data Files. Webpage. https://data.worldbank.org/indicator/NY.GDP.MKTP.CD?locations=NP&msclkid=c583c33ad00811ec9a96c3a8dce184bf. (Accessed 29 April 2024).

Xu, J., Ni, T., 2017. Integrated technological paradigm-based soft paths towards sustainable development of small hydropower. Renew. Sustain. Energy Rev. https://doi.org/10.1016/j.rser.2016.11.021.

Xu, R., Zeng, Z., Pan, M., Ziegler, A.D., Holden, J., Spracklen, D.V., Brown, L.E., He, X., Chen, D., Ye, B., Xu, H., Jerez, S., Zheng, C., Liu, J., Lin, P., Yang, Y., Zou, J., Wang, D., Gu, M., Yang, Z., Li, D., Huang, J., Lakshmi, V., Wood, EricF., 2023. A global-scale framework for hydropower development incorporating strict environmental constraints. Nature Water 1, 113–122. https://doi.org/10.1038/s44221-022-00004-1.

Yong, G.A., Pearce, S., 2013. A beginner's guide to factor analysis: focusing on exploratory factor analysis. Tutor Quant Methods Psychol 9, 79–94.

Zeng, S., Streimikiene, D., Baležentis, T., 2017. Review of and comparative assessment of energy security in Baltic States. Renew. Sustain. Energy Rev. 76, 185–192. https://doi.org/10.1016/j.rser.2017.03.037.

Zou, X., Pradhan, S., Mukhia, A., 2022. Nepal's hydropower development: predicament and dilemma in policy-making. Nat. Resour. Forum 46, 60–72. https://doi.org/10.1111/1477-8947.12241.

4.3 Links and implications

This paper shows that Nepal has been under a 'pseudo energy secure' condition during the last few decades. The country's domestic sector is over-reliant on traditional fuels while the energy intensive development activities in all the productive sectors of the economy are largely suppressed. It is completely governed by an 'import-as-needed' modality for meeting its energy demands. Moreover, the growth in the energy demand is met only marginally by domestic hydropower and other renewables. From this analysis, I found that such an energy system is not sustainable in the long run. Despite some possibilities, cross-border electricity trading to the neighbouring energy hungry countries is economically difficult and technically challenging. But such benefits can be realized through considerable infrastructural development, strengthening of institutional capacity bolstered by genuine political commitment and trust between the participating countries. Moreover, supportive policies play the central role. Hence, a detailed review of the Nepalese energy policy context is necessary which has been carried out in the subsequent paper (Paper #3).

CHAPTER 5: PAPER 3 – EVALUATING FOUR DECADES OF ENERGY POLICY EVOLUTION FOR SUSTAINABLE DEVELOPMENT OF A SOUTH ASIAN COUNTRY - NEPAL: A COMPREHENSIVE REVIEW

5.1 Introduction

This paper (Paper #3) applies a robust methodology to examine how energy policies of Nepal have evolved over the last four decades. I have identified the major achievements the policies have made and also the shortcomings they have suffered during the evolution. This paper directly contributes to the first objective of my research by increasing our understanding of the underlying policy related issues of Nepal.

5.2 Published paper

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Evaluating four decades of energy policy evolution for sustainable development of a South Asian country—Nepal: A comprehensive review

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Abstract

In this study, we assessed the accomplishments and shortcomings of an exhaustive collection of energy policies of Nepal over four decades, using a five-dimensional energy security framework (availability, affordability, technology, sustainability and governance) for sustainable development. We adopted a mixed-method approach involving thorough review of 70 policy documents (1984–2022), systematic review of 86 peer-reviewed journal articles on Nepal's energy policy, and consultations with 11 experts. Our evaluation shows that while there is a progressive trend, Nepal's energy policies face challenges of political instability, governance issues, siloed development practices, lagging research and development, inefficient energy demand management, and heavy reliance on international support. Additionally, we offer four tailored recommendations for the related stakeholders: supply-side management, demand-side management, multi-sector collaboration, and political stability and good governance. The insights and recommendations we provide have significant regional implications, particularly in the context of potential cross-border clean electricity sharing in South Asia.

KEYWORDS

energy policy, energy security framework, mixed-method, review, South Asia, sustainable development

1 | INTRODUCTION

Energy is a nation's building block as well as a gauge to measure its development (Adedoyin et al., 2020; Saidi & Hammami, 2015). Moreover, economic development and energy consumption have a bi-directional cyclic relationship (Chen, Mamon, et al., 2023; Devkota et al., 2022; Mohsin et al., 2021). Therefore, sustainable development needs to holistically consider economic progress, social evolution and environmental safeguarding (Safi et al., 2023). However, developing countries are lagging behind in their development feats, energy being one of the most impacted sectors (Dominguez et al., 2021; Fadly, 2019; Gebreslassie et al., 2022). Equally important, but generally overlooked in these regions, are policies (Aryal et al., 2021; Hartono et al., 2023; Laudari et al., 2020; Maraseni et al., 2019). An effective policy analysis requires a framework that considers multiple objectives, sectors, dynamic interdependencies, uncertainties, and unquantifiable impacts (Heazle & Pillar, 2012). Studies such as Tidwell and Tidwell (2018) build on 'sociotechnical imaginaries' and

Wittmayer et al. (2022) on 'social innovation' to emphasize the need for valuing the general public in policy making instead of only sectoral experts, state and international interventions. Concepts of 'policy paradigms' have been popular in assessing the ways policymakers' ideas are translated into policies through the institutions they represent (Zittoun, 2015).

Although the implementation of policies follows a top-down approach, their formulation and regular revisions ideally require bottom-up trajectories to achieve the desired targets (Pandey & Sharma, 2021; Wu, 2020). Timely incorporating changes in the national level policies concurrent with the global and regional development allows for assessing and reacting to the contemporary needs for national benefits. Iconic studies such as Hall (1993) conceptualized how polices change with the help of *orders* ('first', 'second' and 'third'), in terms of the magnitude of their change. Similarly, some researchers have defined the *mechanisms* of policy change occurrence ('cyclical', 'dialectic', 'linear' and 'teleological') (Capano & Howlett, 2009) while some explain the different *modes* of change (such as 'layering', 'drift' and 'conversion') that policies undergo over a time period (Vij et al., 2018). Scholars have used the notion of 'energy imaginaries' and 'transnational assemblages' to explore how energy aid interventions and bilateral relations are responsible for the changes in policy and implementation levels (Movik & Allouche, 2020). No matter which order, mechanism or mode the change follows, policies are usually guided by public demands. In the case of the global north, people are generally well aware of their rights and needs and are actively involved in policy making (for example as shown by Hill & Connelly, 2018; Johnstone et al., 2020; Sattler et al., 2018; and Borozan, 2022). However, the case is usually different for the global south where illiteracy and unawareness among the general public are dominant leading to striking global north–south disparities in the energy sector and policy making process (Abbas et al., 2022; Lohani et al., 2022; Mittal, 2022; Shakya, Adhikari, et al., 2022; Weko & Goldthau, 2022).

Studies have investigated the varying roles of multiple actors in the policy making process. The influential groups, consisting mostly of politicians and elites, senior bureaucrats, with active involvement of non-government organizations and donors generally influence the public policies in the developing world (Aryal et al., 2021; Vij et al., 2018). Involvement of civil societies, private sector and general public to an extent of persuasion is rather theoretical (Liao et al., 2021; Pandey & Sharma, 2021), although legitimacy of the policies comes through the parliament (which is considered "for the people and by the people"). This leads to delaying of the development activities, which in turn increases the disparity among rich and poor (Hashemi, 2021; Vanegas Cantarero, 2020): it becomes a vicious cycle. Moreover, innovative policies through 'constructive technology assessment', 'responsible research and innovation', and 'transformative change' have been proposed by scholars (Sovacool et al., 2020).

Researchers have explained energy as an indispensable resource for overall development and stress the need for focusing on accessibility and efficiency considering the heterogeneity in supply and demand (Verma et al., 2024). Moreover, the 'energy ladder' hypothesis assumes that as the economic condition gets better, people tend to switch to modern and efficient energy technologies from traditional sources (Dominguez et al., 2021). Recent studies (for example, Sofian et al., 2024) have shown immense possibilities of renewable energy technologies, particularly solar and wind in fulfilling global energy demands and sustainable goals. However, scholars also illustrate the necessity to go beyond solar and wind into other renewables for a sustainable future (Rastegar et al., 2024). Taking the case of developed countries, Pi et al. (2024) not only showed that energy efficiency has a leading role in attaining environmental sustainability but also highlighted the importance of green energy policies to ensure sustainable development. Interestingly, Fan et al. (2024) revealed a strong relationship between energy poverty and health, the vulnerability being higher in the developed countries. Likewise, Adebayo and Ullah (2024) demonstrated the necessity to adopt comprehensive approaches to prioritize energy efficiency, increase use of renewable energy in the generation mix and enhance sustainable urbanization to achieve sustainable development in Sweden. Adha et al. 2024) assessed the dynamic impact of energy efficiency on economic growth and pointed out high levels of energy inefficiencies currently existing in the ASEAN region. Furthermore, Gautam and Bolia (2024) presented the adoption of electric vehicles as a promising intervention for sustainable urban development in India. Similarly, post-COVID studies have shown that energy efficiency measures through technological advancements, supportive policies and collaborative actions have a huge potential for sustainable and resilient energy future (Gorina et al., 2024; Pinczynski et al., 2024). Moreover, collaborative efforts from different sectors of the economy are crucial for achieving energy security and ultimately leading to sustainable development. Hence, we build upon the notion that sustainable development is achieved through combined actions across multiple disciplines (Ruan et al., 2023), among which energy policies play an integral role.

In this paper, we examine the dynamics of energy policies of Nepal — a land-locked developing country in south Asia — during the last four decades. Nepal has been struggling to meet the increasing energy demands through traditional fuels, imported fossil fuels and power rationing (MoF/GoN, 2023; NEA, 2023; WECS/GoN, 2023). As Movik and Allouche (2020) mention, Nepal has had to go through a 'chaotic fragmentation of the energy landscape'. Shakya, Bajracharya, et al. (2022) further point out the role of diesel generated electricity, in substantiating the supply of grid electricity in the commercial areas of Nepal but at the cost of immense fuel import expenses, high levels of air pollution leading to health hazards, adverse impacts on the crops and the overall environment in the absence of amicable policy settings. Aryal et al. (2023) demonstrated integrating end-use electrification and cross-border electricity trade could be highly beneficial from the energy security, environment and financial perspective of Nepal and recommend enabling supportive energy policies. However, there is limited research in Nepal providing policy inputs to the energy sector (NEO22, 2022). There are some studies which explore energy poverty in the developing countries (such as Abbas et al., 2022; Haldar et al., 2023; Shakya, Adhikari, et al., 2022), and cross-border energy/electricity trade possibilities in the South Asian region, for example by Huda and McDonald (2016), Hussain et al. (2019), Mittal (2022) and Saklani et al. (2020). These publications touch upon some aspects of policies, for instance the socio-hydrology by Jaramillo et al. (2018); people's perceptions of energy technologies (Bhattarai, Maraseni, Devkota, & Apan, 2023; Shrestha, Jirakiattikul, Lohani, & Shrestha, 2023); econometrics of energy by Parajuli et al. (2014) and Pokharel (2007); preference of fuels by Koirala and Acharya (2022) and Joshi and Bohara (2017); willingness-to-pay for cooking fuels by Das et al. (2022); power and politics by Suhardiman et al. (2014); pollution and environmental implications related to energy consumption by Raihan and Tuspekova (2022), Sharma and Shrestha (2023), and Shrestha and Dhakal (2019); issues of gender equality and social inclusion in energy policies (Buchy & Shakya, 2023; Khadka et al., 2024); possible co-benefits of demand side management with microgrids of diesel generators and solar PV for energy security (Shakya, Bajracharya, et al., 2022); climate change by Suman (2021); ethnicity/caste-based differentiation in household energy (Nepal et al., 2023; Rahut et al., 2022); and ineffectiveness of donations and subsidies in the energy sector by Bhattarai, Maraseni, Apan, and Devkota (2023). These all follow a piecemeal approach, which have missed portraying the larger picture and therefore have limited policy implications. Furthermore, Baniya et al. (2021) highlights the lack of country-specific studies on policy changes, particularly in the Global South. Moreover, trailing the entire energy development pathway of Nepal over a substantial time-window with a comprehensive holistic "socio-technological perspective" of policy assessments and implications is missing. We aim to address this much needed research gap.

Hence, the overarching objective of this study is to critically examine the energy related polices of Nepal over the last four decades. Specifically, we focus on the following:

1. Synthesizing the progression, achievement, and limitations of the examined policies
2. Identifying current challenges and providing a way forward for sustainable energy future of Nepal

We evaluated the performance of different energy policies developed over time based on the energy security framework encompassing five broad dimensions (availability, affordability, technology development, sustainability and governance) prescribed by Sovacool and Mukherjee (2011). A mixed method of literature review and expert consultations was adopted.

To the knowledge of the authors, this is the first study carrying out such a comprehensive review of policy documents related to the energy sector of Nepal over the last four decades (1984–2022). Therefore, we have two distinct contributions from this study. First, Nepal is one of the least energy consuming (MoF/GoN, 2021) and carbon emitting countries in the world (WB, 2024). Although the current emissions are very less, with future economic development, a sharp increase in energy use and associated emissions can be expected for Nepal. However, studies have shown that the current fuel consumption pattern of Nepal is unsustainable (NEO22, 2022). Hence, this will be a timely study in orienting Nepal's energy development towards a direction that is sustainable. Second, this paper is a significant addition to the energy scholarship of South Asia, in general and Nepal, in particular. Interestingly, a recent study shows that two-thirds of the untapped global hydropower potential is in the Himalayas (Xu et al., 2023) among which Nepal has a significant contribution possibility (Gyanwali et al., 2020; Zou et al., 2022). Moreover, past studies on hydropower development in Nepal with future cross-border electricity trade prospects are encouraging (SARI/EI-IRADe, 2021; SARI/EI/IRADe, 2018; SARI/EI, 2020; Hussain et al., 2019). Therefore, the analysis and recommendations we provide can have regional level significance because of the common socioeconomic, physiographic and political settings across the neighboring countries, particularly for regional energy sharing.

2 | METHODOLOGY

2.1 | Study area

Nepal is a mountainous country situated between India and China (Figure 1): two largest growing economies of the world. Nepal has a very small economy with a GDP of 41.39 billion USD (FY 2022/23) (MoF/GoN, 2023), which is about 1% of South Asia and 0.04% of the world values (WB, 2024). The total annual energy consumption of the country was 14.943 million tons of oil equivalent (toe) in the fiscal year 2022/2023 (WECS/GoN, 2023). Moreover, annual electricity consumption of Nepal was 6789 GWh with a peak demand of 1870 MW (MoF/GoN, 2023; NEA/GoN, 2023). The largest electricity consuming sector was residential (36.6%, 2485 GWh) followed by the industrial sector (30.7%, 2084 GWh) (MoF/GoN, 2023). The total installed power capacity of the country stands at 2666 MW until the end of the FY 2022/23, out of which, 2449 MW is generated from large hydroelectric projects, 75 MW from solar, 53.4 MW from thermal 82 MW from smaller renewable technologies and 6 MW through co-generation technologies from sugar mills (MoF/GoN, 2023).

2.2 | Theoretical background

In this study, we have adopted a comprehensive energy security assessment framework by Sovacool and Mukherjee (2011) to examine the energy policy arena of Nepal. This theory has evolved over time (Sovacool, 2012) and its multiple variants have been used by scholars for different research needs. For example, Sovacool (2013) presented the energy security of a country as an interconnection of availability, affordability, efficiency, sustainability and governance in presenting the case of 18 countries; Narula (2013) assessed four dimensions: availability, acceptability, affordability and efficiency to quantify energy security of India; GIZ (2013) examined the pattern of household fuel usage of eight developing countries using aspects of accessibility, affordability and acceptability; Islar et al. (2017) applied the energy-justice-framework to examine some specific rural energy

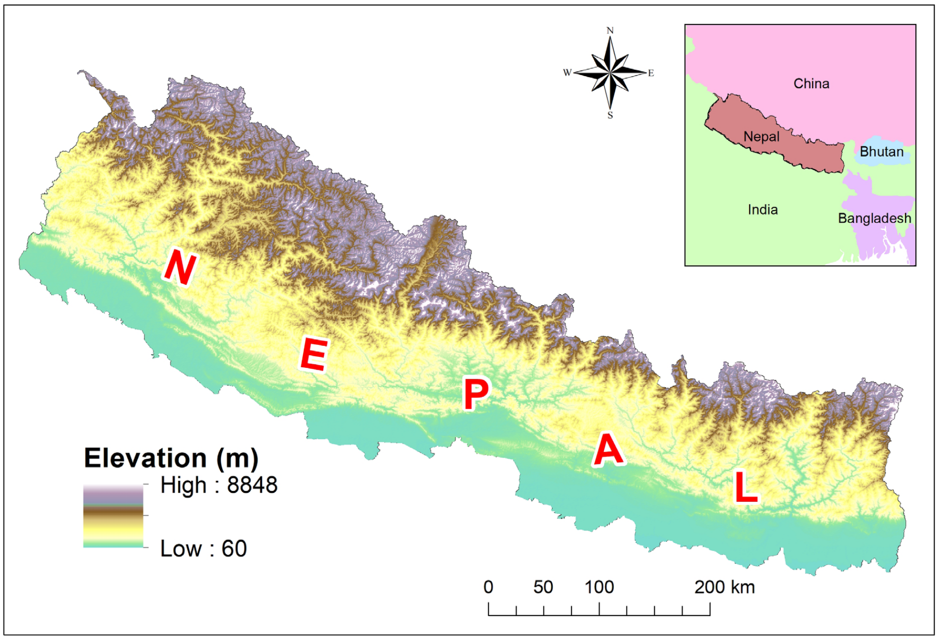

FIGURE 1 Geographical setting of Nepal.

policies in Nepal; and the 4-A (availability, applicability, acceptability, affordability) framework was applied by Malik et al. (2020) for assessing energy security of Pakistan. However, we have chosen the fundamental version of the framework in our case for holistically analyzing the entire energy policy sector of Nepal and providing an unbiased overview of its progression, achievements and limitations. Adapted from Sovacool and Mukherjee (2011), we list below the five dimensions that form the core of our study:

i. *Availability*: This dimension deals with sufficiency and security of energy for all. It further looks into diversification of the energy mix promoting energy sources available domestically.
ii. *Affordability*: This dimension is associated with concerns of generating energy at the lowest cost, enabling equitable access to energy for all, whether rich or poor. It also deals with transparency in pricing and predictability of energy and fuels.
iii. *Technology*: This dimension considers the capacity of the nation to adapt to changing technologies and increasing energy efficiency maintaining high levels of safety, reliability, resilience, investment and employment. It is also associated with research and innovation in energy technologies for achieving better energy efficiency.
iv. *Sustainability*: This dimension is concerned with the environmental and social sustainability of the energy sector. It is also related to concerns of climate change and its mitigation and adaptation.
v. *Governance*: This dimension focuses on principles of rule of law and human rights leading to good governance by emphasizing participatory modes in energy development. It further deals with institutionalization, accountability towards the people, legitimacy of the activities, geopolitics, competition and national/international markets in addition to community level knowledge enhancement.

2.3 | Methods

Mix-methods have been a popular choice among researchers for policy analysis. For instance, Sovacool and Mukherjee (2011) adopted a mix-method approach to develop a practical framework for assessment of energy security with global applicability. Likewise, Movik and Allouche (2020) used mixed-methods approach to examine the historical roles of foreign aid in the energy sector development of low-income countries such as Nepal. A similar method was used by Aryal et al. (2021) for discussing the actors shaping the environmental policy, and by Laudari et al. (2020) for assessing the policy and institutional shifts in Nepal's forestry policy regime. Likewise, Bhattarai et al. (2021) adopted a mix method to analyze ecosystem-based adaptation policies while Pandey and Sharma (2021) implemented a similar process to assess the climate resilient development of Nepal. Therefore, we have adopted a mix-method of literature review and expert consultation for this research. Mix-methods bear high significance as there are a limited number of publications in the energy sector of Nepal and therefore, knowledge shared by experts are extremely important. The workflow of our study is presented in Figure 2 and the methodological steps are explained in the following sections.

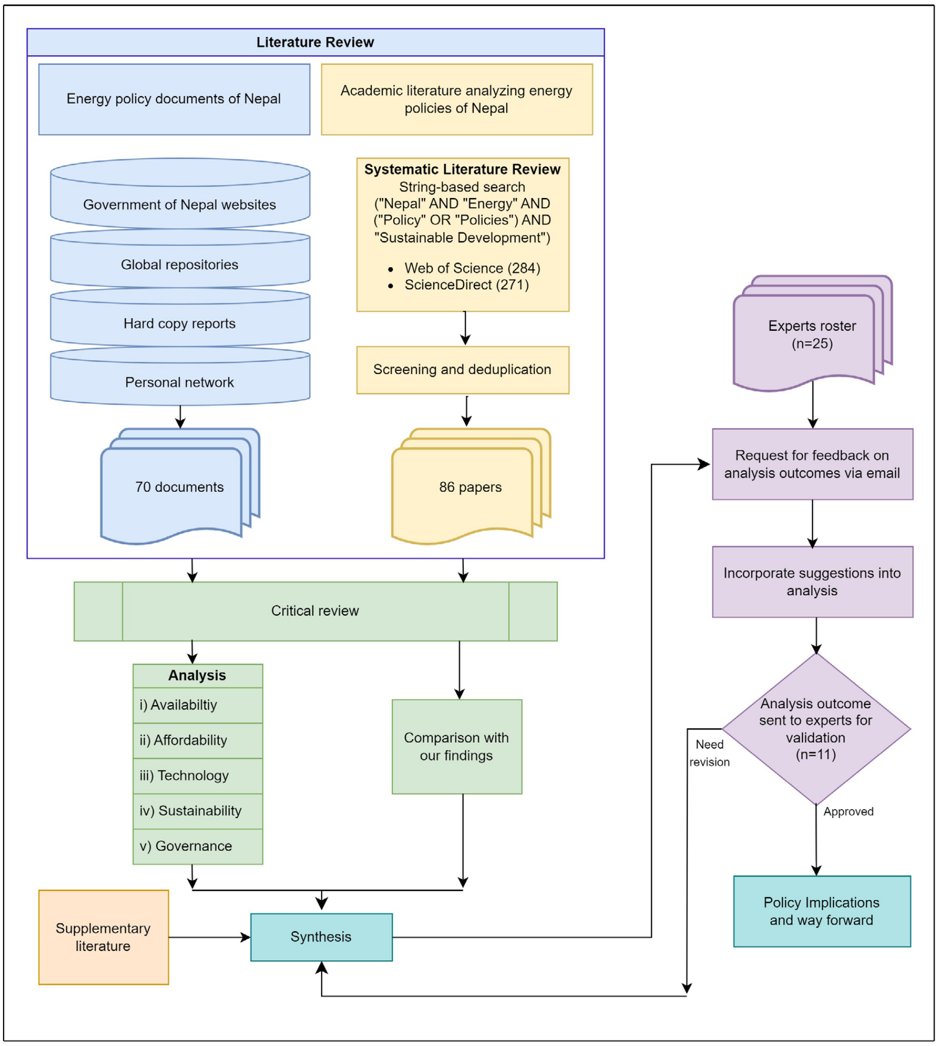

FIGURE 2 Methodological flow diagram.

Literature review consisted of two parts. First, we acquired all the policy documents related to the energy sector of Nepal from 1984 to 2022 through online sources of the Government of Nepal (GoN), international repositories, hard copy reports from the concerned ministries/departments, and through personal networks of the authors who have a considerable experience working in the energy and natural resources sectors of Nepal. For a document to be considered in our list, it should contain at least one statement/clause (or sub-clause) related to energy. This led to the compilation of an exhaustive set of 70 policy documents (listed in Tables A1 and A2; chronological progression presented in Section 3.1). The strengths and achievements of all these policy documents were qualitatively evaluated.

The systematic literature review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) framework (Moher et al., 2010; Rethlefsen et al., 2021). This framework is mostly used in engineering, environment, physical and social sciences (Adeyinka-Ojo, 2016; Adhikari et al., 2024). *ScienceDirect* and *Web of Science* databases have an exhaustive collection of scientific articles published across different disciplines. Moreover, high quality research articles from both open-access and subscription modes are indexed in these databases (Azril et al., 2018). The application of these databases has been recommended by many researchers carrying out systematic literature review (for instance, Aryal et al. (2022) in forestry; Adhikari et al. (2024) and Bhattarai, Maraseni, and Apan (2022) in renewable energy; Bibri (2021) in engineering and infrastructure development; Budhathoki et al. (2024) in agriculture; Maina et al. (2021) in medicine; Hoffmann et al. (2020) in environmental science; and McKeown and Mir (2021) in data science, among others). Our search included published peer-reviewed (original and review) articles in English, excluding books and book series, conference proceedings, editorials, letters, patents, working reports and research notes. Moreover, peer-reviewed journals maintain the scientific credibility and high level of quality of their published papers (Bhattarai, Maraseni, & Apan, 2022). In our search, the first level keyword search yielded 6745 hits from *ScienceDirect* and 503 from *Web of Science* databases, respectively. The title-abstract-keyword level refining led to 284 and 271 articles from the two databases, respectively (Figure 2). The list was further manually screened based on whether they discussed policies and relevancy to our paper through abstract level reading. This list was imported to *EndNote* (in *.ris* format) and deduplication was carried out using the freely available online tool—*IEBH Systematic Review Accelerator* (https://www.sr-accelerator.com/#/) leading to the final retention of 86 articles (Supplementary Material S2) which were reviewed in entirety. Additionally, the study was supplemented by other publications providing significant inputs to our review and discussion. Data extraction from the reviewed publications and analysis were carried out applying statistical and visualization tools in *MS-Excel*. Qualitative investigation was done manually based on judgment and the experience of the authors and bolstered by expert interviews.

The next step consisted of identifying a roster of high-level Nepalese experts who are abreast with the overall energy development of Nepal. After extensive research and series of consultations with key informants, a list of 25 experts from Nepal consisting of academicians, senior government officials (bureaucrats and technocrats, in-service and retired), senior experts from the private sector (mainly NGOs and INGOs) and senior practitioners was developed. The criteria for inclusion in our roster were: (i) the expert had to be well acquainted with energy development in Nepal; and (ii) the expert had to have a professional career of at least 15 years in this field. We shared the preliminary results of our review with all the identified experts through email during December 2022 to February 2023 requesting them for their critical feedback on different aspects through a questionnaire (Supplementary Material S1). This expert consultation was carried out adhering to the Human Ethics Approval (HREC ID H22REA258) from the University of Southern Queensland, Australia. However, only 17 experts got back out of the 25 whom we had reached out to. Among them, six did not provide specific feedback. Hence, we considered the critical comments from 11 experts (Supplementary Material S3). After incorporating their suggestions into our analysis, we further shared our findings with them a second time for validation.

3 | RESULTS

3.1 | Chronological progression of energy policies

A progressive trend can be seen in the number of energy related policies that have been formulated in Nepal over the last four decades (Figures 3, 4). Additional details of their sectoral coverage, technologies, legal arrangements, research focus, promotion of private sector and international collaboration, and organizations involved in the preparation of these documents are presented in Table A1. Interestingly, a direct correlation can be seen in the cumulative number of policies and electricity development trend in the last four decades with 486 GWh in 1986 to 12,369 GWh in 2023 (Figure 3). Although a sharp demarcation is difficult, it can be seen that Nepal's energy sector has broadly evolved through six distinct periods continuously building on the achievements of the preceding ones. These six epochs are discussed below.

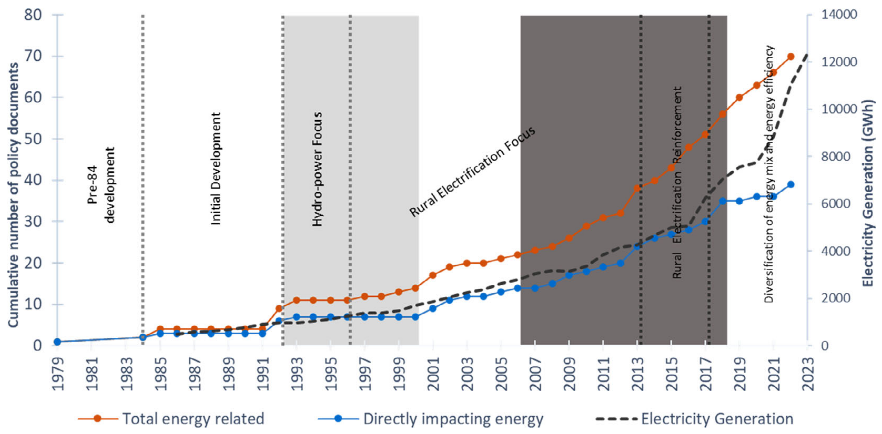

FIGURE 3 Progression of energy related policies and electricity generation in Nepal split into six epochs (shown by the dotted vertical lines). Shaded blocks represent years with electricity 'loadshedding'. The epoch 2006–2018 (dark gray) had up to 16 h while 1992–2000 (light gray) had lesser number of hours of loadshedding daily.

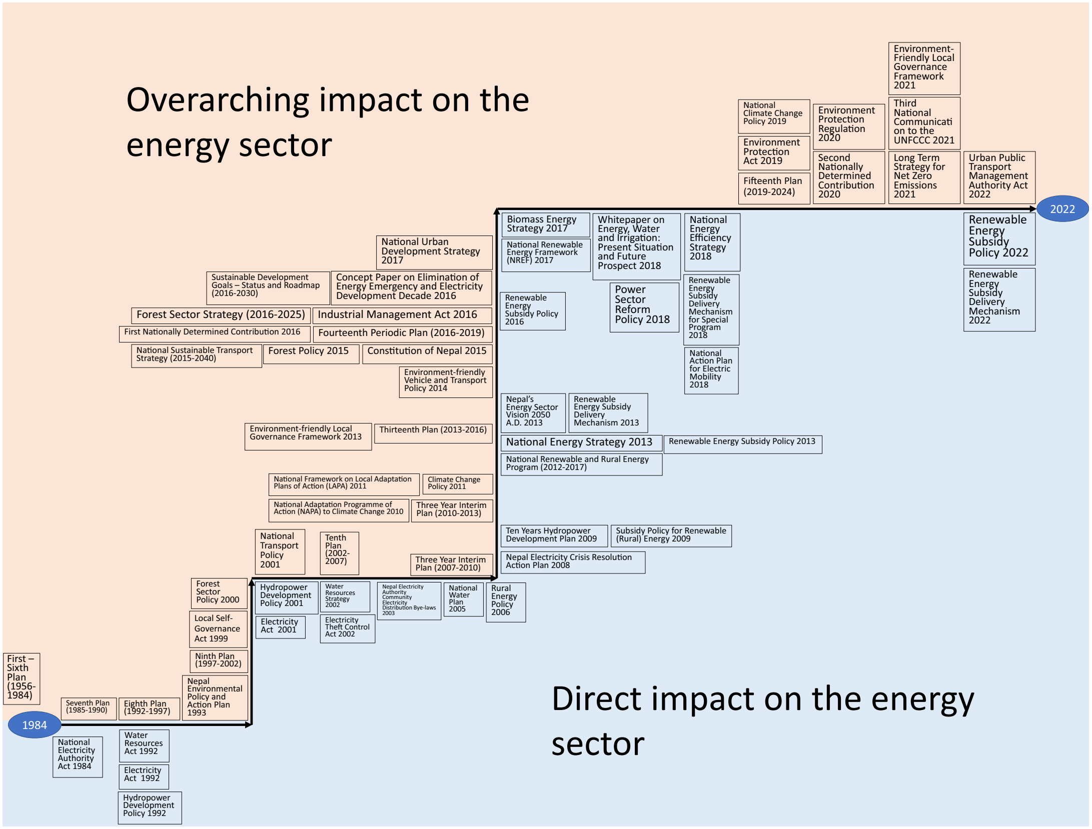

FIGURE 4 Timeline of policies in Nepal from 1984 to 2022 which are directly related to (light blue background) or have overarching impacts (light brown background) on the energy sector.

(i) Pre-84 development: Nepal has always been dependent on traditional agriculture-based fuels for meeting its energy demands. Interestingly, people in Nepal have used hydropower for centuries mainly for milling and grinding grains. The country had a head start in hydroelectricity generation with the first hydro-project (500 kW Pharping Hydropower Plant) commissioned in 1911 (Sharma & Awal, 2013). It was one of the earliest hydropower development projects in Asia. Unfortunately, Nepal could not maintain this momentum. The project was constructed by the Rana rulers during that time for supplying electricity to their Singhadurbar palace located in the centre of the capital city Kathmandu. The general public had no access to this electricity. The second hydropower plant (600 kW Sundarijal) was built in 1934. Only after the construction of the 2.4 MW Panauti project in 1965, electricity became accessible for public use. There were few additions to the hydropower fleet until the early 1980s and the installed capacity of the country became 120 MW (Sharma & Awal, 2013). This period can be considered an elite- and capital-centered development of the energy (mainly electricity) sector.

(ii) Initial development (1984–1992): From the energy standpoint, the Nepal Electricity Authority Act 1984 can be considered a first milestone for modern Nepal. Although the Gandaki River Basin Power Study was conducted in 1979, the plan was not immediately materialized. The Nepal Electricity Act 1984 provisioned the establishment of the Nepal Electricity Authority (NEA, previously functioning as National Electricity Department) to make arrangements for efficient and reliable electricity generation and distribution throughout the country. The Seventh (1985) and Eighth National Plans (1992) envisioned hydropower development and research on water resources and energy. Alternative energy was introduced in the national policy framework instigating policies for micro-hydro, biogas, solar and wind technologies. Improvements in cooking stoves, small water turbines and water mills by providing subsidies and credit facilities were also provisioned.

(iii) Hydropower focus (1992–1996): The Electricity Act 1992 focused on the management of electricity with licensing arrangements. Endorsement of the Hydropower Development Policy 1992 by the Electricity Act 1992 can be considered another milestone. This

policy promoted hydropower (large and small) development for meeting industrial, domestic and transportation demands as well as envisioned national and foreign investment in hydropower. The Nepal Water Resources Act 1992 made licensing provisions for the use of water resources and provisioned the formation of water users groups for the purpose of generating micro-hydro schemes. The Nepal Environmental Policy and Action Plan 1993 recommended optimum utilization of water resources by implementing multi-purpose hydropower projects by promoting rural electrification and minimizing the environmental impacts. Unfortunately, NEA reported technical issues at the Kulekhani Hydropower Project (Nepal's only storage type project till date), because of which the country had to face several hours enforced routine power cuts (popularly known as "loadshedding" in Nepal) in designated areas from 1992 (shown by the light gray block in Figure 3) (NEA/GoN, 1993). Moreover, 'loadshedding' was there to stay for long (Shrestha, 2010).

(iv) Rural electrification focus (1996–2013): The establishment of Alternative Energy Promotion Centre (AEPC) in 1996 marked a milestone in promoting rural energy and alternative energy technologies in Nepal. The Local Self-Governance Act 1999 granted power to the local authorities for mini- and micro-hydropower projects. The electricity generation and demand deficit kept on rising until 2000 which saw the temporary uplifting of loadshedding in Nepal. The 2001 revision of the Hydropower Development Policy, through the Electricity Act 2001, focused on cost minimization, institutional restructuring, demand side management, and rural electrification. The Water Resources Strategy 2002 set short term (5-years), medium term (15-years) and long term (25-years) targets for meeting the country's energy needs. The Tenth Plan 2002 established the Rural Energy Fund (REF) for local-level mobilization. After a temporary relief of a few years, Nepal was again forced to face 'loadshedding' from 2006 onwards (left edge of the dark gray block in Figure 3). The Rural Energy Policy 2006 conceptualized expanding REF to the Central Rural Energy Fund (CREF), emphasized private sector involvement, capital subsidization, and research and development (R&D) in rural energy technologies. Energy poverty reduction has been emphasized by recent studies such as Subedi et al. (2023) and Lohani et al. (2023). The Nepal Electricity Crisis Resolution Action Plan 2008 was targeted at addressing the electricity crisis through short-term and long-term approaches including increase of power imports from India, construction of thermal power plants, expansion of transmission capacity and the prevention of electricity theft. The Subsidy Policy for Renewable Energy 2009 aimed to decrease the rural–urban energy access gap. It further recommended establishing a task force to draft a plan to produce an extra 10,000 MW of hydropower within the next decade. The Energy Sector Synopsis Report 2010 recommended sustainable expansion of energy generation options.

(v) Rural electrification reinforcement (2013–2017): The Nepal's Energy Sector Vision 2050 A.D. 2013 identified hydropower as the leading sector to meet the country's energy needs in the domestic, industrial, commercial and transportation sectors. Recommendations included diversifying the energy generation mix with improved cooking stoves, sustainable use of firewood, and connecting isolated renewable energy systems (mainly from the rural areas) to the national grid (Shakya et al., 2023; Thapa et al., 2021). Some institutional restructuring focused on hydropower and electricity development was also carried out during the 2010s. The Thirteenth Plan 2013 promoted R&D in renewable energy, operationalized the CREF, and encouraged solar, wind, and hybrid technologies for irrigation and domestic water supply. The National Energy Strategy in 2013 aimed to promote new transport technologies such as fuel blending, electric and hybrid vehicles. The Renewable Energy Subsidy Policy 2013 focused on inclusive and accessible subsidies for non-electrification (solar thermal systems, institutional and rural community solar water systems, biogas, biomass and improved water mill) and rural electrification (via off-grid solar home systems, small- and micro-hydropower, wind energy and electricity from biomass energy) (Adhikari et al., 2024; Shakya, Adhikari, et al., 2022; Thapa et al., 2021). The Renewable Energy Subsidy Policy in 2016 targeted a shift from subsidies to credits for rural areas, aligned with UN's SDG7 and the Sustainable Energy for All initiatives by 2030. Lohani et al. (2022) and Bhattarai, Devkota, Maraseni, et al. (2023) underscored the multi-disciplinary benefits of renewable energy to SDGs for Nepal. The policy also strengthened CREF for credit mobilization and revised subsidy rates based on various factors including technology type, cost, capacity, geographical location and targeted beneficiaries. Several such aspects of renewable energy sector policies of Nepal have been highlighted by researchers, for example by Lohani et al. (2022) and Sanjel and Baral (2019).

(vi) Diversification of energy mix and energy efficiency (2017 onwards): The National Renewable Energy Framework (NREF) 2017 is a cornerstone policy in Nepal that emphasizes renewable energy technology for diversifying the energy generation mix as well as increasing the energy efficiency. Jointly owned by the government and development partners, the NREF focuses on strengthening local capacity, transitioning from subsidies to credit-focused financial models, and promoting collaboration between research institutions and the private sector. The Biomass Energy Strategy 2017 aims to generate energy from agri- and forest-residues and organic wastes, partially replacing diesel and petrol with bio-diesel and bio-ethanol. It also targets making Nepal indoor pollution-free by 2022 by ensuring clean cooking technologies and in all households by 2030. The Whitepaper on Energy, Water, and Irrigation: Present Situation and Future Prospect 2018 (Whitepaper) sets ambitious targets for hydropower development and envisions concepts of replacing domestic, transport, industrial and commercial fuels by electricity through implementation of new technologies such as net-metering, tariff revision based on time and season, diversifying energy generation mix including peaking run-of-river, pumped hydropower and other alternatives. Additionally, encouraging cross-border power transfer and integrated development of transmission lines and roads has been recommended by studies (Sanjel & Baral, 2020; SARI/EI, 2021).

The National Energy Efficiency Strategy 2018 introduces initiatives for increasing energy efficiency and sets goals for 2030, including the development of national standards and a National Energy Efficiency Action Plan for institutionalizing energy efficiency. The Renewable Energy Subsidy Delivery Mechanism for Special Program 2018 facilitates off-grid solar schemes, solar lighting in religious places, solar pumps for

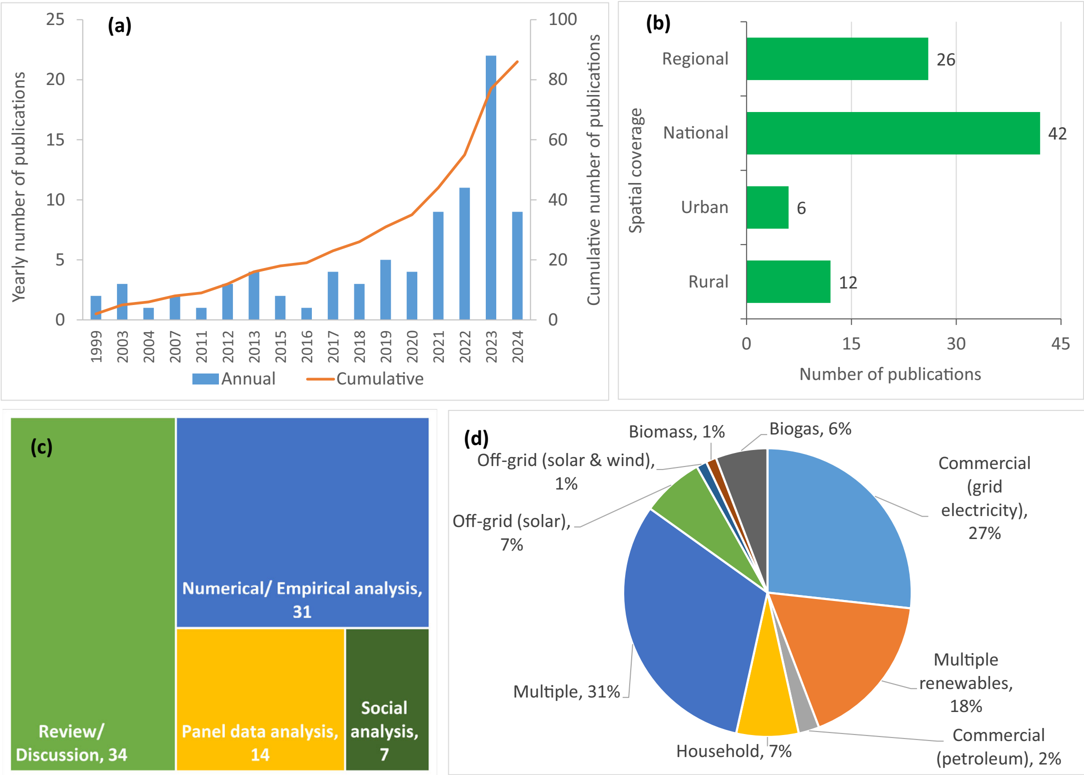

FIGURE 5 Summary of reviewed papers by: (a) number of publications; (b) spatial coverage; (c) type of study; and (d) fuel type ($n = 86$).

irrigation, and disaster response under the Renewable Energy Subsidy Policy 2016. Most importantly, Nepal was finally declared 'loadshedding free' in May 2018 (right edge of the dark gray block in Figure 3). Considering the esthetics of cities, underground cabling of its electricity distribution system in the urban areas is being currently carried out by NEA from 2020.[1] The Renewable Energy Subsidy Policy was updated in 2022 with focus on promoting loans instead of subsidies for the rural poor, reducing capital costs, increasing the renewable energy market, and strengthening local capacity. The Renewable Energy Subsidy Delivery Mechanism 2022 incorporated provisions for reverse auctions and other improvements for providing subsidies for improved off-grid renewable energy technologies in rural areas.

3.2 | Systematic literature review

Our keyword-based search and systematic review yielded a final cumulative list of 86 published papers from 1999 to March 2024 (Figure 5a), many of them have been published after 2020. Additionally, a majority of the articles consider the national energy context of Nepal ($n = 42$), followed by regional analysis ($n = 26$) (Figure 5b). Most of the articles were of review or discussion ($n = 34$) and numerical or empirical analysis ($n = 31$) type (Figure 5c). Similarly, a considerable number of the papers dealt with multiple types of energy sources (31%), studies on commercial grid electricity ranked second (27%) while those on biomass and off-grid solar-wind hybrid ranked last (1% each) (Figure 5d). Most of these studies focus on the applicability of a particular generation technology such as hydropower (Gyanwali et al., 2020; Hussain et al., 2019; Ogino et al., 2019; Singh et al., 2020); solar (Gautam et al., 2015; Kafle et al., 2023; Lin & Kaewkhunok, 2021); biogas (Kevser et al., 2022; Lohani et al., 2024; Rupf et al., 2015; Thapa et al., 2021) and micro- and mini-grids (Yadoo & Cruickshank, 2012). These figures indicate that research on the development and use of multiple types of energy sources and national level planning are slowly gaining attention in Nepal. Studies specifically focused on urban and rural areas and those making socio-technical assessments were limited. Moreover, publications holistically dealing with policy issues were scarce (Supplementary Material S1).

4 | DISCUSSION

4.1 | Availability

Three categories of energy sources, namely, traditional (firewood, agriculture residue and dry dung for direct combustion; 64.2%), commercial (petroleum, coal and grid electricity; 33.3%) and other renewables (2.5%) constituted the energy generation mix of the country in 2022/2023 (WECS/GoN, 2023). The country has made progress (after the enactment of Hydropower Policy 1992, 2001 and Water Resources Act 1992, 2002) in expanding the national electricity grid. Rural electrification through micro-hydro and off-grid solar PV systems, along with household and community level biogas, has been successful in remote areas. AEPC/GoN (2021) reports that the total installed capacity of rooftop solar PV is 10.1 MW, that of micro- and mini-hydropower is 38.8 MW and local hybrid grids is 2.7 MW. The current installed capacity of solar PV (including off-grid as well as local-grid connected systems) is estimated at 75.04 MW (MoF/GoN, 2023). Private sector involvement in electricity generation has also increased significantly. For example, the private sector (called "Independent Power Producers" in Nepal) generated 1,477 MW of hydropower during 2022/23 which accounts for 55% of the total power installed capacity of Nepal (NEA/GoN, 2023). Moreover, off-grid systems are generally successful in remote areas of the country because of the large government subsidies (Bhattarai, Maraseni, Apan, & Devkota, 2023). There has been a decrease in the share of traditional fuels by about 23% in 2022/2023 (64.2%) compared to 2008/2009 (87.1%) but at the cost of 18.2% increase in petroleum and coal (from 10.2% to 28.4%) (WECS/GoN, 2010; WECS/GoN, 2023). Grid electricity has increased from 2 to 4.9% and the share of other renewables has increased from 1.5% to 2.5% during this period (WECS/GoN, 2010; WECS/GoN, 2023). Moreover, household (mainly cooking by traditional fuels) is still the largest energy-consuming sector (~60%) of the country.

Despite changes in magnitude, alteration in the shares of the different clean energy generation technologies and uses is not impressive.[2] The Water Resources Strategy 2002 aimed at generating 820 MW of hydroelectricity domestically by 2007, 2,230 MW by 2017 and 22,000 MW by 2027, which seem very ambitious considering the past developments. Similarly, the National Water Plan 2005 aspired to generate 2,035 MW by 2017, 4,000 MW by 2027 and increase the per capita electricity consumption to 160 kWh by 2017 and 400 kWh by 2027. Nepal has not yet met these targets. The Whitepaper 2018 aimed to increase the per capita consumption of electricity to 700 kWh by 2023 and 1,500 kWh by 2028 by generating 5,000 MW of hydropower by 2023 (which was not achieved) and 15,000 MW by 2028, which looks unachievable under current development trends.

Interestingly, Nepal ranks as the top-most progressive nation in 2020 in terms of its energy equity with a 212% increase from 2000 (WEC, 2021). This has been largely attributed to its "exceptional" increase in urban and rural electrification schemes during this period. Although 94% of the population has access to electricity (WECS/GoN, 2023), the rate of access to 'quality' (as defined by IEA, 2021) grid electricity is about 70%. Almost the entire rural and remote areas are completely reliant on off-grid, low power, intermittent and temporary electricity generated from micro-hydropower, solar and hybrid plants which is barely enough for lighting or small uses like mobile phone charging.[3] Some community level off-grid projects are in operation but the hassle of the user groups and other financial and political issues generally make such projects ineffective over a period of time. Nevertheless, studies have shown that access to electricity leads to multiple benefits particularly for rural women (Shrestha, Jirakiattikul, & Shrestha, 2023). Even the urban areas connected by national grid do not get 'quality' electricity in the required amount throughout the day and year-round. As recent as until seven-eight years ago, NEA was able to provide electricity only for an average of less than 16 h a day to the capital city Kathmandu (NEA/GoN, 2014; NEA/GoN, 2019). As a result, the Nepalese are used to living in a condition of "loadshedding" (which is synonymously used to refer to blackouts in Nepal), meaning an intentional shutdown of power in some designated areas (often managed by weekly rotation) in order to avoid the central electricity system from collapsing when the demand exceeds its capacity. The country was 'loadshedding' free in 2018 with improved management of NEA as well as importing deficit power from India, mainly during the dry season (NEA/GoN, 2019). However, there are concerns among people that such power cuts might be back soon especially in the context of climate change and natural disasters which adversely impact hydropower generation.[4] Hence, such global metrics need to be carefully interpreted considering the ground zero realities of Nepal.

4.2 | Affordability

The domestic sector is largely dependent on traditional fuels (mainly fuelwood) sourced from private land and community forests at cheap rates (MECS/WINROCK, 2022). Fuelwood required for cooking is collected by the people irrespective of whether they get any external support because it is for one of the basic needs of life — food. In other words, the financial support from the government has always been extremely low in this regard.[5] That could be one of the reasons why the government has not been eager to initiate programs and be aggressively involved in replacing the traditional fuels with modern renewable ones. There is evidence in developing countries having to spend one-fifth of their income on wood for cooking, devoting one-quarter of domestic labour collecting fuelwood and ultimately suffering from life-ending pollution from inefficient combustion (Sovacool, 2012).

The transportation sector (with a share of 10.5% of the total energy consumption, WECS/GoN, 2023) relies heavily on fuel imports from India at consistently increasing prices (MoF/GoN, 2023). In the fiscal year 2019/20, Nepal imported fuel worth 1.8 billion USD, contributing to 16% of the total national trade deficit (MoF, 2021). The government regards income from the heavy taxes and duties levied on vehicle imports as a good source of income (DOC, 2020). However, it is creating a massive burden on the public. Likewise, Ghimire et al. (2023) and Shakya et al. (2024) showed that there is a varied perception in the adoption of electric vehicles in Nepal which needs to be leveraged by updating supportive measures. Rajbhandari et al. (2024) demonstrated a highly favorable scenario of energy security and GHGs reduction through electric mobility in the Kathmandu

Valley. Moreover, subsidies to off-grid rural energy systems are regularly revised, but there are doubts as to whether the subsidies are reaching those in need (Bhattarai et al., 2018).

Furthermore, entrepreneurs and industrialists generally maintain petrol/diesel generators energy backup systems and invertors because of lack of quality energy/electricity supply from the state. As a result, the production cost of goods become too high to compete with other cheaper options from India and China. This causes reluctance among the businessmen to invest in the productive sectors hindering economic development.[6] Nepal has a low per capita GDP of 1336.50 (current US$) and is highly susceptible to multidimensional poverty (Abbas et al., 2022; WB, 2024). Availability of sufficient energy for use in the productive sectors (such as manufacturing and commercial) generates economic output. If the country is better off economically, it travels up the energy ladder with increased use of modern energy technologies which further adds to improved living standards of the people, better employment opportunities and increased economic outputs. The government has been trying to establish a one-door policy for small organizations and community level businesses, but there is a lack of coherence among the concerned departments and different in-line agencies.[7] Studies indicate that households and businesses are willing to pay more for a reliable supply of grid electricity and clean energy technologies, reflecting a preference for clean energy over traditional fuels (Das et al., 2022; Niroomand & Jenkins, 2020).

The Nepal Oil Corporation (NOC), responsible for selling petroleum and LPG, consistently sells these fuels at higher prices in Nepal than the international market, but claims losses.[8] This results in unstable fuel prices and erodes trust of the general public on NOC due to opaque pricing methods. However, government policies lack transparency in pricing and cost predictability.[9] Furthermore, despite an increase in domestic hydropower generation, Nepal still has to import electricity from India (for example, 1543 GWh in 2021/22 @ US¢ 6.2/kWh), with very little export (493 GWh @ US¢ 4.3/kWh) at varying rates resulting in rising electricity prices (NEA, 2021). Natural disasters like the 2015 earthquake and the economic blockade imposed by India in 2016 have worsened the situation. The recent rejection of the power sector reform bill by the parliament, which aimed to remove monopolies in NEA and NOC, has added to the uncertainty in the fuel market.

4.3 | Technology

Renewable energy technologies and rural electrification have been consistently emphasized in Nepal from the early 2000s (Pokharel and Chandrashekar, 1998; Bastakoti, 2003; Pokharel, 2003), during the 2010s (Gurung et al., 2012; Nepal, 2012; Sovacool et al., 2011), and until recently (Lohani et al., 2022; Neupane et al., 2022; Zou et al., 2022). However, Nepal's energy generation mix is still dominated by traditional fuels (MoF/GoN, 2023). In rural areas, 51% of the population relies on firewood for cooking, 2.9% use dried dung while only 1.2% use bio-gas and less than 1% use kerosene or other sources (CBS, 2021). Studies have highlighted the importance of national income and extraction of available natural resources for energy accessibility and security in low-income economies (Aryal et al., 2023; Chiwaridzo, 2024; Xia et al., 2023). Hydropower is the main source of electricity, with small contributions from solar and thermal technologies; petroleum and LPG are used for transportation and urban cooking, respectively. Majority of the population lives in cities, where grid electricity is available, but access and availability are challenging in rural areas.[10] Off-grid small-scale renewable energy technologies such as micro-hydro, solar, wind, hybrid technologies and biogas are relatively cheaper. Technologies such as 'Solar Tuki', could be considered a revolution nearly two decades ago (Chitrakar & Shrestha, 2010), but not anymore. Such small off-grid energy systems are not sustainable in the long run as modern electronic appliances require more energy than that provided by small panels and LEDs[11] as people move up the energy ladder (Bharadwaj et al., 2023; Dominguez et al., 2021). However, as Afridi et al. (2023) mentions, renewable energy development in South Asia is dominated by photovoltaic and wind technology but the utilization of available bioresources is generally overlooked. Additionally, Chen, Xu, et al. (2023c) argued that Nepal needs to prioritize improving the operational performance of large biogas plants. Studies such as Parajuli et al. (2023) also show the effectiveness of thermal energy storage devices for energy savings in Nepal while Bhandari and Subedi (2023) see prospect in hydrogen production in the future. Complementary technologies such as wind-solar PV-hydropower have been tested in Latin America with promising results (Gonzalez-Salazar & Poganietz, 2021). Moreover, micro-hydro based mini-grid technologies have been recommended for developing countries (Mainali & Silveira, 2013; Sanjel & Baral, 2021; Yadoo & Cruickshank, 2012). In addition, with Nepal's focus on development of large hydropower projects, grid extension to mountainous and hilly areas has gained momentum after the mid-1990s.[12] Subedi et al. (2023) not only highlights the benefits of decentralized energy systems through micro-hydropower in Nepal, but also depicts the variations in the benefits due to varying topography and socio-economic conditions.

Unfortunately, Nepal lacks domestic capacity to adapt to changing energy environment.[13] Moreover, concerns over the impacts of natural resource availability and extraction and its ecological impacts have been raised by studies such as Sun and Gao (2023). The government owned research institution – Nepal Academy of Science and Technology (NAST) has a poor outreach and academic credibility which it outcasted by bureaucratic and political aggravations.[14] Research carried out in academic institutions are neither action oriented nor applicable in strengthening local indigenous technologies.[15] International support is needed for policy preparation (Table A2). Notwithstanding, the recently commissioned Upper Tamakoshi Hydropower Project (456 MW) and currently under construction projects, such has Tanahu (140 MW), Rasuwagadi (111 MW), Middle Bhotekoshi (102 MW), among others are indicative of a generous electricity supply in the near future (NEA, 2021). The provisions of tax subsidies for energy-efficient manufacturing equipment (for example envisioned by the Industrial Policy 2011 and Industrial Enterprise Act 2020) have not been realized adequately because of administrative and bureaucratic hurdles.[16] Furthermore, the construction of a two-million metric tonnes per year capacity trans-border petroleum pipeline between Motihari (India) and Amlekhgunj (Nepal)[17] raises concerns about India's increasing influence on Nepal's economy through fossil fuel exports,[18] and Nepal's lack of concrete plans to replace fossil fuel usage with domestic energy.[19]

4.4 | Sustainability

Model-based simulations such as WECS (2013), Mali et al. (2022), Dhakal et al. (2021) and Shakya et al. (2023) have explored feasible future energy mix options for Nepal. The current import-as-needed model in Nepal's transportation sector and electricity supply is unsustainable.[20] However, recent studies indicate erratic monsoons, posing risks to Nepal's water and energy supply (Bhattarai, Bhattarai, et al., 2022, Bhattarai, Devkota, et al., 2022, Bhattarai, Devkota, Maraseni, et al., 2023; Marahatta et al., 2022; Chinnasamy et al., 2015). Storage type hydropower projects could buffer these impacts, but adhering to robust environmental considerations are crucial.[21] Despite campaigns to decommission dams in some countries (Moran et al., 2018), Nepal needs storage projects to manage issues related to "too-much" and "too-little" water and energy security issues emphasized in key documents like the 1985 Master Plan of Koshi Basin, 2014 Nationwide Master Plan of Storage Hydropower Development in Nepal by JICA, and WECS (2013). Studies at the global level on small hydropower development show prospects of continuation of this technology if planned carefully (Ptak et al., 2022).

Diversification of the energy generation mix has been the current focus of Nepal's energy policies. Studies have reported a common problem of developing countries such as Nepal in formulating policies only when a development intervention is necessary without pre-planning comprehensive sectoral policies (Luthra et al., 2015). Sustainable Development Goals—Status and Roadmap 2016 focused on the generation of electricity through large hydropower projects for national grid and off-grid micro-hydro and grid connected solar system, prioritizing budget for operation and maintenance for the system for a steady quality of electricity. The Fifteenth Plan (2019–2024) targets a 12% contribution of renewable energy in total energy consumption. The National Environment Policy 2019 envisions reduction of household pollution by renewable energy technologies. The Second Nationally Determined Contribution aims for a 15% contribution of renewables in the energy mix by 2030, including hydropower, electric stoves, solar systems, electric vehicles, and private plantations. The Long-term Strategy for Net Zero Emission 2021 emphasizes conversion of LPG use to electricity and biogas, and reduction of emissions within Nepal and beyond through power trade of hydro- and solar-electricity.

Cross border electricity trade takes place currently between India-Bhutan, India-Nepal and India-Bangladesh which have been made possible by bilateral government-to-government (G2G) arrangements based on case-to-case negotiations (SARI/EI, 2021). Dating back to the 1920s, India-Nepal transborder electricity cooperation has evolved over time with currently 20 interconnection corridors (one at 400 kV capacity; four at 132 kV capacity; and others at 33 and 11 kV capacities) for electricity exchange and trade (SARI/EI, 2021; Sharma & Awal, 2013). India's own hydroelectricity potential is estimated at about 145 GW while the electricity demand of Nepal is about 0.5% of India. Unless the domestic demand for electricity in the industrial, commercial and transportation sectors increases significantly, Nepal will have surplus electricity in the near future which will most likely be wasted if not exported at lucrative rates to the neighbor energy hungry India (USAID-SARI, 2003). In the FY 2022/2023, Nepal purchased 1,855 GWh year-round from India and exported 1,333 GWh (~72% of imported electricity) during June to October but at disproportionate prices (NEA/GoN, 2023). The governments of Nepal and India have recently signed energy sharing agreements in which India has agreed to buy electricity only from the hydropower projects to be built in Nepal with Indian funding/construction contract (for example, 679 MW Arun-4, 900 MW Arun-3, 750 MW West Seti, 900 MW Upper Karnali, 450 MW Seti River-6, 480 Phukot Karnali and 1,902 MW Mugu Karnali, amounting to a total of about 7,000 MW) which is a biased agreement (Qazi, 2022). India gains the larger benefits while Nepal has to deal with the environmental and social implications throughout its project life at the price of a small amount of electricity for domestic consumption. India-Bhutan (SARI/EI, 2017; SARI/EI-IRADe, 2018) and Thailand-Laos models (ADB, 2009; Hecht et al., 2019; Suhardiman et al., 2014) of cross border trades could be beneficial for both parties in which the economically better country invests in the projects and also reaps most of the benefits while the poorer country is also benefitted. Nevertheless, the bilateral agreements of cross-border trade including building and upgrading of the power lines can be considered a milestone for ensuring a foreign market for Nepal's electricity (Shrestha, 2023).

Nepal and China have recently made formal agreements in 2017 to carry out joint feasibility studies of natural gas and petroleum and also establish hydropower projects and transmission lines in Nepal (ET, 2017) boosting its technological and economic development. There have been recent efforts from Nepal and Bangladesh for cross-border electricity trading provided India gives access to the infrastructure for which it had shown reluctancy in the past (Chaudhary, 2023; Shrestha, 2023). Moreover, Nepal's Energy Sector Vision 2050 has identified hydro-power as the "lead" energy sector for meeting the long- and short-term energy demands of the country (WECS/GoN, 2013). Similarly, ADB has also recognized Nepal's efforts in improving energy security and leaping towards economic growth by accelerated sustainable development of hydropower (ADB, 2017). Economic value addition to the products utilizing cheap electricity could fetch high profit margins in the regional market. WEC (2021) very rightly stated that success of net zero targets, committed by many nations in their future energy plans, is primarily governed by the people and practicalities rather than the often-exaggerated political promises and plans. Moreover, sincere political commitment, large investment in technology and infrastructure, institutional capacity building and harmonization of standards and regulations are the key requirements for successful cross-border energy trade models (SARI/EI, 2021).

Therefore, the prospects of surplus electricity export from Nepal, and petroleum products and electricity import from India during the respective high demand times could play a key role in maintaining regional energy balance in South Asia. However, Gyanwali et al. (2023) warns of the possible reduction in hydropower generation and cross-border electricity export as a result of climate change in the future and also recommends diversified generation mix. Sharma and Shrestha (2023) have explored additional energy generation pathways that Nepal needs to adopt to reduce its reliance on petroleum in the short- and long-runs. Additionally, Pokharel and Regmi (2024) have recommended the need for location-specific strategic planning for hydropower projects in Nepal. Although India had nominated the Power Trading Corporation as the focal agency for dealing with matters related to power trade with its counterpart NEA of Nepal in 2001 (ADB, 2007), Nepal has not been able to reap benefits as expected from this collaboration.

Budget availability is a critical factor for the sustainability of development projects in developing countries (Mohsin et al., 2021; Müller et al., 2021). Middle-income countries such as Thailand also have been reported to have concerns over the high capital cost of renewable energy technologies in comparison to conventional energy resources (Adhikari et al., 2008). National funds such as the REF (in the Ninth Plan 1997–2002) and CREF (in the Three-year Interim Plan 2010–2013) have been created and mobilized for rural renewable energy. International support has been provided to Nepal by organizations like SNV and GTZ for off-grid solar and biogas systems (Cheng et al., 2014). Norway has been an important donor for hydropower development in Nepal. However, it has been seen across many developing regions that subsidies and donations are not effective in establishing renewable energy technologies, particularly in the rural areas (Bhattarai, Maraseni, Apan, & Devkota, 2023; Pandey & Sharma, 2021; Windemer, 2023). Instead, soft loans and credit mechanisms through local cooperatives and financial institutions are believed to be more effective (Wagemans et al., 2019; Mainali and Silveira, 2013). Although credits were envisioned from as early as the Eighth Plan (1992–1997), subsidies have dominated the renewable energy sector until recently, impacting its financial sustainability. Sovacool et al. (2013) recommended increasing electricity tariffs. However, this does not seem to be preferred as a large share of the current Nepalese population is already unable to afford electricity at the existing price. Developing an "energy ecosystem" for sustainability has been recommended (Bhattarai, Maraseni, Apan, & Devkota, 2023). Recent revisions of the rural energy policies are indicators of this desired change which needs to be further strengthened.[22]

4.5 | Governance

Good governance needs prime attention in the Global South (Baniya et al., 2021; Haifa et al., 2023). People have their expectations on the availability and use of energy while the government has its limitations. Nepal's energy sector has been impacted by political turmoil, unstable government, and changing national plans, unable to meet the energy expectations. Rural energy policies focus on off-grid isolated renewable energy, while electricity acts push for grid expansion even to the remote areas. However, there are unanswered questions about long-term management of off-grid renewable energy technologies, disposal of energy waste (for example, dead batteries which have been problematic in the past (Alex et al., 2014)), conversion technologies of DC to AC appliances, cost of conversion, the future role of community energy user groups and the exit strategy for organizations such as AEPC that have worked in the rural energy sector for a long time. Connecting to the national electricity grid is still considered a status symbol in rural Nepal.[23] While theft control and transmission losses have decreased (from 25% in 2013 to around 13.5% in 2023 (NEA/GoN, 2023)), with positive roles of policies such as the Electricity Theft Control Act 2002, poverty remains a main driver of theft[24] as with rural people of many developing countries (Luthra et al., 2015). Similarly, corruption and preferential treatment are common in Nepal which is a direct result of weak governance and condition of lawlessness (Sovacool et al., 2011; Sovacool & Bulan, 2012). These problems lead to favouring projects and polices which have vested interests of national and international drivers.[25] Furthermore, Naz & Aslam (2023) highlight the important role of governance in South Asia to moderate the environmental impacts of globalization, financial development through innovative approaches.

The Government of Nepal has established separate institutions to manage the power sector instead of sole reliance on NEA as 'institutional de-bundling' efforts. The Hydroelectricity Investment and Development Company Limited was established in 2011 for management of investment in middle to mega hydropower projects in Nepal.[26] The Rastriya Prasaran Grid Company Limited, established in 2015, is responsible for transmission and evacuation of power for the hydropower sector. It has been successful in preparing a consolidated transmission development plan for Nepal.[27] Similarly, the Vidhyut Utpadan Company Limited was established in 2016 to develop large hydropower projects in the country adopting different development modalities such as public private partnership (PPP) and build-own-operate-transfer (BOOT).[28] Similarly, the Electricity Regulatory Commission was established in 2018 for technical management, electricity tariff fixing, regulation of power purchase rate, address consumer welfare aspects and advising the government on related issues. However, politicization and lack of expertise and resources have hindered the proper functioning of these institutions.

Local authorities have been given more power regarding the use of local resources, including energy generation, for example through the implementation of the Local Self-Governance Act 1999, as well as the Environment-friendly Local Governance Framework 2013 and 2021. However, their capacity for such a transition is questionable.[29] There are concerns that subsidies for renewable energy may actually increase the rich-poor disparity rather than reducing it (Nepal & Paija, 2019; Paudel, 2021). The marginalized and disadvantaged groups are still the largest sufferers in terms of energy access and use

(Lin & Kaewkhunok, 2021; Paudel, 2021; Rahut et al., 2022; Shrestha, Jirakiattikul, Lohani, & Shrestha, 2023). Hydropower projects planned in the 1990s (for instance, the Arun III Hydropower Project (900 MW), Upper Karnali Hydropower Project (900 MW) and Budhigandaki Hydropower Project (1,200 MW)) have been disrupted for decades due to political reasons, local interferences and conflicting national-international interests. There are discrepancies and overlaps in the roles of different organizations of the government in energy development. Moreover, Sovacool et al. (2011) doubts whether Nepal will be able to harness its enormous renewable energy (mostly hydropower) potential without developing an enabling environment through social awareness, community ownership, minimizing corruption and institutional and regulatory reforms. These issues warrant immediate serious consideration.

4.6 | Challenges and future direction

A study by Sovacool et al. (2013) identified six challenges and eight solutions for electricity development while Ghimire and Kim (2018) pointed out six barriers to renewable energy development in Nepal. Moreover, another study (Sovacool et al., 2011) cited political unrest and the economy as barriers to Nepal's hydropower development. Interestingly (from a researcher's perspective) and unfortunately (from the nation's development perspective), most of these issues remain valid today. However, the current policy-practice interface of Nepal faces significant challenges. As Rissman et al. (2020) rightly explains, no single policy is a "silver bullet". Extending this notion, we identify concerns, especially after the federal restructuring, and suggest future directions for sustainable development of Nepal's energy sector.

4.6.1 | Political fragility and weak governance

The impacts of political instability can trickle down across the entire development hierarchical system of a country (Bhattacharya & Jana, 2009). Political instability has had a negative impact on Nepal's energy sector and economy, resulting in insufficient energy generation, inefficient energy use, high dependence on imports, and reliance on international support. Power sector reform can be directly linked to political stability in South Asia (Bhattacharyya, 2007). India was able to adopt a broad energy framework in 2003 which was reinforced in 2008 (Ahlers et al., 2015), however other countries were significantly delayed. Nepal's economy declined considerably after the transition to a democratic system in the early 1990s, with derailed policies and shutdown of government-owned industries in the name of privatization.[30] In addition, the Maoist insurgency devastated the industrial and commercial sectors, causing several energy development (particularly large hydropower) projects to be either significantly delayed or canceled (Sovacool et al., 2013). Policies have been supportive of a positive change (Supplementary Material S3). Moreover, Borozan (2022) argues that even in the G7 countries, a well-developed, stable and transparent economic, energy and environmental policy framework is necessary for attaining energy stability. However, Nepal's past experiences have not proven to be investment-friendly especially in the renewable energy sector,[31] which may retard foreign investment in the foreseeable future.

Nepal's administrative and restructuring activities since becoming a federal state in 2015 have further delayed policy making and caused instabilities.[32] The GoN has taken a crisis-management approach to energy-related problems, for instance, by formulating the Nepal Electricity Crisis Resolution Action Plan 2008. Rural areas are still dependent on conventional fuels for cooking and the transportation sector completely relies on petroleum imports (Bhattarai, Maraseni, Devkota, & Apan, 2023). The urban domestic areas are temporarily provided with 'loadshedding-free' grid electricity while the industrial, manufacturing, and commercial sectors are still minor energy consumers.[33] The Environment-friendly Local Governance Framework 2013 and 2021 have promoted resources utilization at the local level but their operationalization differs significantly because of the difference in hierarchical structure of the government.[34] Moreover, the policies enacted around 2015 (Table A1 and A2) were either automatically repealed or later revised due to national restructuring, limiting the assessment of their effectiveness.

Political instability, social acceptance issues, and lack of energy transition management capabilities have contributed to sluggish power sector development in South Asia (Bhattacharyya, 2007), including Nepal. Besides, in the absence of employment possibilities in the productive industrial and commercial sectors, 23.3% of the households have at least a family member living abroad (out of which 82.2% are males) seeking for better work opportunities CBS (2021). Additionally, excessive reliance on India for construction of large hydropower projects in Nepal (such as the 762 MW Tamor, 679 Lower Arun and 900 MW Arun-3, among others) amounting to over 8,000 MW raises questions about India's unnecessary intervention in Nepal's water resources and power sector.[35] The Upper Karnali Hydropower Project which was identified in the early 1990s was occupied by an Indian company (GMR) for almost three decades,[36] the development of which is extremely slow.

To improve Nepal's energy sector, domestic energy needs should be prioritized by setting short- and long-term policies accordingly. Transparency and responsibility are needed from political parties and leaders to reduce instability and attract private investments from within the country and abroad. Construction of storage-type hydropower projects at strategic locations and strengthening transmission and distribution systems are essential to ensure adequate electricity supply. Increased employment opportunities in industrial and commercial sectors will help alleviate poverty (Thapa-Parajuli et al., 2021) and play a significant role in reduction of corruption and electricity theft. Making policy instruments rigid and improving the variable electricity tariff system will lead to good governance and energy security (as in China (Chen, Xu, et al., 2023)) and avoid repercussions (for instance warned by Wolde-Rufael (2009) in Africa). Additionally, the applicability of modern measures such as net-metering and real-time pricing of electricity also needs careful consideration.

4.6.2 | In-silo operation modality

Recognizing its multi-disciplinary outreach, use of energy in various sectors of the economy is crucial for the prosperity of a country (Huda & McDonald, 2016; Ogino et al., 2019; Rijal, 1999). However, Nepal's approach to energy planning is siloed, with different ministries and agencies working independently, leading to inefficiencies and missed opportunities (Ghimire & Kim, 2018; Lohani et al., 2022). Reasons of administrative hassles, political interferences and corruption can be held responsible.[37] The Electricity Act and Hydropower Development Policy mainly focus on hydropower, while others such as the Rural Energy Policy and Renewable Energy Subsidy Policy target alternative energy technologies for rural areas. Cross-sectoral collaboration among ministries (for example, Ministry of Forests and Environment, Ministry of Education, Science and Technology, Ministry of Physical Infrastructure and Transport, Ministry of Industry, Commerce and Supplies and Ministry of Agriculture and Livestock Department, among others) and other line agencies is necessary for the country's development (Sovacool et al., 2013), with a larger goal of national development rather than focusing on individual interests. The development of the Hydropower Environmental Impact Assessment Manual 2018 is a positive step towards cross-sectoral collaboration. Flexibility in policies and dedication and perseverance among participating agencies are needed. Moreover, a bureaucracy-technocracy-society-synergy is felt necessary.

4.6.3 | Lagging research and development

Research and development (R&D) in Nepal's energy sector is limited. Several dedicated departments and units exist within the government, but they face limitations due to inadequate resources. For instance, the Water and Energy Commission Secretariat (WECS) is the apex institution in providing research and policy feedback on water and energy issues, but its role in energy planning is constrained by limited human resources and institutional capacity. The Ministry of Energy, Water Resources and Irrigation (MoEWRI) has an Electricity and Energy Policy Unit; the Nepal Electricity Authority has a Planning, Monitoring and Information Technology Directorate; and the Water Resources Research and Development Centre under the MoEWRI has the mandate for training, handling laboratories and research facilities. Data collection is centralized in Nepal and access is limited. For example, the Department of Hydrology and Meteorology (DHM) collects hydrological and climatic data through its network of observation stations in the country. However, access to their data is constrained by a lengthy administrative process[38] leading to reliance on global datasets and potential failures in energy generation projects. The Policy Research Institute (PRI)[39] formed in 2018 lacks research professionals and partnerships with academic institutions, limiting its impact. Action research as well as policy research need to be collocated (Creutzig et al., 2014). Investment in R&D is needed to incentivize private/public institutions and integrate awareness of energy-saving among the public for socio-economic development (Tang et al., 2016). Moreover, studies have recommended increasing investments in education, human capital and R&D for sustainable development (Chen & Guo, 2023). With burgeoning issues of climate change, the country has made efforts to promote commercial solar, wind and hybrid projects (Tiwari, 2021). Furthermore, Pandey et al. (2023) demonstrate how climate induced reduction in water availability and mechanical failures of hydropower projects due to lack of regular maintenance are taking a toll on Nepal's electricity sector. Other countries of the global south, for example Brazil, is the ninth-largest electrical sector in the world with a generation mix consisting of 64% hydropower, 26% thermal, 9% wind and 1% solar power plants (Ávila et al., 2021). Recent studies in Nepal have recommended advanced technologies such as pumped storage hydropower (on- and off-rivers) and peaking ROR projects (Baniya et al., 2023; Lohani & Blakers, 2021). The hybridization of technologies to obtain co-benefits such as solar panels over irrigation canals (Kapoor, 2021), agrivoltaics (Barron-Gafford et al., 2019) and floatavoltaics (Almelda et al., 2022), which have been successfully piloted in many developing regions, could be beneficial with customization to local conditions. Recent studies such as Shrestha et al. (2024) show the possibilities of latest methods such as deep learning to optimize power systems for stability and sustainability especially for integrating renewable energy sources into mainstream national power generation system. The government needs to mainstream R&D and allocate sufficient funds, while education policies should encourage energy development in technical curricula.[40]

4.6.4 | Demand side management

Nepal has focused on supply-side management of energy over the past four decades. Despite policies such as the National Energy Efficiency Strategy 2018 and the Industrial Enterprise Act 2020, the provisions have not been effectively put into practice due to lack of public awareness, limited investment in modern appliances, and ineffective promotion of efficient devices by the government.[41] As a result, the domestic sector is still highly reliant on inefficient traditional fuels (CBS, 2021). Energy consumption needs to be controlled efficiently (Butchers et al., 2020; Fares & Webber, 2017). Moreover, Chen, Xu, et al. (2023) concludes that national efforts of controlling energy consumption by 'regulation priority' and 'technology-driven and industrial structure upgrading' have played a key role in China's decarbonization. In the context of Nepal, strengthening local cooperatives and financial institutions and motivating them to invest and promote energy-efficient devices is important. Energy efficiency in the industrial and transportation sectors also need to be promoted. Developing the R&D capabilities of the country to innovate and design efficient technologies is essential for long-term energy security. Paudel et al. (2023) explain how reducing monthly energy expenses and providing uninterrupted supply of electricity is beneficial for sustainable energy transition in Nepal. However, the social acceptance of newer technologies should not be assumed, in the developing world (van der Gaast et al., 2009) and developed world (Windemer, 2023) alike.

Moreover, new renewable energy technologies might not always be efficient, environmentally friendly, cheap and just, as they are usually claimed (Bhattarai, Bhattarai, et al., 2022; Bhattarai, Devkota, et al., 2022; Bhattarai, Maraseni, & Apan, 2022; Pietrosemoli & Rodríguez-Monroy, 2019; Sovacool & Dworkin, 2015). Cloke et al. (2017) argues that three forms of literacy — 'energy systems literacy', 'project community literacy' and 'political literacy' — are required to materialize energy projects. Policies need to address this niche.

4.6.5 | Continued dependence on international support

International donors and technology transfers have played a significant role in Nepal's renewable energy development (Bhandari et al., 2017; Gautam et al., 2015; Pokharel, 2003). Development agencies and international banks had important stakes in hydropower development in the 20th century while local private financial sectors are more involved in recent times (Ahlers et al., 2015). For instance, long-term aids in the energy (particularly hydropower) sector provided by Norway dates back to the 1960s and the aid dependency increased from 34% of the national budget in the mid-1970s to 70% in the mid-1990s (Movik & Allouche, 2020). However, over-reliance on subsidies and lack of collaboration between donors, government, local enterprises, and communities (Alex et al., 2014; Bhattarai et al., 2018; Dhital et al., 2016) have hindered sustainable progress. Nepal's energy assessments and planning still heavily depend on international support (Table A1 and A2), indicating a lack of prioritization of local capacity building. To address this, a "proper energy ecosystem" that focuses on local technical capacity enhancement, strengthening of local enterprises, community empowerment, and building a productive energy market is necessary. This requires a bottom-up approach with active collaboration of beneficiaries (Schulz & Saklani, 2021; Singh et al., 2020) from policy formulation to implementation phases. Vij et al. (2023) have demonstrated an interesting interplay of power at the local to transboundary levels while designing and implementing climate change policies in South Asia. Moreover, the international development partners and donor agencies also need to target their programs in an unbiased, fair and inclusive manner.

We acknowledge some limitations in this study. The main focus of our study was on the qualitative analysis of policy progression. A quantitative assessment of the cross-border trade from Nepal was beyond the scope of this review. In addition, an economic evaluation of the policy impacts on multiple sectors of the economy could be an excellent continuation of this research.

5 | CONCLUSION AND POLICY IMPLICATIONS

Using a mixed-method approach, this study tracked Nepal's energy policy progression from 1984 to 2022 applying a global energy security framework encompassing five broad dimensions (availability, affordability, technology development, sustainability and governance). Our findings reveal a progressive trend in Nepal's energy policies. Moreover, attempts to diversify the energy generation mix and increase energy use efficiency across the rural and urban domestic areas are positive indications. While the government's actions to meet the energy demands of remote rural areas using off-grid small renewable energy technologies are praiseworthy, there are several challenges and opportunities that need to be addressed.

The key take-away messages from our analysis are as follows:

5.1 | Progressive energy policies

Efforts from the Governement of Nepal as well as the private sector supported by policy updates have led to a considerable increase in the energy availability for Nepal. Overall access to electricity has significantly increased from 29% in 2000 to 92% of the population in 2021.

5.2 | Unaffordable energy

Despite the commendable efforts in the past, firewood still remains the primary energy source, especially in rural areas, with reliance of 51% of the population for cooking. Moreover, weak economic conditions, unstable fuel prices, and lack of trust in government agencies make clean energy unaffordable for most Nepalese.

5.3 | Renewable energy potential

Current fossil-fuel based technologies are not sustainable and will increase trade deficits and have long-term environmental implications. Limited renewable energy technologies such as hydropower, solar, and bio-gas are feasible in Nepal. However, the country lacks the technical and financial capacity to adapt to changing energy conditions. Moreover, there are high chances that subsidies for renewable energy may exacerbate the rich-poor divide.

5.4 | Barriers to sustainability

The absence of an "energy ecosystem" considering diverse spheres of the society has been a significant barrier for sustainability. Political turmoil, unstable government, changing national plans, lack of awareness in society, lawlessness, and corruption have hindered the energy sector's progress. Moreover, stakeholders' roles during policy formulation and implementation are often opaque and duplicated.

Based on our review, we provide the following specific policy recommendations:

1. *Supply-side management*: The state must accelerate its initiatives to harness the country's massive hydropower potential through strategic implementation of large storage projects to manage issues of

"too-much" and "too-little" water and energy, while meeting environmental requirements. Benefit sharing between load centres and across provinces, upstream-downstream benefits quantification (particularly for regulated flows in storage type hydropower projects) need careful attention at the policy level. Extension of the national grid to remote areas is necessary in the long run for maintaining energy equity among the urban and rural people. The current energy generation mix of Nepal needs to be diversified: prospects of solar, biogas and other hybrid systems need to be researched and implemented in feasible areas for achieving energy security. New interventions such as pumped storage, hybrid micro grids, net-metering of household solar PV systems into the central grids and real time energy pricing need to be mainstreamed. The federal and local governments should be given authority for resource accounting and planning to optimize the supply of energy locally.

2. *Demand side management*: It is the combined duty of the government as well as the users to utilize the available energy optimally. The government should aggressively raise awareness among the users, mainly the rural poor who are still largely dependent on conventional fuels for their domestic uses. Policies should collaboratively target replacing traditional fuels (primarily firewood) with cleaner alternatives such as electricity and biogas and promote the use of energy efficient appliances. The current trend of switching to LPG is not a sustainable solution. Tax reduction and subsidies for RE penetration are not sustainable, hence, subsidy policies need appropriate revision. Local cooperatives need to be strengthened for providing credits and loans. Moreover, increasing energy efficiency in the industrial, commercial and transportation sectors need to be promoted.
3. *Multi-sector collaboration*: Energy has impacts on various sectors of the economy. Involvement of different stakeholders using a bottom-up approach in the energy policy formulation process is a must. The science-policy interface needs to be strengthened with active collaboration of the concerned ministries/departments, private organizations, financial institutions, academia, community, and international partners. Implementing newer energy technologies by customizing them to the local conditions of Nepal through action-research and making policy recommendations for their establishment and sustainability is today's need. Therefore, roles of academic institutions, research organizations and think tank organizations in this regard should be clearly defined and should be sufficiently resourced through relevant policy reforms. Moreover, a proper "ecosystem" is necessary for proper functioning of the hardware and software of the energy sector. A bureaucracy-technocracy-society-synergy is strongly felt necessary.
4. *Political stability and good governance*: Development and economic prosperity is possible only by attaining a state of political stability, supplemented by supportive policies. The current practice of juggling national plans with frequently changing governments in Nepal needs to be ended. Formulation and intact implementation of a national level energy development plan is necessary irrespective of the change in government. Moreover, policies need to be strict in terms of good governance and regulation so that issues such as corruption, obstruction to energy development projects due to local and political interferences are discouraged. One door policy for the development of energy projects needs to be emphasized. Additionally, Nepal needs to focus on improving its diplomatic relations with the neighboring countries through revision in the foreign policies and foreign aid policies, enabling conducive environment for obtaining technical and financial support as well as exploring energy trade opportunities.

There is a possibility for Nepal to contribute to the ever-growing energy demand of South Asia, particularly of India and China. India is the nearest and the largest electricity market for Nepal. Electricity trades with Bangladesh and China are economically challenging and technically difficult mainly due to reasons of proximity and rugged terrain. The same can be observed for cross-border trade with other SAARC countries. Furthermore, setting up and adhering to a common set of operating rules and tariff fixation are challenging aspects that need to be focused on by the countries collaborating on energy sharing. Nepal should maintain diplomatic relations with its neighbors in which benefits are proportionate and just. In addition, an economic evaluation of the policy impacts on multiple sectors of the economy as well as a quantitative assessment of the cross-border trade from Nepal could be plausible avenues for future research.

Thus, incorporating these critical issues considering their multiple facets in the policy making process is imperative for achieving energy security, economic prosperity and sustainable development of Nepal. Formulation of proper policies in Nepal can be beneficial to South Asia through regional power trade and seasonal energy balance. Lessons learnt from this policy synthesis of Nepal could be insightful for other countries of the Global South sharing similar socio-economic and geo-political attributes.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

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ENDNOTES

[1] https://myrepublica.nagariknetwork.com/news/nea-s-plan-to-lay-underground-electricity-cables-on-main-roads-of-kathmandu-valley-becomes-challenging/.

[2] Response from Expert#1 (government) [Please see Supplementary Material S3 for details of experts].

[3] Response from Expert#9 (international research organization).

[4] Response from Expert#10 (national research organization) and Expert#11 (private sector).

[5] Response from Expert#4 (academician) and Expert#10 (national research organization).

[6] Response from Expert#11 (private sector).

[7] Response from Expert#3 (academician) and Expert#7 (government).

[8] Response from Expert#11 (private sector).

[9] Response from Expert#2 (academician).

[10] Response from Expert#5 (government).

[11] Response from Expert#9 (international research organization).

[12] Response from Expert#10 (national research organization).

[13] Response from Expert#1 (academician).

[14] Response from Expert#9 (international research organization).

[15] Response from Expert#8 (government), Expert#9 (international research organization) and Expert#11 (private sector).

[16] Response from Expert#2 (academician) and Expert#11 (private sector).

[17] https://pib.gov.in/PressReleseDetail.aspx?PRID=1584627 (accessed June 10, 2022).

[18] Response from Expert#9 (national research organization).

[19] Response from Expert#6 (government) and Expert#7 (government).

[20] Response from Expert#3 (academician).

[21] Response from Expert#7 (government).

[22] Response from Expert#9 (international research organization) and Expert#10 (national research organization).

[23] Response from Expert#10 (national research organization).

[24] Response from Expert#8 (government).

[25] Response from Expert#11 (private sector).

[26] https://www.hidcl.org.np/.

[27] https://www.rpgcl.com/.

[28] https://www.vucl.org/.

[29] Response from Expert#10 (national research organization).

[30] Response from Expert#3 (academician) and Expert#10 (national research organization).

[31] Response from Expert#10 (national research organization).

[32] Response from Expert#5 (government), Expert#8 (government) and Expert#10 (national research organization).

[33] Response from Expert#10 (national research organization) and Expert#11 (private sector).

[34] Response from Expert#6 (government).

[35] Response from Expert#8 (government) and Expert#9 (international research organization).

[36] Response from Expert#2 (academician) and Expert#10 (national research organization).

[37] Response from Expert#1 (academician), Expert#6 (government) and Expert#9 (international research organization).

[38] Response from Expert#9 (international research organization), Expert#10 (national research organization) and Expert#11 (private sector).

[39] https://pri.gov.np/ (accessed January 18, 2022).

[40] Response from Expert#1 (academician) and Expert#4 (academician).

[41] Response from Expert#2 (academician), Expert#3 (academician) and Expert#10 (national research organization).

REFERENCES

Abbas, K., Butt, K. M., Xu, D., Ali, M., Baz, K., Kharl, S. H., & Ahmed, M. (2022). Measurements and determinants of extreme multidimensional energy poverty using machine learning. *Energy*, *251*, 123977. https://doi.org/10.1016/j.energy.2022.123977

Ávila, L., Mine, M. R. M., Kaviski, E., & Detzel, D. H. M. (2021). Evaluation of hydro-wind complementarity in the medium-term planning of electrical power systems by joint simulation of periodic streamflow and wind speed time series: A Brazilian case study. *Renewable Energy*, *167*, 685–699. https://doi.org/10.1016/j.renene.2020.11.141

ADB. (2007). *Hydropower development in India: A sector assessment*. Asian Development Bank.

ADB. (2009). Building a sustainable energy future: The greater Mekong subregion. Asian Development Bank. www.adb.org

ADB. (2017). Nepal energy sector assessment, strategy, and roadmap. *Asian Development Bank*. https://doi.org/10.22617/tcs178936-2

Adebayo, T. S., & Ullah, S. (2024). Towards a sustainable future: The role of energy efficiency, renewable energy, and urbanization in limiting CO2 emissions in Sweden. *Sustainable Development*, *32*(1), 244–259.

Adedoyin, F. F., Bekun, F. V., & Alola, A. A. (2020). Growth impact of transition from non-renewable to renewable energy in the EU: The role of research and development expenditure. *Renewable Energy*, *159*, 1139–1145. https://doi.org/10.1016/j.renene.2020.06.015

Adeyinka-Ojo, S. (2016). PRISMA statement and thematic analysis framework in hospitality and tourism research. In C. Cobanoglu & V. D. Corte (Eds.), *Advances in global services and retail management* (pp. 1–10). USF M3 Publishing. https://www.doi.org/10.5038/9781955833035

Adha, R., Hong, C., Yang, S., & Muzayyanah, S. (2024). Re-Unveiling the energy efficiency impact: Paving the way for sustainable growth in ASEAN countries. *Sustainable Development*. Portico. https://doi.org/10.1002/sd.3005

Adhikari, D. R., Techato, K., & Jariyaboon, R. (2024). A systematic literature review on renewable energy technologies for energy sustainability in Nepal: Key challenges and opportunities. *International Journal of Renewable Energy Development*, *13*(2), 206–222. https://doi.org/10.61435/ijred.2024.60032

Adhikari, S., Mithulananthan, N., Dutta, A., & Mathias, A. J. (2008). Potential of sustainable energy technologies under CDM in Thailand: Opportunities and barriers. *Renewable Energy*, *33*(9), 2122–2133. https://doi.org/10.1016/j.renene.2007.12.017

AEPC/GoN. (2021). Progress at Glance: A year in Review FY 2019/20 and 2021/21.

Afridi, Z. U. R., Ullah, K., Mustafa, M. F., Saleem, H., Shaker, B., Ashraf, N., & Aslam, S. (2023). Biogas as sustainable approach for social uplift in south east Asian region. *Energy Reports*, *10*, 4808–4818.

Ahlers, R., Budds, J., Joshi, D., Merme, V., & Zwarteveen, M. (2015). Framing hydropower as green energy: Assessing drivers, risks and tensions in the eastern Himalayas. *Earth System Dynamics*, *6*(1), 195–204. https://doi.org/10.5194/esd-6-195-2015

Alex, Z., Clark, A., Cheung, W., Zou, L., & Kleissl, J. (2014). Minimizing the lead-acid battery bank capacity through a solar PV—wind turbine hybrid system for a high-altitude village in the Nepal Himalayas. *Energy Procedia*, *57*, 1516–1525. https://doi.org/10.1016/j.egypro.2014.10.144

Almelda, R. M., Schmitt, R., Grodsky, S. M., Flecker, A. S., Gomes, C. P., Zhao, L., Liu, H., Barros, N., Kelman, R., & McIntyre, P. B. (2022). Floating solar power: Evaluate trade-offs. *Nature*, *606*, 246–249.

Aryal, K., Laudari, H. K., Neupane, P. R., & Maraseni, T. (2021). Who shapes the environmental policy in the global south? Unpacking the reality of

Nepal. In *Environmental science and policy* (Vol. 121, pp. 78–88). Elsevier Ltd.. https://doi.org/10.1016/j.envsci.2021.04.008
Aryal, K., Maraseni, T., & Apan, A. (2022). How much do we know about trade-offs in ecosystem services? A systematic review of empirical research observations. In *Science of the Total environment* (Vol. 806, 151229). Elsevier B.V. https://doi.org/10.1016/j.scitotenv.2021.151229
Aryal, S., Dhakal, S., & Samrat, K. C. (2023). Integrated analysis of end-use electrification and cross-border electricity trade policies for hydropower enabled energy transformation in Nepal. *Renewable Energy*, *219*, 119467.
Azril, H., Shaffril, M., Eric, S., & Farid, S. (2018). Science of the Total environment a systematic review on Asian's farmers' adaptation practices towards climate change. *Science of the Total Environment*, *644*, 683–695. https://doi.org/10.1016/j.scitotenv.2018.06.349
Baniya, B., Giurco, D., & Kelly, S. (2021). Changing policy paradigms: How are the climate change mitigation-oriented policies evolving in Nepal and Bangladesh? *Environmental Science and Policy*, *124*, 423–432. https://doi.org/10.1016/j.envsci.2021.06.025
Baniya, R., Talchabhadel, R., Panthi, J., Ghimire, G. R., Sharma, S., Khadka, P. D., Shin, S., Pokhrel, Y., Bhattarai, U., Prajapati, R., & Thapa, B. R. (2023). Nepal Himalaya offers considerable potential for pumped storage hydropower. *Sustainable Energy Technologies and Assessments*, *60*, 103423. https://doi.org/10.1016/j.seta.2023.103423
Barron-Gafford, G. A., Pavao-Zuckerman, M. A., Minor, R. L., Sutter, L. F., Barnett-Moreno, I., Blackett, D. T., Thompson, M., Dimond, K., Gerlak, A. K., Nabhan, G. P., & Macknick, J. E. (2019). Agrivoltaics provide mutual benefits across the food–energy–water nexus in drylands. *Nature Sustainability*, *2*(9), 848–855. https://doi.org/10.1038/s41893-019-0364-5
Bastakoti, B. P. (2003). Rural electrification and efforts to create enterprises for the effective use of power. *Applied Energy*, *76*(1–3), 145–155. https://doi.org/10.1016/S0306-2619(03)00055-2
Bhandari, B., Lee, K. T., Chu, W. S., Lee, C. S., Song, C. K., Bhandari, P., & Ahn, S. H. (2017). Socio-economic impact of renewable energy-based power system in mountainous villages of Nepal. *International Journal of Precision Engineering and Manufacturing—Green Technology*, *4*(1), 37–44. https://doi.org/10.1007/s40684-017-0005-2
Bhandari, R., & Subedi, S. (2023). Evaluation of surplus hydroelectricity potential in Nepal until 2040 and its use for hydrogen production via electrolysis. *Renewable Energy*, *212*, 403–414.
Bharadwaj, B., Subedi, M. N., Malakar, Y., & Ashworth, P. (2023). Low-capacity decentralized electricity systems limit the adoption of electronic appliances in rural Nepal. *Energy Policy*, *177*, 113576.
Bhattacharya, S. C., & Jana, C. (2009). Renewable energy in India: Historical developments and prospects. *Energy*, *34*(8), 981–991. https://doi.org/10.1016/j.energy.2008.10.017
Bhattacharyya, S. C. (2007). Power sector reform in South Asia: Why slow and limited so far? *Energy Policy*, *35*(1), 317–332. https://doi.org/10.1016/j.enpol.2005.11.028
Bhattarai, D., Somanathan, E., & Nepal, M. (2018). Are renewable energy subsidies in Nepal reaching the poor? *Energy for Sustainable Development*, *43*, 114–122. https://doi.org/10.1016/j.esd.2018.01.001
Bhattarai, R., Bhattarai, U., Pandey, V. P., & Bhattarai, P. K. (2022). An artificial neural network-hydrodynamic coupled modeling approach to assess the impacts of floods under changing climate in the East Rapti watershed, Nepal. *Journal of Flood Risk Management.*, *15*, 1–19. https://doi.org/10.1111/jfr3.12852
Bhattarai, S., Regmi, B. R., Pant, B., Uprety, D. R., & Maraseni, T. (2021). Sustaining ecosystem based adaptation: The lessons from policy and practices in Nepal. *Land Use Policy*, *104*, 105391. https://doi.org/10.1016/j.landusepol.2021.105391
Bhattarai, U., Devkota, L. P., Marahatta, S., Shrestha, D., & Maraseni, T. (2022). How will hydro-energy generation of the Nepalese Himalaya vary in the future? *A Climate Change Perspective. Environmental Research*, *214*, 113746. https://doi.org/10.1016/j.envres.2022.113746
Bhattarai, U., Devkota, R., Maraseni, T., Devkota, L., & Marahatta, S. (2023). Attaining multiple sustainable development goals through storage hydropower development amidst community vulnerabilities. *Sustainable Development*, *31*(5), 3913–3929. https://doi.org/10.1002/sd.2634
Bhattarai, U., Maraseni, T., Apan, A., & Devkota, L. P. (2023). Rationalizing donations and subsidies: Energy ecosystem development for sustainable renewable energy transition in Nepal. *Energy Policy*, *177*, 113570. https://doi.org/10.1016/j.enpol.2023.113570
Bhattarai, U., Maraseni, T., Devkota, L. P., & Apan, A. (2023). Application of machine learning to assess people's perception of household energy in the developing world: A case of Nepal. *Energy and AI*, *14*, 100303. https://doi.org/10.1016/j.egyai.2023.100303
Bhattarai, U., Maraseni, T., & Apan, A. (2022). Assay of renewable energy transition: A systematic literature review. *Science of the Total Environment*, *833*, 155159. https://doi.org/10.1016/j.scitotenv.2022.155159
Bibri, S. E. (2021). Data-driven smart sustainable cities of the future: An evidence synthesis approach to a comprehensive state-of-the-art literature review. *Sustainable Futures*, *3*, 100047.
Borozan, D. (2022). Asymmetric effects of policy uncertainty on renewable energy consumption in G7 countries. *Renewable Energy*, *189*, 412–420. https://doi.org/10.1016/j.renene.2022.02.055
Buchy, M., & Shakya, S. (2023). Understanding the gap between the gender equality and social inclusion policy and implementation in the energy sector: The case of Nepal. *Energy for Sustainable Development*, *76*, 101297.
Budhathoki, R., Maraseni, T., & Apan, A. (2024). *Enviro-economic and feasibility analysis of industrial hemp value chain: A systematic literature review*. GCB Bioenergy.
Butchers, J., Williamson, S., Booker, J., Tran, A., Karki, B., & Gautam, B. (2020). Understanding sustainable operation of micro-hydropower: A field study in Nepal. https://doi.org/10.5523/bris.1k9cigxbcdiye22kuay4wbt5yu
Capano, G., & Howlett, M. (2009). Introduction: The determinants of policy change: Advancing the debate. *Journal of Comparative Policy Analysis: Research and Practice*, *11*(1), 1–5. https://doi.org/10.1080/13876980802648227
CBS. (2021). Nepal in figures 2021. www.cbs.gov.np Central Bureau of Statistics, Kathmandu, Nepal
Chaudhary, D. R. (2023). Nepal-Bangladesh may be allowed to trade power through Indian corridor. The Economic Times. https://economictimes.indiatimes.com/news/international/world-news/nepal-bangladesh-may-be-allowed-to-trade-power-through-indian-corridor/articleshow/97207571.cms?from=mdr
Chen, L., & Guo, Y. (2023). The drivers of sustainable development: Natural resources extraction and education for low-middle- and high-income countries. *Resources Policy*, *86*(Part B), 104146. https://doi.org/10.1016/j.resourpol.2023.104146
Chen, R., Xu, P., Yao, H., & Ding, Y. (2023). How will China achieve net-zero? A policy text analysis of Chinese decarbonization policies. *Energy Research and Social Science*, *99*, 103051. https://doi.org/10.1016/j.erss.2023.103051
Chen, Y., Mamon, R., Spagnolo, F., & Spagnolo, N. (2023). Sustainable developments, renewable energy, and economic growth in Canada. *Sustainable Development*, *31*, 2950–2966. https://doi.org/10.1002/sd.2561
Cheng, S., Li, Z., Mang, H. P., Neupane, K., Wauthelet, M., & Huba, E. M. (2014). Application of fault tree approach for technical assessment of small-sized biogas systems in Nepal. *Applied Energy*, *113*, 1372–1381. https://doi.org/10.1016/j.apenergy.2013.08.052
Chinnasamy, P., Bharati, L., Bhattarai, U., Khadka, A., Dahal, V., & Wahid, S. (2015). Impact of planned water resource development on current and future water demand in the Koshi River basin, Nepal. *Water*

International, *40*(7), 1004–1020. https://doi.org/10.1080/02508060.2015.1099192

Chitrakar, A., & Shrestha, B. R. (2010). The Tuki: Lighting up Nepal innovations case narrative: Solar-powered Tuki (Winter 2010, Vol. 28). 69–78 http://direct.mit.edu/itgg/article-pdf/5/1/69/1838396/

Chiwaridzo, O. T. (2024). Fostering sustainable practices in Zimbabwean tourism for firewood energy sustainability and efficiency amid costly renewables, weak policies, scarce electricity, and extensive deforestation. *Sustainable Development*, *1-19*. https://doi.org/10.1002/sd.2871

Cloke, J., Mohr, A., & Brown, E. (2017). Imagining renewable energy: Towards a social energy systems approach to community renewable energy projects in the global south. *Energy Research and Social Science*, *31*, 263–272. https://doi.org/10.1016/j.erss.2017.06.023

Creutzig, F., Goldschmidt, J. C., Lehmann, P., Schmid, E., von Blücher, F., Breyer, C., Fernandez, B., Jakob, M., Knopf, B., Lohrey, S., & Susca, T. (2014). Catching two European birds with one renewable stone: Mitigating climate change and Eurozone crisis by an energy transition. *Renewable and Sustainable Energy Reviews*, *38*, 1015–1028. https://doi.org/10.1016/j.rser.2014.07.028

Das, I., Rogers, B., Nepal, M., & Jeuland, M. (2022). Fuel stacking implications for willingness to pay for cooking fuels in peri-urban Kathmandu Valley, Nepal. *Energy for Sustainable Development*, *70*, 482–496. https://doi.org/10.1016/j.esd.2022.08.017

Devkota, L. P., Bhattarai, U., Khatri, P., Marahatta, S., & Shrestha, D. (2022). Resilience of hydropower plants to flow variation through the concept of flow elasticity of power: Theoretical development. *Renewable Energy*, *184*, 920–932. https://doi.org/10.1016/j.renene.2021.11.051

Dhakal, S., Karki, P., & Shrestha, S. (2021). Cross-border electricity trade for Nepal: A SWOT-AHP analysis of barriers and opportunities based on stakeholders' perception. *International Journal of Water Resources Development*, *37*(3), 559–580. https://doi.org/10.1080/07900627.2019.1648240

Dhital, R. P., Ito, Y., Kaneko, S., Komatsu, S., Mihara, R., & Yoshida, Y. (2016). Does institutional failure undermine the physical design performance of solar water pumping systems in rural Nepal? *Sustainability (Switzerland)*, *8*(8), 1–11. https://doi.org/10.3390/su8080770

DoC. (2020). Nepal Foreign Trade Statistics Fiscal Year 2019/20 (2076/77).

Dominguez, C., Orehounig, K., & Carmeliet, J. (2021). Understanding the path towards a clean energy transition and post-electrification patterns of rural households. *Energy for Sustainable Development*, *61*, 46–64. https://doi.org/10.1016/j.esd.2021.01.002

ET. (2017). Nepal, China sign three pacts to boost energy, economic ties. The Economic Times. https://economictimes.indiatimes.com/news/international/world-news/nepal-china-sign-three-pacts-to-boost-energy-economic-ties/articleshow/60075580.cms

Fadly, D. (2019). Low-carbon transition: Private sector investment in renewable energy projects in developing countries. *World Development*, *122*, 552–569. https://doi.org/10.1016/j.worlddev.2019.06.015

Fan, Y., Döring, T., Li, S., Zhang, X., Fang, M., & Yu, Y. (2024). Energy poverty and public health vulnerability: A multi-country analysis. *Sustainable Development*, 1–20. https://doi.org/10.1002/sd.2965

Fares, R. L., & Webber, M. E. (2017). The impacts of storing solar energy in the home to reduce reliance on the utility. Nature. *Energy*, *2*(2), 1–10. https://doi.org/10.1038/nenergy.2017.1

Gautam, B. R., Li, F., & Ru, G. (2015). Assessment of urban roof top solar photovoltaic potential to solve power shortage problem in Nepal. *Energy and Buildings*, *86*, 735–744. https://doi.org/10.1016/j.enbuild.2014.10.038

Gautam, D., & Bolia, N. (2024). Understanding consumer choices and attitudes toward electric vehicles: A study of purchasing behavior and policy implications. *Sustainable Development*, 1–21. https://doi.org/10.1002/sd.2939

Gebreslassie, M. G., Cuvilas, C., Zalengera, C., To, L. S, Baptista, I., Robin, E., Bekele, G., Howe, L., Shenga, C., Macucule, D. A., Kirshner, J., Mulugetta, Y., Power, M., Robinson, S., Jones, D., & Castán Broto, V. (2022). Delivering an off-grid transition to sustainable energy in Ethiopia and Mozambique. *Energy, Sustainability and Society*, *12*(1), 1–18. https://doi.org/10.1186/s13705-022-00348-2

Ghimire, L. P., Kim, Y., & Dhakal, N. R. (2023). Which policies and factors drive electric vehicle use in Nepal? *Energies*, *16*, 7428. https://doi.org/10.3390/en16217428

Ghimire, L. P., & Kim, Y. (2018). An analysis on barriers to renewable energy development in the context of Nepal using AHP. *Renewable Energy*, *129*, 446–456. https://doi.org/10.1016/j.renene.2018.06.011

GIZ. (2013). *Multiple household fuel use–a balanced choice between firewood, charcoal and LPG*. Federal Ministry for Economic Cooperation and Development. GIZ, Eschborn.

Gonzalez-Salazar, M., & Poganietz, W. R. (2021). Evaluating the complementarity of solar, wind and hydropower to mitigate the impact of El Niño southern oscillation in Latin America. *Renewable Energy*, *174*, 453–467. https://doi.org/10.1016/j.renene.2021.04.048

Gorina, L., Korneeva, E., Kovaleva, O., & Strielkowski, W. (2024). Energy-saving technologies and energy efficiency in the post-COVID era. *Sustainable Development*, 1–17. https://doi.org/10.1002/sd.2978

Gurung, A., Ghimeray, A. K., & Hassan, S. H. A. (2012). The prospects of renewable energy technologies for rural electrification: A review from Nepal. *Energy Policy*, *40*(1), 374–380. https://doi.org/10.1016/j.enpol.2011.10.022

Gyanwali, K., Adhikari, P., Khanal, S., Bhattarai, N., Bajracharya, T. R., Komiyama, R., & Fujii, Y. (2023). Integrating glacio-hydrological and power grid models to assess the climate-resiliency of high mountain hydropower in Nepal. *Renewable and Sustainable Energy Reviews*, *183*, 113433.

Gyanwali, K., Komiyama, R., & Fujii, Y. (2020). Representing hydropower in the dynamic power sector model and assessing clean energy deployment in the power generation mix of Nepal. *Energy*, *202*, 117795. https://doi.org/10.1016/j.energy.2020.117795

Haifa, A. A., Zineb, O. T., & Ziad, Q. (2023). Good governance: Concept, basics and relationship to sustainable development from a Palestinian perspective. *Sustainable Development*, *31*, 2122–2136. https://doi.org/10.1002/sd.2530

Haldar, A., Sethi, N., Jena, P. K., & Pradhan, P. C. (2023). Towards achieving sustainable development goal 7 in sub-Saharan Africa: Role of governance and renewable energy. *Sustainable Development*, *31*, 2446–2463. https://doi.org/10.1002/sd.2521

Hall, P. A. (1993). Policy paradigms, social learning, and the state: The case of economic policymaking in Britain. In *Comparative Politics* (Vol. 25(3), pp. 275–296). City University of New York.

Hartono, D., Indriyani, W., Iryani, B. S., Komarulzaman, A., Nugroho, A., & Kurniawan, R. (2023). Carbon tax, energy policy, and sustainable development in Indonesia. *Sustainable Development*, *31*, 2332–2346. https://doi.org/10.1002/sd.2511

Hashemi, M. (2021). The economic value of unsupplied electricity: Evidence from Nepal. *Energy Economics*, *95*, 105124. https://doi.org/10.1016/j.eneco.2021.105124

Heazle, M., & Pillar, P. (2012). *Uncertainty in policy making: Values and evidence in complex decisions*. Routledge.

Hecht, J. S., Lacombe, G., Arias, M. E., Dang, T. D., & Piman, T. (2019). Hydropower dams of the Mekong River basin: A review of their hydrological impacts. *Journal of Hydrology*, *568*, 285–300. https://doi.org/10.1016/j.jhydrol.2018.10.045

Hill, D., & Connelly, S. (2018). Community energies: Exploring the socio-political spatiality of energy transitions through the clean energy for eternity campaign in New South Wales Australia. *Energy Research and Social Science*, *36*, 138–145. https://doi.org/10.1016/j.erss.2017.11.021

Hoffmann, R., Dimitrova, A., Muttarak, R., Crespo Cuaresma, J., & Peisker, J. (2020). A metaanalysis of country-level studies on environmental change and migration. *Nature Climate Change*, *10*, 904–912. https://doi.org/10.1038/s41558-020-0898-6
Huda, M. S., & McDonald, M. (2016). Regional cooperation on energy in South Asia: Unraveling the political challenges in implementing transnational pipelines and electricity grids. *Energy Policy*, *98*, 73–83. https://doi.org/10.1016/j.enpol.2016.07.046
Hussain, A., Sarangi, G. K., Pandit, A., Ishaq, S., Mamnun, N., Ahmad, B., & Jamil, M. K. (2019). Hydropower development in the Hindu Kush Himalayan region: Issues, policies and opportunities. *Renewable and Sustainable Energy Reviews*, *107*, 446–461. https://doi.org/10.1016/j.rser.2019.03.010
IEA. (2021). World energy model documentation. International Energy Agency.
Islar, M., Brogaard, S., & Lemberg-Pedersen, M. (2017). Feasibility of energy justice: Exploring national and local efforts for energy development in Nepal. *Energy Policy*, *105*, 668–676. https://doi.org/10.1016/j.enpol.2017.03.004
Jaramillo, L. V., Stone, M. C., & Morrison, R. R. (2018). An indicator-based approach to assessing resilience of socio-hydrologic systems in Nepal to hydropower development. *Journal of Hydrology*, *563*, 1111–1118. https://doi.org/10.1016/j.jhydrol.2018.05.070
Johnstone, P., Rogge, K. S., Kivimaa, P., Fratini, C. F., Primmer, E., & Stirling, A. (2020). Waves of disruption in clean energy transitions: Sociotechnical dimensions of system disruption in Germany and the United Kingdom. *Energy Research and Social Science*, *59*, 101287. https://doi.org/10.1016/j.erss.2019.101287
Joshi, J., & Bohara, A. K. (2017). Household preferences for cooking fuels and inter-fuel substitutions: Unlocking the modern fuels in the Nepalese household. *Energy Policy*, *107*, 507–523. https://doi.org/10.1016/j.enpol.2017.05.031
Kafle, U., Anderson, T., & Lohani, S. P. (2023). The potential for rooftop photovoltaic Systems in Nepal. *Energies*, *16*(2), 747.
Kapoor, M., & Garg, R. D. (2021). Solar potential assessment over canal-top using geospatial techniques. *Arabian Journal of Geosciences*, *14*(254), 1–13. https://doi.org/10.1007/s12517-021-06674-7/Published
Kevser, M., Tekbaş, M., Doğan, M., & Koyluoglu, S. (2022). Nexus among biomass energy consumption, economic growth, and financial development: Evidence from selected 15 countries. *Energy Reports*, *8*, 8372–8380. https://doi.org/10.1016/j.egyr.2022.06.033
Khadka, M., Uprety, L., Shrestha, G., Shakya, S., Mitra, A., & Mukherji, A. (2024). Can water, energy, and food policies in support of solar irrigation enable gender transformative changes? Evidence from policy analysis in Bangladesh and Nepal. *Frontiers in Sustainable Food Systems*, *7*, 1159867. https://doi.org/10.3389/fsufs.2023.1159867
Koirala, D. P., & Acharya, B. (2022). Households' fuel choices in the context of a decade-long load-shedding problem in Nepal. *Energy Policy*, *162*, 112795. https://doi.org/10.1016/j.enpol.2022.112795
Laudari, H. K., Aryal, K., & Maraseni, T. (2020). A postmortem of forest policy dynamics of Nepal. *Land Use Policy*, *91*, 104338. https://doi.org/10.1016/j.landusepol.2019.104338
Liao, C., Erbaugh, J. T., Kelly, A. C., & Agrawal, A. (2021). Clean energy transitions and human well-being outcomes in lower and middle income countries: A systematic review. *Renewable and Sustainable Energy Reviews*, *145*, 1–8. https://doi.org/10.1016/j.rser.2021.111063
Lin, B., & Kaewkhunok, S. (2021). The role of socio-culture in the solar power adoption: The inability to reach government policies of marginalized groups. *Renewable and Sustainable Energy Reviews*, *144*, 111035. https://doi.org/10.1016/j.rser.2021.111035
Lohani, S. P., Acharya, R., Shrestha, P., Shrestha, S., Manisha, K. C., & Pradhan, P. (2024). Sustainable biogas production potential in Nepal using waste biomass: A spatial analysis. *Sustainable Development*, 1–12. https://doi.org/10.1002/sd.2937
Lohani, S. P., Gurung, P., Gautam, B., Kafle, U., Fulford, D., & Jeuland, M. (2022). Current status, prospects, and implications of renewable energy for achieving sustainable development goals in Nepal. In *Sustainable Development*. John Wiley and Sons Ltd.. https://doi.org/10.1002/sd.2392
Lohani, S. P., Gurung, P., Gautam, B., Kafle, U., Fulford, D., & Jeuland, M. (2023). Current status, prospects, and implications of renewable energy for achieving sustainable development goals in Nepal. *Sustainable Development*, *31*(1), 572–585.
Lohani, S. P., & Blakers, A. (2021). 100% renewable energy with pumped-hydro-energy storage in Nepal. In *Clean energy* (Vol. 5, pp. 243–253). Oxford University Press. https://doi.org/10.1093/ce/zkab011
Luthra, S., Kumar, S., Garg, D., & Haleem, A. (2015). Barriers to renewable/sustainable energy technologies adoption: Indian perspective. In *Renewable and sustainable energy reviews* (Vol. 41, pp. 762–776). Elsevier Ltd.. https://doi.org/10.1016/j.rser.2014.08.077
Müller, F., Neumann, M., Elsner, C., & Claar, S. (2021). Assessing african energy transitions: Renewable energy policies, energy justice, and SDG 7. *Politics and Governance*, *9*(1), 119–130. https://doi.org/10.17645/pag.v9i1.3615
Maina, M. B., Ahmad, U., Ibrahim, H. A., Hamidu, S. K., Nasr, F. E., Salihu, A. T., … Baden, T. (2021). Two decades of neuroscience publication trends in Africa. *Nature Communications*, *12*(1), 3429.
Mainali, B., & Silveira, S. (2013). Alternative pathways for providing access to electricity in developing countries. *Renewable Energy*, *57*, 299–310. https://doi.org/10.1016/j.renene.2013.01.057
Mali, B., Shrestha, A., Chapagain, A., Bishwokarma, R., Kumar, P., & Gonzalez-Longatt, F. (2022). Challenges in the penetration of electric vehicles in developing countries with a focus on Nepal. In *Renewable energy focus* (Vol. 40, pp. 1–12). Elsevier Ltd.. https://doi.org/10.1016/j.ref.2021.11.003
Malik, S., Qasim, M., Saeed, H., Chang, Y., & Taghizadeh-Hesary, F. (2020). Energy security in Pakistan: Perspectives and policy implications from a quantitative analysis. *Energy Policy*, *144*, 111552. https://doi.org/10.1016/j.enpol.2020.111552
Marahatta, S., Bhattarai, U., Devkota, L. P., & Aryal, D. (2022). Unravelling the water-energy-economics-continuum of hydroelectricity in the face of climate change. *International Journal of Energy and Water Resources*, *6*, 323–335. https://doi.org/10.1007/s42108-021-00174-w
Maraseni, T. N., Bhattarai, N., Karky, B. S., Cadman, T., Timalsina, N., Bhandari, T. S., … Poudel, M. (2019). An assessment of governance quality for community-based forest management systems in Asia: Prioritisation of governance indicators at various scales. *Land Use Policy*, *81*, 750–761.
McKeown, S., & Mir, Z. M. (2021). Considerations for conducting systematic reviews: Evaluating the performance of different methods for de-duplicating references. *Systematic Reviews*, *10*, 1–8.
MECS/WINROCK. (2022). *Efficient electric cooking market uptake in Nepal (EECMU)*. WINROCK International. www.winrock.org.np
Mittal, A. (2022). *Assessment of SAARC nations' solar energy potential for sustainable development*. SAGE Publications Inc.. https://doi.org/10.1177/0958305X221120935
MoF/GoN. (2021). *Economic survey 2020/21*. Ministry of Finance.
MoF/GoN. (2023). *Economic survey 2022/23*. Ministry of Finance.
Moher, D., Liberati, A., Tetzlaff, J., & Altman, D. G. (2010). Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement. *International Journal of Surgery*, *8*, 336–341. https://doi.org/10.1016/j.ijsu.2010.02.007
Mohsin, M., Kamran, H. W., Atif Nawaz, M., Sajjad Hussain, M., & Dahri, A. S. (2021). Assessing the impact of transition from nonrenewable to renewable energy consumption on economic growth-environmental nexus from developing Asian economies. *Journal of Environmental Management*, *284*, 111999. https://doi.org/10.1016/j.jenvman.2021.111999
Moran, E. F., Lopez, M. C., Moore, N., Müller, N., & Hyndman, D. W. (2018). Sustainable hydropower in the 21st century. *Proceedings of the*

National Academy of Sciences of the United States of America, *115*(47), 11891–11898. https://doi.org/10.1073/pnas.1809426115
Movik, S., & Allouche, J. (2020). States of Power: Energy imaginaries and transnational assemblages in Norway, Nepal and Tanzania. *Energy Research and Social Science*, *67*, 101548. https://doi.org/10.1016/j.erss.2020.101548
Narula, K. (2013). Is sustainable energy security of India increasing or decreasing? *International Journal of Sustainable Energy*, *33*(6), 1054–1075. https://doi.org/10.1080/14786451.2013.811411
Naz, A., & Aslam, M. (2023). Green innovation, globalization, financial development, and CO_2 emissions: The role of governance as a moderator in South Asian countries. *Environmental Science and Pollution Research*, *30*(20), 57358–57377. https://doi.org/10.1007/s11356-023-26527-y
NEA/GoN. (1993). A year in review fiscal year 1992/93. Nepal electricity authority, government of Nepal.
NEA/GoN. (2014). *A year in review fiscal year 2013/14*. Nepal Electricity Authority, Government of Nepal.
NEA/GoN. (2019). *A Year in Review Fiscal Year 2018/19*. Nepal Electricity Authority, Government of Nepal.
NEA/GoN. (2021). A year in review fiscal year 2020/21. Nepal electricity authority, government of Nepal.
NEA/GoN. (2023). A year in review fiscal year 2022/23. Nepal electricity authority, government of Nepal.
NEO22. (2022). Nepal energy outlook 2022. Kathmandu university, Institute of Engineering, Nepal Energy Foundation and Niti foundation, Kathmandu, Nepal.
Nepal, R. (2012). Roles and potentials of renewable energy in less-developed economies: The case of Nepal. In *Renewable and sustainable energy reviews* (Vol. 16, pp. 2200–2206). Elsevier B.V. https://doi.org/10.1016/j.rser.2012.01.047
Nepal, R., Best, R., & Taylor, M. (2023). Strategies for reducing ethnic inequality in energy outcomes: A Nepalese example. *Energy Economics*, *126*, 106910.
Nepal, R., & Paija, N. (2019). Energy security, electricity, population and economic growth: The case of a developing south Asian resource-rich economy. *Energy Policy*, *132*, 771–781. https://doi.org/10.1016/j.enpol.2019.05.054
Neupane, D., Kafle, S., Karki, K. R., Kim, D. H., & Pradhan, P. (2022). Solar and wind energy potential assessment at provincial level in Nepal: Geospatial and economic analysis. *Renewable Energy*, *181*, 278–291. https://doi.org/10.1016/j.renene.2021.09.027
Niroomand, N., & Jenkins, G. P. (2020). Estimation of households' and businesses' willingness to pay for improved reliability of electricity supply in Nepal. *Energy for Sustainable Development*, *55*, 201–209. https://doi.org/10.1016/j.esd.2020.02.006
Ogino, K., Dash, S. K., & Nakayama, M. (2019). Change to hydropower development in Bhutan and Nepal. *Energy for Sustainable Development*, *50*, 1–17. https://doi.org/10.1016/j.esd.2019.02.005
Pandey, P., & Sharma, A. (2021). Knowledge politics, vulnerability and recognition-based justice: Public participation in renewable energy transitions in India. *Energy Research and Social Science*, *71*, 101824. https://doi.org/10.1016/j.erss.2020.101824
Pandey, R., Shrestha, R., Bhattarai, N., & Dhakal, R. (2023). Problems identification and performance analysis in small hydropower plants in Nepal. *International Journal of Low-Carbon Technologies*, *18*, 561–569.
Parajuli, R., Pokharel, G. R., & Østergaard, P. A. (2014). A comparison of diesel, biodiesel and solar PV-based water pumping systems in the context of rural Nepal. *International Journal of Sustainable Energy*, *33*(3), 536–553. https://doi.org/10.1080/14786451.2012.761221
Parajuli, S., Bhattarai, T. N., Gorjian, S., Vithanage, M., & Paudel, S. R. (2023). Assessment of potential renewable energy alternatives for a typical greenhouse aquaponics in Himalayan region of Nepal. *Applied Energy*, *344*, 121270.
Paudel, J., Sharifi, A., & Khan, G. D. (2023). What are the drivers of sustainable energy transition? Insights from an empirical analysis of household preferences for electric induction cooking in Nepal. *Journal of Cleaner Production*, *417*, 138021. https://doi.org/10.1016/j.jclepro.2023.138021
Paudel, J. (2021). Why are people energy poor? Evidence from ethnic fractionalization. *Energy Economics*, *102*, 105519. https://doi.org/10.1016/j.eneco.2021.105519
Pi, K., Khan, S., Raza, S. A., & Shahzadi, I. (2024). Sustainable energy efficiency, greener energy and energy-related emissions nexus: Sustainability-related implications for G7 economies. *Geological Journal*, *59*(1), 301–312.
Pietrosemoli, L., & Rodríguez-Monroy, C. (2019). The Venezuelan energy crisis: Renewable energies in the transition towards sustainability. *Renewable and Sustainable Energy Reviews*, *105*, 415–426. https://doi.org/10.1016/j.rser.2019.02.014
Pinczynski, M., Kasperowicz, R., Azzopardi, B., Bilan, Y., & Štreimikienė, D. (2024). Malta's low carbon transition towards sustainability. *Sustainable Development*, 1–9.
Pokharel, P., & Regmi, R. K. (2024). Climate change and hydropower resilience in Nepal: An integrated modeling approach in the Madi River basin. *H2Open Journal*, *7*(2), 199–221.
Pokharel, S. (2003). Promotional issues on alternative energy technologies in Nepal. *In Energy Policy*, *31*, 307–318.
Pokharel, S. (2007). An econometric analysis of energy consumption in Nepal. *Energy Policy*, *35*(1), 350–361. https://doi.org/10.1016/j.enpol.2005.11.004
Pokharel, S., & Chandrashekar, M. (1998). A multiobjective approach to rural energy policy analysis. *Energy*, *23*(4), 325–336.
Ptak, T., Crootof, A., Harlan, T., & Kelly, S. (2022). Critically evaluating the purported global "boom" in small hydropower development through spatial and temporal analysis. *Renewable and Sustainable Energy Reviews*, *163*, 112490. https://doi.org/10.1016/j.rser.2022.112490
Qazi, S. (2022). *August 26*. How power project diplomacy plays out in Nepal. https://www.trtworld.com/magazine/china-out-india-in-how-power-project-diplomacy-plays-out-in-nepal-60102
Rahut, D. B., Aryal, J. P., Chhay, P., & Sonobe, T. (2022). Ethnicity/caste-based social differentiation and the consumption of clean cooking energy in Nepal: An exploration using panel data. *Energy Economics*, *112*, 106080. https://doi.org/10.1016/j.eneco.2022.106080
Raihan, A., & Tuspekova, A. (2022). Nexus between economic growth, energy use, agricultural productivity, and carbon dioxide emissions: New evidence from Nepal. *Energy Nexus*, *7*, 100113. https://doi.org/10.1016/j.nexus.2022.100113
Rajbhandari, S., Shrestha, S. L., Bhandari, R., Jha, A. K., & Darlami, H. B. (2024). Contribution to the net-zero emissions target from the transport sector through electric mobility—A case of Kathmandu Valley. *Sustainability*, *16*(3), 1211.
Rastegar, H., Eweje, G., & Sajjad, A. (2024). The impact of environmental policy on renewable energy innovation: A systematic literature review and research directions. *Sustainable Development*, 1–18. https://doi.org/10.1002/sd.2884
Rethlefsen, M. L., Kirtley, S., Waffenschmidt, S., Ayala, A. P., Moher, D., Page, M. J., Koffel, J. B., PRISMA-S Group, Blunt, H., Brigham, T., Chang, S., Clark, J., Conway, A., Couban, R., de Kock, S., Farrah, K., Fehrmann, P., Foster, M., Fowler, S. A., … Young, S. (2021). PRISMA-S: An extension to the PRISMA statement for reporting literature searches in systematic reviews. *Systematic Reviews*, *10*, 39. https://doi.org/10.1186/s13643-020-01542-z
Rijal, K. (1999). Renewable energy policy options for mountain communities: Experiences from China, India, Nepal and Pakistan. *In Renewable Energy*, *16*, 1138–1142.
Rissman, J., Bataille, C., Masanet, E., Aden, N., Morrow, W. R., Zhou, N., Elliott, N., Dell, R., Heeren, N., Huckestein, B., Cresko, J., Miller, S. A., Roy, J., Fennell, P., Cremmins, B., Koch Blank, T., Hone, D., Williams, E. D., de la Rue du Can, S., … Helseth, J. (2020). Technologies and policies to decarbonize global industry: Review and assessment of

mitigation drivers through 2070. In *Applied energy* (Vol. 266, 114848). Elsevier Ltd.. https://doi.org/10.1016/j.apenergy.2020.114848

Ruan, W., Guo, Z., Yang, J., Gao, L., Dong, Y., & Liu, Q. (2023). Assessing the progress toward achieving energy-and climate-related sustainable development goals under four global energy transition outlooks. *Sustainable Development*, 1–13. https://doi.org/10.1002/sd.2873

Rupf, G. V., Bahri, P. A., De Boer, K., & McHenry, M. P. (2015). Barriers and opportunities of biogas dissemination in sub-Saharan Africa and lessons learned from Rwanda. In *And Nepal. In renewable and sustainable energy reviews* (Vol. 52, pp. 468–476). Elsevier Ltd.. https://doi.org/10.1016/j.rser.2015.07.107

Safi, A., Haseeb, M., Islam, M., & Umar, M. (2023). Can sustainable resource management overcome geopolitical risk? *Resources Policy*, *87*(Part B), 104270. https://doi.org/10.1016/j.resourpol.2023.104270

Saidi, K., & Hammami, S. (2015). The impact of CO2 emissions and economic growth on energy consumption in 58 countries. *Energy Reports*, *1*, 62–70. https://doi.org/10.1016/j.egyr.2015.01.003

Saklani, U., Shrestha, P. P., Mukherji, A., & Scott, C. A. (2020). Hydro-energy cooperation in South Asia: Prospects for transboundary energy and water security. *Environmental Science and Policy*, *114*, 22–34. https://doi.org/10.1016/j.envsci.2020.07.013

Sanjel, N., & Baral, B. (2019). A review of renewable energy sector of Nepal Nawaraj. In international (SAARC) youth scientific conference (IYSC) 2019, conference proceedings (peer reviewed). 115–120.

Sanjel, N., & Baral, B. (2020). Technical investigation of Nepalese electricity market–a review. In *Journal of physics: Conference series* (Vol. 1608, 012005). IOP Publishing.

Sanjel, N., & Baral, B. (2021). Modelling and analysis of decentralized energy systems with photovoltaic, micro-hydro, battery and diesel technology for remote areas of Nepal. *Clean Energy*, *5*(4), 690–703. https://doi.org/10.1093/ce/zkab042

SARI/EI-IRADe. (2018). Gains from multilateral electricity trade among BBIN countries modelling study.

SARI/EI/IRADe. (2021). SAFIR working group study report on regulatory interventions for grid discipline and grid reliability in the south Asian region (SAR).

SARI/EI. (2017). Economic benefits from Nepal-India electricity trade analytical study.

SARI/EI. (2020). Prospects of regional energy cooperation and cross border energy trade in the BIMSTEC region.

SARI/EI. (2021). Prospects for sustainable energy infrastructure development and role of cross border energy trade in South Asia challenges, Opportunities and Way forward.

Sattler, S., Gignac, J., Collingsworth, J., Clemmer, S., & Garcia, P. (2018). Achieving a clean energy transition in Illinois: Economic and public health benefits of replacing coal plants in Illinois with local clean energy alternatives. *Electricity Journal*, *31*(10), 52–59. https://doi.org/10.1016/j.tej.2018.11.001

Schulz, C., & Saklani, U. (2021). The future of hydropower development in Nepal: Views from the private sector. *Renewable Energy*, *179*, 1578–1588. https://doi.org/10.1016/j.renene.2021.07.138

Shakya, L. K., Devkota, N., Dhakal, K., Poudyal, R., Mahato, S., Paudel, U. R., & Parajuli, S. (2024). Consumer's behavioural intention towards adoption of e-bike in Kathmandu valley: structural equation modelling analysis. In *Consumer's behavioural intention towards adoption of e-bike in Kathmandu valley: Structural equation modelling analysis* (pp. 1–29). Environment, Development and Sustainability.

Shakya, S. R., Adhikari, R., Poudel, S., & Rupakheti, M. (2022). Energy equity as a major driver of energy intensity in South Asia. *Renewable and Sustainable Energy Reviews*, *170*, 112994. https://doi.org/10.1016/j.rser.2022.112994

Shakya, S. R., Bajracharya, I., Vaidya, R. A., Bhave, P., Sharma, A., Rupakheti, M., & Bajracharya, T. R. (2022). Estimation of air pollutant emissions from captive diesel generators and its mitigation potential through microgrid and solar energy. *Energy Reports*, *8*, 3251–3262. https://doi.org/10.1016/j.egyr.2022.02.084

Shakya, S. R., Nakarmi, A. M., Prajapati, A., Pradhan, B. B., Rajbhandari, U. S., Rupakheti, M., & Lawrence, M. G. (2023). Environmental, energy security, and energy equity (3E) benefits of net-zero emission strategy in a developing country: A case study of Nepal. *Energy Reports*, *9*, 2359–2371.

Sharma, B., & Shrestha, A. (2023). Petroleum dependence in developing countries with an emphasis on Nepal and potential keys. *Energy Strategy Reviews*, *45*, 101053.

Sharma, R. H., & Awal, R. (2013). Hydropower development in Nepal. *Renewable and Sustainable Energy Reviews*, *21*, 684–693. https://doi.org/10.1016/j.rser.2013.01.013

Shrestha, A., Marahatta, A., Rajbhandari, Y., & Gonzalez-Longatt, F. (2024). Deep reinforcement learning approach to estimate the energy-mix proportion for secure operation of converter-dominated power system. *Energy Reports*, *11*, 1430–1444. https://doi.org/10.1016/j.egyr.2024.01.008

Shrestha, P. M. (2023). Nepal, India reach 'milestone' deal on trade, transmission of electricity. The Kathmandu Post. https://kathmandupost.com/national/2023/02/19/nepal-and-india-agree-to-increase-power-trade-build-more-cross-border-power-line

Shrestha, R. P., Jirakiattikul, S., Lohani, S. P., & Shrestha, M. (2023). Perceived impact of electricity on productive end use and its reality: Transition from electricity to income for rural Nepalese women. *Energy Policy*, *183*, 113839.

Shrestha, R. P., Jirakiattikul, S., & Shrestha, M. (2023). "Electricity is result of my good deeds": An analysis of the benefit of rural electrification from the women's perspective in rural Nepal. *Energy Research & Social Science*, *105*, 103268.

Shrestha, R. S. (2010). Electricity Crisis (Load Shedding) in Nepal, Its Manifestations and Ramifications. Hydro Nepal issue no. 6 January, 2010.

Shrestha, S., & Dhakal, S. (2019). An assessment of potential synergies and trade-offs between climate mitigation and adaptation policies of Nepal. *Journal of Environmental Management*, *235*, 535–545. https://doi.org/10.1016/j.jenvman.2019.01.035

Singh, R. P., Nachtnebel, H. P., & Komendantova, N. (2020). Deployment of hydropower in Nepal: Multiple stakeholders' perspectives. *Sustainability (Switzerland)*, *12*(16), 1–17. https://doi.org/10.3390/SU12166312

Sofian, A. D. A. B. A., Lim, H. R., Siti Halimatul Munawaroh, H., Ma, Z., Chew, K. W., & Show, P. L. (2024). Machine learning and the renewable energy revolution: Exploring solar and wind energy solutions for a sustainable future including innovations in energy storage. *Sustainable Development*, 1–26. https://doi.org/10.1002/sd.2885

Sovacool, B. K. (2012). The political economy of energy poverty: A review of key challenges. In *Energy for sustainable development* (Vol. 16, pp. 272–282). Elsevier B.V. https://doi.org/10.1016/j.esd.2012.05.006

Sovacool, B. K. (2013). An international assessment of energy security performance. *Ecological Economics*, *88*, 148–158. https://doi.org/10.1016/j.ecolecon.2013.01.019

Sovacool, B. K., Dhakal, S., Gippner, O., & Bambawale, M. J. (2011). Halting hydro: A review of the socio-technical barriers to hydroelectric power plants in Nepal. *Energy*, *36*(5), 3468–3476. https://doi.org/10.1016/j.energy.2011.03.051

Sovacool, B. K., Dhakal, S., Gippner, O., & Jain Bambawale, M. (2013). Peeling the energy pickle: Expert perceptions on overcoming Nepal's electricity crisis. *South Asia: Journal of South Asia Studies*, *36*(4), 496–519. https://doi.org/10.1080/00856401.2013.788469

Sovacool, B. K., & Bulan, L. C. (2012). Energy security and hydropower development in Malaysia: The drivers and challenges facing the Sarawak corridor of renewable energy (SCORE). *Renewable Energy*, *40*(1), 113–129. https://doi.org/10.1016/j.renene.2011.09.032

Sovacool, B. K., & Dworkin, M. H. (2015). Energy justice: Conceptual insights and practical applications. *Applied Energy*, *142*, 435–444. https://doi.org/10.1016/j.apenergy.2015.01.002

Sovacool, B. K., Hess, D. J., Amir, S., Geels, F. W., Hirsh, R., Rodriguez Medina, L., Miller, C., Alvial Palavicino, C., Phadke, R., Ryghaug, M., Schot, J., Silvast, A., Stephens, J., Stirling, A., Turnheim, B., van der

Vleuten, E., van Lente, H., & Yearley, S. (2020). Sociotechnical agendas: Reviewing future directions for energy and climate research. *Energy Research & Social Science*, *70*, 101617. https://doi.org/10.1016/j.erss.2020.101617

Sovacool, B. K., & Mukherjee, I. (2011). Conceptualizing and measuring energy security: A synthesized approach. *Energy*, *36*(8), 5343–5355. https://doi.org/10.1016/j.energy.2011.06.043

Subedi, M. N., Bharadwaj, B., & Rafiq, S. (2023). Who benefits from the decentralised energy system (DES)? Evidence from Nepal's micro-hydropower (MHP). *Energy Economics*, *120*, 106592.

Suhardiman, D., Wichelns, D., Lebel, L., & Sellamuttu, S. S. (2014). Benefit sharing in Mekong region hydropower: Whose benefits count? *Water Resources and Rural Development*, *4*, 3–11. https://doi.org/10.1016/j.wrr.2014.10.008

Suman, A. (2021). Role of renewable energy technologies in climate change adaptation and mitigation: A brief review from Nepal. *Renewable and Sustainable Energy Reviews*, *151*, 111524. https://doi.org/10.1016/j.rser.2021.111524

Sun, Y., & Gao, J. (2023). Natural resource endowment and its impact on ecological efficiency. *Resources Policy*, *87*(Part B), 104272. https://doi.org/10.1016/j.resourpol.2023.104272

Tang, C. F., Tan, B. W., & Ozturk, I. (2016). Energy consumption and economic growth in Vietnam. In *Renewable and sustainable energy reviews* (Vol. 54, pp. 1506–1514). Elsevier Ltd.. https://doi.org/10.1016/j.rser.2015.10.083

Thapa-Parajuli, R., Aryal, S., Alharthi, M., & Paudel, R. C. (2021). Energy consumption, export performance and economic growth in a land-locked developing country: The case of Nepal. *AIMS Energy*, *9*(3), 516–533. https://doi.org/10.3934/ENERGY.2021025

Thapa, S., Morrison, M., & Parton, K. A. (2021). Willingness to pay for domestic biogas plants and distributing carbon revenues to influence their purchase: A case study in Nepal. *Energy Policy*, *158*, 112521. https://doi.org/10.1016/j.enpol.2021.112521

Tidwell, J. H., & Tidwell, A. S. D. (2018). Energy ideals, visions, narratives, and rhetoric: Examining sociotechnical imaginaries theory and methodology in energy research. In *Energy research and social science* (Vol. 39, pp. 103–107). Elsevier Ltd.. https://doi.org/10.1016/j.erss.2017.11.005

Tiwari, A. (2021). 10 megawatts of solar power evacuated to national grid in province 2. Webpage. https://kathmandupost.com/money/2021/03/01/10-megawatts-of-solar-power-evacuated-to-national-grid-in-province-2

USAID-SARI. (2003). Economic Impact of Poor Power Quality on Industry Nepal Economic Impact of Poor Power Quality on Industry Nepal. www.sari-energy.org

van der Gaast, W., Begg, K., & Flamos, A. (2009). Promoting sustainable energy technology transfers to developing countries through the CDM. *Applied Energy*, *86*(2), 230–236. https://doi.org/10.1016/j.apenergy.2008.03.009

Vanegas Cantarero, M. M. (2020). Of renewable energy, energy democracy, and sustainable development: A roadmap to accelerate the energy transition in developing countries. In *Energy research and social science* (101716). Elsevier Ltd. https://doi.org/10.1016/j.erss.2020.101716

Verma, P., Chodkowska-Miszczuk, J., & Raghubanshi, A. S. (2024). Are cities ready for low-carbon inclusive strategies? Household energy management under heterogeneous socioeconomic conditions. *Sustainable Development*, 1–17. https://doi.org/10.1002/sd.2922

Vij, S., Stock, R., Ishtiaque, A., Gardezi, M., & Zia, A. (2023). Power in climate change policy-making process in South Asia. *Climate Policy*, *24*(1), 104–116. https://doi.org/10.1080/14693062.2023.2271440

Vij, S., Biesbroek, R., Groot, A., & Termeer, K. (2018). Changing climate policy paradigms in Bangladesh and Nepal. *Environmental Science and Policy*, *81*, 77–85. https://doi.org/10.1016/j.envsci.2017.12.010

Wagemans, D., Scholl, C., & Vasseur, V. (2019). Facilitating the energy transition-the governance role of local renewable energy cooperatives. *Energies*, *12*(21), 1–20. https://doi.org/10.3390/en12214171

WB. (2024). World Bank national accounts data, and OECD National Accounts data files. Webpage. https://data.worldbank.org/indicator/NY.GDP.MKTP.CD?locations=NP&msclkid=c583c33ad00811ec9a96c3a8dce184bf (accessed on 29 March, 2024).

WEC. (2021). World Energy Trilemma Index 2021. www.worldenergy.org

WECS/GoN. (2010). Energy sector synopsis report. www.wec.gov.np water and energy commission secretariat, Government of Nepal, Singhadurbar, Kathmandu, Nepal

WECS/GoN. (2013). *Nepal's energy sector vision 2050 a.D. water and energy commission secretariat*. Government of Nepal.

WECS/GoN. (2023). *Nepal energy sector synopsis Report-2023*. Water and Energy Commission Secretariat.

Weko, S., & Goldthau, A. (2022). Bridging the low-carbon technology gap? Assessing energy initiatives for the global south. *Energy Policy*, *169*, 113192. https://doi.org/10.1016/j.enpol.2022.113192

Windemer, R. (2023). Acceptance should not be assumed. How the dynamics of social acceptance changes over time, impacting onshore wind repowering. *Energy Policy*, *173*, 113363. https://doi.org/10.1016/j.enpol.2022.113363

Wittmayer, J. M., Hielscher, S., Fraaije, M., Avelino, F., & Rogge, K. (2022). A typology for unpacking the diversity of social innovation in energy transitions. *Energy Research and Social Science*, *88*, 102513. https://doi.org/10.1016/j.erss.2022.102513

Wolde-Rufael, Y. (2009). Energy consumption and economic growth: The experience of African countries revisited. *Energy Economics*, *31*(2), 217–224. https://doi.org/10.1016/j.eneco.2008.11.005

Wu, S. (2020). The evolution of rural energy policies in China: A review. In *Renewable and sustainable energy reviews* (Vol. 119, 109584). Elsevier Ltd.. https://doi.org/10.1016/j.rser.2019.109584

Xia, L., Wan, L., Wang, W., Luo, J., & Yan, J. (2023). Energy accessibility via natural resources: Do natural resources energy accessibility in low income countries? *Resources Policy*, *86*(Part B), 104145. https://doi.org/10.1016/j.resourpol.2023.104145

Xu, R., Zeng, Z., Pan, M., Ziegler, A. D., Holden, J., Spracklen, D. V., Brown, L. E., He, X., Chen, D., Ye, B., Xu, H., Jerez, S., Zheng, C., Liu, J., Lin, P., Yang, Y., Zou, J., Wang, D., Gu, M., … Wood Eric, F. (2023). A global-scale framework for hydropower development incorporating strict environmental constraints. *Nature Water*, *1*(1), 113–122. https://doi.org/10.1038/s44221-022-00004-1

Yadoo, A., & Cruickshank, H. (2012). The role for low carbon electrification technologies in poverty reduction and climate change strategies: A focus on renewable energy mini-grids with case studies in Nepal, Peru and Kenya. *Energy Policy*, *42*, 591–602. https://doi.org/10.1016/j.enpol.2011.12.029

Zittoun, P. (2015). From policy paradigm to policy statement: A new way to grasp the role of knowledge in the policymaking process. In J. Hogan & M. Howlett (Eds.), *Policy paradigms in theory and practice* (pp. 117–140). Palgrave Macmillan UK. https://doi.org/10.1057/9781137434043_7

Zou, X., Pradhan, S., & Mukhia, A. (2022). Nepal's hydropower development: Predicament and dilemma in policy-making. *Natural Resources Forum*, *46*(1), 60–72. https://doi.org/10.1111/1477-8947.12241

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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APPENDIX A

TABLE A1 List of policies directly related to the energy sector of Nepal from 1979 to 2022 and their coverage.

			Sectors						Technologies													
			Domestic		Transportation				Hydropower		Solar				Biogas							
S. N	Policies	Year	Urban	Rural	Passenger	Freight	Industrial & Commercial	Others	Large & medium (grid electricity)	Small & micro	Off-grid	Grid connected	Wind	Hybrid	Household	Community	Others	Demand side management & efficiency	Legal/ institutional arrangements	Promotion of private/ international sector collaboration	Focus on Research and Development	Involved organizations
1	Gandaki River Basin Power Study	1979							✓													HMG, UNDP, SMEC, EPA, NED
2	National Electricity Act	1984							✓										✓			HMG
3	Master Plan Study on The Kosi River Water Resources Development	1985							✓													HMG, JICA
4	Water Resources Act	1992							✓										✓			HMG
5	Electricity Act	1992							✓													HMG
6	Hydropower Development Policy	1992	✓	✓	✓	✓	✓	✓	✓											✓		HMG
7	Electricity Rules	1993	✓						✓										✓			HMG
8	Hydropower Development Policy	2001							✓	✓								✓		✓		HMG
9	National Transport Policy	2001			✓	✓			✓			✓										MoPPW/ HMG
10	Water Resources Strategy	2002	✓	✓	✓	✓	✓		✓													WECS/HMG
11	Electricity Theft Control Act	2002	✓	✓					✓										✓			HMG
12	Nepal Electricity Authority Community Electricity Distribution Bye-Laws	2003		✓					✓											✓		NEA

(Continues)

TABLE A1 (Continued)

			Sectors						Technologies													
			Domestic		Transportation				Hydropower		Solar				Biogas							
S. N	Policies	Year	Urban	Rural	Passenger	Freight	Industrial & Commercial	Others	Large & medium (grid electricity)	Small & micro	Off-grid	Grid connected	Wind	Hybrid	Household	Community	Others	Demand side management & efficiency	Legal/ institutional arrangements	Promotion of private/ international sector collaboration	Focus on Research and Development	Involved organizations
13	National Water Plan	2005	✓	✓					✓													CIDA, WB, HMG, NISP
14	Rural Energy Policy	2006		✓						✓	✓	✓	✓		✓	✓	✓			✓	✓	GoN
15	Nepal Electricity Crisis Resolution Action Plan	2008	✓	✓					✓	✓	✓	✓	✓				✓	✓		✓		GoN
16	Ten Years Hydropower Development Plan	2009							✓	✓	✓	✓	✓		✓	✓		✓	✓	✓		MOWR/GoN
17	Subsidy Policy for Renewable (Rural) Energy	2009		✓						✓	✓	✓	✓		✓	✓	✓			✓		AEPC/GoN
18	Energy Sector Synopsis Report	2010	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓					WECS/GoN
19	Industrial Policy	2011					✓		✓	✓		✓	✓			✓	✓	✓				GoN
20	National Renewable and Rural Energy Program (2012–2017)	2012		✓						✓	✓		✓							✓		GoN
21	National Energy Strategy of Nepal	2013							✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓		WECS/GoN
22	Renewable Energy Subsidy Policy	2013		✓						✓	✓	✓	✓		✓	✓	✓			✓		MoSTE/GoN
23	Nepal's Energy Sector Vision 2050 A. D.	2013	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓		WECS/GoN
24	Renewable Energy Subsidy Delivery Mechanism	2013		✓						✓	✓	✓	✓	✓	✓	✓	✓					AEPC/ MoSTE/GoN
25	Nationwide Master Plan Study on Storage-type Hydroelectric Power Development in Nepal	2014	✓						✓									✓	✓		✓	NEA, JICA, EPDC

TABLE A1 (Continued)

			Sectors						Technologies													
			Domestic		Transportation				Hydropower		Solar				Biogas							
S. N	Policies	Year	Urban	Rural	Passenger	Freight	Industrial & Commercial	Others	Large & medium (grid electricity)	Small & micro	Off-grid	Grid connected	Wind	Hybrid	Household	Community	Others	Demand side management & efficiency	Legal/ institutional arrangements	Promotion of private/ international sector collaboration	Focus on Research and Development	Involved organizations
26	Environment-friendly Vehicle and Transport Policy	2014			✓	✓			✓			✓		✓			✓		✓			MoPIT/GoN
27	National Sustainable Transport Strategy (2015–2040)	2015	✓	✓	✓	✓			✓									✓				MoPIT/GoN, UNCRD
28	Renewable Energy Subsidy Policy	2016		✓						✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	GoN
29	Biomass Energy Strategy	2017	✓	✓											✓	✓	✓		✓		✓	MoPE/GoN
30	National Renewable Energy Framework	2017		✓				✓		✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	AEPC/GoN
31	Whitepaper on Energy, Water and Irrigation: Present Situation and Future Prospect	2018	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	MoEWRI/ GoN
32	National Energy Efficiency Strategy	2018	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	MOFE/GoN
33	Renewable Energy Subsidy Delivery Mechanism for Special Program	2018	✓	✓						✓	✓	✓	✓	✓	✓	✓	✓					AEPC/ MoPE/GoN
34	National Action Plan for Electric Mobility	2018			✓	✓			✓										✓			MoFE/ MoPIT/GGGI
35	Hydropower Environmental Impact Assessment Manual	2018	✓						✓	✓												MOFE/GoN, IFC, ICIMOD, SDIP, GoJ
36	Industrial Enterprise Act	2020					✓		✓									✓	✓			MoITC/GoN
37	Energy Sector Synopsis Report 2021/22	2022	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓					WECS/GoN

(Continues)

TABLE A1 (Continued)

			Sectors						Technologies													
			Domestic		Transportation				Hydropower		Solar				Biogas							
S. N	Policies	Year	Urban	Rural	Passenger	Freight	Industrial & Commercial	Others	Large & medium (grid electricity)	Small & micro	Off-grid	Grid connected	Wind	Hybrid	Household	Community	Others	Demand side management & efficiency	Legal/ institutional arrangements	Promotion of private/ international sector collaboration	Focus on Research and Development	Involved organizations
38	Renewable Energy Subsidy Policy	2022		✓						✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	AEPC/ MoEWRI/ GoN
39	Renewable Energy Subsidy Delivery Mechanism	2022	✓	✓						✓	✓	✓	✓	✓	✓	✓	✓					AEPC/ MoEWRI/ GoN

Abbreviations: AEPC, alternative energy promotion centre; CIDA, Canadian international development agency; EPA, environmental planning associates; EPDC, electric power development company limited, Nepal electricity authority; GGGI, global green growth institute (Korea); GoJ, government of Japan; HMG, his majesty's government of nepalf; IFC, international finance corporation, international centre for integrated mountain development; JICA, Japan international cooperation agency; MoEWRI, ministry of energy, water resources and irrigation; MOFE, ministry of forests and environment; MoITC, ministry of industry trade and commerce; MoPE, ministry of population and environment; MoPIT, ministry of physical infrastructure and transport; MOPPW, ministry of physical planning and works; MoSTE, ministry of science, technology and environment; MOWR, ministry of water resources; NED, Nepal electricity department; NISP, Nepal irrigation sector project; SDIP, sustainable development investment portfolio, Australia; SMEC, snowy mountain engineering corporation; UNCRD, united nations center for regional development (Japan); UNDP, united nations development programme; WB, world bank; WECS, water and energy commission secretariat.

TABLE A2 List of policies with an overarching impact on the energy sector of Nepal from 1979 to 2022.

S. N	Policy documents	Year	S. N	Policy documents	Year
1	Seventh Plan (1985–1990)	1985	17	Forest Policy	2015
2	Eighth Plan (1992–1997)	1992	18	Fourteenth Periodic Plan (2016–2019)	2016
3	Industrial Enterprise Act	1992	19	First Nationally Determined Contribution	2016
4	Nepal Environmental Policy and Action Plan	1993	20	Forestry Sector Strategy (2016–2025)	2016
5	Ninth Plan (1997–2002)	1997	21	Sustainable Development Goals—Status and Roadmap (2016–2030)	2016
6	Local Self-Governance Act	1999	22	National Urban Development Strategy	2017
7	Forest Sector Policy	2000	23	Fifteenth Plan (2019–2024)	2019
8	Tenth Plan (2002–2007)	2002	24	Environment Protection Act	2019
9	Three Year Interim Plan (2007–2010)	2007	25	National Climate Change Policy	2019
10	Three Year Interim Plan (2010–2013)	2010	26	Second Nationally Determined Contribution	2020
11	National Adaptation Program of Action (NAPA) to Climate Change	2010	27	Environmental Protection Regulation	2020
12	Climate Change Policy	2011	28	Long Term Strategy for Net Zero Emissions	2021
13	National Framework on Local Adaptation Plans for Action (LAPA)	2011	29	Third National Communication to the UNFCC	2021
14	Thirteenth Plan (2013–2016)	2013	30	Environment-friendly Local Governance Framework	2021
15	Environment-friendly Local Governance Framework	2013	31	Urban Public Transport Management Authority Act	2022
16	Constitution of Nepal	2015			

5.3 Links and implications

From this paper, I find that Nepal has had a progressive energy policy trajectory during the last four decades. Rural energy policy focusing on off-grid renewable technologies have undergone multiple improvements during this period. At the central level, hydropower has gained considerable attention in addition to expansion of energy generation mix along with increasing the energy efficiency at the users' level. However, I conclude that the domestic energy sector has not yet got the required attention at the policy level. Moreover, the policy formulation process is still state-centric with very limited community involvement. International assistance along with support from the government plays a large role in shaping the energy policies, the impacts trickling down to the implementation levels for the country to transition to clean and renewable energy systems. Hence, it is found essential to assess the impact of international donations and government subsidies in the renewable energy transition of Nepal. The extent of such an influence is examined in the next paper (Paper #4).

CHAPTER 6: PAPER 4 – RATIONALIZING DONATIONS AND SUBSIDIES: ENERGY ECOSYSTEM DEVELOPMENT FOR SUSTAINABLE RENEWABLE ENERGY TRANSITION IN NEPAL

6.1 Introduction

This paper (Paper #4) assesses the role of international donations and government subsidies on Nepal's energy landscape, focusing on renewable energy development. In this paper, I considered multiple sources of Nepal's energy generation mix and examined how they have been impacted by donations and subsidies in the past. This paper is a direct contribution to the first objective of my research by advancing our knowledge of these important financial stimuli on the overall renewable energy transition of Nepal.

6.2 Published paper

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Rationalizing donations and subsidies: Energy ecosystem development for sustainable renewable energy transition in Nepal

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ABSTRACT

Donor-driven research and implementations in renewable energy (RE) might not necessarily resonate with the physical, social, economic and political settings of the developing world. We take a developing South Asian country – Nepal – to examine why solar and wind technologies have failed despite tremendous donor-support and subsidies during the last three decades. We combine extensive literature review, expert interviews and own readings from our two decades-long professional career in the RE sector of Nepal to arrive at rational conclusions. Almost all past internationally funded and government-subsidized off-grid solar and wind energy projects failed upon discontinuation of funds. Furthermore, the pristine Himalayan environment was forced to bear the burden of hazardous waste management. Nepal, being one of the best countries for hydropower, should concentrate on this technology. The suitability, convenient availability of other feasible alternatives and social acceptance decides the fate of technologies. Donations/subsidies need to be better utilized by developing a bottom-up "ecosystem" fostering new technologies to be a part of the energy mix sustainably. Through this paper, we provide specific recommendations for the use of donations and subsidies in the RE sector which have been drawn from the Nepal case but are applicable to the Global South in general.

1. Introduction

In order to achieve long-term economic growth, tackle climate-change related risks and attain the Sustainable Development Goals, a clean energy revolution from the current fossil-fuel laden energy systems is an immediate requirement. Extensive research and development (R&D) on renewables has been undertaken across the world (Adjei et al., 2022; Bundschuh et al., 2017; Johnstone et al., 2020; Rodríguez-Segura et al., 2023). Considerable efforts are being made by rich countries in expanding access to renewable energy (RE) in the developing countries. Renewables contributed to ~20% of the global primary energy consumption in 2019 (REN21, 2021). Hydropower constituted 2.5% while solar, geothermal, wind and other renewables had a cumulative contribution of 2.2% of the total global energy supply (IEA, 2021). The current RE research direction of developed countries is dominated by solar and wind technologies (BP, 2020). As a result, the cumulative global installed capacity of wind and solar PV amounted to 733 GW and 714 GW respectively in 2020 (IRENA, 2020). However, the Global North-South disparities are prevalent in the RE sector (Weko and Goldthau, 2022). Studies in the developing world have identified lack of financial resources, technology and expertise as the major hindrances for a successful RE transition (Liao et al., 2021).

Moreover, renewables, especially in the case of donor-driven technologies, are not devoid of controversies and conflicts despite being seen as efficient, economical, environment-friendly and just (Chapman et al., 2018; Pietrosemoli and Rodríguez-Monroy, 2019). For example, Sovacool and Drupady (2012), point out that donor agencies imposing a particular technology instead of a holistically utilizing the energy services to improve people's standards of living and productivity lead to failed implementations. Recent studies have highlighted that most of the current energy transitions of the developing countries are donor-driven which face high chances of being counter-welcomed in the other half of

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the world with completely different settings of their R&D conditions (Bhattarai et al., 2022b; Weko and Goldthau, 2022). Furthermore, the voices of the Global South are less heard in the research arena and global discourse. We focus our discussion on this issue, assessing the effectiveness of donations and subsidies on solar- and wind-power in a developing country, Nepal.

Ready-to-install isolated solar and wind technologies have been promoted by the Government of Nepal (GoN) through donor-support, mainly because of their low capital costs and convenience in installation and operation. United Nations (UN), World Bank (WB), Asian Development Bank (ADB), European Union (EU), European Commission (EC), Danish International Development Agency (DANIDA) and the Norwegian Agency for Development Cooperation (NORAD) have been the prime donor agencies for these projects in Nepal. However, these RE technologies have only been able to provide a mere 3.2% share of the total energy consumption of Nepal until the end of 2019/20 (MoF/GoN, 2021) clearly indicating their meager role in the transition towards renewables. In this study, we critically examined why the implementations of solar and wind technologies have been unsuccessful in Nepal despite donations and heavy subsidies during the last few decades. We carried out review of relevant scientific publications as well as gray literature. In parallel, we conducted one-to-one discussions during January–March 2022 with a total of ten experts (key government officials, faculties from the academia, scholars from research institutes, private sector representatives and officials from international agencies) working in the areas of RE in Nepal. Through this paper we argue that donor-driven and subsidized technology “transfers” are not sustainable if they fail to consider the convenient availability of local resources, existing technologies in use, and vernacular societal preferences and requirements. We infer that the funds need to be better utilized by taking a pragmatic approach in developing an entire “ecosystem” allowing these technologies to be a part of the energy mix in a sustainable way. We further propose that the need for R&D should be assessed using a bottom-up approach in the developing world for effectiveness and sustainability of RE transition.

2. Current energy status of Nepal

Nepal is land-locked mountainous country located in the central Himalayan region with an area of 147,181 km^2 and a population of ~30.4 million (CBS, 2021). It has a very small economy with a GDP of 33.66 billion USD (2020), which is about 1% of South Asia and 0.04% of the world values (WB, 2021). With an extremely limited number of industries and energy intensive sectors, the total annual energy consumption of Nepal was 14.464 million tons of oil equivalent (toe) in the fiscal year 2019/2020 (MoF/GoN, 2021). Three categories of sources, namely, traditional (firewood, agriculture residue and dry dung for direct combustion), commercial (petroleum, coal and grid electricity) and other off-grid renewables (popularly known as “alternative energy” in Nepal) constitute the energy generation mix of the country. Traditional sources had the highest contribution (68.7%) in the mix by far compared to the others (commercial: 28.2% and renewable: 3.2%) in 2019/2020 (MoF/GoN, 2021).

The total electricity connected to the national grid of Nepal is 1458 MW generated cumulatively by the government, private sector and import while the peak demand was 1482 MW in 2021 (NEA/GoN, 2021). Out of the total electricity generation, 1299 MW (89%) is generated from large hydroelectric projects, 30.14 MW (2.1%) from solar, 53.4 MW (3.7%) from thermal and 75 MW (5.2%) from other smaller RE technologies (MoF/GoN, 2021). Despite low consumption, people have been forced to suffer long hours of electricity blackouts due to large energy deficits and suppressed demands. This has adversely impacted the quality of public life and economic development of the country (Koirala and Acharya, 2022). The above figures clearly imply that solar, wind and other forms of RE are still not able to contribute adequately to the energy mix of Nepal.

3. Renewable energy technologies in Nepal

3.1. Solar

The average solar radiation in Nepal varies from 3.6 to 6.2 kWh/m^2/day; sun shines for about 300 days a year and the number of sunshine hours amounts to 6.8 h per day (about 2100 h per year) (Gautam et al., 2015). Thus, solar technology may seem lucrative from these figures. International donors and the government have pushed isolated solar technologies mainly because of their less expensive upfront cost and immediate installation. As a result, household solar lights (Chitrakar and Shrestha, 2010), water pumping systems (Dhital et al., 2016), electro-chlorination of water supply systems (Otter et al., 2020), solar disinfection of drinking water (Rainey and Harding, 2005) and domestic space and water heating (Thapa et al., 2022) are some implementations of solar energy technology in Nepal over the last few decades. Nepal’s first commercial solar power plant (i.e., the Devighat Energy Project with an installed capacity of 25 MW) started generating electricity (1.25 MW) from 2020 (Lohani and Blakers, 2021). The GoN has ambitious plans to soon develop a 250 MW solar power project in the Terai plains which also includes a 20 MW capacity storage system (Rai, 2021). However, numerous difficulties have been reported with these systems. We discuss the most important ones subsequently.

Firstly, contrary to the popular belief, solar is not a “free” technology. Nature provides sunlight, wind and water free of cost on the earth, but their conversion to energy in a useable form is expensive. The per unit capital cost of a solar project is quite high as all the components are to be imported from Germany, China, India and USA, among other countries (Bhattarai et al., 2018). For example, the 25 MW Devighat Energy Project is constructed under a concessional loan from the WB’s Grid Solar and Energy Efficiency Project at a cost of USD38 million which equates to around USD1520/kW. Gautam et al. (2015) highlights that the government subsidies are not effective in solar PV systems without battery storage facilities in order to cater to the peak demands. Batteries make the systems expensive and are difficult to dispose of when their functional life is over, adding environmental challenges. In the past, some 350,000 isolated solar PV home systems were installed mainly in the high lying Himalayan areas of Nepal between 2001 and 2013 (Alex et al., 2014). The ‘Solar Tuki’ (a small handheld battery powered rechargeable solar lamp charged by a three-Watt panel) was considered a highly successful example of household level solar systems (Chitrakar and Shrestha, 2010). These programs were supported by donations from international donors and I/NGOs such as the Global Environmental Facility of the UN, WB’s Development Marketplace and subsidies from the GoN. However, almost 50–70% of these systems were non-functional within a short timespan because of sub-standard materials, lack of end-user awareness, inability to maintain and lack of after-sales service (Alex et al., 2014). In general, the systems became defunct when the subsidy period ended. Furthermore, a considerable number of the dead batteries were simply abandoned unsafely (Alex et al., 2014). This is a critical waste management issue which can cause severe toxic hazard to the pristine Himalayan environment in the long run.

Moreover, such household technologies generating very less energy could be considered a revolution two decades ago, but not anymore. People’s desire to be able to use modern electronic appliances warrant much more energy than that provided by such small panels and LEDs. The expectation of the rural poor that they should get these technologies for free discourages the private sector to be involved in such projects (Bhattarai et al., 2018). There have even been recent cases of the private banks backing out on providing loans to the private producers of solar energy projects because of unsuccessful past inferences (ADB, 2017). Furthermore, a study in rural Nepal concluded that solar thermal technologies are financially viable only if most of the materials are available free of cost and the systems are constructed and maintained by the community without charging any cost from the users (Fuller and Zahnd, 2012). Such assumptions cannot be treated as pragmatic with massive implications on the sustainability.

Secondly, there are very few observation stations within Nepal which measure and record solar radiation and other related climatic parameters. Thus, most of the solar systems till date are designed using global datasets which have been found to be very poor in capturing the diverse local micro-climatic conditions prevalent within the country leading to large under/over-estimations. Past studies such as AEPC/GoN (2008) and even the most recent ones like Lohani and Blakers (2021) have relied on global datasets for their analysis with very limited ground truthing because of lack of observation stations.

Thirdly, solar panels need to be set up on a surface, which in most cases, is land. Household rooftops can be used to accommodate small solar panels for domestic electrification, catering to a very small demand. Additional issues of costs and energy losses because of DC to AC conversion technology limits its applicability for higher power systems. Large scale commercial application of this technology requires "solar farms". A recent addition of 10 MW electricity to Nepal's national grid was from the Dhalkebar Solar Project by installing solar panels on 6.3 ha of agricultural land (Tiwari, 2021). With increasing food insecurity, deforestation, erosion and adverse impacts of climate change, land is a very precious resource. Thus, converting fertile agricultural fields and forests to house solar panels for such solar farms could be undesirable in many places across the world (Capellán-Pérez et al., 2017), including Nepal. Moreover, it would be very challenging to construct such large solar farms in the hills and mountains of Nepal which are prone to landslides and mass failures due to the young and fragile geology and rugged terrain. Bird's-eye studies have shown that Nepal possesses a huge solar potential, for example by Lohani and Blakers (2021), but specifics of proper landuse management and co-benefits such as agrivoltaics need to be explored in detail at the grass-root level before coming to conclusions. GoN's plans for a 250 MW mega solar project is at the cost of a massive area of fertile agricultural land in the Terai (part of Indo-Gangetic) plains. Nevertheless, solar panels over irrigation canals in India (Kapoor et al., 2021) or floating panels in Europe (Mukhtarov et al., 2020) or parking lots in Australia (Guidolin and Alpcan, 2019) or floating panels in hydropower reservoirs "floatavoltaics" (Almelda et al., 2022) could be some potential areas of further research in Nepal. But whether they will be welcomed and how they are expected to perform cannot yet be deterministically ascertained.

Finally, international funding and subsidies play a huge role in the fate of (generally off-grid) RE technologies in many developing countries (Bhandari et al., 2017). For example, the EC supported the GoN by implementing solar technologies through the 5-year Renewable Energy Project in 2003 which was delayed until 2012 with an investment of about 11 million Euros. Unfortunately, a field-level inspection after two years showed only about 10% of the systems to be performing normally (Ha and Kumar, 2021). Gautam et al. (2015) show doubt whether (household level) solar PV systems can be extended beyond the rural areas to urban centers of Nepal because of lack of government support and high per unit costs. Bhandari and Stadler (2011) stresses that solar PV systems are not the economic solutions for grid-connected urban or remote areas in Nepal alike. They suggest that rather than providing subsidies to solar PV for residences, GoN should focus on productive areas including electricity generation using hydropower. Studies have even raised concerns about whether solar power systems with battery storage would actually be beneficial economically and environmentally as claimed (Fares and Webber, 2017; Sivaram and Kann, 2016). Moreover, Dhital et al. (2016) also warns that subsidies and other financial support from the government or donor agencies tend to lead to installation of under/over-designed systems. The most likely reason for this is that the systems are tested in conditions that might be completely different from those of the implementation sites. Studies have also reported that the international donor's involvement has been time consuming, expensive at most times, and conflicting with the procurement procedures of the GoN leading to failed systems (Ha and Kumar, 2021). Balachandra (2015) further underscores that donor agencies have been found to be in a hurry to release funds too quickly without a proper sense of responsibility directly impacting the project. Furthermore, the capability of the projects to get easily maintained and repaired is equally important for their sustainability (Butchers et al., 2020). Nepal lacks such services for solar and wind projects.

3.2. Wind

It has been reported that Nepal has a wind electricity generation potential of more than 3,000 MW, out of which commercial viability is estimated at about 448 MW (AEPC/GoN, 2008). It is to be noted here that most of the potential sites lie in the high and middle mountains of the country. The WB in 1977 identified Khumbu region (located higher than 3300 meters above sea level, masl) as a potential site for wind energy generation; the Department of Hydrology and Meteorology (DHM) recommended wind power for electricity generation in the hills and for irrigation and pumping water in the Terai plains (WECS/GoN, 2013). DANGRID in 1992 estimated a wind potential of about 200 MW electricity from Kagbeni and Chusang (both located around 3,000 masl) in Mustang district.[1] The Water and Energy Commission Secretariat (WECS), DHM, Alternative Energy Promotion Center (AEPC) and Nepal Academy of Science and Technology (NAST) collaboratively concluded that Nepal does not possess high potential of wind energy except for some locations like Thakmarpha, Khumbu, and Khanjiroba (all around 3000 masl) which are on the high mountains with no infrastructure development.[2] Moreover, a small population of people live in these areas due to the harsh climatic conditions. The Kagbeni Wind Power Project (installed capacity of 20 KW) built in 1987 with the support of DANIDA was a head start in wind generation in Nepal (KC et al., 2011). Unfortunately, funding was discontinued upon its completion and the project failed mainly due to inadequate data collection on installation site, lack of maintenance and poor technical base (Pokharel, 2003).

Similar to the solar case, Upreti and Shakya (2009) reported that there were fewer than 29 DHM wind stations in 2008. Except for a slight increase in the number of stations, the quality of data has not improved much even today after more than a decade.[3] Furthermore, these high potential areas are largely disaster prone due to high winds. Because of lack of research, limited publications are available on wind energy development in Nepal; most share experiences of failure. Some pilot projects have been carried out recently by AEPC (mostly as wind-solar hybrid systems such as in Pyuthan, Palpa and Sindhupalchowk and Nawalparasi districts, supported by ADB) (AEPC/GoN, 2021) which are mostly of experimental type and have not been scaled up commercially. For instance, the 35 kW wind-solar hybrid project in Hariharpurgadhi, Sindhuli was built as part of the ADB's South Asia Subregional Economic Cooperation Power System Expansion Project with a financial support of USD 16.2 million which started operation from 2018 generating 110kWh per day for 83 rural households (ADB, 2017). Additionally, being a relatively new technology to Nepal, there is not enough expertise in this sector. As a result, the county needs to rely on external experts and technologies for any type and scale of research or implementation of wind energy generation projects. Moreover, the operation of current projects is in a state of infancy to come to conclusions regarding their feasibility, investment worth and sustainability. The rugged terrain, difficulty in access and operation, limited observed data and lack of expertise could be the reasons for a laggard response to wind energy in Nepal.

[1] Expert interview (Government of Nepal and international agencies).
[2] Expert interview (Academia and Government of Nepal).
[3] Expert interview (Government of Nepal and private sector).

3.3. Hydropower

Nepal has an extremely steep terrain, the elevation varying from 60 masl to 8,848 masl (Mt. Everest) within an average north-south aerial distance of less than 150 m. Annual water yield of 225 billion cubic meters draining out of the country supplemented with high head is highly favourable for hydropower generation in Nepal (WECS/GoN, 2011). The theoretical hydropower potential of the country is estimated at 83,000 MW, out of which, 45,000 MW is economically feasible. For these reasons, past studies have recognized hydropower to be the most efficient, cost effective, environment friendly and locally suited RE technology for Nepal which needs to be promoted for future energy security (Alam et al., 2017; Jha, 2010; Sharma and Awal, 2013). However, only ~3% of the economically feasible hydropower potential has been harnessed (NEA/GoN, 2021). As of 2021, major hydropower projects produced 563 MW, small hydropower plants generated 581 MW while off-grid micro hydropower schemes generated 72 MW of electricity (AEPC/GoN, 2021; NEA/GoN, 2021).

People in Nepal have used hydropower for centuries mainly for milling and grinding grains. The country had a headstart in hydroelectricity generation with the first hydro-project (500 kW Pharping Hydropower Plant) commissioned in 1911, which was among the earliest projects in Asia (Sharma and Awal, 2013). However, the nation could not maintain continuous progress in this sector for a long time. Small-scale hydroelectricity generation can be dated back to the 1960s when (then) His Majesty's Government of Nepal promoted subsidies for remote installations (Balachandra, 2015). The semi government Nepal Electricity Authority is responsible for the major hydropower projects. The AEPC was established as an autonomous institution in 1996 to promote large-scale use of RE in a sustainable manner under the Ninth National Plan. It has been mandated to improve different renewable energy technologies in Nepal. However, the number of micro-hydro projects implemented through AEPC outnumber the projects using other technologies (AEPC/GoN, 2021). Rural Energy Policy 2006 and the National Renewable Energy Framework 2017 provided further impetus. Nepal's Energy Sector Vision 2050 has identified hydro-power as the "lead" energy sector for meeting the long- and short-term energy demands of the country (WECS/GoN, 2013). Moreover, recent development of large hydropower projects without the financial support from international donors (for example, the almost completed 456 MW Upper Tamakoshi Hydropower Project) has been considered a milestone for Nepal.

3.4. Other technologies

The share of renewables in the total energy consumption of Nepal was 3.2% in 2021 which consisted of micro- and small-hydropower projects, solar and wind projects, hybrid projects and biogas collectively generating ~72 MW (MoF/GoN, 2021). There are about 450 large and over 400,000 household biogas plants registered at AEPC in Nepal until 2021. However, the exact number of plants in operation has not been documented anywhere. There are no other forms of RE currently operating in Nepal.

4. Dissection of past failures of solar and wind power projects in Nepal

Solar and wind technology interventions in Nepal date back to the 1960s (Bhandari and Stadler, 2011). Governance and regulatory issues of corruption and misuse/mismanagement of funds play an overarching role in slowing all development activities. Moreover, the inability to consider the suitability, availability of other options conveniently and social acceptance aspects of these technologies can be considered as the main reasons of their failure.

a. **Suitability**

Suitability encompasses a wide array of requirements such as natural resources (for example, climatic conditions, topography and terrain), national policies, generation and distribution technologies and the capacity to invest in advancements without having to undergo expensive alterations. In the remote mountain areas of Nepal, biogas is unsuitable because fermentation takes more time at higher altitudes while solar technology is not favourable due to extended periods of constant fog and cloud cover. Nepal does not have tidal energy as it is a landlocked country; it has very low prospects of geothermal energy and hydrogen cell technology because of lack of identified potential, expertise and humongous exploration and conversion costs.

We visualize the series of requirements and their impact on the suitability as a schematic shown in Fig. 1. Technology is fostered by supportive policies. For example, IEA (2020) reports that Australia had the highest solar PV capacity per capita of 644W in 2019 because of a range of favourable policies. It is to be noted that the suitability of a project is largely increased with the availability of finance (particularly in the case of developed countries) as compared to the other requirements. Polices have been promulgated in Nepal and are also going through continuous revisions. However, all energy policies (renewable and non-renewable sources) are formulated at the national level.[4] The GoN has been emphasizing RE in the supply mix since the Seventh National Plan (1985–1990) until the present Fifteenth Periodic Plan (2019–2024). National funds such as the Rural Energy Fund (in the Ninth National Plan: 1997–2002) and Central Renewable Energy Fund (in the Three-year Interim Plan: 2010–2013) have been created and mobilized. Moreover, the Second Nationally Determined Contribution 2020 sets out an ambitious target of ensuring 15% contribution from renewables in the total energy mix by 2030 with individual short-term goals for the transport (25% electric vehicles by 2025) and residential sectors (25% electric stoves by 2025). Furthermore, a comprehensive National Climate Change Policy has also been formulated in 2019 which is aimed at contributing to multiple themes of development. The Environment Policy 2019, Long Term Strategy for Net Zero Emissions 2021, Renewable Energy Subsidy Policy 2022 and National Renewable Energy Framework 2022 are all directed towards expanding access to renewables and reducing the impacts of traditional fuels.

Unfortunately, the impacts of these policies are mostly limited to paper and the ground reality is far from what is targeted. For example, the total number of vehicles registered in Nepal until 2019 is 3.8 million out of which only ~50,000 (<1.4%) are electric vehicles, which are expensive compared to the petroleum counterparts and cannot be afforded by the general public. As with most developing countries, the focus of the nation is on other development activities with less attention to adoption of electric vehicles which could be significantly important on the public transport sector (Mali et al., 2022). Moreover, due to the ever-going political instabilities, policies and attention of the nation frequently change with the change of government. Sadly, solar and wind potentials have not been accurately estimated for Nepal. Due to these reasons, projects pushed by donor agencies are very much likely to be constructed but unsuccessful because the other pre-requirements of resource availability, policy-to-practice and the necessary technology and expertise might not have been met. Besides, past experiences have not proven Nepal to be an investment friendly country in the RE sector which is likely to retard foreign investment, at least in the foreseeable future.

b. **Availability of other options**

Within the domain of technically and economically feasible projects, some RE generation technologies might not be considered appropriate when other already existing or better options are available. If alternates are readily available with ease, are cheaper or if there are existing

[4] Expert interview (Government of Nepal and academia).

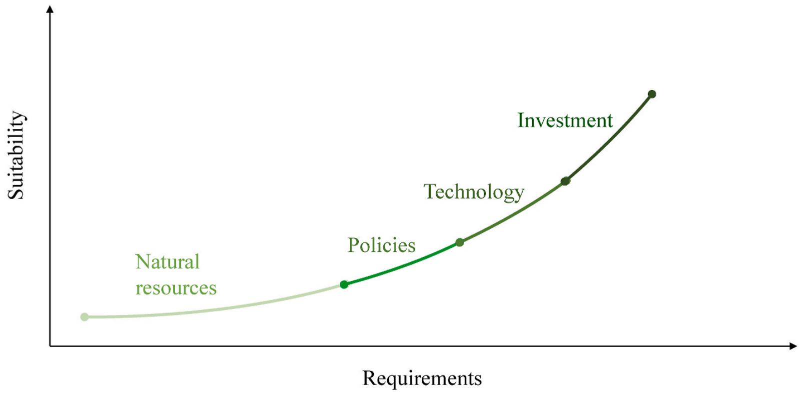

Fig. 1. Schematic showing the relation between the requirements and suitability of energy generation technologies.

technologies which can be modified/updated with less effort, they would be preferred over others (Fig. 2). Many European countries have already harnessed their full hydro-potential and are in need for additional renewable sources such as solar, wind and tidal, among others, to meet their ever-growing energy demands (Ćetković and Buzogány, 2019; Child et al., 2019). Many energy generation technologies have reached their retirement age which need to be demolished to make way for new ones (Child et al., 2019). Studies have reported that there are approximately 230,000 dams in 13 European countries, many of which are for hydropower generation (Habel et al., 2020). Countries such as UK (Scotland) and Australia are trying to excel in wind power because of their better potential in these regions compared to the other RE sources (Cowell et al., 2017; Guidolin and Alpcan, 2019). Countries (mostly from the Global South) that have significant water resources and a relatively smaller energy demand are largely dependent on hydropower; for instance, more than 90% of the national electricity is supplied by hydropower in Albania, Congo, Mozambique, Paraguay, Nepal and Uruguay (IEA, 2020). Moreover, even some large consumers of electricity such as Norway, Brazil and Canada have 95, 65 and 59% contributions respectively from hydropower (IEA, 2020). Recent studies such as Selçuklu et al. (2023) project hydro to be the most feasible option while solar to be one of the least desirable options for Turkey, an OECD member country.

Nepal is one of the best countries for hydropower generation (Chinnasamy et al., 2015; Devkota et al., 2022; Marahatta et al., 2022). It is a well-proven and established technology. The government, local communities, manufacturers, and developers as well as the end users are well-acquainted with the technology. The distribution system has been designed accordingly and the national grid is being steadily expanded by the state to remote areas (NEA/GoN, 2021). Even off-grid systems of micro- and small-hydropower projects have proven to be very successful (AEPC/GoN, 2021). However, solar and wind are relatively new and expensive technologies for the developers and the beneficiaries to be completely assured of their success.

c. **Social acceptance**

Whether a new energy generation technology is acceptable by the people is another important aspect ascertaining its realization and development (Fig. 3). It is largely depended on how the technology has been embedded into the socio-cultural, political and ecological context (Adesanya et al., 2020; Butchers et al., 2020). For example, there might be rejection from the community regarding using the water for irrigation from a hydropower project due to some superstitions and misbeliefs.[5] Lin and Kaewkhunok (2021) showed a divided preference over the cast hierarchy prevalent in the community on the adoption of solar power technology in the case of a Nepalese village. Similarly, strong opposition may arise in the use of cooking gas generated from animal/human waste because of cultural issues. Cases of mixed perceptions of RE technologies regarding their sites, operation and continuation have been reported recently in the developed countries too, for example in Europe (Rodríguez-Segura et al., 2023; Windemer, 2023). In addition to the technical difficulties, issues of lack of awareness, their diverse uses and benefits largely impact the uptake of a technology in the society, for example in Nigeria (Anugwom et al., 2020). Theft caused by unaffordability of electricity is another serious issue faced by the poor countries (Wabukala et al., 2023). Additionally, it is human to try to avoid change and stick to the options to which people have been habituated. Interestingly, in Nepal, being connected to the national electricity grid is considered as a symbol of prosperity and economic status in the society.[6] Despite boasting a 93% electrification rate in 2021 by GoN (NEA/GoN, 2021), the reliability and usability of the supplied electricity is extremely poor. Furthermore, obtaining electricity in the desired amount when required is not guaranteed. The tariffs have been set in such a way that at least a flat minimum cost has to be paid by the users even when their consumption is very low. In many cases, even the subsidized monthly electricity fare becomes too high for a huge majority of the rural community to afford (Butchers et al., 2020). As a result, the O&M and performance of the energy generation systems are likely to suffer. Moreover, people may simply not wish to use electric appliances which seem expensive in the short run but are more economical than the existing inefficient options eventually.[7] Similar findings have been reported in Chile in which electrification of firewood for space heating can lead to energy poverty conditions for the people in the lowest socio-economic category (Navarro-Espinosa and Thomas-Galán, 2023). Such reasons have delayed the penetration of alternative energy generation in Nepal despite an increase in the role of supportive government policies.

A study carried out in South Asia highlights the fact that off-grid systems generally lack organized delivery models and are primarily undertaken through community-centred projects (Palit and Bandyopadhyay, 2016). Additionally, the study has identified weak institutional designs, no linkage with income generating opportunities, poor technology management and lack of supportive policies as the reasons for failure of such off-grid systems. The study also rightly points out that solar home systems have been often installed at locations where a micro-hydro scheme would have been more appropriate. These

[5] Expert interview (private sector and research institutes).

[6] Expert interview (private sector and research institutes).

[7] Expert interview (private sector and research institutes).

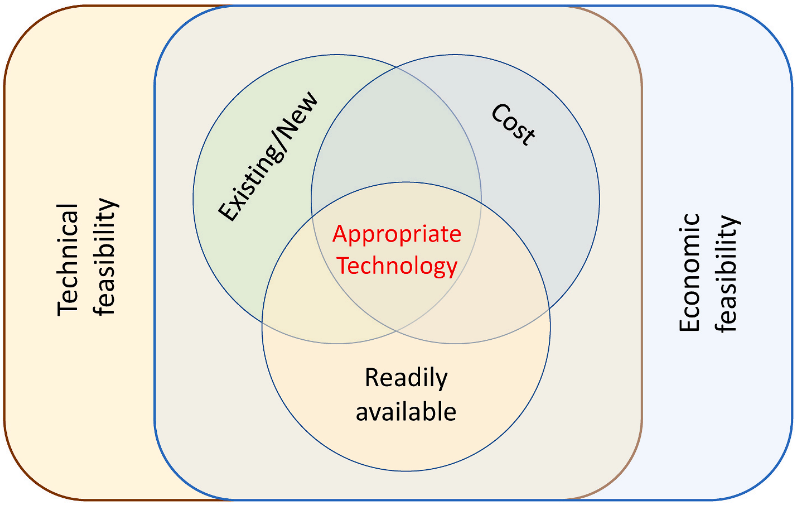

Fig. 2. Factors governing the choice of energy technologies among alternatives.

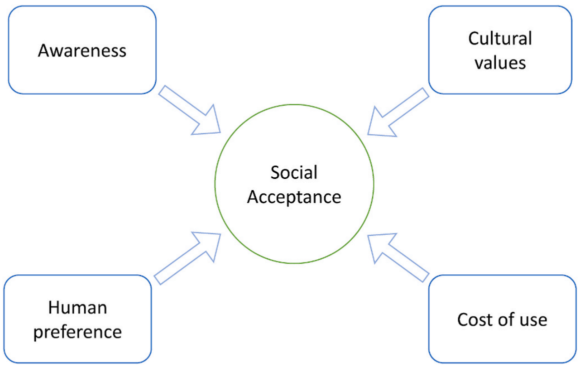

Fig. 3. Various dimensions to social acceptance of energy generation technologies.

conditions have also been seen to be prevalent in the Nepalese RE sector.

5. Comparison of major renewable energy generation technologies

With every technology comes advantages and challenges. Table 1 is a comparison between the three sources of RE discussed in this paper. It can be seen that less per unit capital cost, proven technology, capacity to provide base load and multipurpose use are the major advantages of hydropower (Adjei et al., 2022). The WB prescribed that for off-grid communities around the world, hydroelectric systems can offer the cheapest generation cost compared to every other commercially available technology of the same size including solar home systems and diesel and gasoline generation (Balachandra, 2015; WB, 2007). Studies, for example in the UK, have shown that micro-hydropower systems have a strong positive environmental balance which presents a long-term sustainable opportunity for the water industry (Gallagher et al., 2015). However, large hydropower projects suffer from a major drawback of environmental impacts, huge upfront cost and large dependency on climate. Although "environmental flow" is maintained in the downstream areas during the dry periods, it still cannot compensate for the disturbance/loss of natural aquatic conditions. Both solar and wind technologies are generally implemented with smaller capacities as direct systems (without storage) and hence requires less initial investment although being expensive than hydropower on a per unit comparison (Best, 2017). Operation and maintenance cost of wind power systems are generally much higher (20–25% of the project cost) compared to hydropower systems (2–3%) (IHA, 2020). All these technologies are dependent on the climatic conditions in some way: water availability for hydropower, sunshine hours and irradiance for solar, and continuous wind for wind projects. Furthermore, they also have risks associated with them. Hydropower projects are prone to landslide, floods and other water induced disasters; solar projects could be ineffective because of the location and terrain, and wind projects face risks of stability of the infrastructure due to gusts. Moreover, it can be technically challenging and financially difficult to integrate solar and wind energy (for example, through mini-grids) into existing national grids which requires digital solutions and advanced technical transformation (Rossi et al., 2022; Wen et al., 2023). Likewise, improvements over the conventional hydropower system such as pumped storage systems and offshore systems (utilizing tidal waves) to overcome future uncertainties also being studied with promising results (IHA, 2020).

Global practices show that diversifying the energy mix is the most logical approach to energy transition. A strong government-society synergy with proper institutionalization and capacity strengthening of local enterprises are key to a successful transition. As Vanegas Cantarero (2020) highlights, a large quantity of the remaining RE potential yet to be harnessed is located in the developing countries which could be extremely valuable for the future. Successful implementation and longevity of the transition is an outcome of strong policy initiatives supporting scientific advancements (Ćetković and Buzogány, 2019); however, achieving these in the developing world is a challenge due to regional geo-politics, social poverty and lack of capital cost (Mohsin et al., 2021; Müller et al., 2021). Interestingly, research has even shown that subsidies are likely to lead to inefficient energy generation and consumption (Aryanpur et al., 2022). Effectiveness of energy co-operatives in the transition have been proven in many parts of the world, for example in Spain (Capellán-Pérez et al., 2018) and the Netherlands (Wagemans et al., 2019). Promoting hybrid technologies to tackle climate related challenges and variable load issues have been recommended (Parag and Ainspan, 2019). Realizing the need for research on hydropower in Nepal, there have been a number of interesting studies recently analyzing its multiple facets (for example, Bhattarai et al., 2022a; Devkota et al., 2022; Magaju et al., 2020; Marahatta et al., 2022) with encouraging findings. Moreover, international collaboration

Table 1
Comparison of hydropower, solar and wind technologies in the developing world.

Technology	Advantages	Challenges
Hydropower	• One of the oldest and well-tested technologies (Tomczyk and Wiatkowski, 2020) • Energy efficiency is high (Siri et al., 2021) • Applicable for providing the base energy/electricity • Per unit cost of generation and O&M costs are less compared to most other existing renewable energy technologies (Best, 2017; IHA, 2020) • Large projects are generally connected to national grids; small ones are managed using local mini-grids (Lohani and Blakers, 2021) • Hydro-meteorological data are generally available at reasonably good resolutions • Temporal energy planning can be achieved through storage type projects • Spatial energy planning can be done using inter-basin transfers • Reservoirs can be utilized for multiple purposes such as irrigation, domestic water supply, flood control and sediment regulation (Wang et al., 2022) • Optimum use of water can be achieved through pumped storage systems and cascades (Lohani and Blakers, 2021) • Lot of employment opportunities are generated during construction and operation with a positive impact on the local economy • Additional community benefits such as access roads and electrification to project locations are achieved • Local enterprises are mostly capable of customizing and repairing the systems • Hybrid systems with solar and/or wind have become common in recent times • Advanced hybrid systems such as "floatavoltaics" are being researched (Almelda et al., 2022)	• Abundant water availability and favourable terrain with high head is required • Largely dependent on hydrology and climate • Huge upfront cost particularly for large projects • Considerable environmental impacts such as inundation, altered micro-climate, hydrological regime, sediment transport and water quality, changed aquatic ecosystem, flora and fauna, changes in landcover and landscape, for storage type projects (Elagib and Basheer, 2021) • Possibilities of water-induced disasters such as landslides, floods and dam breach, GLOFs and seismic threats • Chances of eutrophication in reservoirs adjacent to arable lands • Requirement of a large volume of construction materials • Lengthy construction period • Primarily governed by the socio-political condition (Habel et al., 2020) • Difficult to connect to the national grid from remote locations (Bhattarai et al., 2018; Lohani and Blakers, 2021)
Solar	• Mostly suitable for off-grid and/or isolated remote areas • Convenient and quick installation and operation • Direct (operating during sunshine) systems are relatively cost effective (Cook et al., 2022) • No mechanical/moving parts, hence less O&M costs • Possibilities of on- and off-shore implementations • Mini-grids can be used to supplement national grids for meeting peak loads during the day time • Isolated rooftop systems can be used to fulfill small household electricity demands during the day time • No significant impact on the environment compared to hydropower • Hybrid systems with hydropower and/or wind have become common in recent times (Parag and Ainspan, 2019) • Improved systems such as "agrivoltaics" are being researched (Barron-Gafford et al., 2019)	• Considerable number of sunshine hours and incident solar radiation is required • Relatively new to the developing world • Per unit cost of energy generation compared to hydropower is more (Best, 2017) • Variable and intermittent nature of energy • Not suitable for areas with less sunshine hours (for example in the high Himalayas) • Large land requirements to meet the increasing electricity demand (Capellán-Pérez et al., 2017) • Energy efficiency is low • Direct systems can be operated only during the day time (Cook et al., 2022) • Systems with battery storage are expensive and may not be cost effective (Fares and Webber, 2017) • Smaller systems are not enough to meet large energy requirements • Could be challenging to integrate mini-grids to national grids • Local sunshine related meteorological data are likely to be unavailable in the desired quality (resolution, length and spatial coverage)
Wind	• Mostly suitable for off-grid and/or isolated remote areas • Convenient and quick installation and operation • Can generate energy night and day whenever wind is available • No significant impact on the environment compared to hydropower • Mostly applicable for supplementing base electricity from national grids during peak hours • Possibilities of on- and off-shore implementations (Capellán-Pérez et al., 2017) • Hybrid systems with hydropower and/or solar have become common in recent times (ADB, 2017; Parag and Ainspan, 2019)	• Relatively new to the developing world • Per unit capital cost is large (Best, 2017) • O&M costs are large (IHA, 2020) • Variable and intermittent nature of energy (Agbonaye et al., 2022) • Stability issues of the structures due to gusts in extremely windy areas • Local wind related meteorological data are likely to be unavailable in the desired quality (resolution, length and spatial coverage) • Could be challenging to integrate mini-grids to national grids (Bhattarai et al., 2018; Wen et al., 2023)

between the global North and South is seen to be necessary for mutual benefits. Most importantly, providing grant and subsidies without understanding the local context and building an appropriate "ecosystem" accordingly will merely be a waste.

6. Conclusion and policy implications

The Global South is lagging far behind in RE transition; and their voices are usually not heard in the global arena. Donor-driven technologies are being experimented on in the developing world for wider application with a top-down approach. However, this does not always necessarily resonate with the physical, social, economic and political conditions of all developing countries.

In this study, we took the case of a developing South Asian country, Nepal, and evaluated the reasons for the failure of donor-driven and heavily subsidized solar and wind technologies in the past three decades. Almost all the projects failed immediately upon discontinuation of funds. Efforts to meet the electricity demands of remote rural areas of Nepal can be concentrated using off-grid small RE technologies for the time being. But the state should be responsible for harnessing the huge hydropower potential of the country by constructing large projects adopting environment friendly measures to achieve maximum benefits in the future.

Based on the evidences from Nepal provided in this paper, we infer that the way donations and subsidies were used in the RE sector in the past was highly inappropriate. Imposing technologies as "technology transfers" without creating a proper techno-social base has been identified as the primary reason for the failures. Instead, those funds should have been devoted to developing an "ecosystem" comprising of context-specific needs for the RE systems and capacity strengthening of the people, local enterprises and the government for sustainability. Lack of quality climate observation stations is a major hindrance to successful implementation of new technologies. Simply providing subsidies and grants will surely not be sustainable in the long run which will just be a repetition of unsuccessful history.

Specifically, the donations and subsidies need to be utilized rationally in the following areas of developing countries:

i) **Subsidies at the household level**: This is necessary during the initial phase of project implementation in order to overcome people's limitation of upfront cost and encourage them transition to renewables. However, making arrangements to discontinue the subsidies steadily afterwards is critical to avoid people being solely dependent on the provided fund.
ii) **Starting small**: Starting small such as (in the Nepalese context) by providing exchange offers conducted by the local government or cooperatives in which the general public can get a new energy efficient device (for example, an electrical cooktop) in exchange of their existing device (for example, a kerosene-wick stove or an LPG stove) is effective. Minimization of the financial burden to the users while habituating them on the use of energy efficient devices should be targeted.
iii) **Easy-financing for upgrades**: Ample opportunities of easy-financing need to be provided to the households willing to upgrade to larger (solar) home systems capable of running small industries. This directly reduces the additional load on the national grid.
iv) **Net-metering**: The government needs to make arrangements by providing technical and financial support to conveniently promote net-metering for interested households in order to reap long-term benefits.
v) **Technical capacity development**: Appropriate RE technologies need to be incorporated in the academic curriculum of colleges, universities and vocational training institutes with possibilities of international exchange programmes and exposure visits for the promotion of RE technologies.
vi) **Capacitating local enterprises**: Providing financial and technical support to the local enterprises for carrying out maintenance, servicing and customization activities related to the new technologies is key to sustainability of RE transition.
vii) **Data self-sufficiency**: Increasing the number of climate data observation stations spatially and temporally as well as strengthening the existing ones for data self-sufficiency and knowledge-base development is necessary to prevent designing of local systems based on global/regional data which face high risk of under/over-estimation.
viii) **Grid integration**: Integration of existing electricity transmission line infrastructure to adapt to smart grids of RE for more operational flexibility is a challenge to the developing countries. Building the technical capacity and procuring financial support in this regard is important for future energy security.
ix) **Demand side management**: Minimizing energy use is as important as diversifying the energy generation mix. Facilitating demand side management and promoting energy saving measures is critical because of the likely increased dependence on isolated and mini-grid energy systems in the future.

The largest energy consuming sector (for example, the domestic sector in Nepal) needs to be the main target area for penetration of renewables followed by the other sectors. With development and increase in energy consumption in the other sectors in due course, RE technologies should be scaled up diversifying the energy mix to meet the increasing future demands. Furthermore, more research on assessing the individual RE potential of each country is seen as an immediate requirement for global energy security and environmental concerns rather than blind reliance on donations and technology transfers. Lack of financial resources for implementation and O&M of RE projects still remains the major setback in the developing world. In addition, corruption and misuse/mismanagement of funds is a common problem across the Global South which need to be regulated and minimized for the overall prosperity of the nation including the RE sector. We conclude that the development of RE should be based on a bottom-up approach duly considering the availability of local resources, existing technologies in use and societal preferences.

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CRediT authorship contribution statement

Utsav Bhattarai: Conceptualization, Methodology, Data collection, Writing – original draft. **Tek Maraseni:** Conceptualization, Supervision, Writing – review & editing. **Armando Apan:** Supervision, Writing – review & editing. **Laxmi Prasad Devkota:** Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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References

ADB, 2017. Nepal's largest wind-solar hybrid power system switched on to connect a small village to the world. https://www.adb.org/news/nepals-largest-wind-solar-hybrid-power-system-switched-connect-small-village-world. (Accessed 15 April 2022) [WWW Document]. Webpage. URL.
Adesanya, A.A., Sidortsov, R.v., Schelly, C., 2020. Act locally, transition globally: grassroots resilience, local politics, and five municipalities in the United States with 100% renewable electricity. Energy Res. Social Sci. 67 https://doi.org/10.1016/j.erss.2020.101579.
Adjei, E.A., Amoabeng, K.O., Ayetor, G.K.K., Obeng, G.Y., Quansah, D.A., Adusei, J.S., 2022. Assessing the impact of hydro energy project on poverty alleviation: the case of Bui Dam in Ghana. Energy Pol. 170 https://doi.org/10.1016/j.enpol.2022.113227.
AEPC/GoN, 2008. Solar and Wind Energy Resource Assessment in Nepal (SWERA). Alternative Energy Promotion Centre, Government of Nepal. Kathmandu, Nepal.
AEPC/GoN, 2021. Progress at Glance: A Year in Review FY 2019/20 and 2021/21. Alternative Energy Promotion Centre, Government of Nepal, Kathmandu, Nepal.
Agbonaye, O., Keatley, P., Huang, Y., Odiase, O.F., Hewitt, N., 2022. Value of demand flexibility for managing wind energy constraint and curtailment. Renew. Energy. https://doi.org/10.1016/j.renene.2022.03.131.
Alam, F., Alam, Q., Reza, S., Khurshid-Ul-Alam, S.M., Saleque, K., Chowdhury, H., 2017. A review of hydropower projects in Nepal. In: Energy Procedia. Elsevier Ltd, pp. 581–585. https://doi.org/10.1016/j.egypro.2017.03.188.
Alex, Z., Clark, A., Cheung, W., Zou, L., Kleissl, J., 2014. Minimizing the lead-acid battery bank capacity through a solar PV - wind turbine hybrid system for a high-altitude village in the Nepal Himalayas. In: Energy Procedia. Elsevier Ltd, pp. 1516–1525. https://doi.org/10.1016/j.egypro.2014.10.144.

Almelda, R.M., Schmitt, R., Grodsky, S.M., Flecker, A.S., Gomes, C.P., Zhao, L., Liu, H., Barros, N., Kelman, R., McIntyre, P.B., 2022. Floating solar power: evaluate trade-offs. Nature 606, 246–249.
Anugwom, E.E., Anugwom, K.N., Eya, O.I., 2020. Clean energy transition in a developing society: Perspectives on the socioeconomic determinants of Solar Home Systems adoption among urban households in southeastern Nigeria. African Journal of Science, Technology, Innovation and Development 12, 653–661. https://doi.org/10.1080/20421338.2020.1764176.
Aryanpur, V., Fattahi, M., Mamipour, S., Ghahremani, M., Gallachóir, B., Bazilian, M.D., Glynn, J., 2022. How energy subsidy reform can drive the Iranian power sector towards a low-carbon future. Energy Pol. 169 https://doi.org/10.1016/j.enpol.2022.113190.
WB, 2007. Technical and Economic Assessment of Off-Grid, Mini-Grid and Grid Electrification Technologies. The World Bank.
WB, 2021. World Bank national accounts data, and OECD National Accounts data files. https://data.worldbank.org/indicator/NY.GDP.MKTP.CD?locations=NP&msclkid=c583c33ad00811ec9a96c3a8dce184bf. (Accessed 17 April 2022) [WWW Document]. Webpage. URL.
Balachandra, P., 2015. Review of energy access, poverty, and development: the governance of small-scale renewable energy in developing Asia. Energy J. 360.
Barron-Gafford, G.A., Pavao-Zuckerman, M.A., Minor, R.L., Sutter, L.F., Barnett-Moreno, I., Blackett, D.T., Thompson, M., Dimond, K., Gerlak, A.K., Nabhan, G.P., Macknick, J.E., 2019. Agrivoltaics provide mutual benefits across the food–energy–water nexus in drylands. Nat. Sustain. 2, 848–855. https://doi.org/10.1038/s41893-019-0364-5.
Best, R., 2017. Switching towards coal or renewable energy? The effects of financial capital on energy transitions. Energy Econ. 63, 75–83. https://doi.org/10.1016/j.eneco.2017.01.019.
Bhandari, R., Stadler, I., 2011. Electrification using solar photovoltaic systems in Nepal. Appl. Energy 88, 458–465. https://doi.org/10.1016/j.apenergy.2009.11.029.
Bhandari, B., Lee, K.T., Chu, W.S., Lee, C.S., Song, C.K., Bhandari, P., Ahn, S.H., 2017. Socio-economic impact of renewable energy-based power system in mountainous villages of Nepal. Int. J. Precis. Eng. Manuf. Green Technol. 4, 37–44. https://doi.org/10.1007/s40684-017-0005-2.
Bhattarai, D., Somanathan, E., Nepal, M., 2018. Are renewable energy subsidies in Nepal reaching the poor? Energy Sustain. Dev. 43, 114–122. https://doi.org/10.1016/j.esd.2018.01.001.
Bhattarai, U., Devkota, L.P., Marahatta, S., Shrestha, D., Maraseni, T., 2022a. How will hydro-energy generation of the Nepalese Himalaya vary in the future? A climate change perspective. Environ. Res. 214, 113746 https://doi.org/10.1016/j.envres.2022.113746.
Bhattarai, U., Maraseni, T., Apan, A., 2022b. Assay of renewable energy transition: a systematic literature review. Sci. Total Environ. 833, 155159 https://doi.org/10.1016/j.scitotenv.2022.155159.
BP, 2020. bp Statistical Review of World Energy 2020. BP p.l.c, London, UK.
Bundschuh, J., Chen, G., Tomaszewska, B., Ghaffour, N., Mushtaq, S., Hamawand, I., Reardon-Smith, K., Maraseni, T., Hacene, T.B., Mattheus, G., Mahmoudi, D.L., 2017. Solar, wind and geothermal energy applications in agriculture: back to the future? In: Bundschuh, J., Chen, G., Chandrasekharam, D., Piechocki, J. (Eds.), Geothermal, Wind and Solar Energy Applications in Agriculture and Aquaculture. Taylor and Francis, London.
Butchers, J., Williamson, S., Booker, J., Tran, A., Karki, B., Gautam, B., 2020. Understanding Sustainable Operation of Micro-hydropower: a Field Study in Nepal ☆ https://doi.org/10.5523/bris.1k9cigxbcdiye22kuay4wbt5yu.
Capellán-Pérez, I., de Castro, C., Arto, I., 2017. Assessing vulnerabilities and limits in the transition to renewable energies: land requirements under 100% solar energy scenarios. Renew. Sustain. Energy Rev. https://doi.org/10.1016/j.rser.2017.03.137.
Capellán-Pérez, I., Campos-Celador, Á., Terés-Zubiaga, J., 2018. Renewable Energy Cooperatives as an instrument towards the energy transition in Spain. Energy Pol. 123, 215–229. https://doi.org/10.1016/j.enpol.2018.08.064.
CBS, 2021. Nepal in Figures 2021. Central Bureau of Statistics, National Planning Commission, Government of Nepal, Kathmandu, Nepal.
Ćetković, S., Buzogány, A., 2019. The political economy of EU climate and energy policies in central and eastern Europe revisited: shifting coalitions and prospects for clean energy transitions. Polit. Govern. 7, 124–138. https://doi.org/10.17645/pag.v7i1.1786.
Chapman, A.J., McLellan, B.C., Tezuka, T., 2018. Prioritizing mitigation efforts considering co-benefits, equity and energy justice: fossil fuel to renewable energy transition pathways. Appl. Energy 219, 187–198. https://doi.org/10.1016/j.apenergy.2018.03.054.
Child, M., Kemfert, C., Bogdanov, D., Breyer, C., 2019. Flexible electricity generation, grid exchange and storage for the transition to a 100% renewable energy system in Europe. Renew. Energy 139, 80–101. https://doi.org/10.1016/j.renene.2019.02.077.
Chinnasamy, P., Bharati, L., Bhattarai, U., Khadka, A., Dahal, V., Wahid, S., 2015. Impact of planned water resource development on current and future water demand in the Koshi River basin, Nepal. Water Int. 40, 1004–1020. https://doi.org/10.1080/02508060.2015.1099192.
Chitrakar, A., Shrestha, B.R., 2010. The Tuki: Lighting up Nepal Innovations Case Narrative: Solar-Powered Tuki. Innovations: Technology / Governance / Globalisation 5 (1), 69–78. https://doi.org/10.1162/itgg.2010.5.1.69.
Cook, J., di Martino, M., Allen, R.C., Pistikopoulos, E.N., Avraamidou, S., 2022. A decision-making framework for the optimal design of renewable energy systems under energy-water-land nexus considerations. Sci. Total Environ. 827, 154185 https://doi.org/10.1016/j.scitotenv.2022.154185.
Cowell, R., Ellis, G., Sherry-Brennan, F., Strachan, P.A., Toke, D., 2017. Energy transitions, sub-national government and regime flexibility: how has devolution in the United Kingdom affected renewable energy development? Energy Res. Social Sci. 23, 169–181. https://doi.org/10.1016/j.erss.2016.10.006.
Devkota, L.P., Bhattarai, U., Khatri, P., Marahatta, S., Shrestha, D., 2022. Resilience of hydropower plants to flow variation through the concept of flow elasticity of power: theoretical development. Renew. Energy 184, 920–932. https://doi.org/10.1016/j.renene.2021.11.051.
Dhital, R.P., Ito, Y., Kaneko, S., Komatsu, S., Mihara, R., Yoshida, Y., 2016. Does institutional failure undermine the physical design performance of solar water pumping systems in rural Nepal? Sustainability 8. https://doi.org/10.3390/su8080770.
Elagib, N.A., Basheer, M., 2021. Would Africa's largest hydropower dam have profound environmental impacts? Environ. Sci. Pollut. Control Ser. 28, 8936–8944. https://doi.org/10.1007/s11356-020-11746-4/Published.
Fares, R.L., Webber, M.E., 2017. The impacts of storing solar energy in the home to reduce reliance on the utility. Nat. Energy 2. https://doi.org/10.1038/nenergy.2017.1.
Fuller, R., Zahnd, A., 2012. Solar greenhouse technology for food security: a case study from Humla District, NW Nepal. Mt. Res. Dev. 32, 411–419. https://doi.org/10.1659/MRD-JOURNAL-D-12-00057.1.
Gallagher, J., Styles, D., McNabola, A., Williams, A.P., 2015. Life cycle environmental balance and greenhouse gas mitigation potential of micro-hydropower energy recovery in the water industry. J. Clean. Prod. 99, 152–159. https://doi.org/10.1016/j.jclepro.2015.03.011.
Gautam, B.R., Li, F., Ru, G., 2015. Assessment of urban roof top solar photovoltaic potential to solve power shortage problem in Nepal. Energy Build. 86, 735–744. https://doi.org/10.1016/j.enbuild.2014.10.038.
Guidolin, M., Alpcan, T., 2019. Transition to sustainable energy generation in Australia: interplay between coal, gas and renewables. Renew. Energy 139, 359–367. https://doi.org/10.1016/j.renene.2019.02.045.
Ha, Y.H., Kumar, S.S., 2021. Investigating decentralized renewable energy systems under different governance approaches in Nepal and Indonesia: how does governance fail? Energy Res. Social Sci. 80 https://doi.org/10.1016/j.erss.2021.102214.
Habel, M., Mechkin, K., Podgorska, K., Saunes, M., Babiński, Z., Chalov, S., Absalon, D., Podgórski, Z., Obolewski, K., 2020. Dam and reservoir removal projects: a mix of social-ecological trends and cost-cutting attitudes. Sci. Rep. 10 https://doi.org/10.1038/s41598-020-76158-3.
IEA, 2020. Energy Technology Perspectives 2020. International Energy Agency, France.
IEA, 2021. Key World Energy Statistics 2021. International Energy Agency, France.
IHA, 2020. Hydropower Status Report 2020. International Hydropower Association, London, United Kingdom.
IRENA, 2020. Global Renewables Outlook: Energy Transformation 2050. International Renewable Energy Agency, Abu Dhabi.
Jha, R., 2010. Total run-of-river type hydropower potential of Nepal. Hydro Nepal J. Water, Energy Environ. 7, 8–13. https://doi.org/10.3126/hn.v7i0.4226.
Johnstone, P., Rogge, K.S., Kivimaa, P., Fratini, C.F., Primmer, E., Stirling, A., 2020. Waves of disruption in clean energy transitions: sociotechnical dimensions of system disruption in Germany and the United Kingdom. Energy Res. Social Sci. 59 https://doi.org/10.1016/j.erss.2019.101287.
Kapoor, M., Rahul, Garg, D., 2021. Solar potential assessment over canal-top using geospatial techniques. Arabian J. Geosci. 14, 1–13. https://doi.org/10.1007/s12517-021-06674-7/Published.
KC, S., Khanal, S.K., Shrestha, P., Lamsal, B., 2011. Current status of renewable energy in Nepal: opportunities and challenges. Renew. Sustain. Energy Rev. https://doi.org/10.1016/j.rser.2011.07.022.
Koirala, D.P., Acharya, B., 2022. Households' fuel choices in the context of a decade-long load-shedding problem in Nepal. Energy Pol. 162 https://doi.org/10.1016/j.enpol.2022.112795.
Liao, C., Erbaugh, J.T., Kelly, A.C., Agrawal, A., 2021. Clean energy transitions and human well-being outcomes in Lower and Middle Income Countries: a systematic review. Renew. Sustain. Energy Rev. https://doi.org/10.1016/j.rser.2021.111063.
Lin, B., Kaewkhunok, S., 2021. The role of socio-Culture in the solar power adoption: the inability to reach government policies of marginalized groups. Renew. Sustain. Energy Rev. 144 https://doi.org/10.1016/j.rser.2021.111035.
Lohani, S.P., Blakers, A., 2021. 100% renewable energy with pumped-hydro-energy storage in Nepal. Clean Energy. https://doi.org/10.1093/ce/zkab011.
Magaju, D., Cattapan, A., Franca, M., 2020. Identification of run-of-river hydropower investments in data scarce regions using global data. Energy Sustain. Dev. 58, 30–41. https://doi.org/10.1016/j.esd.2020.07.001.
Mali, B., Shrestha, A., Chapagain, A., Bishwokarma, R., Kumar, P., Gonzalez-Longatt, F., 2022. Challenges in the Penetration of Electric Vehicles in Developing Countries with a Focus on Nepal. Renewable Energy Focus. https://doi.org/10.1016/j.ref.2021.11.003.
Marahatta, S., Bhattarai, U., Devkota, L.P., Aryal, D., 2022. Unravelling the water-energy-economics-continuum of hydroelectricity in the face of climate change. Int. J. Energy and Water Resour. https://doi.org/10.1007/s42108-021-00174-w.
MoF/GoN, 2021. Economic Survey 2020/21. Ministry of Finance, Government of Nepal, Singha Durbar, Kathmandu, Nepal.
Mohsin, M., Kamran, H.W., Atif Nawaz, M., Sajjad Hussain, M., Dahri, A.S., 2021. Assessing the impact of transition from nonrenewable to renewable energy consumption on economic growth-environmental nexus from developing Asian economies. J. Environ. Manag. 284 https://doi.org/10.1016/j.jenvman.2021.111999.

Mukhtarov, S., Mikayilov, J.I., Humbatova, S., Muradov, V., 2020. Do high oil prices obstruct the transition to renewable energy consumption? Sustainability 12. https://doi.org/10.3390/su12114689.
Müller, F., Neumann, M., Elsner, C., Claar, S., 2021. Assessing african energy transitions: renewable energy policies, energy justice, and SDG 7. Polit. Govern. 9, 119–130. https://doi.org/10.17645/pag.v9i1.3615.
Navarro-Espinosa, A., Thomas-Galán, M., 2023. Firewood electrification in Chile: effects on household expenditure and energy poverty. Energy Pol. 173, 113337 https://doi.org/10.1016/j.enpol.2022.113337.
NEA/GoN, 2021. A Year in Review Fiscal Year 2020/21. Nepal Electricity Authority, Ministry of Energy, Water Resources and Irrigation, Government of Nepal, Kathmandu, Nepal.
Otter, P., Sattler, W., Grischek, T., Jaskolski, M., Mey, E., Ulmer, N., Grossmann, P., Matthias, F., Malakar, P., Goldmaier, A., Benz, F., Ndumwa, C., 2020. Economic evaluation of water supply systems operated with solar-driven electro-chlorination in rural regions in Nepal, Egypt and Tanzania. Water Res. 187 https://doi.org/10.1016/j.watres.2020.116384.
Palit, D., Bandyopadhyay, K.R., 2016. Rural electricity access in South Asia: is grid extension the remedy? A critical review. Renew. Sustain. Energy Rev. https://doi.org/10.1016/j.rser.2016.03.034.
Parag, Y., Ainspan, M., 2019. Sustainable microgrids: economic, environmental and social costs and benefits of microgrid deployment. Energy Sustain. Dev. 52, 72–81. https://doi.org/10.1016/j.esd.2019.07.003.
Pietrosemoli, L., Rodríguez-Monroy, C., 2019. The Venezuelan energy crisis: renewable energies in the transition towards sustainability. Renew. Sustain. Energy Rev. 105, 415–426. https://doi.org/10.1016/j.rser.2019.02.014.
Pokharel, S., 2003. Promotional Issues on Alternative Energy Technologies in Nepal. Energy Pol. 31 (4), 307–318. https://doi.org/10.1016/S0301-4215(02)00043-5.
Rai, S.B., 2021. Biggest solar power plant in Nepal worth 250 MW in banke and kapilvastu | study and research goes underway. https://www.greenesa.com/news/biggest-solar-power-plant-in-nepal. (Accessed 5 February 2022) [WWW Document]. Webpage. URL.
Rainey, R.C., Harding, A.K., 2005. Drinking water quality and solar disinfection: effectiveness in peri-urban households in Nepal. J. Water Health 3, 239–248. https://doi.org/10.2166/wh.2005.036.
Ren21, 2021. Renewables 2021 Global Status Report. REN21 Secretariat, c/o UN Environment Programme, Paris, France.
Rodríguez-Segura, F.J., Osorio-Aravena, J.C., Frolova, M., Terrados-Cepeda, J., Muñoz-Cerón, E., 2023. Social acceptance of renewable energy development in southern Spain: exploring tendencies, locations, criteria and situations. Energy Pol. 173, 113356 https://doi.org/10.1016/j.enpol.2022.113356.
Rossi, J., Srivastava, A., Hoang, T.T., Tran, Q.T., Warneryd, M., 2022. Pathways for the development of future intelligent distribution grids. Energy Pol. 169 https://doi.org/10.1016/j.enpol.2022.113140.
Selçuklu, S.B., Coit, D.W., Felder, F.A., 2023. Electricity generation portfolio planning and policy implications of Turkish power system considering cost, emission, and uncertainty. Energy Pol. 173 https://doi.org/10.1016/j.enpol.2022.113393.
Sharma, R.H., Awal, R., 2013. Hydropower development in Nepal. Renew. Sustain. Energy Rev. https://doi.org/10.1016/j.rser.2013.01.013.
Siri, R., Mondal, S.R., Das, S., 2021. Alternative energy sources. In: Pathak, P., Srivastava, R.R. (Eds.), Alternative Energy Resources: the Way to Sustainable Modern Society. Springer Nature, pp. 93–114. https://doi.org/10.1007/698_2020_635.
Sivaram, V., Kann, S., 2016. Solar power needs a more ambitious cost target. Nat. Energy. https://doi.org/10.1038/NENERGY.2016.36.
Sovacool, B.K., Drupady, I.M., 2012. Energy access, poverty, and development. In: The Governance of Small-Scale Renewable Energy in Developing Asia. Ashgate Publishing Limited, Surrey.
Thapa, B., Wang, W., Williams, W., 2022. Life-cycle cost optimization of a solar combisystem for residential buildings in Nepal. J. Asian Architect. Build Eng. 21, 1137–1148. https://doi.org/10.1080/13467581.2021.1928502.
Tiwari, A., 2021. 10 megawatts of solar power evacuated to national grid in Province 2. https://kathmandupost.com/money/2021/03/01/10-megawatts-of-solar-power-evacuated-to-national-grid-in-province-2. (Accessed 5 November 2022) tkpo.st/2NN4U6s [WWW Document]. Webpage. URL.
Tomczyk, P., Wiatkowski, M., 2020. Challenges in the Development of Hydropower in Selected European Countries. Water, Switzerland. https://doi.org/10.3390/w12123542.
Upreti, B.N., Shakya, A., 2009. Wind Energy Potential Assessment in Nepal [WWW Document]. Global COE Program. Tokyo Polytechnic Institute, Japan.
Vanegas Cantarero, M.M., 2020. Of renewable energy, energy democracy, and sustainable development: a roadmap to accelerate the energy transition in developing countries. Energy Res. Social Sci. https://doi.org/10.1016/j.erss.2020.101716.
Wabukala, B.M., Mukisa, N., Watundu, S., Bergland, O., Rudaheranwa, N., Adaramola, M.S., 2023. Impact of household electricity theft and unaffordability on electricity security: a case of Uganda. Energy Pol. 173, 113411 https://doi.org/10.1016/j.enpol.2022.113411.
Wagemans, D., Scholl, C., Vasseur, V., 2019. Facilitating the energy transition-the governance role of local renewable energy cooperatives. Energies 12. https://doi.org/10.3390/en12214171.
Wang, Yitong, Xie, J., Xu, Y.P., Guo, Y., Wang, Yuanjian, 2022. Scenario-based multi-objective optimization of reservoirs in silt-laden rivers: a case study in the Lower Yellow River. Sci. Total Environ. 829 https://doi.org/10.1016/j.scitotenv.2022.154565.
WECS/GoN, 2011. Water Resources of Nepal in the Context of Climate Change. Water and Energy Commission Secretariat. Government of Nepal Singha Durbar, Kathmandu, Nepal.
WECS/GoN, 2013. Nepal's Energy Sector Vision 2050 A.D. Water and Energy Commission Secretariat, Government of Nepal. Singha Durbar, Kathmandu, Nepal.
Weko, S., Goldthau, A., 2022. Bridging the low-carbon technology gap? Assessing energy initiatives for the Global South. Energy Pol. 169 https://doi.org/10.1016/j.enpol.2022.113192.
Wen, C., Lovett, J.C., Kwayu, E.J., Msigwa, C., 2023. Off-grid households' preferences for electricity services: policy implications for mini-grid deployment in rural Tanzania. Energy Pol. 172 https://doi.org/10.1016/j.enpol.2022.113304.
Windemer, R., 2023. Acceptance should not be assumed. How the dynamics of social acceptance changes over time, impacting onshore wind repowering. Energy Pol. 173 https://doi.org/10.1016/j.enpol.2022.113363.

6.3 Links and implications

From this study, I find that international donations and national government subsidies have had substantial impacts on the overall energy landscape of Nepal over the last few decades. Rural renewable energy is almost completely reliant on such financial incentives. In addition, the urban domestic sector and industrial and commercial energy settings are also significantly impacted. These findings induce further study on how the socio-economic contexts influence energy behaviours of the country, particularly the largest energy consuming residential sector, which has been examined in the next article (Paper #5).

CHAPTER 7: PAPER 5 – APPLICATION OF MACHINE LEARNING TO ASSESS PEOPLE'S PERCEPTION OF HOUSEHOLD ENERGY IN THE DEVELOPING WORLD: A CASE OF NEPAL

7.1 Introduction

The main goal of this multidisciplinary paper (Paper #5) integrating energy, social science and machine learning is to examine the factors that explain the highly non-linear people's energy behaviour of the domestic sector of Nepal. This paper is a direct contribution to the second objective of my research by providing the contextual information and explaining the intricacies between the socio-economic factors influencing end-user energy consumption.

7.2 Published paper

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Application of machine learning to assess people's perception of household energy in the developing world: A case of Nepal

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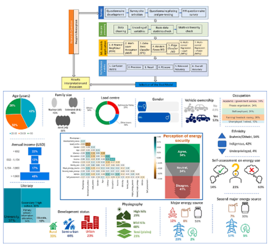
HIGHLIGHTS

- Data driven ML models are better in classifying people's energy perceptions.
- Economy and lack of awareness contribute most to resist energy behaviour changes.
- Fuel-stacking is prevalent due to distrust in the state.
- Grass-root level responses have strong policy implications.

GRAPHICAL ABSTRACT



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ABSTRACT

Research on social aspects of energy and those applying machine learning (ML) is limited compared to the 'hard' disciplines such as science and engineering. We aim to contribute to this niche through this multidisciplinary study integrating energy, social science and ML. Specifically, we aim: (i) to compare the applicability of different ML models in household (HH) energy; and (ii) to explain people's perception of HH energy using the most appropriate model. We carried out cross-sectional survey of 323 HHs in a developing country (Nepal) and extracted 14 predictor variables and one response variable. We tested the performance of seven ML models: *K-Nearest Neighbors (KNN)*, *Multi-Layer Perceptron (MLP)*, *Extra Trees Classifier (ETC), Random Forest (RF)*, *Ridge Classifier (RC)*, *Multinomial Regression–Logit (MR-L)* and *Probit (MR-P)* in classifying people's responses. The models were evaluated against six metrics (*confusion matrix, precision, f1 score, recall, balanced accuracy* and *overall accuracy*). In this study, *ETC* outperformed all other models demonstrating a *balanced accuracy* of 0.79, 0.95 and 0.68 respectively for the *Agree, Neutral* and *Disagree* response categories. Results showed that, compared to conventional statistical models, data driven ML models are better in classifying people's perceptions. It was seen that the majority of the surveyed people from rural (68%) and semi-urban areas (67%) tend to resist energy changes due to economic constraints and lack of awareness. Interestingly, most (73%) of the urban residents are open to changes, but still resort to fuel-stacking because of distrust in the state. These grass-root level responses have strong policy implications.

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1. Introduction

Scholars have recommended against "assuming" social behaviour, particularly related to perception and adoption of new technologies, because of the highly uncertain dynamics between different dimensions of the society [1,2]. The energy sector, in particular, impacts multiple disciplines and operates on various scales, ranging from households to national and regional levels [3–6]. Furthermore, energy is both a building block of the nation as well as a gauge to measure its development [7,8].

Studies have explored different social aspects of energy. For instance, Conradie et al. [9] examined people's behaviour regarding space heating in Europe while Braito et al. [10] assessed photovoltaic investment in Austria and Italy. Similarly, adoption of renewable energy technologies at the household (HH) scale in Germany was studied by Jacksohn et al. [11] and six Mediterranean countries by Strazzera and Statzu [12]. Tekler et al. [13] presented a case study of acceptance of better energy technologies in the workplace in Singapore. Tsvetanov [14] showed that inappropriate policies might actually hinder solar PV penetration rather than encouraging it, taking the case of US. Additionally, studies highlight the importance of awareness, information dissemination [15], and policy reforms [16] in promoting sustainable energy practices. However, distinct global north-south disparities are evident. The developed regions have higher economic and technological resource base [9,17,18], greater awareness [19–21], access to efficient appliances [22,23], and investments in research and development [24,25]. Moreover, Ren and Sovacool [26] show that energy research in the global north is mainly focused on problems facing the industrialized world where there is abundance of research funds.

Contrarily, developing countries suffer from impacts of poverty [27,28], political instabilities [29,30], weak governance [31,32], corruption [33,34], and low literacy rates [35,36]. That is why, these nations are massively reliant on traditional/conventional (mostly fossil and biomass) fuels in their generation mix while using energy inefficient appliances [37]. Furthermore, vulnerabilities associated with energy technologies, such as storage type hydropower, also play a huge role in their adoption in the developing region [38]. The energy choices people are provided by the state are limited [39,40,41]. Therefore, chances of transitioning to cleaner and more efficient energy technologies are rather lean despite willingness and efforts [42–44]. Moreover, Sovacool [45] and Sovacool et al. [46] highlighted that 'hard' disciplines such as economics, statistics, physics, mathematics and engineering have outcasted social and behavioural sciences in energy research. Hence, comprehending people's voices from bottom-up is necessary for policy making, planning and implementation, particularly in the developing world [47]. Catering to the social aspects of energy research in a developing country is a key contribution of this study.

Modelling social behaviour with econometric models is common among researchers. The popularly used models include linear regression and logistic regression (for example, *logit, probit* variants) with binomial/multinomial types. These models have found application across different disciplines mainly to understand people's perceptions and behaviour such as in agriculture [48]; food security [49,50]; livestock [51]; health [52,53]; climate change [54,55]; disasters [56,57]; and energy [58,59], among others. Researchers typically select a set of independent variables, based on literature review, informant interviews and expert judgement, and regress them against dependent variables [60]. Such models generally assume a linear relationship between predictor and dependent variables [61] and/or are usually based on assumptions of no multicollinearity, no heteroskedasticity, normal distribution of error terms and no omitted variable bias [60,62–66], which may not always hold true. Whenever people's behaviours are influenced by an interplay of intertwined societal factors [67–69], non-linearities become more prominent. While the conventional statistical models have been successful in explaining such behaviours to some extent, their representations might turn out to be inapt. This is where application of data driven machine learning (ML) methods can be more efficient. Our contribution lies in targeting this niche, taking the case of a South Asian developing country - Nepal. We test the performance of seven ML models using multiple evaluation metrics to arrive at a rational choice of the 'best' model for the social context of the study region.

Hence, this study carries twin objectives and is aimed at understanding people's perception of energy at the HH level of Nepal using a ML approach. Specifically, this study aims:

1 To evaluate the applicability of ML modelling to understand energy related concerns at the HH level using primary data
2 To analyze and explain people's perception of the adequacy of the current energy generation technologies and HH consumption practices using the most appropriate ML model

2. Machine learning modelling of socio-economic inter-relationships

Studies show that level of education, awareness and tendency towards positive change are generally expected to be positively and linearly related [70–72]. In addition, people living in the economically better-off urban areas are expected to be willing to adopt new fuels and energy efficient technologies [73–76]. However, studies in Nepal have shown that people from the rural and urban areas alike are habituated to the existing fuels, they feel safe (in terms of energy security) in continuing the use of current fuels and also have a myopic impression that newer technologies are expensive [29,59]. When these types of non-linearities arise, prediction or classification of people's perceptions and behaviour becomes a challenging task.

Data driven machine learning (ML) methods can be more efficient in explaining social responses compared to conventional statistical models. A distinct difference between these two types of models is that the former is concentrated on predictive accuracy and controlling overfitting leveraging the flexibility of data and model structures to explain problems more efficiently while the latter focus on statistical properties of estimators for hypothesis testing [60]. Moreover, supervised/unsupervised ML models have gained popularity due to advancements in computational capabilities and easy access to software/codes [77,78]. Hence, researchers have visualized ML as an applied econometric approach [79].

As a result, there has been considerable research in ML methods applied to agriculture [80,81], healthcare [78,82], economics [60], education [83], materials science [66], construction [84], energy [37,85–87], natural disasters [88], among many others disciplines. Furthermore, studies such as Storm et al. [60], Benos et al. [77], Liakos et al. [89], Shaik et al. [78] and Meshram et al. [90] provide extensive review of the applicability of ML models to various sectors of the society However, application of ML models in energy has mostly been concentrated in electricity and power sectors [91–95] and energy storage and conversion technologies [87,96–98]. Studies modelling social side of energy has not got much attention compared to the other areas. Furthermore, different types of ML models such as non-parametric and instance-based, neural networks, tree-based, and linear, among others are more versatile in handling various types of observed data (binary, categorical, continuous, ordinal, etc.) and do not require strict assumptions of normality or those of conventional statistical models [61]. However, selecting the best ML model for a given dataset is a challenge which we aim to address through this research by implementing a robust evaluation approach.

3. Study area

Nepal is a landlocked mountainous country in South Asia situated between India and China (Fig. 1). The country can be divided broadly into four physiographic regions, namely, mountains, high hills, mid-hills and Terai plains. Nepal's total energy consumption amounted to 14.9million tons of oil equivalent (toe) in the fiscal year 2020/2021

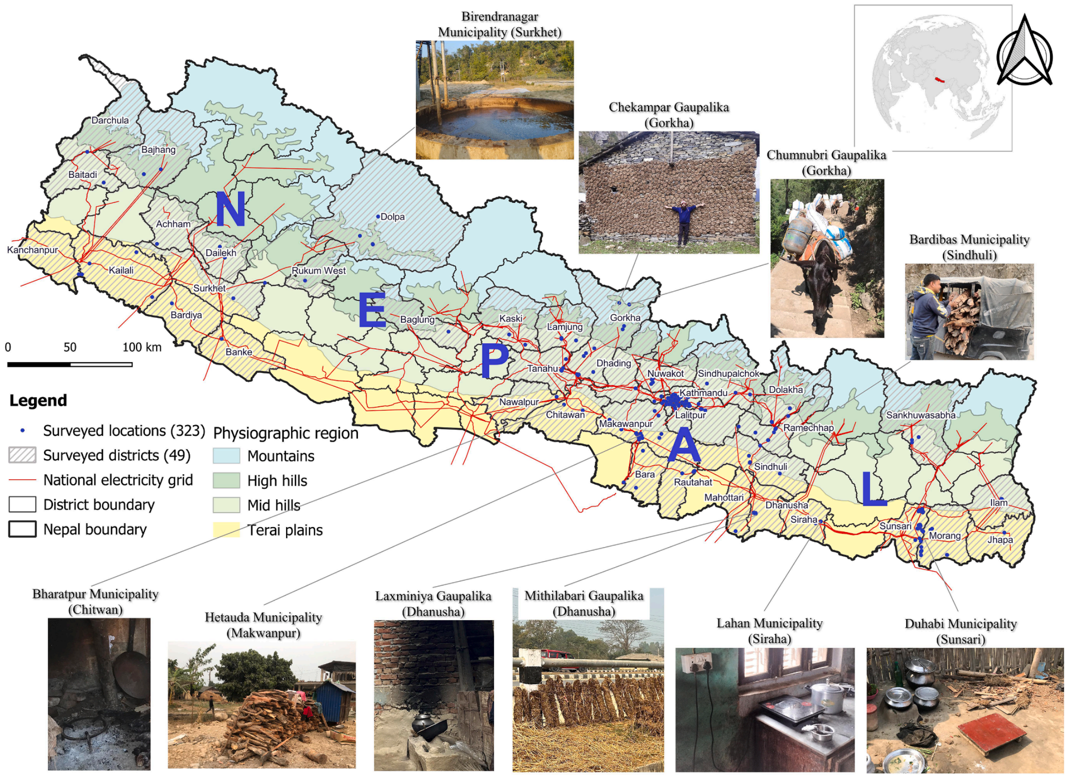

Fig. 1. Location map of Nepal with surveyed points along with districts (in parentheses) and peculiar fuels used for household use. Photos from field team: community biogas plant in Surkhet and 2,000W electric cooktop in a rural house in Siraha (PC: Nawaraj Sanjel); circular shaped 'guitha' sun dried on walls in Gorkha (Nabraj Dhakal); firewood being transported in an auto rickshaw in Sindhuli (Ashish Chapagain); three-legged iron stove for burning firewood in Chitwan and firewood being sundried at a yard in Makwanpur (Insaf Aryal); dung sun dried on footpath and mud stoves for burning them in Dhanusha and Sunsari, and mule carrying LPG cylinder on its back in a remote village of Gorkha (Bipin Dahal).

[99]. The energy generation mix is comprised of three sources: traditional (firewood, agricultural residue, and dry dung used for direct combustion), commercial (petroleum, coal, and grid electricity from large and medium hydropower projects), and other off-grid renewables (micro-hydropower, solar and biogass). In 2020/2021, traditional sources had the largest contribution (65%) to the energy mix , while commercial sources had 32% and renewables had 3% [99]. As for electricity generation, the national grid of Nepal was connected to a total of 2205 MW, generated cumulatively by the government, private sector, and imports and the total annual electricity consumption was 10,686 GWh [100]. The total length of transmission lines in Nepal at the end of 2021/22 was 5329 circuit km (3,816 km of 132 kV; 897 km of 220 kV; 514 km of 66 kV and 102 km of 400 kV) [100]. Most of the electricity generation (92%) comes from large hydroelectric projects, with only 2.2% from solar, 2.3% from thermal, and 3.5% from other smaller renewable energy sources [99].

4. Methodology

We adopted a mixed-method approach in this multi-disciplinary study (Fig. 2). It consisted of six stages: household survey, data preprocessing, application of seven ML models, evaluation of the models based on six performance metrics, and selection of the best model. The final step consisted of examining people's perception of the domestic energy sector of Nepal by analyzing the socio-economic characteristics of the study area based on the feature importance obtained from the best-fit model.

4.1. Household survey

We conducted a cross-sectional survey in Nepal, gathering data from 350 households. Questionnaires were developed in order to collect information on the explanatory variables based on extensive literature [9–12,14–16,18–23,29,34,38,39,41,101–108]. The questionnaire was shared with nine experts (academicians, government officials and energy practitioners) who are well acquainted with the energy sector of Nepal. Based on their suggestions, it was refined and pre-tested at five HHs before the survey rollout. The in-person HH questionnaire surveys were administered from December 2022 to February 2023 using a random sampling approach. Trained interviewers conducted the interviews at the participant's home strictly following ethical requirements of clearance *HREC ID H22REA258* issued by the Human Research Ethics Committee, University of Southern Queensland, Australia. Respondents were chosen in such a way that they were knowledgeable about the energy related concerns in their HHs. HH heads were preferable, however, in many cases it was found that the younger members of the family were more aware of and had a better say in energy related decisions in their houses. Koirala and Acharya [59] even suggest a possibility that elderly people might be scared to try new technologies in Nepal.

It is important that the sampled households are representative of a number of attributes pertaining to our research objectives. Therefore, diversity in the use of energy was the major criteria for survey site selection. This was further governed by whether a house was electrified or non-electrified. Use of grid electricity is the proxy variable to identify

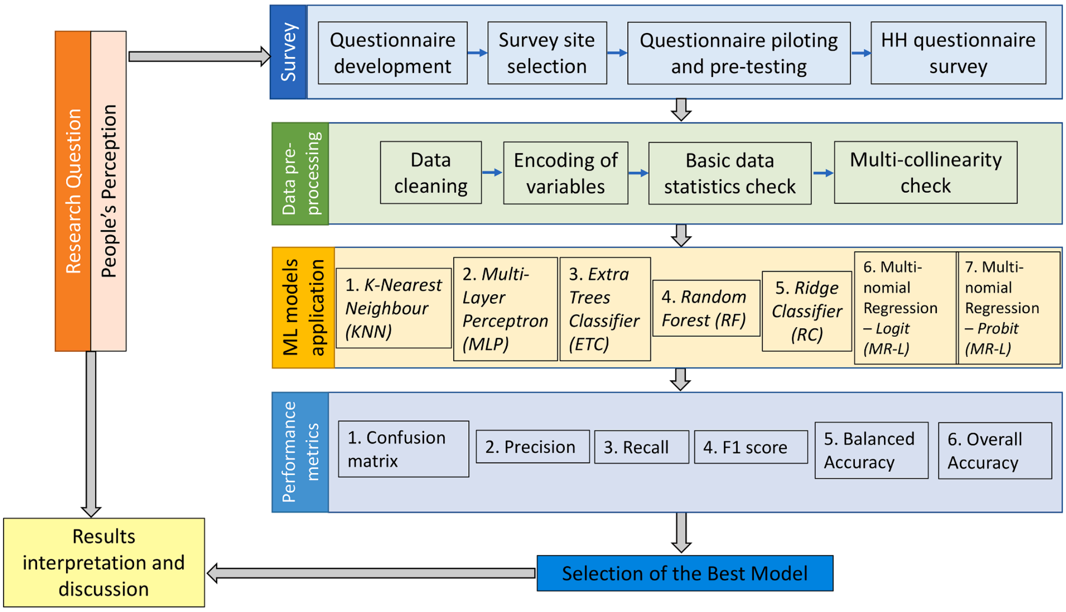

Fig. 2. Overall research methodology of this study; ML – machine learning.

the electrification condition. Additionally, urban, rural and semi-urban areas have different energy consumption patterns in Nepal. Hence, this was chosen as another important deciding factor for survey site selection. Moreover, physiographical region and load centres are two variables which indicate the remoteness of a location. In addition, diverse energy (mainly electricity) generation technologies are prevalent in Nepal. Hence, this criteria of including as many such technologies as possible was adopted during site selection. Locations were fixed such that information from the residents of industrial areas, major hydropower projects (currently under operation and planned), representative micro-hydropower projects and solar projects were obtained during the survey. The survey site selection criteria adopted in this study has been presented in Annex Table A1.

A considerable homogeneity can be seen in the energy consumption pattern and social settings across villages throughout the country. Similarly, the energy scenario is very much similar across the urban areas (cities and towns). Likewise, homogeneity within and diversity across the classes of *physiography* (high hills, mid hills and terai plains), *family size* (nuclear, extended and join), *gender* (female and male), age (20-35, 35-50, >50), *literacy* (illiterate, primary school/informal education, secondary/high school, university), *load centres* (Kathmandu city, other towns, others), *major sources of energy* (grid electricity, LPG, petroleum and renewables), *annual HH income* (< USD 692, 692 – 1,154, 1,154 – 1,960 and >1,960) and *primary occupation* (academic/government service, farming/livestock rearing, private organization, self-employed and unemployed/retired) was maintained by the sample size. Therefore, based on the homogeneity of the sample clusters, the sample size utilized in this study is deemed adequate. Furthermore, it has been made sure that a minimum sample size of 30 has been maintained for each cluster, ensuring a robust representation for analysis and representation (Annex Table A1 and Annex Table B1).

4.2. Data pre-processing

Out of the 350 HH survey responses, 27 were excluded because they were either incomplete, irrelevant or not specific, leading to a final sample size of 323. A total of 14 independent (predictor) variables and one response variable were selected to answer our research question of people's perception of energy availability and consumption at the HH level. The predictor variables were of mixed type including continuous, binary and categorical data. The predictor variables were categorized into different classes; justification for the classification is presented in Annex Table B1. As discussed earlier, homogeneity within and diversity across the classes of each predictor variable was key to our classification. Furthermore, the response variable was one hot encoded to make it multilabel in order to estimate the contributions of the individual predictor variable on each label. After encoding, the basic statistics of the observed data, spread of each predictor variable in the different classes and multi-collinearity were checked (Fig. 3).

4.3. Application of machine learning models

Our dataset consisted of multiple types of variables. Based on the multilabel classification of the response variable, we chose seven ML models (Table 1) capable of handling multiple categorical data for our study. A brief description of each model is given in the table while the details of the models are provided in Annex C. These models were implemented in *python* using *sklearn, imblearn, statsmodels* in addition to *pandas, numpy, scipy, matplotlib* and *seaborn* libraries.

4.4. Performance metrics

Different types of performance metrics are useful for evaluating and comparing the effectiveness of a classification algorithm. We have adopted six metrics (*confusion matrix, accuracy, balanced accuracy, precision, recall*, and *f1 score*) in this study. Details of these metrics are provided in Table 2. Using these performance metrics, we carried our cross-validation for all the models to assess how well they perform on datasets for which they have not been trained. We performed runs for four simulations by varying the training-testing data split taking 80:20, 70:30, 60:40 and 50:50 values to evaluate the robustness of all the models. This approach ensures that the model results are well-validated and can be confidently used for feature selection.

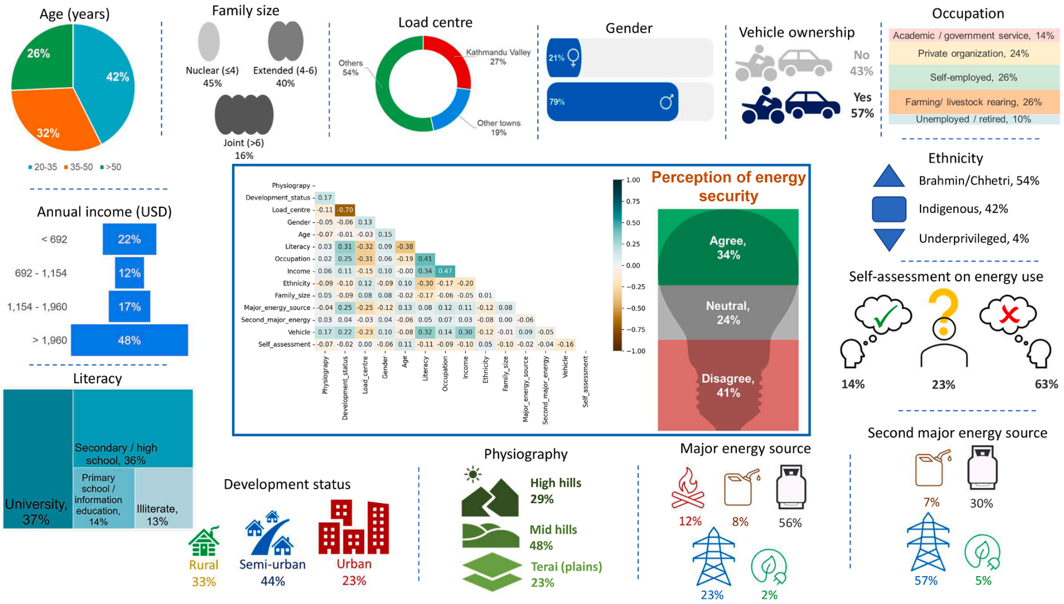

Fig. 3. Spread of data from the sampled households across the different classes of explanatory and response variables. Please refer to Annex B for the categorization of the explanatory variables.

4.5. Selection of the best model

Models may demonstrate varying performances in terms of the metrics discussed above. However, an effective model will exhibit high *precision, recall*, f1 *score, balanced accuracy, overall accuracy*, and show a desirable *confusion matrix* with well-distributed results. Hence, we adopted a robust methodology for best model selection in this study and assessed the performance of each ML model using six metrics (Table 2). Finally, we selected the model that consistently performed well across all evaluation metrics.

The feature importance derived from the best performing model provides information on the relative importance of the explanatory variables on the response variable. Since we have used a multi-label classification of the dependent variable, the feature importance of each variable on each label was extracted and analysed separately. This led to a comprehension of the segregated impacts of each explanatory variable on each response class which was useful in explaining people's perception. Key policy aspects relating to the people's perception of HH energy were also discussed inducing evidence-based policy implications.

5. Results

5.1. Survey data summary

There are 14 descriptive variables considered in this study. Among them, 'Age', 'Family size', 'Load centre', 'Vehicle ownership', 'Occupation', 'Annual income', 'Literacy', 'Development status' and 'Physiography' were found balanced across the different classes (Fig. 3). This indicates that our sample size and the ML classification strategy adopted are less likely to give biased results. There is an imbalance in some variables such as 'Gender' and 'Ethnicity' which is expected because of the social context in Nepal. Likewise, a very small number of the people reported using renewable energy as their major and/or second major source of HH energy. Moreover, it can be seen from the correlation matrix that the dataset is not affected by the issue of multi-collinearity (correlation coefficient of almost all the variables are below 0.6).

To obtain information of people's perception of HH energy sector, we asked a question as a proxy to all the respondents: "Do you think that the existing energy availability and technologies you are using in your household are sufficient to meet your current and future energy needs?" Three possible responses were *Agree, Disagree* or remain *Neutral*. People agreeing to our question did not feel the need to adopt any changes to their HH energy. However, people disagreeing to our question identified the need to make changes in the energy sources as well as consumption pattern for a better and sustainable energy secure future. The respondents who remained neutral were mostly either unaware of the possible energy alternatives or were constrained financially and socially. It can be seen that the spread of the response (perception) variable in our dataset is relatively balanced across the three labels of *Agree* (34%), *Neutral* (24%) and *Disagree* (41%) (Fig. 3).

5.2. Evaluation of models

Seven machine learning models were fitted to the HH data collected during field survey and six performance metrics were evaluated for each model (Table 3). The models were evaluated against each label of the 'Perception' variable (*Agree, Neutral* and *Disagree*) (Annex Table B1). Additionally, each response of the 'Perception' class was further segregated when the response conditions was met (shown by *TRUE*) or otherwise (*FALSE*), as listed in the fourth column of Table 3. It is essential to analyze these metrics within the specific problem and domain context. For example, precision is a more suitable metric when "False Positives" are of a higher concern than "False Negatives". Similarly, recall is usually a better option when "False Negatives" are more important than "False Positives" [114,115]. Hence, *confusion matrix, precision, recall* and *f1 score* was calculated for each combination and the overall accuracy of the model to predict each response class was then evaluated. It can be seen that *Multi-Layer Perceptron (MLP), Multinomial Regression – Logit (MR-L)* and *Multinomial Regression – Probit (MR-P)* have the poorest performance in estimating the response of the predictand variable in all the combinations of the metrics tested. For example, the *MLP* estimates *Agree* with a *precision* of 0.53, *recall* of 0.42 and *f1 score* of

Table 1
Seven machine learning models adopted in this study.

S. N.	Model	Type	Features
1	K-Nearest Neighbors (KNN)	Non-parametric and instance-based	Assumes that similar instances or data points tend to exist in proximity in the feature space
2	Multi-Layer Perceptron (MLP)	Neural networks	Functions by defining the input and output layers, assigning weights to the connections between neurons, and applying activation functions
3	Extra Trees Classifier (ETC)	Tree-based	Is an ensemble learning method where multiple decision trees are trained on different subsets of the training data and their predictions are combined to make final predictions
4	Random Forest (RF)	Tree-based	Combines multiple decision trees to solve classification tasks trained on a randomly sampled subset of the training data, and the final prediction is determined by aggregating the predictions of all individual trees
5	Ridge Classifier (RC)	Linear	Is a linear classifier for multilabel classification tasks based on Ridge Regression (regularized with L2-norm penalty)
6	Multinomial Regression – Logit (MR-L)	Regression-based statistical	Is a type of regression analysis used to model the probability of a binary outcome assuming the relationship between the dependent variable and the independent variables is linear on the logit scale
7	Multinomial Regression – Probit (MR-P)	Regression-based statistical	Is a type of regression analysis used to model the probability of a binary outcome assuming linear relationship between the dependent variable and the independent variables which is transformed using the cumulative distribution function

Information sourced from Das et al. [29]; Diesenroth et al. [61]; Er et al. [109]; Kumaravelan and Behera [110]; Storm et al. [60]; Wu et al. [111]; and Zhang and Zhou [112].

0.47 in the case of 80:20 training-testing split. The confusion matrix of the *True-Agree* class shows that 30 positives were predicted correctly (true positives – shown in the first row and first column of the confusion matrix) while 17 true negatives were predicted correctly (second row, second column of the confusion matrix). The errors are 15 false positives and 23 false negatives. Similarly, the model is able to estimate *False-Agree* with a *precision, recall* and *f1 score* of 0.57, 0.67 and 0.61 respectively. The *balanced accuracy* of the model for the *Agree* condition is 0.55. The *Extra Trees Classifier (ETC)* model demonstrated a *balanced accuracy* of 0.79, 0.95 and 0.68 for the *Agree, Neutral* and *Disagree* categories. We performed cross-validation of the models for three more scenarios based on the training-testing data split taking 70:30, 60:40 and 50:50 values. Carrying out a number of cross-validation simulations is a standard practise in ML to evaluate the robustness of all the models. From these scenarios, it is evident that *ETC* outperformed the other models in terms of all six evaluation metrics. Hence, *ETC* has been selected as the best fit model in explaining all three classes of the response variable of our dataset.

5.3. Feature importance

The relative feature importance of the considered 14 variables in explaining the three labels (*Agree, Neutral* and *Disagree*) of the response variable derived from the best fit *Extra Trees Classifier (ETC)* model has been presented in Fig. 4. The values for each label (column) add up to one. The relative importance of the variables ranges from 2.5% (*Agree*: 'Ethnicity') to 13.1% (*Agree*: 'Occupation') across all the three output categories. For the *Agree* category, 'Occupation' has the highest contribution of 13.1%, followed by 'Major energy source' contributing 10.5%. Similarly, the third in row is 'Second energy source' (9.6% contribution), 'Development status' ranks fourth (8.4%) followed by 'Literacy' (8.1%). These five factors are capable of explaining a cumulative 50% response in the *Agree* category. 'Ethnicity' has the least contribution of 2.6%. Similarly, 'Self-assessment' (12% contribution), 'Physiography' (10.7%), 'Income' (9.1%), 'Family size' (8.4%) and 'Development status' and 'Age' (8% each) respectively rank first to fifth in the *Neutral* category. Likewise, 'Occupation' (11.2%), 'Development status' (10.6%), 'Income' and 'Family size' (9.1% each), 'Literacy' and 'Second major energy' (8% each), and 'Ethnicity' (7.2%) are respectively the top five contributors of the *Disagree* response category. 'Gender' was found to have the least contribution in both the *Neutral* (3.3%) and *Disagree* (4.1%) response categories.

It is seen from Fig. 4 that 'Development status' is common among the top five influencing variables for all the three labels of the response variable. 'Occupation' and 'Literacy' are common between the *Agree* and *Disagree* labels. Similarly, 'Income' and 'Family size' are common across the *Neutral* and *Disagree* categories. Additionally, 'Load centre' and 'Age' are among the variables that have moderate effect (sixth to tenth in line) on all the three labels of the response variable. Interestingly, 'Gender' is among the least influential variables for all the three labels. 'Ethnicity' is common in the last four ranking variables between the *Agree* and *Neutral* categories. Moreover, 'Physiography' is common in the last four explanatory variables among *Agree* and *Disagree* while 'Vehicle ownership' is between *Neutral* and *Disagree* categories.

5.4. People's perception

Cross tabulation of the explanatory variables with the response variable, considering the sample of 323 datasets, allowed for visualization of the distribution across their different categories (Table 4). For instance, across the 'Primary occupation' category, a considerable number of people working in the private organizations (31) felt that the current energy supply and consumption at their HHs is adequate for meeting the current and future energy needs while a sizeable number of self-employed people (42) felt the need of change at their HHs; the largest group remaining *Neutral* are farmers (33), results being significant at 95% confidence level. Similarly, a sizable number of HHs earning more than USD 1,960 per year felt the need for a change in the energy behaviour (73) while a fair number of HHs (52) felt otherwise ($p < 0.05$). Likewise, in the 'Physiography' category, most of the people living in the mid hills either want a change in the HH energy behaviour (52) or do not prefer any changes (74) while a majority with *Neutral* (32) responses were from the high hills (results significant with $p < 0.05$). Additionally, it can be seen that most respondents from the rural (45) and semi-urban (46) areas perceived that the current conditions of HH energy is adequate. On the other hand, a considerable number of people from semi-urban (63) areas felt that there is a need for change in the existing energy status of their houses. Thus, it is evident that the responses pertaining to the people's perception and response vary across the different categories of the explanatory variables (Table 4).

6. Discussion

6.1. Application of machine learning

An important reading from Fig. 4 is that none of the explanatory variables have a contribution larger than 13% in explaining the output response across all labels. This is a validation that the variables used for this study are all important but with varying relative influences. It is to be noted that feature importance values (Fig. 4) are different from

Table 2
Performance metrics used to evaluate the machine learning methods in our study.

<table>
<tr><th>S.N.</th><th>Metric</th><th>Explanation</th><th>Mathematical denotation</th></tr>
<tr><td>1</td><td>Confusion matrix</td><td>Is a table used to evaluate the performance of a classification algorithm on a set of test data for which the true values are known. It summarizes the number of correct and incorrect predictions made by the algorithm, broken down by each class in the problem.</td><td><table>
<tr><td></td><td></td><td colspan="2">Actual Labels</td></tr>
<tr><td></td><td></td><td>Positive</td><td>Negative</td></tr>
<tr><td rowspan="2">Predicted Labels</td><td>Positive</td><td>True Positives (TP)</td><td>False Positives (FP)</td></tr>
<tr><td>Negative</td><td>False Negatives (FN)</td><td>True Negatives (TN)</td></tr>
</table></td></tr>
<tr><td>2</td><td>Accuracy</td><td>Accuracy is the proportion of correctly classified data points (sum of the diagonal elements of the confusion matrix divided by the total number of sample points).</td><td>$Accuracy = \frac{TP + TN}{TP + FP + TN + FN}$</td></tr>
<tr><td>3</td><td>Balanced Accuracy</td><td>In multi-label classification, the concept of balanced accuracy can be extended to compute the accuracy as defined earlier for each individual label and then take the average of these accuracies.</td><td>Same as for ‘Accuracy’ but calculated for each label separately</td></tr>
<tr><td>4</td><td>Precision</td><td>Precision is the proportion of correctly classified positive predictions (i.e., true positives divided by the sum of true positives and false positives).</td><td>$Precision = \frac{TP}{TP + FP}$</td></tr>
<tr><td>5</td><td>Recall</td><td>Recall (also called sensitivity) is the proportion of actual positive instances that are correctly classified (i.e., true positives divided by the sum of true positives and false negatives)</td><td>$R = \frac{TP}{TP + FN}$</td></tr>
<tr><td>6</td><td>F1 score</td><td>F1 score is the harmonic mean of precision and recall, which provides a single measure of overall performance.</td><td>$F1\ score = 2\ \frac{(Precision * Recall)}{(Precision + Recall)}$</td></tr>
</table>

Information sourced from de Carvalho and Freitas [113]; Heydarian et al. [114]; Tsoumakas and Katakis [115]; Vaizman et al. [116]; Wu et al. [111]; Zhang et al. [117]; and Zohair [118].

regression coefficients (that are obtained from regression analysis and used to analyze the marginal effect of a particular variable on the regressed variable). This study is about classification and not prediction/regression. Hence, the commonly used evaluation indicators such as mean absolute error (MAE), mean relative error (MRE), root mean square error (RMSE), correlation coefficient (R), coefficient of variation (R^2 or its variants such as pseudo-R^2, adjusted R^2, etc.) have not been used in our analysis because these are generally applicable to linear regression unlike data driven models [61,66]. Instead, we have chosen to adopt a more robust set of evaluation metrics comprising of *confusion matrix, precision, f1 score, recall* and *accuracy* for checking the applicability of the models to the considered dataset. The confusion matrix is able to clearly provide evidence of the true and false estimations of a particular response class.

In this study, we adopted seven ML models: *RF* and *ETC* (tree-based), *MR-L* and *MR-P* (statistical), *KNN* (non-parametric and instance-based), *RC* (linear) and *MLP* (neural networks). Based on the evaluation results (Table 3), tree-based models outperformed other models in multi-label classification of people’s perception of HH energy. Among the tree-based models, *ETC* achieved the best performance in terms of all six evaluation metrics. The popularly used statistical models *MR-L* and *MR-P* were the least performing. This proves the need for exploring models other than linear/conventional statistical models to better analyse such non-linear social behaviour.

In ML applications, there is a general issue of class-imbalance meaning that the trained model is likely to be biased towards the majority class [119,117]. We adopted random oversampling technique to balance multi labels as a standard practise [120–122]. Furthermore, to evaluate the performance of each ML model in classification of each label, we implemented the *balanced accuracy* metric (in addition to *overall accuracy*) which calculates the accuracy of classifying each label [118]. We found that *ETC* model performed the best in all the scenarios irrespective of the test-train data split.

Furthermore, an advantage of using tree-based ML models is that the process of assigning features importance to the explanatory variables with respect to the response variable can be conveniently explained using tree visualization [123]. The tree visualization is constructed by recursively splitting the training data into smaller subsets based on the feature combination that provides the most information gain. To build a tree, the algorithm evaluates the different features to determine which

Table 3
Evaluation of models in explaining the *Agree, Neutral* and *Disagree* classes of the 'Perception' variable.

S.N	Models	Perception Class	Boolean condition	Confusion Matrix	Precision	Recall	F1 score	Balanced Accuracy	Overall Accuracy
1	K-Nearest Neighbors (KNN)	Agree	FALSE	[[23 17]] [[21 24]]	0.59	0.53	0.56	0.55	0.54
			TRUE	[[24 21]] [[17 23]]	0.52	0.57	0.55		
		Neutral	FALSE	[[33 20]] [[19 26]]	0.57	0.58	0.57	0.60	
			TRUE	[[26 19]] [[20 33]]	0.63	0.62	0.63		
		Disagree	FALSE	[[17 18]] [[17 24]]	0.57	0.59	0.58	0.54	
			TRUE	[[24 17]] [[18 17]]	0.50	0.49	0.49		
2	Multi-Layer Perceptron (MLP)	Agree	FALSE	[[17 23]] [[15 30]]	0.57	0.67	0.61	0.55	0.51
			TRUE	[[30 15]] [[23 17]]	0.53	0.42	0.47		
		Neutral	FALSE	[[25 28]] [[20 25]]	0.47	0.56	0.51	0.51	
			TRUE	[[25 20]] [[28 25]]	0.56	0.47	0.51		
		Disagree	FALSE	[[8 27]] [[13 28]]	0.51	0.68	0.58	0.47	
			TRUE	[[28 13]] [[27 8]]	0.38	0.23	0.29		
3	Extra Trees Classifier (ETC)	Agree	FALSE	[[33 7]] [[7 38]]	0.84	0.84	0.84	0.84	0.74
			TRUE	[[38 7]] [[7 33]]	0.82	0.82	0.82		
		Neutral	FALSE	[[52 1]] [[5 40]]	0.98	0.89	0.93	0.94	
			TRUE	[[40 5]] [[1 52]]	0.91	0.98	0.95		
		Disagree	FALSE	[[19 16]] [[4 37]]	0.70	0.90	0.79	0.74	
			TRUE	[[37 4]] [[16 19]]	0.83	0.54	0.66		
4	Random Forest (RF)	Agree	FALSE	[[30 10]] [[15 30]]	0.75	0.67	0.71	0.71	0.68
			TRUE	[[30 15]] [[10 30]]	0.67	0.75	0.71		

(*continued on next page*)

Table 3 (*continued*)

		Neutral	FALSE	[[49 4] [10 35]]	0.90	0.78	0.83	0.86	
			TRUE	[[35 10] [4 49]]	0.83	0.92	0.88		
		Disagree	FALSE	[[21 14] [10 31]]	0.69	0.76	0.72	0.68	
			TRUE	[[31 10] [14 21]]	0.68	0.60	0.64		
5	Ridge Classifier (RC)	Agree	FALSE	[[21 19] [18 27]]	0.59	0.60	0.59	0.56	0.53
			TRUE	[[27 18] [19 21]]	0.54	0.53	0.53		
		Neutral	FALSE	[[26 27] [16 29]]	0.52	0.64	0.57	0.56	
			TRUE	[[29 16] [27 26]]	0.62	0.49	0.55		
		Disagree	FALSE	[[14 21] [15 26]]	0.55	0.63	0.59	0.53	
			TRUE	[[26 15] [21 14]]	0.48	0.40	0.44		
6	Multinomial Regression – Logit (MR-L)	Agree	FALSE	[[21 19] [25 20]]	0.51	0.44	0.48	0.48	0.51
			TRUE	[[20 25] [19 21]]	0.46	0.53	0.49		
		Neutral	FALSE	[[50 3] [41 4]]	0.57	0.09	0.15	0.55	
			TRUE	[[4 41] [3 50]]	0.55	0.94	0.69		
		Disagree	FALSE	[[3 32] [5 36]]	0.53	0.88	0.66	0.51	
			TRUE	[[36 5] [32 3]]	0.38	0.09	0.14		
7	Multinomial Regression – Probit (MR-P)	Agree	FALSE	[[21 19] [25 20]]	0.51	0.44	0.48	0.48	0.51
			TRUE	[[20 25] [19 21]]	0.46	0.53	0.49		
		Neutral	FALSE	[[50 3] [41 4]]	0.57	0.09	0.15	0.55	
			TRUE	[[4 41] [3 50]]	0.55	0.94	0.69		
		Disagree	FALSE	[[3 32] [5 36]]	0.53	0.88	0.66	0.51	
			TRUE	[[36 5] [32 3]]	0.38	0.09	0.14		

Note: This table presents the evaluation metrics of the models training and testing carried out at 80:20 split of the data. Randomized oversampling has been introduced to remove the data-related bias for model training and testing (n=323).

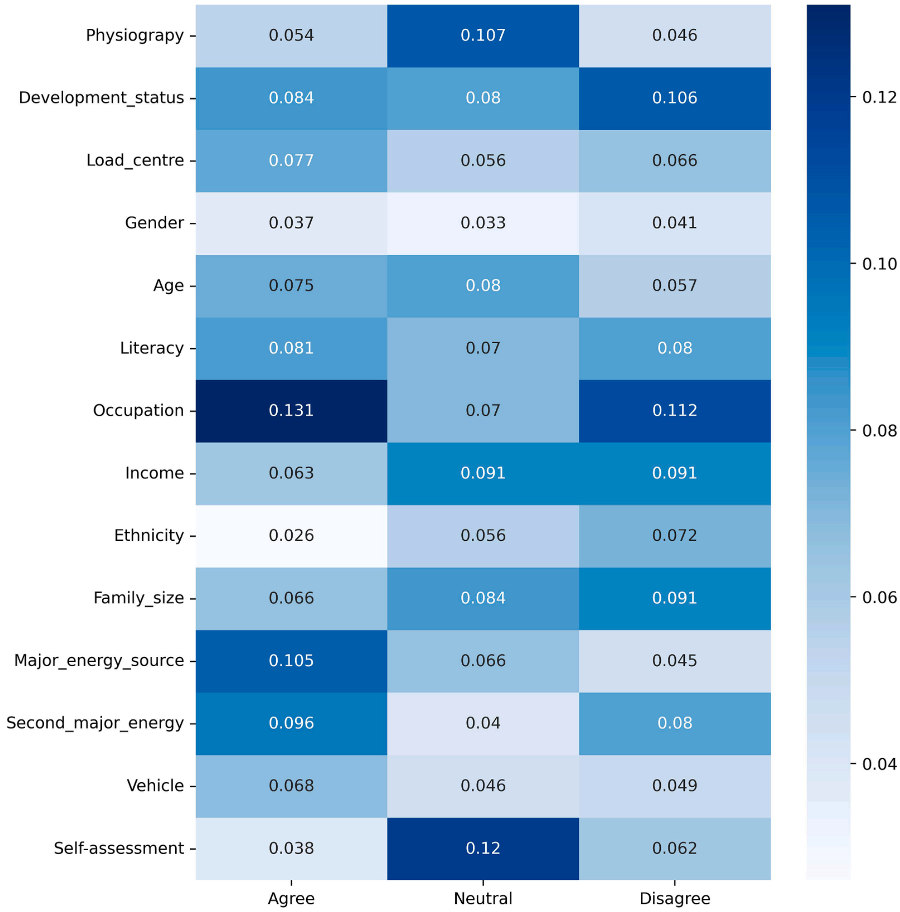

Fig. 4. Heat map of feature importance of the explanatory variables against the three classes, *Agree, Neutral* and *Disagree*, of the response variable derived from the *Extra Trees Classifier (ETC)* model.

one provides the most information gain, i.e., the feature that maximizes the separation of the classes or reduces the variance of the response variable [111] as shown in Fig. 5. The tree we have presented here for the purpose of illustration is one among the many considered in the analysis. In this figure, the 'second major energy source' (depth=1) has the highest information which is further split into two categories: first with class 1 ('grid-electricity'), 2 ('LPG'), and 3 ('petroleum') which is shown on the left-hand side and the second with class 4 ('renewables') shown on the right-hand side. The second level split (depth = 2) is based on 'gender' while the third level split (depth = 3) is based on 'ethnicity', 'load centre' and 'occupation', depending upon their classes. The process is further continued until the information of the entire dataset is converged. Also, each class of all the explanatory variables is segregated according to three labels of the response variable (denoted by yellow: *Agree*, blue: *Neutral*, and green: *Disagree*) for each depth (Fig. 5). The final values of feature importance obtained from the *ETC* model is calculated by taking an average of multiple trees formed in the same way. For example, if a tree-based model is trained using 100 trees, the final feature importance of the explanatory variables and classification of multi-labels of response variable are derived based on the average of the 100 trees.

6.2. *Public perception of HH energy*

Energy consumption patterns in Nepalese households are such that cooking is the primary use of energy, while lighting and other uses have lower consumption values [99,124]. Room heating/cooling is not that common. Traditional heating mechanism include bonfires in open areas or charcoal fire in iron pans for room heating. The Terai (southern plains) has a relatively hotter climate and those HHs that can afford, use table or ceiling fans mostly during summer. The hilly areas are cooler and people who can afford buy electric or LPG heaters. Air-conditioners/coolers and central heating/cooling systems are limited to the upper most class of the urban areas.

It was found that residents of the rural and semi-urban areas tend to resist changing energy sources due to economic constraints and lack of awareness (example response Annex D1). On the contrary, most people living in the urban areas were found more open to change due to better economic conditions and education. This is evident from the fact that 'Occupation' and 'Literacy' are the most influencing features common across the *Agree* and *Disagree* categories (Fig. 4). People's willingness to pay for electricity generation from renewables as a better option for the future has been reported by studies such as Chaikumbung [58]. Moreover, people in the urban areas generally have a smaller family size and better incomes which can afford expensive modern fuels [125,126]. As a

Table 4
Cross tabulation results of the explanatory variables and people's perception (count) on the continuation of current energy sources for energy security at the household level.

Explanatory variables	Classes	Perception			Total	Chi-square (p-value)
		Agree	Neutral	Disagree		
Physiography	High hills	34	32	29	95	**9.727 (0.045)**
	Mid hills	52	29	74	155	
	Terai (plains)	25	18	30	73	
Development status	Rural	45	29	34	108	7.281 (0.121)
	Semi-urban	46	32	63	141	
	Urban	20	18	36	74	
Family size (Mean: 4.9; SD: 1.9)	Nuclear (<=4)	49	38	57	144	1.831 (0.766)
	Extended (4-6)	42	32	55	129	
	Joint (>6)	20	9	21	50	
Gender	Female	16	25	27	68	**8.321 (0.015)**
	Male	95	54	106	255	
Age (Mean: 40.6; SD: 13.6)	20-35	48	28	61	137	2.374 (0.667)
	35-50	34	28	41	103	
	>50	29	23	31	83	
Literacy	Illiterate	15	20	8	43	4.592 (0.331)
	Primary school/ Informal education	12	13	21	46	
	Secondary/ High school	38	27	50	115	
	University	46	19	54	119	
Load centres	Kathmandu	27	22	38	87	5.817 (0.213)
	Other towns	18	12	33	63	
	Others	66	45	62	173	
Self evaluation	Agree	73	33	99	205	**41.733 (0.000)**
	Disagree	20	7	15	42	
	Neutral	18	39	19	76	
Second major energy source	Grid-electricity	62	43	80	185	4.886 (0.558)
	LPG	37	21	39	97	
	Petroleum	8	8	8	24	
	Renewables	4	7	6	17	
Annual household income (USD)	< 692	20	28	20	68	**19.015 (0.004)**
	692 – 1,154	13	12	12	37	
	1,154 – 1,960	17	14	22	53	
	> 1,960	52	23	73	148	
	ND	9	2	6	17	
Major energy source	Agriculture-residue	19	10	10	39	11.455 (0.177)
	Grid-electricity	30	17	26	73	
	LPG	55	43	83	181	
	Petroleum	5	7	13	25	
	Renewables	2	2	1	5	
Primary occupation	Academic/ government service	16	5	23	44	**22.385 (0.004)**
	Farming/ livestock rearing	26	33	24	83	
	Private organization	31	13	34	78	
	Self-employed	25	18	42	85	
	Unemployed/ retired	13	10	10	33	
Total		111	79	133	323	

Bold *p*-values are significant at 95% confidence level; ND: preferred not to disclose

result, 'Income' and 'Family size' are found to be among the common influencing features in the *Neutral* and *Disagree* categories.

Contrary to our expectation, the sources of energy that people are currently using ('Major energy source' and 'Second major energy source') have varying influences on the response classes (Fig. 4 and Table 4). Grid electricity was found to be the major energy source in areas which are connected to the national grid. LPG was found to be the major energy source for HHs in most urban and semi-urban areas for cooking. People having access to grid electricity and LPG (mostly in the urban areas with a better economic condition) do not choose to make any changes to their HH energy condition for future energy sufficiency (example responses in Annex D2 and Annex D3). On the other hand, the existing sources of energy were not found to be that important for the *Neutral* and *Disagree* response classes, irrespective of their location or economic condition.

'Age' and 'Gender' were seen to respectively have moderate and the least influence on all the three response categories (Fig. 4). We consider this reasonable as female members mostly have little say on the choice of HH energy technologies, an observation common across the rural, semi-urban and urban areas of Nepal [29,59]. The response of the male members of the family varied by location, occupation, income level, awareness and age. Furthermore, extended and joint families are common in Nepal, and it is not always the HH head that decides on the use of energy technologies. The younger members of the family are generally more educated and are better exposed to latest technologies. Moreover, the young and educated are likely to earn more and have a better influence in energy related decisions at the HH level.

6.3. Rural HH energy

Rural cooking of Nepal relies on traditional fuels (firewood, dry dung and agriculture residue) while LPG and kerosene are the mostly used urban cooking fuels. In rural areas, 51% of the population depends on firewood for cooking, 2.9% use dried dung while only 1.2% use bio-gas and less than 1% use kerosene or other sources [124]. The marginalized and the most disadvantaged are still the largest sufferers in terms of inclusiveness in energy access and use. A HH being connected to the national electricity grid is still considered a status symbol in Nepal, particularly in the remote areas (example: electric cooktop in Fig. 1). Therefore, reliance on traditional fuels is extremely high (examples shown in Fig. 1). Moreover, there is ethnicity/caste-based differentiation in cooking energy [76,127]. Firewood is directly collected from

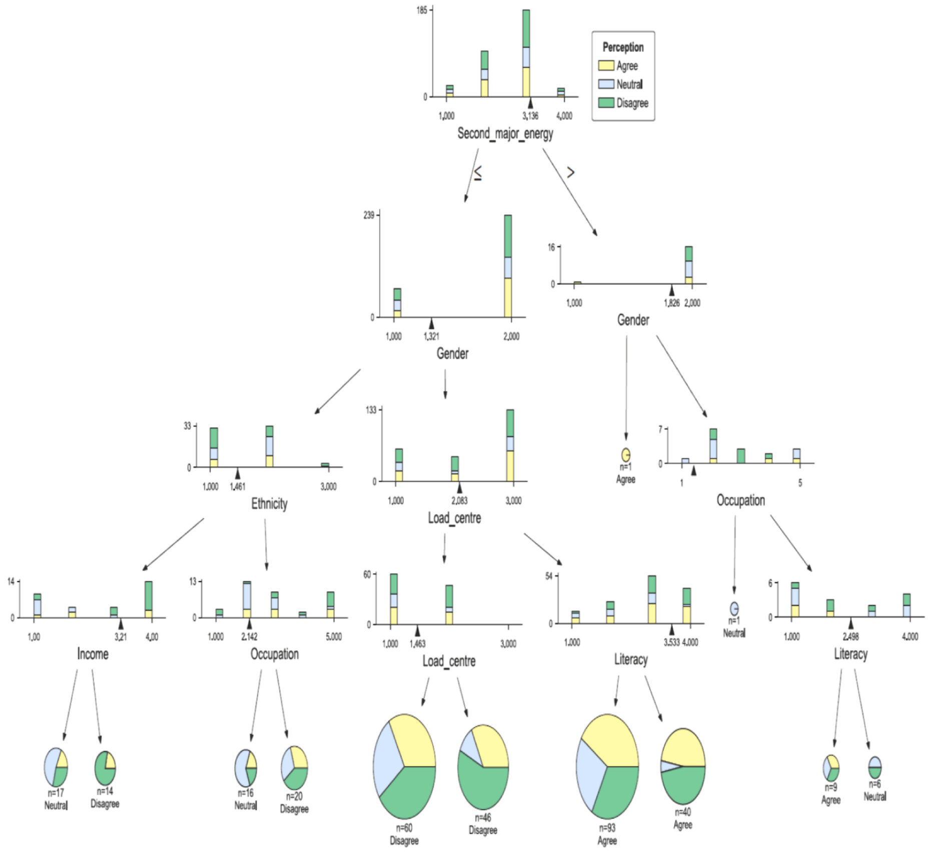

Fig. 5. Process of assigning features importance to the explanatory variables with respect to the response variable using tree-based visualization. A sample tree is presented here for illustration.

privately sources or nearby (community managed or national) forests at cheap rates [128]. Dried dung (called 'guitha' in local dialect) is prepared mixing cows/buffalo dung with husk, hay and firewood. They are sundried and commonly used as fuel for cooking (example response in Annex D1). 'Guitha' is prepared in a circular shape in the hills while they are mostly wrapped around firewood in the Terai plains of Nepal (Fig. 1). Generally, making 'guitha' is considered a household chore and women are responsible for it [129]. Interestingly, our survey team observed a recent trend of switching to LPG[1] from traditional (wood and 'guitha') stoves in the rural areas in all the three physiographic regions (example picture of mule carrying LPG cylinder on its back in a remote village in Gorkha in Fig. 1).

Fuelwood and 'guitha' are managed by the people irrespective of whether they get any external support because it is for one of the basic needs of life — food [38]. That could be the main reason why the government has not been eager to initiate programs to replace traditional fuels with modern renewables. Furthermore, there is evidence of developing countries having to spend one-fifth of their income on wood for cooking, devoting one-quarter of domestic labour collecting fuelwood and ultimately suffering from life-ending pollution from inefficient combustion [130].

Off-grid small scale renewable energy technologies such as micro-hydro, solar PV, biogas and hybrid systems are relatively cheaper options for the rural areas (Fig. 1) because of their low capital cost and large government subsidies [33,107]. AEPC [131] reports that the total national installed capacity of rooftop solar PV is 10 MW, that of micro and mini-hydropower is 37.7 MW and local hybrid grids is 3 MW. Formulation of the Renewable Energy Subsidy Policy 2006, 2009, 2013, 2016 and 2022, establishment of AEPC in 1996, provisioning of Renewable Energy Fund (REF) in 2002 and the Central Renewable Energy Fund (CREF) in 2007 can be considered as milestones in this regard [132]. Similarly, considerable increase in the number of biogas plants and international support, for example through SNV from 1992, GTZ between 1997 and 2011 [133,134], are notable achievements. In many cases, even the subsidized monthly electricity fare becomes too high for a large majority of the rural community to afford [135]. Moreover, small off-grid energy systems are not sustainable in the long run as modern electronic appliances require more energy than that provided by small panels and LEDs as people move up the energy ladder [28]. Additionally, one-time subsidy particularly for rural communities have been proven ineffective in many instances (example response in Annex D1). A similar resistance was found in cooking in Chile which warranted efficient management of impacts due to multiple social factors [136]. Most of our rural respondents were found unaware about how they can switch to better energy alternatives through government subsidies; and how they are economically and environmentally beneficial in the long run. This leads to reluctance in transitioning to modern fuels and technologies.

Complementary technologies such as wind-solar PV-hydropower have been tested in Latin America with promising results [137]. With the recent construction of large hydropower projects, grid extension to

[1] It is noted here that 1 kg of LPG has a useful energy value of 20.7 MJ which is equivalent to 21.2 kg of raw wood burnt in conventional stoves [129].

rural hilly and mountainous areas has gained momentum after the mid-1990s [33]. However, not all such projects have been welcomed by the people (example response in Annex D4). Moreover, micro-hydro based mini-grid technologies have been recommended for developing countries such as Nepal [40,138–140]. Technology transfer and donations without proper ecosystem development have also proven inefficient [33]. Hence, the choice of off-grid technologies needs to be rationally made based on their fit to the local context.

6.4. HH energy use in urban areas

Kathmandu Valley is the largest load centre followed by other smaller cities. Despite boasting a 93% electrification rate of Nepal in 2022 by GoN [100], reliability and usability of the supplied electricity are poor because of which the per capita electricity consumption is low (229 kWh/year) [141]. Nepal has struggled to tap into its significant renewable energy potential [34,142,143]. As a result, loadshedding (a scheduled power outage) was implemented in 1992, lifted in 2000, reintroduced in 2006, and finally ended in 2018 due to improved management and power imports from India [100]. As Movik and Allouche [144] mention, Nepal has had to go through a 'chaotic fragmentation of the energy landscape'. Moreover, political instability, social acceptance issues, and lack of energy transition management capabilities have contributed to sluggish power sector development in South Asia [145], including Nepal.

Studies have found that even in urban areas where people have the financial capacity, they are hesitant to climb up the 'energy ladder' [59,70] due to a lack of trust and reliability (example responses in Annex D2 and Annex D3). Fuel-stacking is prevalent, where people rely on multiple fuel options due to uncertainty about existing supplies [59]. While people express a willingness to pay more for reliable electricity supply at the HH level [29], past incidents of the 1988 and 2016 economic blockades on Nepal by India and the 2015 Great Earthquake have undermined public trust in the state's fuel supply. As a result, urban HHs continue to use various fuel options, including grid electricity, LPG, kerosene, rooftop solar PV, and firewood, instead of transitioning fully to renewable energy (example responses in Annex D). Semi-urban areas demonstrate energy patterns which are in between the rural and urban contexts.

With the enactment of Hydropower Policy 1992, 2001 and Water Resources Act 1992, 2002, the country has made efforts of developing micro-, small- and large-hydropower projects, targeting the urban and rural areas alike. As a result, the cumulative hydropower installed capacity of the nation stands at 2205 MW in 2022 [100]. However, there is a lack of concrete measures to replace traditional fuel consumption at the household level. The ambitious targets set in policies like the Water Resources Strategy (generating 22,000 MW hydropower by 2027), the National Water Plan (generating 4,000 MW hydropower by 2027 with increased per capita electricity consumption), and the Second Nationally Determined Contribution 2020 (ensuring achieving 25% electric stoves by 2025) is not likely to be met under current conditions.

Increasing electricity tariffs has been recommended as one of the options for increasing the efficiency of Nepal's electricity sector [146]. However, this does not seem feasible because a large share of the current Nepalese population (even in the urban areas) is already unable to afford electricity at the existing price (example responses in Annex D1, Annex D2 and Annex D3). Similar findings have been reported in Chile in which electrification of firewood for space heating can lead to energy poverty conditions for the people in the lowest socio-economic category [147].

Furthermore, studies have shown that research on the development and use of multiple types of energy sources and national level planning are slowly gaining attention in Nepal [72,127,148,149]. Chen [150] concludes that national efforts of controlling energy consumption by 'regulation priority' and 'technology-driven and industrial structure upgrading' have played a key role in China's decarbonization. In the context of Nepal, strengthening local cooperatives and financial institutions and motivating them to invest in and promote energy-efficient devices is important [33,151]. Although diversification of the energy generation mix has been the current focus of Nepal's energy policies, it has not been seen to be effective [152]. Furthermore, Nepal lacks the domestic capacity to adapt to changing energy conditions, particularly in the context of climate change [153]. Our results indicate that a bottom-up trajectory is required for policy formulations with active involvement of the stakeholders [32,154] because policies are usually guided by public demands (example responses in Annex D4, Annex D5 and Annex D6). Incorporating these grass-root level issues during policy formulation and implementation paves way for sustainable development.

7. Conclusion

Social and behavioural sciences in energy research have been outcasted by the 'hard' disciplines such as economics, statistics, physics, mathematics and engineering. Hence, catering to the social aspects of energy research in a developing country is a key contribution of this study. In this multidisciplinary research, we explained the social behaviour of the general public with regards to household energy taking the case of a South Asian country – Nepal using machine learning models. We adopted a mixed-method approach consisting of six stages: household survey, data pre-processing, application of seven ML models, evaluation of the models based on six performance metrics, selection of the best model and explaining people's perception. We carried out cross-sectional survey gathering data from 323 households to extract 14 independent (predictor) variables and one response variable with three labels.

Our results showed that, compared to conventional statistical models, data driven ML models are better in classifying non-linear social responses. Furthermore, among the ML models, tree-based models were found to be more robust and have better interpretability of the process to arrive at the feature importance. In our particular dataset, the *Extra Trees Classifier (ETC)* was the best fitting model which demonstrated a *balanced accuracy* of 0.79, 0.95 and 0.68 respectively for the *Agree, Neutral* and *Disagree* categories of the response variable.

We found that 'Development status' has a large role in people's perceptions. It was seen that people from rural and semi-urban areas tend to resist changing their current energy sources and consumption pattern due to economic constraints and lack of awareness. Fuelwood and 'guitha' are managed by the rural people irrespective of whether they get any external support because it is for one of the basic needs of life — food. However, a recent trend of switching to LPG from traditional fuels was observed in the rural areas in all the three physiographic regions which is extremely counter-productive. Off-grid small scale renewable energy technologies such as micro-hydro, solar PV, biogas and hybrid systems are relatively cheaper options for the rural areas because of their low capital cost and large government subsidies. Moreover, such small off-grid energy systems are not sustainable in the long run as modern electronic appliances require more energy than that provided by these technologies as people move up the energy ladder. The marginalized and the most disadvantaged are still the largest sufferers in terms of inclusiveness in energy access and use. Urban residents with access to electricity grid and LPG were found against switching to better alternatives; rather fuel-stacking is prevalent due to a lack of trust and reliability in the government. Furthermore, there is a lack of concrete measures from the government to replace traditional fuel consumption at the household level despite some progress at the policy level. As a result, the ambitious targets set out in the policies are not likely to be met under current conditions.

Hence, lack of awareness, financial constraints and trust in modern and efficient energy technologies are evident from the grass-root level responses compiled in this research. Comprehending people's voices from bottom-up is necessary for effective policy making, planning and implementation, particularly in the developing world. Moreover, it is important to consider country-specific factors and involve stakeholders in the planning and implementation processes for an altered energy landscape of Nepal. Small off-grid technologies could be a temporary rural measure, but Nepal should aggressively promote domestic hydropower and other renewables to cater to the household energy demands of both urban and rural areas.

There were limitations in our study, particularly related to the sample size, type of survey, and number of ML models used. Additionally, understanding people's perception can be extended to their preference of transitioning to better alternative energies at the HH level of Nepal. Moreover, a longitudinal survey at a regular interval could be another arena for extension of this research to analyse the temporal pattern of change in people's perception. Similarly, the choice of an appropriate ML model is highly dependent on the type of data it can process. Our primary criterion for selecting the seven models is their ability to handle categorical and multi-label data. There might be other complex ML models that fit this criterion. However, the models evaluated in this study were chosen because of their simplicity in execution and interpretability. Incorporating other models in the evaluation framework could be explored further.

CRediT authorship contribution statement

Utsav Bhattarai: Conceptualization, Methodology, Data curation, Software, Formal analysis, Writing – original draft. **Tek Maraseni:** Conceptualization, Supervision, Writing – review & editing. **Laxmi Prasad Devkota:** Supervision, Writing – review & editing. **Armando Apan:** Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Annex A

Table A1

Table A1
Survey districts selection criteria.

S. N	Survey districts	Sample size	Physio-graphy	Dev. Status	Electri-fication status	Alt. electricity	Remarks
1	Kathmandu/ Bhaktapur / Lalitpur	60	Mid hills	Urban/ semi-urban	Electrified	HH solar	Core city/ semi-urban areas
2	Makwanpur/ Chitwan / Nawalpur	30	Mid hills / Terai	Semi-urban	Electrified/ non-electrified	HH/ local grid solar/ micro hydro/ diesel	Kulekhani cascade, Lower Bagmati hydropower and diesel plant areas
3	Gorkha/ Lamjung/ Tanahu/ Kaski/ Baglung	45	High hills/ Mid hills	Semi-urban/ rural	Electrified/ non-electrified	HH/ local grid solar/ micro hydro	Budhigandaki, Marsyangdi and Tanahu hydropower project areas
4	Rautahat/ Bara / Dhanusha / Siraha/ Mahottari	45	Terai	Semi-urban/ rural	Electrified/ non-electrified	HH/ local grid solar/ micro hydro	Bagmati multipurpose project & Chandranighapur Solar project areas
5	Dolakha/ Ramechhap/ Kabhrepalanchok/ Sindhupalchok	45	Mid hills/ High hills	Urban/ semi-urban/ rural	Electrified/ non-electrified	HH/ local grid solar /micro hydro	Upper Tamakoshi, Khimti hydropower & Sunkoshi cascade project areas
6	Sankhuwasabha/ Illam/ Jhapa	30	High hills/ Mid hills/ Terai	Semi-urban/ rural	Electrified/ non-electrified	HH/ local grid solar/ micro hydro	Arun III/ Kimathanka and many other hydropower project areas
7	Morang/ Sunsari	30	Terai	Urban/ semi-urban	Electrified	HH/ local grid solar/ diesel	Duhabi industrial corridor/ Biratnagar/ Dharan
8	Dolpa/ Rukum West/ Dailekh / Surkhet / Achham/ Bajhang / Baitadi / Darchula	35	High hills	Rural	Electrified/ non-electrified	HH/ local grid solar/ micro hydro	
9	Banke/ Bardiya/ Kailali/ Kanchanpur	30	Terai	Urban/ semi-urban/ rural	Electrified/ non-electrified	HH/ local grid solar/ micro hydro	Biggest solar project, Bhalubang, Naumure & other project areas
	Total	**350**					

Annex B

Table B1

Table B1
Adopted explanatory and response variables with their classes and justification for the classification.

S. N	Variables	Given name	Classes	Code	Justification
Explanatory variables					
1	Physiographic region	*Physiography*	High hills Mid hills Terai (plains)	1 2 3	Nepal can be broadly categorized into four physiographic regions, among which we excluded the High Mountains. There are distinct prominent energy generation and consumption practices in the respective physiographic regions. Hence, this categorization has been adopted to capture such variation.
2	Development status	*Development_status*	Rural Semi-urban Urban	1 2 3	The energy sources available to the rural, semi-urban and urban areas differ very much. As a result, the consumption practices are also remarkably different. Therefore, this heterogeneity has been captured in our survey through the adopted categorization.
3	Load centre	*Load_centre*	Kathmandu Other towns Others	1 2 3	This variable pertains mainly to the availability and consumption of grid electricity. Kathmandu is the capital city with a very high population density and large electricity coverage. Other towns have relatively lesser residents and smaller electricity consumption. While the remaining areas are not important from the electricity viewpoint
4	Gender	*Gender*	Female Male	1 2	These are obvious natural categories.
5	Age	*Age*	20-35 years 35-50 years > 50 years	1 2 3	This is not the age of the household head. Rather it is the age of the people who are more aware of the energy related aspects within the household. The first group (Code 1) represents the young people including students and early career professionals. Similarly, the second category is representative of mid-aged people who have a relatively stable career and are mature enough to make household decisions. The third category refers to the retired or people who work less compared to the other two classes.
6	Literacy status	*Literacy*	Illiterate Primary school/ informal education Secondary / high school University	1 2 3 4	These conventional categories have been chosen to identify people's level of awareness based on their education level.
7	Occupation	*Occupation*	Unemployed/ retired Farming/ livestock rearing Self-employed Academic/ government service Private organization	1 2 3 4 5	People's level of thinking, living standard and household practices differ with their economic condition which is directly related to occupation. A stable occupation allows people to make planned and sustainable household decisions whereas unemployment or unstable professions most likely lead to temporary decisions. The response of such varying categories of people have been examined through this classification.
8	Annual household income (USD)	*Income*	< 692 692 – 1,154 1,154 – 1,960 > 1,960	1 2 3 4	The thresholds adopted here for the annual income correspond to the World Bank's three values of the international poverty line, that of lower middle-income countries and upper middle-income countries. Annual value of NRs 90,000 is equivalent to US$ 692 per year and US$ 1.90 per day; NRs 150,000 is equivalent to US$1,154 per year and US$3.20 per day; and NRs 255,000 is equivalent to US$ 1,960 per year and US$5.50 per day using the conversion rate of US$ 1 ≈ NRs 130 during the time this research was designed.
9	Ethnicity	*Ethnicity*	Brahmin/ Chhetri Indigenous Marginalized/ Underprivileged	1 2 3	These three classes are representative of the caste/ethnicity system in Nepal which follows a privileged, indigenous and underprivileged hierarchy. Access to amenities, services and information varies significantly across these classes.
10	Household family size	*Family_size*	Nuclear (≤4 members) Extended (4-6 members) Joint (> 6 members)	1 2 3	While extended family type (including grandparents) is commonly found in semi-urban and rural areas, nuclear family has started to become the most common type in the urban areas. There are still joint families including grandparents, uncles, aunts, nephews and nieces living in the same house, mostly in the rural and remote areas.
11	Major source of household energy	*Major_energy_source*	Firewood/ dung/ agriculture residue Petroleum (kerosene) Liquified petroleum gas (LPG) Grid-electricity Renewables	1 2 3 4 5	These categories are the most common type of fuels used in Nepalese households. Their availability, prices, environmental and health impacts and people's preferences largely vary across the households using different types of energy sources.
12	Second major source of household energy	*Second_major_energy*	Petroleum (kerosene) Liquified petroleum gas (LPG) Grid-electricity Renewables	1 2 3 4	These categories are the most common type of fuels used in Nepalese households. Their availability, prices, environmental and health impacts and people's preferences largely vary across the households using different types of energy sources.
13	Vehicle ownership	*Vehicle*	No Yes	1 2	This variable has been included in our analysis to see whether having a vehicle either running on petroleum or electricity has an impact on the response of the people.

(*continued on next page*)

Table B1 (*continued*)

S. N	Variables	Given name	Classes	Code	Justification
14	Self assessment of current energy usage	*Self_assessment*	Agree Neutral Disagree	1 2 3	This acts as a triangulating variable in which people judge their activities related to energy at the household level themselves in order to provide a logical connection to their response.
Response variable					
1	People's perception of security of current household energy condition	*Perception*	Agree Neutral Disagree	1 2 3	The security of current energy condition is inclusive of available energy sources as well as the consumption pattern of the household.

Annex C: Details of the adopted ML models

1. **K-Nearest Neighbors (KNN)** works on the principle of similarity or proximity. It assumes that similar instances or data points tend to exist in close proximity in the feature space. The algorithm makes predictions by comparing the new instance to be classified with its k nearest neighbors and assigns it the majority class label among those neighbors. The value of k is a hyperparameter that needs to be defined before applying the KNN algorithm. It influences the performance and decision boundary of the model. A larger k value considers more neighbors, potentially resulting in smoother decision boundaries but may also introduce more bias. A smaller k value may lead to more localized decision boundaries but may be more sensitive to noise [112].
2. **Multi-Layer Perceptron (MLP)** consists of interconnected layers of nodes called neurons. The mathematical representation involves defining the input and output layers, assigning weights to the connections between neurons, and applying activation functions for non-linearity. Forward propagation is performed to calculate the output of each neuron, followed by an activation function at the output layer. A suitable loss function is chosen to measure the difference between predicted and true labels. Backpropagation is used to adjust the weights of the network using gradient descent optimization. This process is repeated for a number of epochs until convergence. Finally, the trained model is used to make predictions by applying forward propagation and determining the predicted labels based on output probabilities. The specific details such as the number of layers, neurons, activation functions, and optimization algorithm depend on the specific problem and dataset [109].
3. **Extra Trees Classifier (ETC)** is an ensemble learning method where multiple decision trees are trained on different subsets of the training data and their predictions are combined to make final predictions. ETC differs from Random Forest in that it selects random subsets of features at each split, leading to further diversity and potentially increased generalization performance. The algorithm assigns importance scores to features based on their ability to improve prediction accuracy. In multi-label classification, ETC can be applied by using a binary relevance approach, treating each label as a separate binary classification task. The final predictions for the multi-label classification problem can be obtained by combining the predictions from each binary classifier associated with the individual labels [123].
4. **Random Forest (RF)** is a popular ensemble learning algorithm that combines multiple decision trees to solve classification tasks, including multi-label classification. In RF, each decision tree is trained on a randomly sampled subset of the training data, and the final prediction is determined by aggregating the predictions of all individual trees. For multi-label classification, RF can be applied using a binary relevance approach, treating each label as a separate binary classification task. The algorithm constructs decision trees by recursively partitioning the feature space based on splitting criteria (e.g., Gini impurity or entropy). The feature importance in RF can be quantified using metrics such as mean decrease impurity or mean decrease accuracy. These metrics assess the contribution of each feature in reducing the impurity or improving the accuracy of the predictions. The final predictions for the multi-label classification problem are obtained by combining the predictions of the individual binary classifiers associated with each label [111].
5. **Ridge Classifier (RC)** is a linear classifier that can be used for multilabel classification tasks. It is based on Ridge Regression, which is a linear regression model regularized with L2-norm penalty. RC extends this concept to the classification setting by applying a thresholding function to the continuous output of Ridge Regression. The mathematical representation of RC involves finding the coefficients that minimize the sum of squared errors subject to the L2-norm penalty. The cost function or loss function to be optimized for RC can be expressed as:

$$\text{arg}min_{\beta_0,\beta}\left\{\frac{1}{N}\sum_{i=1}^{N}\left(y_i-\beta_0-\sum_{j=1}^{p}x_{ij}\beta_j\right)^2\right\}+\gamma\sum_{j=1}^{p}\beta_j^2$$

where, N is the sample size, xi is a p-dimensional vector of features and each yi is the associated response variable, βj is the regression weights and β0 is the intercept (bias) term, γ is the regularization coefficient.

The coefficients of the cost function are determined by the following closed form solution

$$\beta = \left(X^TX+\gamma I\right)^{-1}X^TY$$

Where, X and Y are the features and associated response respectively.

The output of RC is obtained by applying a thresholding function, such as the sign function, to the linear combination of the features and co-efficients. The regularization term helps control the complexity of the model and prevent overfitting. For multilabel classification, RC can be applied independently to each label, treating it as a separate binary classification task. The coefficients obtained for each label represent the importance of the corresponding features in predicting that particular label [110].

6. **Multinomial Regression – Logit (MR-L)**: The logit model is a type of regression analysis used to model the probability of a binary outcome. Like logistic regression, the logit model assumes that the relationship between the dependent variable and the independent variables is linear on the logit scale. However, the logit model is often used in econometrics, and it assumes that the error term follows a logistic distribution.

7. **Multinomial Regression – Probit (MR-P)**: The probit model is also used to model the probability of a binary outcome, but it assumes that the error term follows a normal distribution instead of a logistic distribution. The relationship between the dependent variable and the independent variables is also linear, but it is transformed using the cumulative distribution function of a normal distribution instead of the logit function. The probit model is commonly used in finance and economics.

Annex D: Some interesting responses from the survey participants

D1: A housewife from a rural municipality (Laxminiya Gaunpalika, Ward no. 6, Dhanusha district) explained during our field survey that 'guitha' is the only convenient option available to her family for cooking and sometimes heating too. They rear cows and buffalos and so the dung gets utilized as fuel free of cost. Interestingly, she expressed her dissatisfaction over people complaining of health issues due to burning 'guitha' these days and argued that they have been cooking in 'guita' since ages without such complaints. Reluctance to switch to other alternatives of cooking was clearly visible in her response. She further mentioned that efforts to introduce alternatives like LPG stoves have been met with resistance in the past due to affordability issues. The whole village reverted to 'guitha' from LPG because it was beyond what they could afford (~USD19 per 15 kg cylinder) which would hardly last a month. Interestingly, she mentioned that food cooked in the conventional way is much tastier than LPG stoves.

D2: A graduate in environmental science from Lalitpur Metropolitan (Ward no. 18), Lalitpur District admitted she did not know that domestic sector was the largest energy-consumer of Nepal. She further mentioned that the general people (including herself) would not be able to completely rely on renewables for HH energy because these new technologies are expensive.

D3: A university-educated self-employed resident of Lalitpur Metropolitan (Ward no. 16) informed us that his family is used to cooking in LPG gas stoves for more than a decade now. He feels that LPG is convenient to use, does not cause odour or smoke, and the gas cylinders are readily available for refilling. Moreover, his family is reluctant to depend completely on (electric) inductions cooktops because of the 'loadshedding' (a term used to denote scheduled power cuts in Nepal) problem. He even raised concerns over why the country can generate sufficient electricity in the monsoon but not in the dry season.

D4: A rural farmer from Besisahar Ward no. 2, Lamjung district expressed his dissatisfaction over the installation of electricity transmission towers of low height in his village which obstructed other activities such as construction of houses and roads. The villagers felt that the transmission lines and towers were built in an unplanned manner. More importantly, he pointed out that the (local) government should have involved them (the stakeholders) while designing these projects. But the villagers came to know about the project only after the towers were constructed. He further mentioned that no authority is ready to register or listen to their complaints now. These issues have eroded trust in government activities among the general population.

D5: A respondent from Nagarjun Municipality Ward no.2, Kathmandu district felt that he learned many new things about the energy sector of Nepal by interacting with our survey team. However, he expressed his dissatisfaction over the government in failing to inform the local people who are the actual energy consumers and to build trust in the new energy technologies.

D6: Another resident of Banepa Municipality Ward no.1, Kavrepalanchowk district expressed his lack of awareness of renewable energy technologies particularly regarding those that are applicable to the general people at the HHs level. However, based on how much he knew, he was positive about switching to clean energy for the sake of a better and sustainable future.

D7: A schoolteacher from Khairahan Gaupalika Ward no.8, Chitwan district felt that awareness about the benefits of renewable energy technologies for Nepal should be included in the school curriculum. Moreover, he stressed that enough subsidies need to be provided to actually implement renewable energy technologies in the community as individuals will not be able to afford such a transformation on their own.

References

[1] Martinez N, Komendantova N. The effectiveness of the social impact assessment (SIA) in energy transition management: stakeholders' insights from renewable energy projects in Mexico. Energy Policy 2020;145. https://doi.org/10.1016/j.enpol.2020.111744.
[2] Windemer R. Acceptance should not be assumed. How the dynamics of social acceptance changes over time, impacting onshore wind repowering. Energy Policy 2023;173. https://doi.org/10.1016/j.enpol.2022.113363.
[3] Azuatalam D, Lee WL, de Nijs F, Liebman A. Reinforcement learning for whole-building HVAC control and demand response. Energy AI 2020;2. https://doi.org/10.1016/j.egyai.2020.100020.
[4] Millot A, Krook-Riekkola A, Maïzi N. Guiding the future energy transition to net-zero emissions: lessons from exploring the differences between France and Sweden. Energy Policy 2020;139. https://doi.org/10.1016/j.enpol.2020.111358.
[5] Mohsin M, Kamran HW, Atif Nawaz M, Sajjad Hussain M, Dahri AS. Assessing the impact of transition from nonrenewable to renewable energy consumption on economic growth-environmental nexus from developing Asian economies. J Environ Manage 2021;284. https://doi.org/10.1016/j.jenvman.2021.111999.
[6] Shah M, Koirala K, Upreti S, Sanjel N. Techno-economic analysis of energy systems in Thakle Namuna Basti - a case study. IOP Confer Series Mater Sci Eng 2023;1279(1):012007. https://doi.org/10.1088/1757-899x/1279/1/012007.
[7] Adedoyin FF, Bekun FV, Alola AA. Growth impact of transition from non-renewable to renewable energy in the EU: The role of research and development expenditure. Renew Energy 2020;159:1139–45. https://doi.org/10.1016/j.renene.2020.06.015.
[8] Saidi K, Hammami S. The impact of CO2 emissions and economic growth on energy consumption in 58 countries. Energy Rep 2015;1:62–70. https://doi.org/10.1016/j.egyr.2015.01.003.
[9] Conradie P, Van Hove S, Pelka S, Karaliopoulos M, Anagnostopoulos F, Brugger H, Ponnet K. Why do people turn down the heat? Applying behavioural theories to assess reductions in space heating and energy consumption in Europe. Energy Res Soc Sci 2023;100:103059. https://doi.org/10.1016/j.erss.2023.103059.
[10] Braito M, Flint C, Muhar A, Penker M, Vogel S. Individual and collective socio-psychological patterns of photovoltaic investment under diverging policy regimes of Austria and Italy. Energy Policy 2017;109:141–53. https://doi.org/10.1016/j.enpol.2017.06.063.
[11] Jacksohn A, Grösche P, Rehdanz K, Schröder C. Drivers of renewable technology adoption in the household sector. Energy Econ 2019;81:216–26. https://doi.org/10.1016/j.eneco.2019.04.001.
[12] Strazzera E, Statzu V. Fostering photovoltaic technologies in Mediterranean cities: consumers' demand and social acceptance. Renew Energy 2017;102:361–71. https://doi.org/10.1016/j.renene.2016.10.056.
[13] Tekler ZD, Low R, Blessing L. User perceptions on the adoption of smart energy management systems in the workplace: design and policy implications. Energy Res Soc Sci 2022;88. https://doi.org/10.1016/j.erss.2022.102505.
[14] Tsvetanov T. When the carrot goes bad: The effect of solar rebate uncertainty. Energy Econ 2019;81:886–98. https://doi.org/10.1016/j.eneco.2019.05.028.
[15] Matavel CE, Kächele H, Hafner JM, Rybak C, Uckert G, Hoffmann H, Kipkulei HK, Massuque J, Steinke J, Sieber S. How to increase cookstove adoption? Exploring cost-effective dissemination techniques in Central Mozambique. Energy Res Soc Sci 2023;100. https://doi.org/10.1016/j.erss.2023.103082.
[16] Ko I. Rural opposition to landscape change from solar energy: explaining the diffusion of setback restrictions on solar farms across South Korean counties. Energy Res Soc Sci 2023;99. https://doi.org/10.1016/j.erss.2023.103073. Elsevier Ltd.
[17] Hurlbert M, Osazuwa-Peters M, McNutt K, Rayner J. Transitioning from coal: Toward a renewables-based socio-technical regime in Saskatchewan. Environ Innov Soci Trans 2020;36:321–30. https://doi.org/10.1016/j.eist.2019.11.005.
[18] Liao C, Erbaugh JT, Kelly AC, Agrawal A. Clean energy transitions and human well-being outcomes in lower and middle income countries: a systematic review. Renew Sustain Energy Rev 2021;145. https://doi.org/10.1016/j.rser.2021.111063. Elsevier Ltd.
[19] Bayulgen O. Localizing the energy transition: Town-level political and socio-economic drivers of clean energy in the United States. Energy Res Soc Sci 2020;62. https://doi.org/10.1016/j.erss.2019.101376.

[20] Munro FR. Renewable energy and transition-periphery dynamics in Scotland. Environ Innov Soc Transit 2019;31:273–81. https://doi.org/10.1016/j.eist.2018.09.001.

[21] Roberts J. Power to the people? Implications of the Clean Energy Package for the role of community ownership in Europe's energy transition. Rev Eur Compar Int Environ Law 2020;29(2):232–44. https://doi.org/10.1111/reel.12346.

[22] Salari M, Javid RJ, Noghanibehambari H. The nexus between CO2 emissions, energy consumption, and economic growth in the U.S. Econ Anal Policy 2021;69:182–94. https://doi.org/10.1016/j.eap.2020.12.007.

[23] Wiehe J, Thiele J, Walter A, Hashemifarzad A, Zum Hingst J, von Haaren C. Nothing to regret: reconciling renewable energies with human wellbeing and nature in the German Energy Transition. Int J Energy Res 2021;45(1):745–58. https://doi.org/10.1002/er.5870.

[24] Gümüş YK. International Journal of Energy Economics and Policy How Secure is the European Union Energy Policy after the Ukraine Crisis? International J Energy Econ Policy 2015;5(4):1016–21. www.econjournals.com.

[25] Shahzadi I, Yaseen MR, Iqbal Khan MT, Amjad Makhdum MS, Ali Q. The nexus between research and development, renewable energy and environmental quality: Evidence from developed and developing countries. Renew Energy 2021. https://doi.org/10.1016/j.renene.2021.10.050.

[26] Ren J, Sovacool BK. Quantifying, measuring, and strategizing energy security: Determining the most meaningful dimensions and metrics. Energy 2014;76:838–49. https://doi.org/10.1016/j.energy.2014.08.083.

[27] Azhgaliyeva, D., & Mishra, R. (2022). Feed-in tariffs for financing renewable energy in Southeast Asia. In Wiley Interdisciplinary Reviews: *Energy and Environment* (Vol. 11, Issue 3). John Wiley and Sons Ltd. 10.1002/wene.425.

[28] Dominguez C, Orehounig K, Carmeliet J. Understanding the path towards a clean energy transition and post-electrification patterns of rural households. Energy Sustain Dev 2021;61:46–64. https://doi.org/10.1016/j.esd.2021.01.002.

[29] Das I, Rogers B, Nepal M, Jeuland M. Fuel stacking implications for willingness to pay for cooking fuels in peri-urban Kathmandu Valley, Nepal. Energy Sustain Dev 2022;70:482–96. https://doi.org/10.1016/j.esd.2022.08.017.

[30] Sadiqa A, Gulagi A, Breyer C. Energy transition roadmap towards 100% renewable energy and role of storage technologies for Pakistan by 2050. Energy 2018;147:518–33. https://doi.org/10.1016/j.energy.2018.01.027.

[31] Do TN, Burke PJ, Baldwin KGH, Nguyen CT. Underlying drivers and barriers for solar photovoltaics diffusion: the case of Vietnam. Energy Policy 2020;144. https://doi.org/10.1016/j.enpol.2020.111561.

[32] Pandey P, Sharma A. Knowledge politics, vulnerability and recognition-based justice: Public participation in renewable energy transitions in India. Energy Res Soc Sci 2021;71. https://doi.org/10.1016/j.erss.2020.101824.

[33] Bhattarai U, Maraseni T, Apan A, Devkota LP. Rationalizing donations and subsidies: Energy ecosystem development for sustainable renewable energy transition in Nepal. Energy Policy 2023;177:113570. https://doi.org/10.1016/j.enpol.2023.113570.

[34] Ghimire LP, Kim Y. An analysis on barriers to renewable energy development in the context of Nepal using AHP. Renew Energy 2018;129:446–56. https://doi.org/10.1016/j.renene.2018.06.011.

[35] Hanger S, Komendantova N, Schinke B, Zejli D, Ihlal A, Patt A. Community acceptance of large-scale solar energy installations in developing countries: evidence from Morocco. Energy Res Soc Sci 2016;14:80–9. https://doi.org/10.1016/j.erss.2016.01.010.

[36] Vanegas Cantarero MM. Of renewable energy, energy democracy, and sustainable development: a roadmap to accelerate the energy transition in developing countries. Energy Res Soc Sci 2020;70. https://doi.org/10.1016/j.erss.2020.101716. Elsevier Ltd.

[37] Mukelabai MD, Wijayantha KGU, Blanchard RE. Using machine learning to expound energy poverty in the global south: understanding and predicting access to cooking with clean energy. Energy AI 2023;14:100290. https://doi.org/10.1016/j.egyai.2023.100290.

[38] Bhattarai U, Devkota R, Maraseni T, Devkota L, Marahatta S. Attaining multiple sustainable development goals through storage hydropower development amidst community vulnerabilities. Sustain Develop 2023. https://doi.org/10.1002/sd.2634.

[39] Kim ES, Chung JB, Seo Y. Korean traditional beliefs and renewable energy transitions: Pungsu, shamanism, and the local perception of wind turbines. Energy Res Soc Sci 2018;46:262–73. https://doi.org/10.1016/j.erss.2018.07.024.

[40] Sanjel N, Baral B. Modelling and analysis of decentralized energy systems with photovoltaic, micro-hydro, battery and diesel technology for remote areas of Nepal. Clean Energy 2021;5(4):690–703. https://doi.org/10.1093/ce/zkab042.

[41] Winkler B, Lewandowski I, Voss A, Lemke S. Transition towards renewable energy production? Potential in smallholder agricultural systems in West Bengal, India. *Sustainability* (Switzerland) 2018;10(3). https://doi.org/10.3390/su10030801.

[42] Hunt J, Riley B, O'Neill L, Maynard G. Transition to renewable energy and indigenous people in Northern Australia: enhancing or inhibiting capabilities? J Hum Develop Capab 2021;22(2):360–78. https://doi.org/10.1080/19452829.2021.1901670.

[43] Israel A, Jehling M. How modern are renewables? The misrecognition of traditional solar thermal energy in Peru's energy transition. Energy Policy 2019;133. https://doi.org/10.1016/j.enpol.2019.110905.

[44] Maennel A, Kim HG. Comparison of greenhouse gas reduction potential through renewable energy transition in South Korea and Germany. Energies 2018;11(1). https://doi.org/10.3390/en11010206.

[45] Sovacool BK. Energy studies need social science. Nature 2014;511:529–30.

[46] Sovacool BK, Axsen J, Sorrell S. Promoting novelty, rigor, and style in energy social science: Towards codes of practice for appropriate methods and research design. Energy Res Soc Sci 2018;45:12–42. https://doi.org/10.1016/j.erss.2018.07.007. Elsevier Ltd.

[47] Bhattarai U, Maraseni T, Apan A. Assay of renewable energy transition: a systematic literature review. Sci Total Environ 2022;833:155159. https://doi.org/10.1016/j.scitotenv.2022.155159.

[48] Fahad S, Wang J. Farmers' risk perception, vulnerability, and adaptation to climate change in rural Pakistan. Land Use Policy 2018;79:301–9. https://doi.org/10.1016/j.landusepol.2018.08.018.

[49] Ali A, Erenstein O. Assessing farmer use of climate change adaptation practices and impacts on food security and poverty in Pakistan. Clim Risk Manage 2017;16:183–94. https://doi.org/10.1016/j.crm.2016.12.001.

[50] Makuvaro V, Walker S, Masere TP, Dimes J. Smallholder farmer perceived effects of climate change on agricultural productivity and adaptation strategies. J Arid Environ 2018;152:75–82. https://doi.org/10.1016/j.jaridenv.2018.01.016.

[51] Acosta A, Nicolli F, Karfakis P. Coping with climate shocks: The complex role of livestock portfolios. World Dev 2021;146. https://doi.org/10.1016/j.worlddev.2021.105546.

[52] Raut NK, Tanaka R. Monitoring health services delivery: Evidence from civil conflict in Nepal. World Dev 2021;146. https://doi.org/10.1016/j.worlddev.2021.105543.

[53] Yoo C. Stress coping and mental health among adolescents: applying a multi-dimensional stress coping model. Child Youth Serv Rev 2019;99:43–53. https://doi.org/10.1016/j.childyouth.2019.01.030.

[54] Hussain A, Memon JA, Hanif S. Weather shocks, coping strategies and farmers' income: a case of rural areas of district Multan, Punjab. Weather Clim Extremes 2020;30. https://doi.org/10.1016/j.wace.2020.100288.

[55] Sertse SF, Khan NA, Shah AA, Liu Y, Naqvi SAA. Farm households' perceptions and adaptation strategies to climate change risks and their determinants: evidence from Raya Azebo district, Ethiopia. Int J Disaster Risk Reduct 2021;60. https://doi.org/10.1016/j.ijdrr.2021.102255.

[56] Devkota R, Bhattarai U, Devkota L, Maraseni TN. Assessing the past and adapting to future floods: a hydro-social analysis. Clim Change 2020;163(2):1065–82. https://doi.org/10.1007/s10584-020-02909-w.

[57] Gunaratne CD, Kremer PJ. The long-term impact of the 2004 tsunami on Sri Lankan survivors: Exploring the socio-cultural influences on resilience. Int J Disaster Risk Reduc 2021;64. https://doi.org/10.1016/j.ijdrr.2021.102519.

[58] Chaikumbung M. Institutions and consumer preferences for renewable energy: a meta-regression analysis. Renew Sustain Energy Rev 2021;146. https://doi.org/10.1016/j.rser.2021.111143.

[59] Koirala DP, Acharya B. Households' fuel choices in the context of a decade-long load-shedding problem in Nepal. Energy Policy 2022;162. https://doi.org/10.1016/j.enpol.2022.112795.

[60] Storm H, Baylis K, Heckelei T. Machine learning in agricultural and applied economics. Eur Rev Agric Econ 2020;47(3):849–92. https://doi.org/10.1093/erae/jbz033.

[61] Deisenroth MP, Faisal AA, Ong C, Soon. Mathematics for machine learning. 1st ed. Cambridge University Press; 2020 Vol. 1 https://mml-book.com.

[62] Antonakis J, Dietz J. Looking for validity or testing it? The perils of stepwise regression, extreme-scores analysis, heteroscedasticity, and measurement error. Person Indiv Differ 2011;50(3):409–15. https://doi.org/10.1016/j.paid.2010.09.014.

[63] Carapeto M, Holt W. Testing for heteroscedasticity in regression models. J Appl Statist 2003;30(1):13–20. https://doi.org/10.1080/0266476022000018475.

[64] Cattaneo MD, Jansson M, Newey WK. Inference in linear regression models with many covariates and heteroscedasticity. J Am Statist Assoc 2018;113(523):1350–61. https://doi.org/10.1080/01621459.2017.1328360.

[65] Klein AG, Gerhard-Lehn C, Bochner R, Diestel S. The Detection of Heteroscedasticity in Regression Models for Psychological Data. Psychol Test Assess Model 2015;4:542–68. https://www.researchgate.net/publication/311518028.

[66] Xu P, Ji X, Li M, Lu W. Small data machine learning in materials science. Npj Comput Mater 2023;9(1). https://doi.org/10.1038/s41524-023-01000-z. Issue*Nature Research*.

[67] Nepal R. Roles and potentials of renewable energy in less-developed economies: the case of Nepal. Renew Sustain Energy Rev 2012;16(Issue 4):2200–6. https://doi.org/10.1016/j.rser.2012.01.047.

[68] Schulz C, Saklani U. The future of hydropower development in Nepal: Views from the private sector. Renew Energy 2021;179:1578–88. https://doi.org/10.1016/j.renene.2021.07.138.

[69] Shrestha S, Dhakal S. An assessment of potential synergies and trade-offs between climate mitigation and adaptation policies of Nepal. J Environ Manage 2019;235:535–45. https://doi.org/10.1016/j.jenvman.2019.01.035.

[70] Joshi J, Bohara AK. Household preferences for cooking fuels and inter-fuel substitutions: unlocking the modern fuels in the Nepalese household. Energy Policy 2017;107:507–23. https://doi.org/10.1016/j.enpol.2017.05.031.

[71] Pokharel S. Promotional issues on alternative energy technologies in Nepal. Energy Policy 2003;31.

[72] Yadoo A, Cruickshank H. The role for low carbon electrification technologies in poverty reduction and climate change strategies: a focus on renewable energy mini-grids with case studies in Nepal, Peru and Kenya. Energy Policy 2012;42:591–602. https://doi.org/10.1016/j.enpol.2011.12.029.

[73] Gautam BR, Li F, Ru G. Assessment of urban roof top solar photovoltaic potential to solve power shortage problem in Nepal. Energy Build 2015;86:735–44. https://doi.org/10.1016/j.enbuild.2014.10.038.

[74] Mali B, Shrestha A, Chapagain A, Bishwokarma R, Kumar P, Gonzalez-Longatt F. Challenges in the penetration of electric vehicles in developing countries with a focus on Nepal. Renew Energy Focus 2022;40:1–12. https://doi.org/10.1016/j.ref.2021.11.003. Elsevier Ltd.
[75] Nepal R, Paija N. Energy security, electricity, population and economic growth: the case of a developing South Asian resource-rich economy. Energy Policy 2019; 132:771–81. https://doi.org/10.1016/j.enpol.2019.05.054.
[76] Rahut DB, Aryal JP, Chhay P, Sonobe T. Ethnicity/caste-based social differentiation and the consumption of clean cooking energy in Nepal: An exploration using panel data. Energy Econ 2022;112. https://doi.org/10.1016/j.eneco.2022.106080.
[77] Benos L, Tagarakis AC, Dolias G, Berruto R, Kateris D, Bochtis D. Machine learning in agriculture: a comprehensive updated review. Sensors 2021;21(Issue 11). https://doi.org/10.3390/s21113758. MDPI AG.
[78] Shaik T, Tao X, Higgins N, Li L, Gururajan R, Zhou X, Acharya UR. Remote patient monitoring using artificial intelligence: Current state, applications, and challenges. Wiley Interdisc Rev Data Mining Knowl Discov 2023;13(2). https://doi.org/10.1002/widm.1485. IssueJohn Wiley and Sons Inc.
[79] Mullainathan S, Spiess J. Machine learning: An applied econometric approach. J Econ Perspect 2017;31(2):87–106. https://doi.org/10.1257/jep.31.2.87.
[80] Arumugam K, Swathi Y, Sanchez DT, Mustafa M, Phoemchalard C, Phasinam K, Okoronkwo E. Towards applicability of machine learning techniques in agriculture and energy sector. Mater Today: Proc 2022;51:2260–3. https://doi.org/10.1016/j.matpr.2021.11.394.
[81] Jagtap ST, Phasinam K, Kassanuk T, Jha SS, Ghosh T, Thakar CM. Towards application of various machine learning techniques in agriculture. Mater Today: Proc 2021;51:793–7. https://doi.org/10.1016/j.matpr.2021.06.236.
[82] Shaik T, Tao X, Higgins N, Gururajan R, Li Y, Zhou X, Acharya UR. FedStack: personalized activity monitoring using stacked federated learning. Knowl Based Syst 2022. https://doi.org/10.1016/j.knosys.2022.109929.
[83] Shaik T, Tao X, Li Y, Dann C, McDonald J, Redmond P, Galligan L. A review of the trends and challenges in adopting natural language processing methods for education feedback analysis. IEEE Access 2022;10:56720–39. https://doi.org/10.1109/ACCESS.2022.3177752.
[84] Wang J, Mohammed AS, Macioszek E, Ali M, Ulrikh DV, Fang Q. A novel combination of PCA and Machine learning techniques to select the most important factors for predicting tunnel construction performance. Buildings 2022;12(7). https://doi.org/10.3390/buildings12070919.
[85] García-Martín E, Rodrigues CF, Riley G, Grahn H. Estimation of energy consumption in machine learning. J Parallel Distrib Comput 2019;134:75–88. https://doi.org/10.1016/j.jpdc.2019.07.007.
[86] Schreiber J, Sick B. Model selection, adaptation, and combination for transfer learning in wind and photovoltaic power forecasts. Energy AI 2023;14. https://doi.org/10.1016/j.egyai.2023.100249.
[87] Yao Z, Lum Y, Johnston A, Mejia-Mendoza LM, Zhou X, Wen Y, Aspuru-Guzik A, Sargent EH, Seh ZW. Machine learning for a sustainable energy future. Nat Rev Mater 2023;8(3):202–15. https://doi.org/10.1038/s41578-022-00490-5.
[88] Bhattarai R, Bhattarai U, Pandey VP, Bhattarai PK. An artificial neural network-hydrodynamic coupled modeling approach to assess the impacts of floods under changing climate in the East Rapti Watershed, Nepal. J Flood Risk Manage 2022. https://doi.org/10.1111/jfr3.12852.
[89] Liakos KG, Busato P, Moshou D, Pearson S, Bochtis D. Machine learning in agriculture: a review. *Sensors* (Switzerland) 2018;18(Issue 8). https://doi.org/10.3390/s18082674. MDPI AG.
[90] Meshram V, Patil K, Meshram V, Hanchate D, Ramkteke SD. Machine learning in agriculture domain: a state-of-art survey. Artific Intell Life Sci 2021;1:100010. https://doi.org/10.1016/j.ailsci.2021.100010.
[91] Gallego F, Martín C, Díaz M, Garrido D. Maintaining flexibility in smart grid consumption through deep learning and deep reinforcement learning. Energy AI 2023;13. https://doi.org/10.1016/j.egyai.2023.100241.
[92] Machlev R, Heistrene L, Perl M, Levy KY, Belikov J, Mannor S, Levron Y. Explainable Artificial Intelligence (XAI) techniques for energy and power systems: review, challenges and opportunities. Energy AI 2022;9. https://doi.org/10.1016/j.egyai.2022.100169. Elsevier B.V.
[93] Mohandes SR, Zhang X, Mahdiyar A. A comprehensive review on the application of artificial neural networks in building energy analysis. Neurocomputing 2019; 340:55–75. https://doi.org/10.1016/j.neucom.2019.02.040.
[94] Wang Z, Wang Y, Zeng R, Srinivasan RS, Ahrentzen S. Random forest based hourly building energy prediction. Energy Build 2018;171:11–25. https://doi.org/10.1016/j.enbuild.2018.04.008.
[95] Widmer F, Nowak S, Bowler B, Huber P, Papaemmanouil A. Data-driven comparison of federated learning and model personalization for electric load forecasting. Energy AI 2023;14. https://doi.org/10.1016/j.egyai.2023.100253.
[96] Abdullah AG, Shafii MA, Pramuditya S, Setiadipura T, Anzhar K. Multi-criteria decision making for nuclear power plant selection using fuzzy AHP: Evidence from Indonesia. Energy AI 2023;14. https://doi.org/10.1016/j.egyai.2023.100263.
[97] Pawłowski P, Buchaniec S, Prokop T, Iwai H, Brus G. Microstructure evolution of Solid Oxide Fuel Cell anodes characterized by persistent homology. Energy AI 2023;14. https://doi.org/10.1016/j.egyai.2023.100256.
[98] Wu B, Widanage WD, Yang S, Liu X. Battery digital twins: perspectives on the fusion of models, data and artificial intelligence for smart battery management systems. Energy AI 2020;1. https://doi.org/10.1016/j.egyai.2020.100016.
[99] MoF/GoN. Economic Survey 2021/22. Ministry of Finance. Government of Nepal; 2022.
[100] NEA/GoN. (2022). A year in review fiscal year 2021/22. Nepal Electricity Authority (NEA), Government of Nepal.
[101] Anditi C, Musango JK, Smit S, Ceschin F. Addressing gender dimensions in energy innovations: A gender analysis framework for informal urban settlements in Africa. Energy Res Soc Sci 2022. https://doi.org/10.1016/j.erss.2021.102476 (Vol. 88). Elsevier Ltd.
[102] Bhandari, D., Uprety, M., Ghimire, G., Kumal, B., Pokharel, L., & Khadka, P. (2018). Nepal flood 2017 wake up call for effective preparedness and response. www.practicalaction.org.
[103] Cloke J, Mohr A, Brown E. Imagining renewable energy: towards a social energy Systems approach to community renewable energy projects in the Global South. Energy Res Soc Sci 2017;31:263–72. https://doi.org/10.1016/j.erss.2017.06.023.
[104] Ha YH, Kumar SS. Investigating decentralized renewable energy systems under different governance approaches in Nepal and Indonesia: How does governance fail? Energy Res Soc Sci 2021;80. https://doi.org/10.1016/j.erss.2021.102214.
[105] Klok CW, Kirkels AF, Alkemade F. Impacts, procedural processes, and local context: rethinking the social acceptance of wind energy projects in the Netherlands. Energy Res Soc Sci 2023;99. https://doi.org/10.1016/j.erss.2023.103044.
[106] Pesch U. Elusive publics in energy projects: The politics of localness and energy democracy. Energy Res Soc Sci 2019;56. https://doi.org/10.1016/j.erss.2019.101225. Elsevier Ltd.
[107] Sanjel N, Baral B. A review of renewable energy sector of Nepal. In: *International (SAARC) Youth Scientific Conference (IYSC)* 2019 Proceedings; 2019. p. 115–20.
[108] Sovacool BK, Drupady IM. Energy Access, Poverty, and Development: The Governance of Small-Scale Renewable Energy in Developing Asia. Ashgate Publishing Limited; 2012.
[109] Er MJ, Venkatesan R, Wang N. An online universal classifier for binary, multi-class and multi-label classification. In: *IEEE International Conference on Systems, Man, and Cybernetics SMC* 2016; 2016. p. 1–6.
[110] Kumaravalen G, Behera B. Deployment of supervised machine learning and deep learning algorithms in biomedical text classification. In: Krishnan S, Kesavan R, Surendiran B, Mahalakshmi GS, editors. Handbook of Artificial Intelligence in Biomedical Engineering. 1st ed. Apple Academic Press; 2021. p. 22. Vol. 1.
[111] Wu X, Gao Y, Jiao D. Multi-label classification based on Random Forest algorithm for non-intrusive load monitoring system. Processes 2019;7(6). https://doi.org/10.3390/pr7060337.
[112] Zhang, M.-L., & Zhou, Z.-H. (2005). A k-nearest neighbor based algorithm for multi-label classification. http://mips.gsf.de/proj/yeast/catalogues/funcat/.
[113] de Carvalho AC, Freitas AA. A tutorial on multi-label classification techniques. Found Comput Intell 2009;5:177–95. VolumeFunction Approximation and Classification.
[114] Heydarian M, Doyle TE, Samavi R. MLCM: multi-Label Confusion Matrix. IEEE Access 2022;10. https://doi.org/10.1109/ACCESS.2022.3151048. 19083–19095.
[115] Tsoumakas G, Katakis I. Multi-label classification: an overview. *Int J Data Warehousing Mining* (IJDWM) 2007;3(3):1–13.
[116] Vaizman Y, Weibel N, Lanckriet G. Context recognition in-the-wild. Proc ACM on Interactive Mobile Wearable Ubiquitous Technol 2018;1(4):1–22. https://doi.org/10.1145/3161192.
[117] Zhang T, Chen J, Li F, Zhang K, Lv H, He S, Xu E. Intelligent fault diagnosis of machines with small & imbalanced data: a state-of-the-art review and possible extensions. ISA Trans 2022;119:152–71. https://doi.org/10.1016/j.isatra.2021.02.042.
[118] Zohair LMA. Prediction of Student's performance by modelling small dataset size. Int J Educ Technol Higher Educ 2019;16(1). https://doi.org/10.1186/s41239-019-0160-3.
[119] Tahir MA, Kittler J, Yan F. Inverse random under sampling for class imbalance problem and its application to multi-label classification. Pattern Recognit 2012;45 (10):3738–50. https://doi.org/10.1016/j.patcog.2012.03.014.
[120] Chawla NV, Bowyer KW, Hall LO, Kegelmeyer WP. SMOTE: synthetic minority over-sampling technique. J Artific Intell Res 2002;16.
[121] Ferrer CA, Aragón E. Note on "A Comprehensive Analysis of Synthetic Minority Oversampling Technique (SMOTE) for handling class imbalance. Inform Sci 2023; 630:322–4. https://doi.org/10.1016/j.ins.2022.10.005.
[122] Yi H, Jiang Q, Yan X, Wang B. Imbalanced classification based on minority clustering synthetic minority oversampling technique with wind turbine fault detection application. IEEE Trans Ind Inf 2021;17(9):5867–75. https://doi.org/10.1109/TII.2020.3046566.
[123] Das P, Sangma JW, Pal V, Yogita. Predicting adverse drug reactions from drug functions by binary relevance multi-label classification and MLSMOTE. In: Rocha M, Fdez-Riverola F, Mohamad MS, Casado-Vara R, editors. *Practical Applications of Computational Biology & Bioinformatics*, 15th International Conference (PACBB 2021). Springer International Publishing; 2022. p. 165–73.
[124] CBS. Nepal in Figures 2021. Central Bureau of Statistics, Government of Nepal; 2021. www.cbs.gov.np.
[125] Abbas K, Li S, Xu D, Baz K, Rakhmetova A. Do socioeconomic factors determine household multidimensional energy poverty? Empirical evidence from South Asia. Energy Policy 2020;146. https://doi.org/10.1016/j.enpol.2020.111754.
[126] Sharma SV, Han P, Sharma VK. Socio-economic determinants of energy poverty amongst Indian households: a case study of Mumbai. Energy Policy 2019;132: 1184–90. https://doi.org/10.1016/j.enpol.2019.06.068.
[127] Lin B, Kaewkhunok S. The role of socio-Culture in the solar power adoption: the inability to reach government policies of marginalized groups. Renew Sustain Energy Rev 2021;144. https://doi.org/10.1016/j.rser.2021.111035.
[128] MECS/WINROCK. (2022). Efficient electric cooking market uptake in Nepal (EECMU). www.winrock.org.np.

[129] GIZ. Multiple-Household Fuel Use-a balanced choice between firewood, charcoal and LPG. German Development Cooperation (GIZ); 2014.
[130] Sovacool BK. The political economy of energy poverty: a review of key challenges. Energy Sustain Dev 2012;16(3):272–82. https://doi.org/10.1016/j.esd.2012.05.006. IssueElsevier B.V.
[131] AEPC/GoN. Progress at Glance: A year in Review FY 2019/20 and 2021/21. Alternative Energy Promotion Centre, Government of Nepal; 2021.
[132] Sanjel N, Baral B. Technical investigation of Nepalese electricity market-A review. In: 1608; 2020. https://doi.org/10.1088/1742-6596/1608/1/012005.
[133] Cheng S, Li Z, Mang HP, Neupane K, Wauthelet M, Huba EM. Application of fault tree approach for technical assessment of small-sized biogas systems in Nepal. Appl Energy 2014;113:1372–81. https://doi.org/10.1016/j.apenergy.2013.08.052.
[134] Islar M, Brogaard S, Lemberg-Pedersen M. Feasibility of energy justice: exploring national and local efforts for energy development in Nepal. Energy Policy 2017;105:668–76. https://doi.org/10.1016/j.enpol.2017.03.004.
[135] Butchers, J., Williamson, S., Booker, J., Tran, A., Karki, B., & Gautam, B. (2020). Understanding sustainable operation of micro-hydropower: a field study in Nepal. 10.5523/bris.1k9cigxbcdiye22kuay4wbt5yu.
[136] Boso À, Garrido J, Álvarez B, Oltra C, Hofflinger Á, Gálvez G. Narratives of resistance to technological change: Drawing lessons for urban energy transitions in southern Chile. Energy Res Soc Sci 2020;65. https://doi.org/10.1016/j.erss.2020.101473.
[137] Gonzalez-Salazar M, Poganietz WR. Evaluating the complementarity of solar, wind and hydropower to mitigate the impact of El Niño Southern Oscillation in Latin America. Renew Energy 2021;174:453–67. https://doi.org/10.1016/j.renene.2021.04.048.
[138] Gallagher J, Styles D, McNabola A, Williams AP. Life cycle environmental balance and greenhouse gas mitigation potential of micro-hydropower energy recovery in the water industry. J Clean Prod 2015;99:152–9. https://doi.org/10.1016/j.jclepro.2015.03.011.
[139] Mainali B, Silveira S. Alternative pathways for providing access to electricity in developing countries. Renew Energy 2013;57:299–310. https://doi.org/10.1016/j.renene.2013.01.057.
[140] Parag Y, Ainspan M. Sustainable microgrids: Economic, environmental and social costs and benefits of microgrid deployment. Energy Sustain Dev 2019;52:72–81. https://doi.org/10.1016/j.esd.2019.07.003.
[141] WB. (2021). World Bank national accounts data, and OECD National Accounts data files. Webpage. https://data.worldbank.org/indicator/NY.GDP.MKTP.CD?locations=NP&msclkid=c583c33ad00811ec9a96c3a8dce184bf.
[142] Gyanwali K, Komiyama R, Fujii Y. Representing hydropower in the dynamic power sector model and assessing clean energy deployment in the power generation mix of Nepal. Energy 2020;202. https://doi.org/10.1016/j.energy.2020.117795.
[143] Hashemi M. The economic value of unsupplied electricity: evidence from Nepal. Energy Econ 2021;95. https://doi.org/10.1016/j.eneco.2021.105124.
[144] Movik S, Allouche J. States of power: energy imaginaries and transnational assemblages in Norway, Nepal and Tanzania. Energy Res Soc Sci 2020;67. https://doi.org/10.1016/j.erss.2020.101548.
[145] Bhattacharya SC, Jana C. Renewable energy in India: Historical developments and prospects. Energy 2009;34(8):981–91. https://doi.org/10.1016/j.energy.2008.10.017.
[146] Sovacool BK, Dhakal S, Gippner O, Jain Bambawale M. Peeling the energy pickle: Expert perceptions on overcoming Nepal's electricity crisis. South Asia J South Asia Stud 2013;36(4):496–519. https://doi.org/10.1080/00856401.2013.788469.
[147] Navarro-Espinosa A, Thomas-Galán M. Firewood electrification in Chile: effects on household expenditure and energy poverty. Energy Policy 2023;173:113337. https://doi.org/10.1016/j.enpol.2022.113337.
[148] Kevser M, Tekbaş M, Doğan M, Koyluoglu S. Nexus among biomass energy consumption, economic growth, and financial development: Evidence from selected 15 countries. Energy Rep 2022;8:8372–80. https://doi.org/10.1016/j.egyr.2022.06.033.
[149] Singh RP, Nachtnebel HP, Komendantova N. Deployment of hydropower in Nepal: Multiple stakeholders' perspectives. *Sustainability* (Switzerland) 2020;12(16). https://doi.org/10.3390/SU12166312.
[150] Chen R, Xu P, Yao H, Ding Y. How will China achieve net-zero? A policy text analysis of Chinese decarbonization policies. Energy Res Soc Sci 2023;99. https://doi.org/10.1016/j.erss.2023.103051.
[151] Marahatta S, Bhattarai U, Devkota LP, Aryal D. Unravelling the water-energy-economics-continuum of hydroelectricity in the face of climate change. Int J Energy Water Resour 2022. https://doi.org/10.1007/s42108-021-00174-w.
[152] Devkota LP, Bhattarai U, Khatri P, Marahatta S, Shrestha D. Resilience of hydropower plants to flow variation through the concept of flow elasticity of power: theoretical development. Renew Energy 2022;184:920–32. https://doi.org/10.1016/j.renene.2021.11.051.
[153] Bhattarai U, Devkota LP, Marahatta S, Shrestha D, Maraseni T. How will hydro-energy generation of the Nepalese Himalaya vary in the future? A climate change perspective. Environ Res 2022;214:113746. https://doi.org/10.1016/j.envres.2022.113746.
[154] Wu S. The evolution of rural energy policies in China: a review. Renew Sustain Energy Rev 2020;119. https://doi.org/10.1016/j.rser.2019.109584. Elsevier Ltd.

7.3 Links and implications

Through this paper, I have contributed to the social aspects of energy research in a developing context. It was seen that people from rural and urban areas have differing views, practices, perceptions and expectations related to the energy options available to them and their current and anticipated future consumption patterns. These findings underscore the necessity of analyzing such varying social behaviours and incorporating them in future energy planning. I have carried out such an assessment through energy planning model in the next paper (Paper #6).

CHAPTER 8: PAPER 6 – LEARNING FROM THE PAST AND PLANNING FOR NEPAL'S SUSTAINABLE ENERGY FUTURE: BOTTOM-UP MODELLING IN LEAP

8.1 Introduction

Building on a bottom-up approach, I customized an energy planning model in LEAP (BU-NEP) in this paper (Paper #6) to assess the implications of different policy measures on the future energy scenarios of Nepal. I setup a comprehensive model considering four demand sectors (domestic, industrial, commercial, and transportation), 20 end-uses, 11 major fuel-types and eight supply side technologies. The BU-NEP model was calibrated for 2019, validated for 2021 and 2022, and simulated from 2021-2050 at annual timesteps. This paper directly contributes to the second objective and is a core part of the modelling framework of this research.

8.2 Submitted paper

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Learning from the Past and Planning for Nepal's Sustainable Energy Future: Bottom-up modelling in LEAP

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Abstract

To achieve net-zero emissions by 2045, Nepal has set ambitious energy-related goals, yet many targets remain unmet. This study examined eight future energy scenarios for Nepal which reflected continuation of past development trends and policy sphere aligned to its historical commitments. The cases were identified through an extensive review of 53 policies from 1984 to 2022 and consultations with nine energy experts. Using the Low Emissions Analysis Platform (LEAP), a bottom-up model for Nepal (BU-NEP) was setup considering four demand sectors (domestic, industrial, commercial, and transportation), 20 end-uses, 11 major fuel-types and eight supply side technologies. The BU-NEP model was calibrated for 2019, validated for 2021 and 2022, and simulated from 2021-2050 at annual timesteps, utilizing comprehensive secondary data from multiple national and international sources. The results indicate significant potential for savings in energy consumption (up to 300 Mtoe until 2050) and emissions reduction (from 66.6 $MtCO_2$-e in baseline to 10.5 $MtCO_2$-e by 2050) through integrated demand and supply interventions. Modernizing the household sector by adopting cleaner energy and efficient appliances could potentially reduce energy consumption by 53% by 2050. Furthermore, energy-related emissions across all sectors could be decreased by at least 60% by 2050. Therefore, a sustainable and self-sufficient energy future of Nepal could be achieved from diversified energy mix, with hydropower playing a crucial role, while also addressing the challenges of petroleum dependence and underutilized domestic renewables, supported by agile policy measures rather than 'bike shedding'. The findings emphasize the need for targeted sectoral strategies and strong policy frameworks to balance energy security, economic growth, and environmental sustainability. A holistic approach integrating supply-side and demand-side management, along with government-society synergy and capacity building, is crucial for long-term energy goals, relevant to other developing nations as well.

Keywords: Energy policy; Energy modelling; LEAP; Emissions; Renewable energy; Nepal

1. Introduction

1.1 Background

The world is very likely to face a warming of 1.5 to 2 °C within this century if the emissions from fuels are not checked with topmost urgency (Masson-Delmotte et al., 2021). The total final energy consumption amounted to 399 EJ globally in 2023 (IEA, 2023b) with 37.5 Gt CO_2 energy-related emissions which is about three-quarters of the total emissions worldwide (IEA, 2023a). Modern renewables contributed to only about 13% of the total final energy consumption in 2022 (REN21, 2024). Some notable initiatives such as the ratification of the Kyoto Protocol in COP 3 (1997), Doha Amendment (2012), Paris Agreement (COP 21: 2015), COP 27 (2022) until the recent Dubai COP28 have provided impetus to global emission reduction, with developing countries leading the way (Bigerna et al., 2021). At COP28, 130 countries joined hands to pledge to triple the world's renewable energy capacity and double the energy efficiency improvements by 2030 (REN21, 2024). However, scholars warn that the existing efforts are not sufficient (Nijsse et al., 2023; Murshed, 2023). Moreover, distinct north-south disparities can be seen in the global energy landscape (Bashir et al., 2024), primarily due to variations in people's energy behaviour (Windemer, 2023), socio-economic conditions (Ahmad et al., 2023), technological diversity (Ferdoush et al., 2024), policy (Werner and Lazaro, 2023), social imbalance and governance (Sinha et al., 2023) and sustainability issues (Nižetić et al., 2023). The developed regions are better off economically and technologically with large investments being made in research and development (Shahzadi et al., 2021). The level of awareness is greater among the general public (Hussain et al., 2023) and they have convenient access to efficient energy appliances (Salari et al, 2021). On the contrary, developing countries are plagued with poverty (Azhgaliyeva and Mishra, 2021), low levels of literacy and awareness (Cantarero, 2020), corruption (Bhattarai et al., 2023b) and limited energy choices from the state (Sanjel and Baral, 2021). On a positive note, the developed countries are making considerable efforts in expanding access to renewable energy in the developing countries (Weko and Goldthau, 2022), for example in solar (Ha and Kumar, 2021), wind (Dietzenbacher et al., 2020) and other hybrid technologies (ADB, 2017). Nevertheless, the developing countries are falling behind in their economic progression in the absence of sufficient energy supply and efficient usage (Gebreslassie et al., 2022). Such imbalance is prominent in South Asia which is one of the fastest-growing regions in the world (Tripathi, 2020).

The two largest energy consumers in the region are China and India, demonstrating high dependence on fossil fuels (IEA, 2023b), a status also replicated in other developing countries in Asia such as Afghanistan, Bangladesh, Nepal and Pakistan (WB, 2024). The latter rely on traditional fuels and experience acute energy shortages (SARI/EI, 2021). Moreover, it is inevitable that Asian economies plan well in advance how the increasing demands will be timely met in concurrence with global and regional developments (Vakulchuk et al., 2022). Countries have proposed their mid-term and long-term energy and emission pathways in the form of Nationally Determined Contributions (NDCs). Proper and timely translation of the policies into appropriate interventions are key to sustainable energy management and emissions reduction (Werner and Lazaro, 2023). In order to facilitate energy planning, modelling different supply- and demand-side scenarios has been a common approach among researchers and planners in recent times (Johannsen et al., 2023). In this study, the case of a south Asian developing country, Nepal was taken to assess the shortcomings of the past energy studies, policies and their implementation and then to examine its future energy pathways derived from policy synthesis applying a bottom-up model – LEAP, which reflects continuation of past development trends and policy sphere aliged to its historical commitments.

1.2 Energy Modelling

Different types of energy planning models are available which vary in their applicability depending upon the data availability, spatial disaggregation of the supply and demand entities, top-down/bottom-up approaches, and other factors. Many top-down approaches, such as computable general equilibrium and econometric models endogenize energy demands to macro-economic variables (Indra Al Irsyad et al., 2017). On the other hand, bottom-up models such as Energy Flow Optimization Model (EFOM), Low Emissions Analysis Platform (LEAP) (McPherson and Karney, 2014), MAED-MARKet Allocation (MARKAL) (Nakarmi et al., 2016), and The Integrated MARKAL-EFOM System (TIMES) (Aryal and Dhakal, 2022), consider exogenous inputs. In the context of Nepal, past studies have attempted to model the energy conditions of the country under different projection scenarios using various models such as LEAP (Bhattarai and Bajracharya, 2016; Malla, 2013; Poudyal et al., 2019; Shakya et al., 2023); MAED (WECS/GoN 2017; 2013); MAED-MARKEL (Nakarmi et al., 2016); MAED-TIMES (Aryal et al., 2023); EEDA (Malla, 2022), and econometric modelling (Parajuli et al., 2014), among others. Machine learning models have also become a recent addition in the energy modelling domain (Yao et al., 2023). For example, El Alaoui et al. (2023) applied machine learning models to predict heating energy usage in an administrative building in Morocco while Mukelabai et al. (2023) used it to explain energy poverty of the global south considering energy for cooking. Likewise, Durmanov et al. (2023) used structural equation modelling to identify the influential factors for greenhouse development in the agricultural sector Uzbekistan while Bhattarai et al. (2023c) applied machine learning to understand the socio-economic factors responsible for the domestic energy behaviour of Nepal.

Moreover, LEAP is a widely applied modelling platform that has been used for energy planning in more than 190 countries worldwide, out of which 37 countries used it to help develop their NDCs (SEI, 2022). The model is popular because of its extensive capabilities in conducting comprehensive energy and environment modelling, convenience in calculating future scenario-based energy demand, supply and GHG emissions, a powerful built-in database for various energy and emissions related parameters and a user-friendly graphical interface (Heaps, 2022).

Some applications of LEAP have been provided as examples. For instance, Di Sbroiavacca et al. (2016) evaluated the impact of climate change policies on energy sector and emissions of Nigeria until the mid of this century. Similarly, Liya and Jianfeng (2018) and Mirjat et al. (2018) examined the carbon emission abatement impacts of electric power planning policy scenarios of China and Pakistan, respectively. Likewise, Azam et al. (2015) quantified energy consumption and emissions from the road transport sector in Malaysia. Similarly, Kuldna et al. (2015) discussed the development of the national level energy plan of Estonia while Amo-Aidoo et al. (2022) demonstrated how appropriate renewable energy policy can be beneficial to solar energy development in Ghana. Ates (2015) explored the future energy efficiency potential of iron and steel industry in Turkey. Shakya et al. (2023) analyzed the Long-term Strategy for Net-zero Emissions and examined the co-benefits of energy security, energy equity and reduction in air pollution of Nepal in the near future. Likewise, a long-term energy outlook of Nepal utilizing the vast renewable energy resources was presented by Poudyal et al. (2019).

1.3 Research Gaps and Contribution

Most of the past energy studies in Nepal have modelled demands for the current as well as future economic growth conditions using a top-down econometric approach (Aryal et al., 2023). Research gaps are evident in this regard. Firstly, a top-down approach is likely to under/over-estimate the energy estimations considerably in data scarce regions. Secondly, studies have mostly focused on isolated sectors. For instance, Pradhan et al. (2006) and Pokharel et al. (2021) simulated the transportation sector while Bhattarai and Bajracharya (2016) and Singh and Shakya (2016) studied the industrial sector. Likewise, Bhattarai and Jha (2015) modelled the commercial sector whereas Subedi and Shakya (2016) examined the tourism sector. Thirdly, studies have mostly modelled a smaller spatial domain within Nepal. For example, Shrestha et al. (2017) and Shrestha and Rajbhandari (2010) modelled the Kathmandu valley. Similarly, Dulal and Shakya (2020) modelled Koshi Province while Dhaubanjar et al. (2019) assessed Panauti municipality in the Bagmati Province. The study by Poudyal et al. (2019) utilized energy generation mix distribution data from 2015 and the sector-wise power consumption data from 2018. The energy condition has changed considerably in this decade. For instance, the contribution of biomass was 78% on Nepal's total energy generation mix in 2015 (MoF/GoN, 2015) whereas it reduced to 64% in 2022 (WECS/GoN, 2023). Likewise, the residential sector accounted for 48% of the total nation power consumption in 2018 (NEA/GoN, 2017) whereas it was 42% in 2022 (MoF/GoN, 2023). Moreover, the study extrapolated the energy consumption data that was available from FY 2011/12 until 2016/17 at the time of study to predict future energy consumption until 2042 using an optimistic business-as-usual scenario. With altered energy conditions, the need for updated predictions was felt which formed the basis of our study. Moreover, some studies such as Aryal et al. (2023), Budhathoki et al. (2021) and Shakya et al. (2023) have considered multiple economic sectors but lack proper validation of the models.

It is found that the current magnitudes of energy supply, use and energy-related emissions of the country is quite different to the values projected by past studies for this decade. For example, WECS/GoN (2013b) estimated the total energy consumption of the country to be 497 million GJ by 2020 and 566 million GJ by 2025 under high economic growth scenario. However, the total energy consumption of Nepal was already 597 million GJ in 2019 under business-as-usual conditions. The national peak power plant capacity is expected to reach 2167, 3933 and 7648 MW by 2020, 2025 and 2030 (WECS/GoN, 2013a). Bhattarai and Bajracharya (2016) estimated the industrial energy demand to be 200 million GJ by 2020 and 250 million GJ by 2025 under business-as-usual conditions; however, the industrial demand is 138 million GJ for 2022 (MoF/GoN, 2022). Similarly, VRock (2021) projects large variations in the projected emissions (142.6, 40.48 and 4.56 million metric tonnes CO_2 in high, reference and low growth scenarios) missing the net zero targets by 2050 despite extensive hydropower development. In general, it was found that the adopted growth (or reduction) rates of the modelled variables in most of these studies were too optimistic and highly unrealistic under the current energy development trends of the country.

Moreover, proper accounting of the energy demands supply is important for Nepal because of the steady increase in energy usage (NEA/GoN, 2022), non-availability of petroleum, natural gas and other sources (WECS/GoN, 2022), and limited capabilities to harness domestic alternative renewable sources (AEPC/MoEWRI/GoN, 2022a) including hydropower (Shakya et al., 2023). Additionally, energy-related emissions and environmental concerns have gained much attention in recent times. Nepal aspires to minimize emissions and sustainably achieve net-zero emissions by the year 2045 (GoN, 2021). Recent studies optimistically demonstrate possibilities of cross border energy sharing through hydropower enabled energy transformation (Hussain et al., 2019), sustainable energy infrastructure development (SARI/EI, 2021), effective trade policies (Aryal et al., 2023), and strengthening of institutional capacity and genuine political commitment (Bhattarai et al., 2024a). Hence, the contribution of this study lies in providing scientific evidence for informed policy making for Nepal using future estimates of the energy demand and supply conditions considering historical development trends and assuming the development pathways do not deviate from its policy commitments. The findings of this study will be a good reference to other developing contexts, encouraging them to harness the domestically available clean energy sources for a sustainable energy future.

Therefore, the overarching aim of this study is to examine where Nepal failed to achieve the energy targets envisioned by past policies and how this information can be useful in planning future energy scenarios which are achievable. In this context, the specific objectives are:

i) To carry out extensive review of energy related policies (1984-2022) of Nepal and conduct expert consultations to derive future energy scenarios
ii) To assess the different future energy supply, demand and emissions scenarios using the LEAP model and compare them against baseline conditions

2. Materials and methods

2.1 Study Area

This study has been carried out in a developing country – Nepal (Figure 1). Nepal's total energy consumption was 14.464 million tons of oil equivalent (toe) in the fiscal year 2019/2020 which is the base year for our analysis (MoF/GoN, 2021). The net GHG emissions of Nepal amounted to 60 million metric tons of CO_2 equivalent (mMtCO_2-e) (100-year GWP) in 2019 with a growth rate of 4.8% per year during 2010 to 2019 (GoN, 2021). The energy generation mix consists of three primary sources: traditional, commercial and other off-grid renewables. Traditional sources include firewood, agricultural residue and dry dung for direct combustion. Commercial sources mainly include petroleum, coal, and grid electricity generated from large and medium hydropower projects. Other off-grid renewable sources consist of micro-hydropower, solar, biogas and hybrid systems. In the fiscal year 2019/2020, traditional energy sources contributed the majority, accounting for 69%, commercial sources made up 28%, while renewables constituted 3% of the overall energy generation mix (MoF/GoN, 2021). The total length of the electricity transmission line is 4,874 km which supplied a total power of 1,458 MW with annual electricity generation of 6,528 GWh, cumulatively from governmental, private sector, and import-driven initiatives (NEA/GoN, 2021). The predominant share of electricity generation (89%) is attributed to extensive hydroelectric projects, while only 2.1%

is generated from solar, 3.7% from thermal sources, and 5.2% from various smaller renewable energy sources (MoF/GoN, 2021).

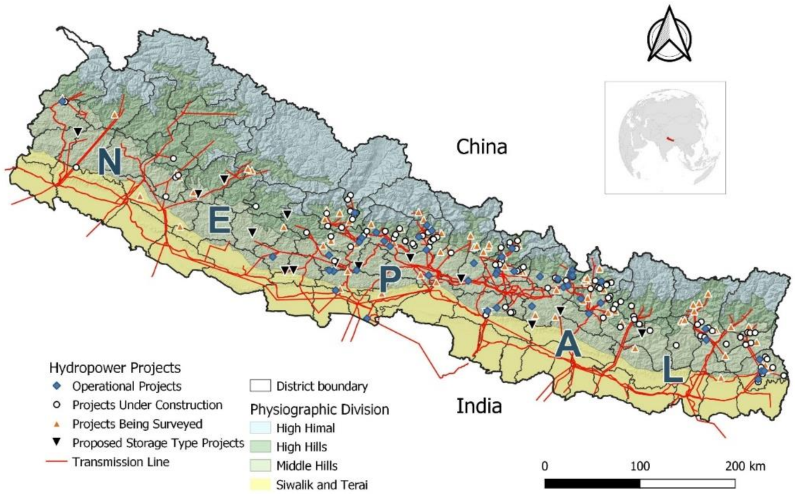

Figure 1: Geographical setting of Nepal showing the locations of hydropower projects [The project locations and transmission lines data were acquired from the Department of Energy Development (DOED), Government of Nepal; administrative and physiographic data from the Department of Survey, Government of Nepal; map generated by the authors for this research].

2.2 Methods

As the first step, energy related policies of Nepal promulgated over the last four decades (1984-2022) were reviewed. The aspirations of these polices were translated to scenarios which were forced into the well-calibrated and validated bottom-up model in LEAP. LEAP is a popular modelling framework developed by the Stockholm Environment Institute (SEI) for energy planning and climate change mitigation assessments (SEI, 2022). LEAP was applied to model multiple energy demand, supply and emission scenarios until the mid of this century, which are specifically derived from extensive policy review and synthesis, under the continuation of an optimistic business-as-usual scenario. The overall workflow of the study is presented in Figure 2 and the details are provided subsequently.

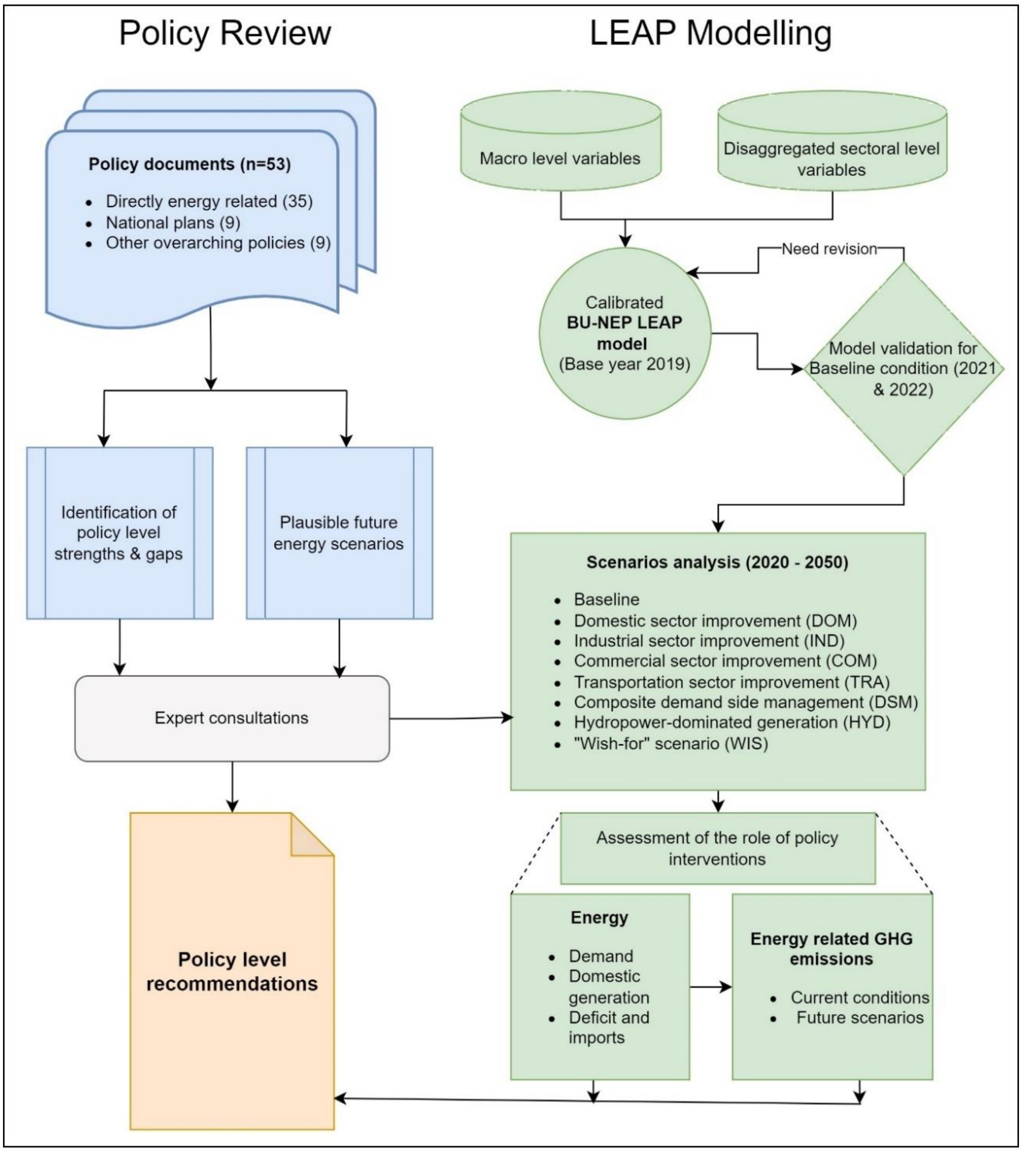

Figure 2: Methodological approach for policy synthesis and assessment of future energy and emission scenarios of Nepal using LEAP (LEAP: Low Emissions Analysis Platform; BU-NEP LEAP: Bottom Up – Nepal LEAP)

2.2.1 Policy Review

All the policy documents pertaining to the energy sector of Nepal from 1984 to 2022 were collected through online sources of the Government of Nepal (GoN), international repositories such as World Bank (2022) and IEA (2023b), hard copy reports from the concerned ministries/departments, and through personal networks. Our list of policy documents included acts, strategies, legislations, white papers, national plans, master plan studies, rules, programs, long term strategies, synopsis reports, frameworks and NDCs. For a document to be considered in our list, it should contain at least one statement/clause (or sub-clause) related to energy. This led to the compilation of an exhaustive set of 53 documents, out of which 35 were directly energy related, nine were national level plans and the remaining nine were other overarching policies. The strengths and achievements of all these policy documents were subjectively evaluated. This was followed by in-person consultations with nine energy experts (listed in Supplementary Material S2) who were well acquainted with the energy conditions of Nepal. Their feedback on our policy synthesis was incorporated into the scenario-building process. This led to the finalization of eight future energy scenarios which were then simulated in the LEAP modelling framework for analysis.

2.2.2 LEAP modelling

A bottom-up approach for modelling the energy condition of Nepal was implemented in LEAP considering four demand sectors (domestic, industrial, commercial, and transportation), 20 end-uses and 11 major fuel types comprising data at the activity level and intensity levels aggregated in a hierarchical order. We have referred to 'availability' as the supply side capacity while 'usage' as the demand side values in the manuscript. The model was named "Bottom-up Nepal LEAP (BU-NEP LEAP)". The schematic framework of the model is shown in Figure 3.

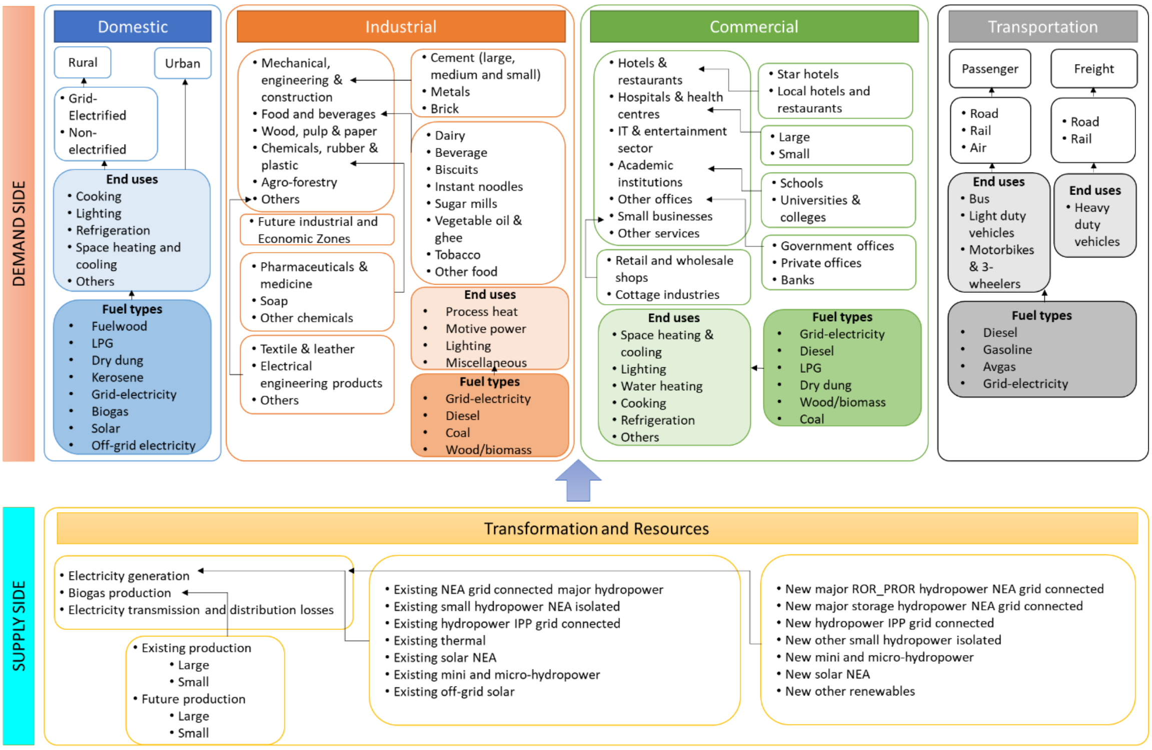

Figure 3: Schematic framework of the BU-NEP LEAP model implemented in this study.

The model has been customized to include four demand sectors: domestic, industrial, commercial, and transportation (Figure 3). The major fuels for residential purposes, namely, fuelwood, animal dung, LPG, electricity, kerosene and biogas have been modelled individually whereas those with smaller contributions such as bio-briquettes, pellets, and agricultural residue have been clubbed together. Similarly, the major fuels for the industrial and commercial sectors (electricity, diesel and coal), and transportation sector (petrol, diesel, electricity and avgas) have been considered in the BU-NEP LEAP model. The hourly system load curve was derived based on NEA/GoN (2021) splitting the modelled year into a 1000 hours' time-window (Heaps, 2022). Likewise, the supply side consisted of eight types of technologies including grid-connected (large) and isolated hydropower (small, mini, micro), thermal, gridder-solar and off-grid solar and biogas production. Control over whether existing power plants are active and the timing of operation of planned ones have been modelled based on their commencement dates. Electricity transmission and distribution losses have been added as percentages of the total generation (Supplementary Material S1.6).

The BU-NEP LEAP model was calibrated for the base year 2019 and validated for two recent years: 2021 and 2022. The year 2020 was excluded from the analysis because of the impacts of COVID-19 on the overall energy sector, globally, regionally and within Nepal. Calibration and validation were done by comparing the simulated versus the actual values for two sets of variables: i) sectoral distribution and total annual energy consumption, and ii) annual electricity demand, net domestic electricity generation, electricity losses and electricity import. The well-calibrated and validated model was used to calculate the energy conditions and the corresponding GHG emissions for the baseline and seven future scenarios. No major policy level interventions are assumed to occur for the baseline condition. Model simulation was carried out from 2021 until 2050 at annual timesteps.

The total energy demand is calculated using Equation 1.

$$D_t = \sum_{i=1}^{n} \sum_{j=1}^{m} \sum_{k=1}^{l} E_{i,j,k,t} A_{i,j,k,t} \qquad \text{.................... Eq (1)}$$

Where, D_t is the total energy demand for the t^{th} year of simulation; E is the energy intensity and A is the activity level value; i corresponds to the number of sectors for aggregation ($n = 4$); j represents the number of sub-sectors (m varies by sector); k is the fuel type for the j^{th} sub-sector of the i^{th} sector (l varies by sub-sector).

The total energy supply calculation is calculated using Equation 2.

$$S_t = \sum_{p=1}^{q} C_p A_p U_p - Losses \qquad \text{.................... Eq (2)}$$

Where, S_t is the total energy supplied during the t^{th} year; p represents the number of energy generation technologies; C_p is the total installed capacity of the i^{th} technology; A_p is the availability factor for the p^{th} technology indicating the share of the time it is available for operation; and U_p is the usage factor for the i^{th} technology indicating the average intensity of the devices (default value considered is one); *Losses* cumulatively include the generation, transmission and distribution losses.

And the deficit for each energy technology in the t^{th} year is calculated using Equation 3

$$Deficit_t = \sum_{i=1}^{n} D_{i,t} - \sum_{p=1}^{q} S_{p,t} \qquad \text{.................... Eq (3)}$$

The deficit is either fulfilled by imports or left unmet, depending upon the energy generation technology and the demand sector.

Similarly, the energy-related total GHG emissions is calculated using Equation 4.

$$EM_t = \sum_{i=1}^{n} \sum_{j=1}^{m} \sum_{k=1}^{l} EC_{i,j,k,t} \varepsilon_k \qquad \text{.................... Eq (4)}$$

Where EM_t is the total GHG emissions in the t^{th} year; $EC_{i,j,k,t}$ is the total energy consumption and ε_k is the emission factor for the k^{th} fuel type; i, j, k, n, m and l as defined in Equation 1. The emission factors for the respective fuel types have been taken from IPCC within the internal database of LEAP (Heaps, 2022).

a) Data

A single door data repository containing output tables at the required disaggregation level does not exist for Nepal. Hence, it was required to source data from multiple sources include national data repositories, international data repositories, national level government reports, reports from private I/NGOs working in Nepal and South Asia, published academic and other grey literature and personal networks. Disaggregated end-use energy data for the different economic sectors at the activity level and intensity levels were used in the BU-NEP LEAP model. Similar data collection approach has been implemented by past modelling studies in Nepal, for example, by Bastola and Sapkota (2015) to assess the relationships between energy, pollution and economic growth; Bhandari and Pandit (2018) to examine the socio-economic impacts of renewable energy technology in mountainous villages; Malla (2022) to evaluate the impact on clean energy transformation on household demand; Nakarmi et al. (2016) to project future energy scenarios; Paudel et al. (2021) to assess transition in cooking energy; Shakya et al. (2023) to quantify the environmental, energy security and energy equity benefits of renewable energy transition; and Subedi and Shakya (2016) to study the impacts of energy efficiency and low carbon strategies on rural tourism, among others. Details of the data and their sources for the model are presented in Supplementary Material S1. The demographic data is given in Supplementary Material S1.1, the household sector demand data are provided in Supplementary Material S1.2. Likewise, the industrial sector demand data is given in Supplementary Material S1.3 while the commercial sector demand data is given in Supplementary Material S1.4. Similarly, the transportation sector demand data is provided in Supplementary Material S1.5 and the electricity generation sources are listed in Supplementary Material S1.6.

b) Policy Scenarios

Our review shows that until the mid-1980s, Nepal saw very little development in modern energy technologies. The country was almost completely reliant on traditional energy sources and people had very little access to electricity (Sharma and Awal, 2013). A progressive trend can be seen in the number of energy related policies that have been formulated in Nepal over the last four decades (Figure 4).

Key policy milestones emerged through the decades. Initiatives such as the Nepal Electricity Authority Act (1984) and subsequent Seventh (1985) and Eighth Plans (1992) emphasized hydropower development and alternative energy like micro-hydro, biogas, solar, and wind technologies. The 1990s marked pivotal legislations such as the Electricity Act (1992) Hydropower Development Policy (1992), Nepal Water Resources Act (1992), and Nepal Environmental Policy and Action Plan (1993) which promoted hydropower (of all scales), opened avenues to the private sector, envisioned national and foreign investment in hydropower, facilitated water resource use through licensing, established the power purchasing agreement (PPA) system, and prioritized multi-purpose hydropower projects. Moreover, the establishment of Alternative Energy Promotion Centre (AEPC) in 1996 can be considered a milestone in promoting isolated renewable energy technologies for rural Nepal.

The new millennium saw strategic policy enhancements aimed to bridge the rural-urban energy gap. The Hydropower Development Policy was revised in 2001 focusing on the minimization of energy generation costs, institutional restructuring, demand side management and rural electrification. The Water Resources Strategy (2002) set short-, medium- and long-term targets for meeting the country's energy needs. Nepal's Energy Sector Vision 2050 A.D. (2013) identified hydropower as the leading energy sector, diversifying energy generation and promoting rural electrification. The Rural Energy Policy (2006) established the Central Rural Energy Fund, Renewable Energy Subsidy Policy (2013) focused on various small renewable technologies. Moreover, the enactment of the new constitution in 2015 promoted renewable energy development in Nepal, ensuring low cost and dependable supply to meet the basic energy needs of the Nepalese citizens.

Likewise, the National Energy Strategy (2013) aimed to promote new transport technologies while the National Renewable Energy Framework (2017) facilitated shifting to credit-based financial models fostering collaboration. The Biomass Energy Strategy (2017) sought sustainable use of agri- and forest-residues. Additionally, the Whitepaper on Energy, Water, and Irrigation (2018) set ambitious hydropower development goals and modern energy management technologies such as net-metering, time- and season-based tariffs and pumped hydropower. The National Energy Efficiency Strategy (2018) emphasized on increasing the efficiency. The revised Renewable Energy Subsidy Policy in 2022 promoted loans to the rural poor, fostering rural market growth and strengthening local capacity building.

Initially, 12 scenarios were derived from policy review under business-as-usual conditions to assess the differential impacts on the sectors, activity level and intensity levels. After undergoing series of expert consultations, the final number of scenarios for modelling was fixed to eight (Table 1). Some studies, such as Nepal's Long-term Strategy for Net-Zero Emissions 2021 (LTS) and Shakya et al. (2023), consider two scenarios "With Existing Measures (WEM)" and "With Additional Measures (WAM)" in their models to include all low carbon policy interventions envisioned by the Government of Nepal. However, the scenarios in this paper are derived considering not only the LTS document, but additional policies, including Energy Sector Synopsys 2021/22, the Renewable Energy Subsidy Policy 2022, and others comprehensively, as shown in Table 1. In essence, the WEM scenario of the LTS document corresponds to the 'Baseline' while the WAM scenario corresponds to the other sectoral scenarios of this paper.

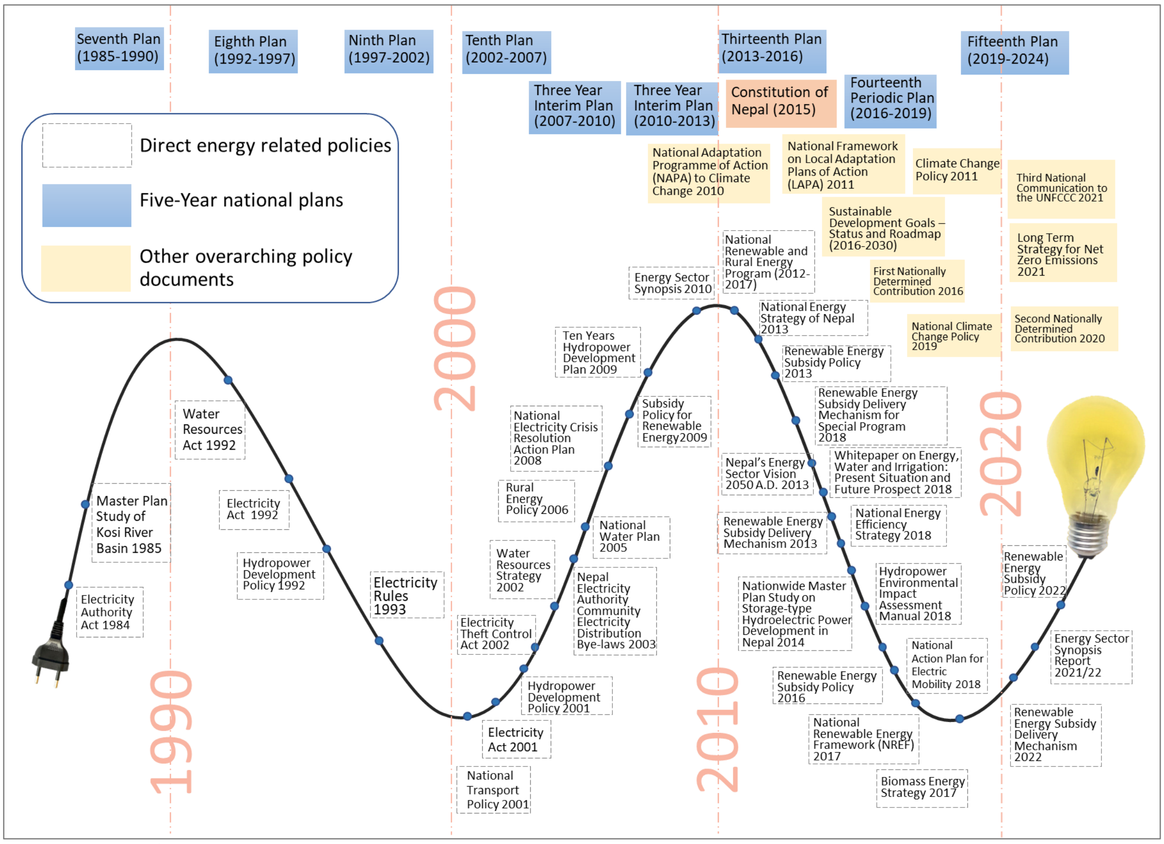

Figure 4: Timeline of energy related policy development in Nepal

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The first scenario is the baseline condition which assumes that the current energy supply and demand trends continue during the period of simulation without any new policy interventions. Four demand side management scenarios were analysed each targeting the domestic (DOM), industrial (IND), commercial (COM) and transportation (TRA) sector separately as well as a fifth composite scenario (DSM). One supply side management scenario (HYD) was also analysed in which the operational, planned and proposed energy projects (mostly hydropower and other renewables) are considered. Additionally, an integrated demand- and supply-side management scenario ("Wish-for", WIS) has also been analysed. Emissions are indirectly calculated internally by LEAP based on the amount of fuel used during the generation and consumption processes. Despite quantification of emissions targets for net zero conditions by Second Nationally Determined Contribution (GoN, 2020) and Long-term Strategy for Net-Zero Emissions (GoN, 2021) by 2045, these served as indirect targets for our simulation. Further details of each scenario are provided in Table 1. The future change in the energy and emissions conditions was evaluated for each scenario against the baseline condition.

Table 1: Scenarios analyzed in this study listing their respective policy targets

Scenarios	Assumptions and targets at the activity and intensity levels
Baseline	• The current trends in the activity level across the sectors continue with the same trends until the end of the simulation period • The values of the intensity levels across all the sectors remain constant as in the base year • No new policy interventions are implemented during the simulation period
Demand side	
Domestic sector improvement (DOM)	• 100% electric cooking stoves in urban households by 2030 • 25% electric stoves nationally by 2030 • 100% lighting by electricity by 2030 • 100% lighting by efficient LED lights by 2050 • 20% improved cooking stoves, 50% LPG stoves and 30% electric stoves in rural areas by 2050 • 100% of urban population and 50% of rural population will be using electric refrigerators by 2050 • 100% electrification in space heating in the urban areas and 80% in the grid-electrified rural areas by 2050
Industrial sector improvement (IND)	• 75% electrification in the process heat and boilers of mechanical engineering, cement and metallurgy industries; 100% electrification in motive power by 2050 • 50% electrification in process heat and boilers of food, beverages and tobacco industries; 100% electrification in motive power by 2050 • 50% electrification in process heat and boilers of wood, paper and pulp industries; 100% electrification in motive power by 2050 • 50% electrification in the process heat and boilers of chemicals, rubber and plastic industries; 100% electrification in motive power by 2050

	• 100% electrification in the process heat and boilers of electrical engineering, textile, leather and other mechanical industries; 100% electrification in motive power by 2050 • 50% electrification in the process heat and boilers of future industrial and economic zones • 100% efficient kilns in the brick industries with improved fuel mix by 2030; 100% electrification in motive power by 2050 • Energy intensity efficiency increased by 1.5% per year
Commercial sector improvement (COM)	• Complete replacement of LPG, wood and diesel with 100% electricity in the hotels and restaurants with efficient lighting by 2050 • 100% electrification of hospitals and health centres with efficient lighting by 2050 • 100% electrification of IT and entertainment sector with efficient lighting by 2050 • 100% electrification of the academic institutions with efficient lighting by 2050 • 100% electrification of the offices and other institutions with efficient lighting by 2050 • 100% electrification of the shops, cottage industries and other service sector with efficient lighting by 2050
Transportation sector improvement (TRA)	• Share of road passengers limited to 80%, air passengers to 15% and rail passengers to 5% by 2050 • 50% of the mass passenger transport will be electric by 2050 • 50% of the private passenger transport (two, three and four-wheelers) will be electric by 2050 • Electric passenger rail will be operated by 2050 • 50% of the freight transport will be electric by 2050 • Electric freight rail will be operated by 2050 • Efficiency of the fuels and energy technologies will be increased at the rate of 0.5% per year until 2050
Composite Demand Side Management (DSM)	• All the conditions of DOM, IND, COM and TRA are superimposed for management of all the demand sectors
	Supply side
Hydropower Dominated Supply Side Management (HYD)	• Grid extension to 75% of population by 2030 • Share of isolated hydropower to be increased to 12% by 2030 • Increase hydropower production to 21,000 MW by 2050 • Share of other alternative renewable energy technologies to be increased to 5% by 2030 • Electrification to additional 9% of rural population from 2010 by 2020 • Rural electrification to reach 100% by 2030 • 0.2 million units of household biogas plants by 2024 • Development of large and small hydropower projects for industrial use • Solar PV plant capacity to reach 2000 MW by 2030

	• The grid electricity transmission and distribution and losses will be reduced to 12% by 2050 • Half of the existing hydropower and other renewable projects will be retired by 2050
Wish-for (WIS)	• All the conditions of DOM, IND, COM and TRA along with the HYD scenarios are superimposed for management of all the demand sectors and supply side

Note: The scenarios are developed based on the recommendations of these policy documents: AEPC/MoEWRI/GoN (2022a); AEPC/MoEWRI/GoN (2022b); CBS, 2021; GoN (2012); GoN (2016); GoN (2020); GoN (2021); HMG/N (1985); HMG/N (1992a); HMG/N (1992b); HMG/N (1992c); HMG/N (1992d); HMG/N (1993a); HMG/N (1993b); HMG/N (1999a); HMG/N (1999b); HMG/N (2001); MoE/GoN (2006); MoE/GoN (2010); MoEWRI/GoN (2018); MoF&E/GoN (2021); MoF&SC/GoN (2016); MoFA&LD/GoN (2013); MoFA&GM/GoN (2021); MoP&E/GoN 2016); MoPIT/GoN (2022); MoSTE/GoN (2013); NPC/GoN (2016a); NPC/GoN (2016b); NPC/GoN (2019); WECS/HMG/N (2002); WECS/GoN (2013b); WECS/GoN (2022).

3. Results

3.1 BU-NEP LEAP Model calibration and validation

For calibrating and validating the BU-NEP LEAP model, the extrapolated (simulated) values of total annual and sectoral energy consumption for the baseline condition were compared with the respective actual values (Table 2). It can be seen that there is a difference of -0.9% in the base case calibrated total energy consumption. Moreover, the differences for the various sectors ranged from -3.3% (commercial) to 0.2% (household). Similarly, the total energy consumption for the years 2021 and 2022 were simulated with 0.2% and -1.6% errors. The differences in the simulated and observed values by sectors varied from -2.3% (commercial) to 2.3% (transportation) for 2021 and from -5% (commercial) to 6.9% (transportation) for 2022.

Additionally, the modelled total electricity demand and generation during calibration (base year 2019) and validation (2021 and 2022) were compared with the respective actual values (Table 3). During calibration, the differences in the actual and modelled values are 2.1, 2.9, 2.6 and -1.3% for total electricity demand, net domestic electricity generation, transmission and distribution losses and import, respectively. Likewise, differences in the total electricity demand were 2.4% and -4.0% for 2021 and 2022, respectively. Similarly, the differences were 5.1% and -1.8% for net domestic electricity generation, 2.3% and 5.3% for the losses and -5.1% and -9% for import, respectively, for 2021 and 2022.

Hence, the simulated and actual values are in close agreement with each other which indicates that the BU-NEP LEAP model is well calibrated and validated.

Table 2: BU-NEP LEAP model calibration and validation results for total annual energy consumption by sector

	Calibration			Validation					
Year	2019			2021			2022		
Energy Consumption & Sector	Actual (million GJ)	Modelled (million GJ)	% diff	Actual (million GJ)	Modelled (million GJ)	% diff	Actual (million GJ)	Modelled (million GJ)	% diff
Household	375	376	0.2	388	388	-0.1	413	401	-2.9
Industrial	127	124	-2.4	129	131	1.2	138	138	-0.1
Commercial	42	41	-3.3	43	42	-2.3	46	44	-5.0
Transportation	53	51	-3.0	56	57	2.3	59	63	6.9
Total	597	592	-0.9	617	618	0.2	655	645	-1.6

Note: Actual energy consumption values extracted from MoF/GoN (2020); MoF/GoN (2021); and MoF/GoN (2022).

Table 3: BU-NEP LEAP model calibration and validation results for total electricity demand and generation

	Calibration			Validation					
Year	2019			2021			2022		
Electricity Demand and Generation	Actual (GWh)	Modelled (GWh)	% diff	Actual (GWh)	Modelled (GWh)	% diff	Actual (GWh)	Modelled (GWh)	% diff
Total Electricity Demand	7,741	7,901	2.1	8,960	9,178	2.4	10,686	10,262	-4.0
Net Domestic Electricity Generation	7,405	7,623	2.9	7,767	8,163	5.1	10,862	10,669	-1.8
Losses	1,393	1,429	2.6	1,613	1,647	2.1	1,719	1,811	5.3
Import	1,729	1,707	-1.3	2,806	2,662	-5.1	1,543	1,404	-9.0

Note: Actual energy consumption and generation values extracted from NEA/GoN (2020); NEA/GoN (2021); and NEA/GoN (2022).

3.2 Future energy supply and demand scenarios

LEAP tries to fulfill the aggregated demands across all the end-uses and sectors by the total available supply. The BU-NEP LEAP model is customized to fulfill the unmet demands by imports.

3.2.1 Energy condition by fuel type

The total energy consumption was 14.1 Mtoe for 2019 which is expected to increase to 34.5 Mtoe in 2050 under the baseline condition (Figure 5). However, with interventions at the demand side, the total energy consumption can be reduced to 16.3, 32.1, 33.2, 13.7 and 13.7 Mtoe for the DOM (2050), IND (2050), TRA (2050), DSM (2050) and WIS (2050) scenarios, respectively. The demand increases by 1.2 Mtoe in the COM (2050) compared to the Baseline

(2050) case but with increased contribution of cleaner and efficient energy technologies, mainly hydropower and other renewables.

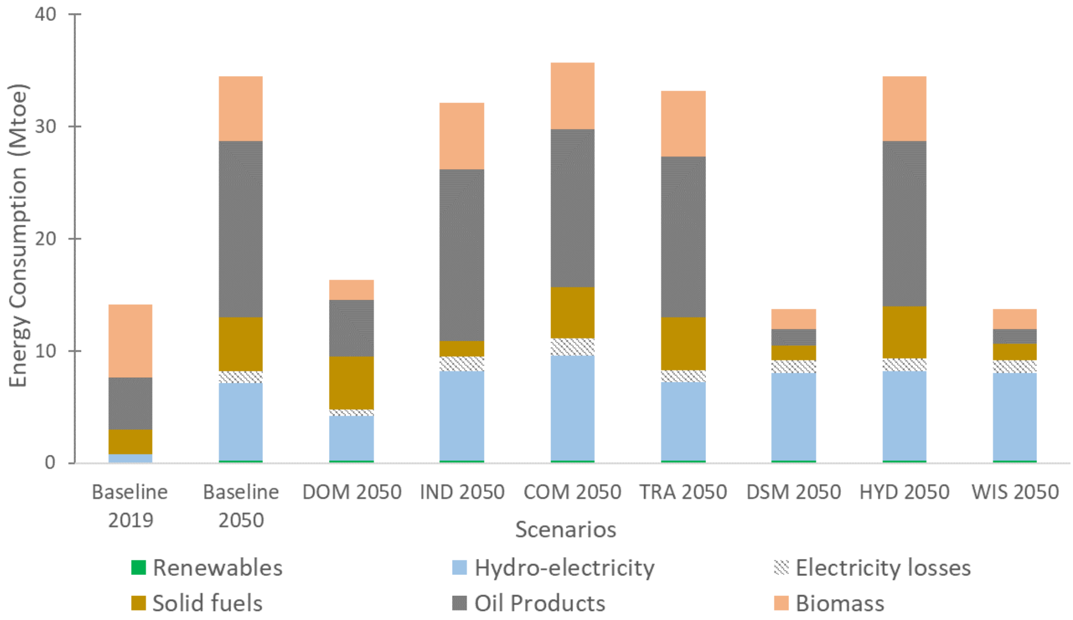

Figure 5: Comparison of energy consumption for the baseline and future scenarios by fuel type

Additionally, it is seen that the share of biomass can be expected to reduce from 46.1% in 2019 to 16.8% in 2050 in the baseline condition at the cost of increased oil products from 32.6% to 45.5% and hydroelectricity from 3.5% to 20% (Figure 5). Such an increase in the share of renewables (22%) has been reported by Nakarmi et al. (2016). However, the magnitude of biomass does not change much across the other scenarios except for DOM (2050), DSM (2050) and WIS (2050). Such changes in the traditional biomass (in the range of 20%) have also been projected by Shakya et al. (2023). Significant decrease in the shares of all the fuels and the total energy can be expected under the DOM (2050), DSM (2050) and WIS (2050) scenarios in which hydroelectricity will have a significant contribution. Although other renewables will have increased shares from <0.1% in 2019 to 0.6% in 2050 under the baseline, its share can go as high as 1.5% (0.2 Mtoe) in the DSM (2050) and WIS (2050) scenarios. These findings are concurrent with those of Nakarmi et al. (2016), Shakya et al. (2023) and WECS/GoN, (2013a). Although the trends of increase/decrease are consistent with our study, the magnitudes vary due to the data, methods and the applied models. Interestingly, it can be seen that despite interventions, oil products will still have significant contributions in energy supply until 2050 because of increased demands across all sectors which is met by imports.

3.2.2 Energy distribution by sector

The shares of the four sectors (domestic, industry, commercial and transportation) for the base year (2019) and baseline 2050 have been presented along with the predictions of 2050 for the seven future scenarios in Figure 6. It can be seen that under the baseline conditions, the shares of the different sectors on the total energy are not likely to vary much.

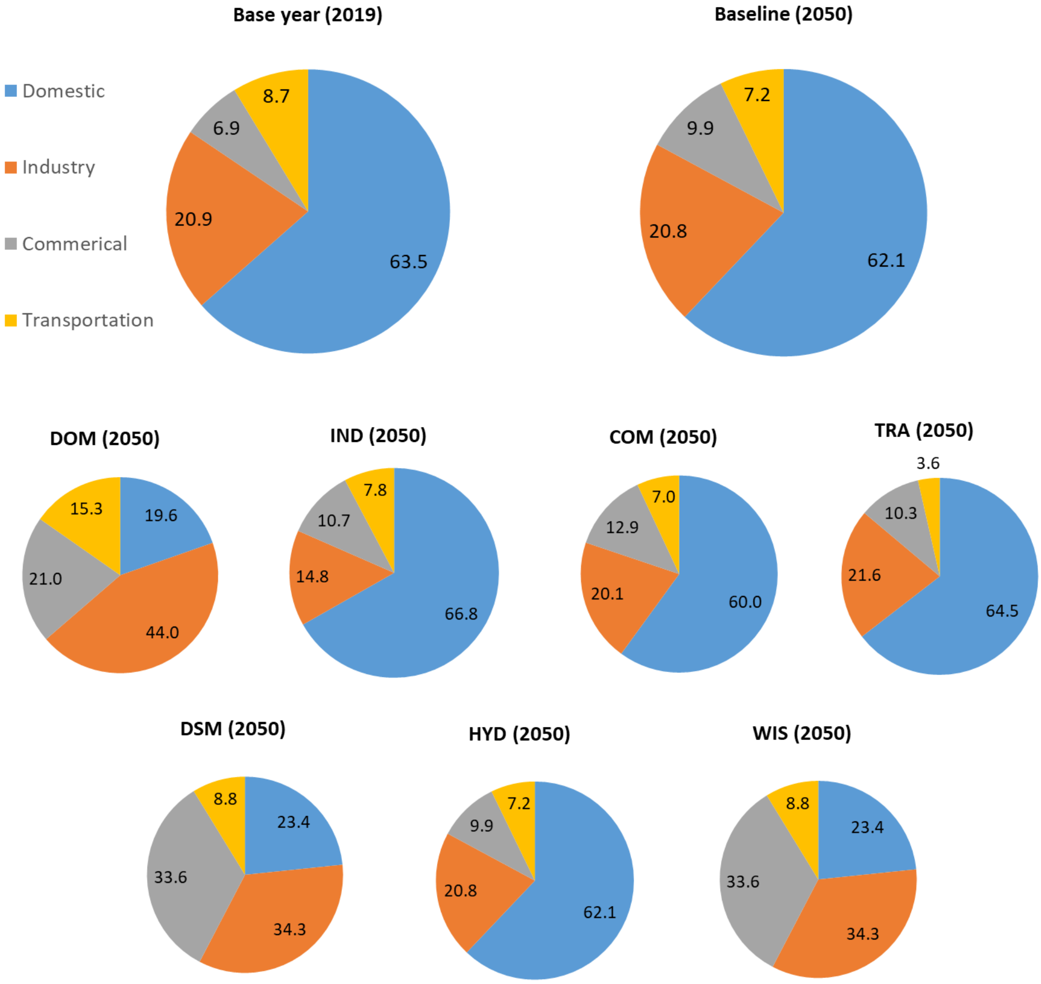

Figure 6: Share (in %) of domestic, industrial, commercial and transportation sectors on future energy consumption for the different scenarios

The domestic sector, with high reliance on traditional fuels, can be expected to decrease only slightly over the next three decades (from 63.5% in 2019 to 62.1% in 2050). In the DOM (2050) scenario, the contribution of the domestic sector in the total energy consumption is expected to reduce to 19.6% from 62.1% in the baseline. Increasing rates of household energy demands in the range of 0.1 to 0.7% per year until 2051 have been reported by Malla et al. (2022) due to increased share of modern fuels in cooking and energy efficiency. The discrepancies are most likely due to the spatial disaggregation of the model which they have done at the provincial level. In the IND (2050) case, the share of industrial energy use is expected to slightly increase from 7.2% in the baseline to 7.8% but with significant increase in the efficient use of clean energy meeting the increased industrial demand. Gyanwali and Bajracharya (2013) have concluded similar decreases in the industrial sector demand by 2030. The COM (2050) shows an anticipated increase in the energy share from 9.9% in the baseline to 12.9% but with a 100% reliance on electricity from hydropower and other renewable technologies. Similar increases in the commercial sector energy demand (in the range of 1 to 7%) has been projected by Bhattarai and Jha (2015) by 2030. In the TRA (2050) scenario, the energy demand for the transportation sector has been projected to increase by 0.8% compared to the baseline. However, as with the other scenarios, the reliance of the transportation sector on electricity and efficient technologies is projected to increase considerably for meeting the future requirements. The DSM (2050) has an integrated impact on the distribution of the sectoral energy consumption with industry having the highest (34.3%) while transportation having the lowest (8.8%) shares. As expected, the WIS (2050) shows a similar pattern as of DSM (2050).

3.3.3 Cumulative energy saving

Interestingly, it is seen that considerable amount of energy can be cumulatively saved by Nepal until 2050 under different scenarios compared to the baseline (Figure 7). The total cumulative energy consumption until 2050 under the baseline condition is estimated to be 680 Mtoe. With the sectoral demand management interventions in place, the cumulative savings are expected to be 257, 33, 21, 300 and 300 Mtoe for the DOM, IND, TRA, DSM and WIS scenarios, respectively. These savings are respectively 38, 5, 3, 44 and 44% of the 2050 baseline values. These values are comparable to the findings of Nakarmi et al. (2016), Parajuli et al. (2014), Shakya et al. (2023). Furthermore, the cumulative imports from 2021 until 2050 have been estimated at 248 Mtoe which is 37% of the total consumption. The imports can be drastically reduced particularly in the DOM (by 182 Mtoe), DSM (227 Mtoe) and WIS (286 Mtoe) scenarios by increasing domestic generation and efficiency of energy technologies. Similar reduction in import (~35%) has been reported by Nakarmi et al. (2016) in the future due to high electrification and energy efficiency scenarios.

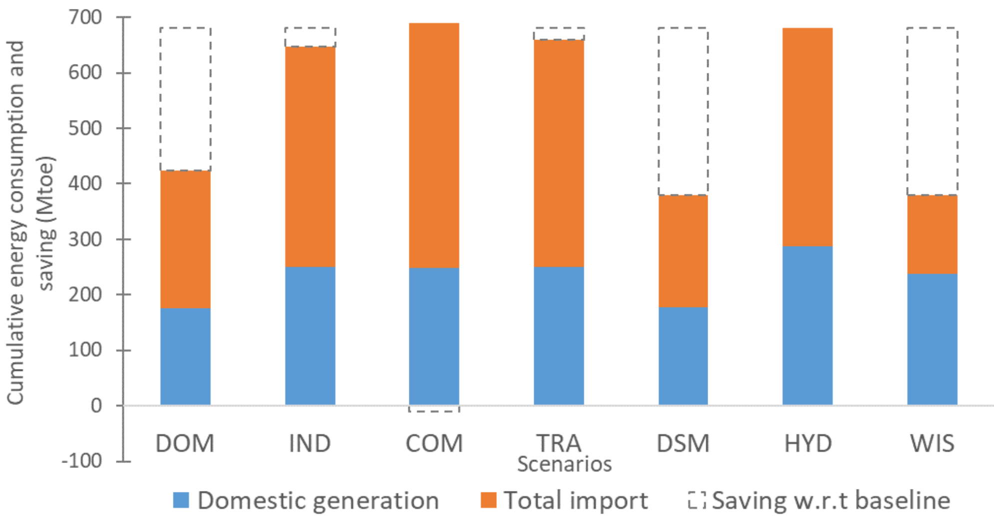

Figure 7: Cumulative energy generation, import, consumption and saving under different intervention scenarios compared to the baseline (2050)

3.4 Energy-related GHG emissions

The total GHG emissions from the energy sector amount to 25 million metric tonnes CO_2 equivalent ($MtCO_2$-e) for the base year 2019 distributed across the different sectors, namely industry (10.7), domestic (8.9), transportation (3.6) and commercial (1.8) (Table 3). The emission is estimated to increase to 35.7 $MtCO_2$-e by 2030 and 66.6 $MtCO_2$-e by 2050 under the baseline condition with similar sectoral contributions as in the base year. Under the DOM scenario, the emissions can be reduced to 24.7 (3.1 from the domestic sector) and 34.1 $MtCO_2$-e (1.1 from the domestic sector) in 2030 and 2050, respectively. Similarly, under the IND scenario, the estimated emissions amount to 32.3 (11.3 from the industrial sector) and 52.3 $MtCO_2$-e (7.0 from the industrial sector), respectively, in 2030 and 2050. These values are very close to those (in the range of 6.6 to 10.8 $MtCO_2$-e) forecasted by Gyanwali and Bajracharya (2013) for the industrial sector under different growth scenarios. The most reduction can be achieved under the DSM and WIS scenarios (19 and 10.5 $MtCO_2$-e in 2030 and 2050, respectively).

Table 3: Total simulated GHG emissions by year and sector for the different scenarios

		Total GHG emissions ($MtCO_2$-e)							
		Baseline	DOM	IND	COM	TRA	DSM	HYD	WIS
2019	Domestic	8.9							
	Industry	10.7							
	Commercial	1.8							
	Transportation	3.6							
	Total	25.0							
2030	Domestic	14.1	3.1	14.1	14.1	14.1	3.1	14.1	3.1
	Industry	14.7	14.7	11.3	14.7	14.7	11.3	14.7	11.3
	Commercial	2.3	2.3	2.3	1.5	2.3	1.5	2.3	1.5
	Transportation	4.6	4.6	4.6	4.6	3.1	3.1	4.6	3.1
	Total	35.7	24.7	32.3	34.9	34.2	19	35.7	19
2050	Domestic	33.6	1.1	33.6	33.6	33.6	1.1	33.6	1.1
	Industry	21.3	21.3	7.0	21.3	21.3	7.0	21.3	7.0
	Commercial	5.1	5.1	5.1	0.0	5.1	0.0	5.1	0.0
	Transportation	6.6	6.6	6.6	6.6	2.4	2.4	6.6	2.4
	Total	66.6	34.1	52.3	61.5	62.4	10.5	66.6	10.5

Likewise, it can be seen from Figure 8 that a reduction in 97% of emissions can be achieved compared to the baseline for 2050 in the domestic sector under the DOM scenario. Similarly, the possible reductions in emissions from the industrial, commercial and transportation sectors have been estimated to be 67%, 100% and 64% respectively for 2050 under the IND, COM and TRA scenarios. Moreover, the combined effects can be seen in the composite DSM and WIS scenarios.

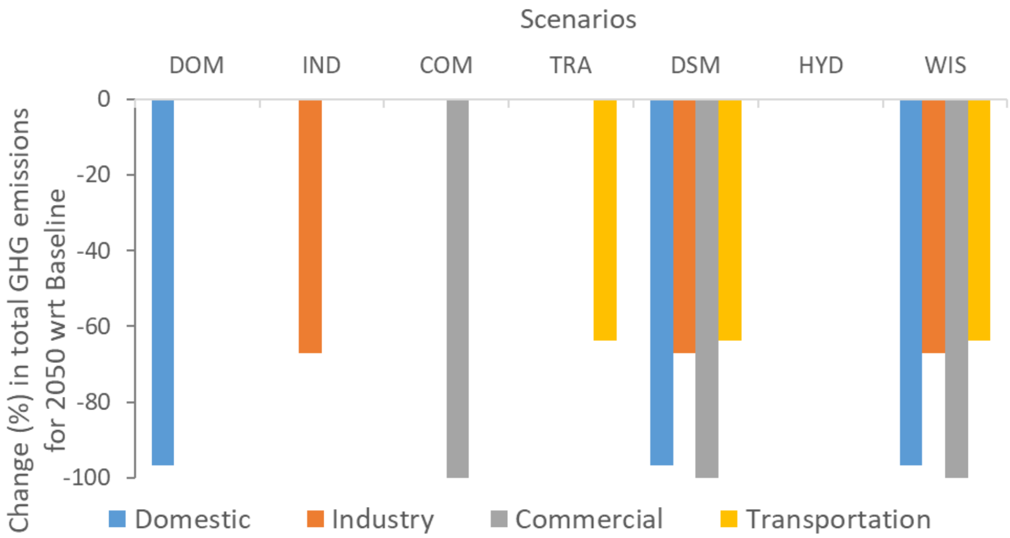

Figure 8: Change (%) in total GHG emissions for 2050 of different scenarios with respect to baseline

4. Discussion

4.1 Lessons Learnt from the Past

Results of this study show that Nepal has had a progressive policy development trajectory (Figure 4). However, the implementation side has not been as expected. Constrained economic conditions for energy generation (MoF/GoN, 2022), rising demands (NEA/GoN, 2022) and limited fuel import capabilities (MoICS/GoN, 2022a) could be major contributing factors. As a result, traditional sources still constituted the largest share of the energy mix in Nepal in the fiscal year 2021/22, with 64.2% of the total, while commercial sources accounted for 33.3% and 2.5%, respectively (WECS/GoN, 2023).

This study also shows that Nepal has been adopting a 'meet-with-import' approach to fulfill current unmet energy demands. This is evident in three major sectors: the household sector (particularly urban) through the import of large amounts of LPG, and the transportation and industrial sectors through the import petrol and diesel (MoF/GoN, 2022). These are also the major sources of energy-related emissions, as demonstrated by the HYD and WIS scenarios in this paper. On the demand side, the household sector is still not adequately addressed by policies. It remains the largest energy-consuming sector in the country, with a share of 64.2% and 53% of the rural population still relying on firewood and dry dung for cooking (CBS, 2021).

Different types of energy sources are feasible in different parts of the world. Some regions are rich in natural gas and coal (such as Australia), while some have abundant petroleum (such as the Middle East) (Cook et al., 2022). The Himalayan region has a very high potential for hydropower development (Lutz et al., 2022; Xu et al., 2023). Nepal's energy landscape has been historically dominated by hydropower. Encouraging policies such as the Water Resources Strategy, Hydropower Development Policy and the Twenty Years Hydropower Development Plan of Nepal, among others, underscore its commitment to the use of renewables

(WECS/HMG/N, 2002; MoE/GoN, 2009). Moreover, the importance of hydropower development in Nepal, as highlighted by Baniya et al. (2023), Bhattarai et al. (2022a), Devkota et al. (2022), Marahatta et al. (2022), and Sharma and Awal (2013), and others, resonates with the global efforts of efficient renewable energy generation (IHA, 2024). Hydropower is a well-established, efficient energy generation technology characterized by high energy return on investment, lower per unit capital cost, and base load stability (Garcia-olivares et al., 2018; Siri et al., 2021; Tomczyk and Wiatkoswki, 2020). Furthermore, the resilience of storage-type hydropower projects to climatic shocks aligns with the global need for sustainable and adaptable energy infrastructures in the face of climate change.

The current capacity of other renewables such as micro-hydro, solar, pumped storage hydropower, wind, biogas, and hybrid systems in Nepal collectively amounts to approximately 82 MW (MoF/GoN, 2022). Studies by Lohani and Blakers (2021), Sanjel and Baral (2021) and Baniya et al. (2023) point to the untapped potential for diversification and resilience which are in line with global trends towards hybrid energy systems and energy self-sufficiency. However, the sustainability of renewable energy projects largely depends on technological reliability, financial viability and community participation and acceptance (Butchers et al., 2020). Bhattarai et al. (2023a) underscore the importance of building an "energy ecosystem" assessing context specific energy needs, availability and viability of technologies and local capacity strengthening for sustainability. Researchers have identified environmental and social vulnerabilities associated with energy technologies such as storage type hydropower (Hecht et al., 2019; Kelman et al., 2016; McVittie & Faccioli, 2020). However, studies have also highlighted ways to minimize these vulnerabilities without hampering the development of such projects, which could be multi-dimensionally beneficial (Bhattarai et al., 2023b).

4.2 Future directions for Nepal

Nepal faces a suppressed energy demand, impacting its energy security (Bhattarai et al., 2024). Hence, creating sufficient energy demand within the country is equally important to avoid energy spill and ensure the economic feasibility of the existing and planned energy generation projects. The residential sector, which has received little attention in energy planning (Das et al., 2022; Koirala and Acharya, 2022; Bhattarai et al., 2023c), is a significant part of this demand. The household sector improvement scenario (DOM) of this study emphasizes replacing traditional technologies with modern, energy-efficient appliances and increasing the use of renewables. Moreover, not all sectors have equal economic benefits to Nepal and therefore, should be treated differently in terms of energy planning and emissions reduction. We anticipate the respective sectoral shares on the total demand not to drastically differ in the near future from the current values. Efficient energy consumption, as recommended by Butchers et al. (2020) and Fares and Webber (2017), alongside incentives for clean energy use (Israel and Jehling, 2019; Pablo-Romero et al., 2021), could improve energy security if these incentives reach those in need (Bhattarai et al., 2018). Furthermore, we have tried to avoid using overly hypothetical estimates in the supply side in our analysis. Hence, there is very less difference in the energy balance between the DSM and WIS scenarios.

The transportation sector of Nepal, which is heavily reliant on fossil fuels, could benefit from shift toward clean energy vehicles. However, the operationalization of existing policies has been challenging (JICA/DOR/KVDA, 2017; Mali et al., 2022). Without a clear development trajectory and the necessary infrastructure, a clean energy revolution in this sector seems unlikely in the near future, despite its potential for energy savings and emissions reductions by 2050 (TRA scenario in this study shows a cumulative energy saving of 21 Mtoe and reduction in emissions by 4 $MtCO_2$-e by 2050).

The service and commercial sectors, particularly tourism and information technology, present promising opportunities for Nepal's energy future. Electrification of these sectors using domestically generated clean electricity, could drive economic growth with minimal infrastructure investments. Although the government has identified these sectors for foreign investment (MoICS/GoN, 2022b), provisions for tax subsidies on energy-efficient manufacturing equipment (for example, envisioned by the Industrial Policy 2011 and Industrial Enterprise Act 2020) have not been realized.

Nepal's industrial sector faces unique challenges as a landlocked country. The need to import raw materials, coupled with competition from established markets like China and India, limits the economic benefits of expanding manufacturing industries. The energy demand can only be partially met by domestically generated electricity (WECS/GoN, 2023), at least in the near future. Theoretically, expanding the manufacturing industries will have multiple economic benefits. However, to what extent and how much beneficial it can be is again another topic of research. Conversely, increased manufacturing industries could lead to a rise in fuel imports, stressing the economy without necessarily yielding profitable outcomes in the international market (USAID-SARI, 2003). Likewise, mechanization of the agriculture sector has some positive impacts in the reduction of traditional fuels but could likely lead to increased dependence on imported fuels. The IND scenario in this paper reflects these conditions in which the cumulative energy saving amounts to 33 Mtoe and reduction in emissions amounts to 14.3 $MtCO_2$-e by 2050.

Additionally, issues such as increasing tax on electric vehicles (Mali et al., 2022), improper allocation of renewable energy subsidies (Bhattarai et al., 2018) and institutional failures (Dhital et al., 2016), particularly in the rural remote areas, hinder sustainable development. Furthermore, setting politically driven targets, such as renewable energy farms (Rai, 2021) or petroleum pipelines (PIB/GoI, 2019) could lead to major concerns of sustainability and economic viability, which seek immediate attention. The DSM scenario (Figure 5) indicates that changes in energy behaviour across sectors could significantly reduce energy consumption (cumulative reduction by 38%) and emissions (reduction by 48%) by 2050.

Nepal's reliance on run-of-river hydropower projects has led to challenges in meeting energy demands, particularly during the dry season, emphasizing the need for a diversified energy mix. Strengthening domestic energy supply, particularly through hydropower and other renewables, is crucial. Developing storage-type hydropower projects at strategic locations (Pokharel and Regmi, 2024), along with innovations like pumped storage (Baniya et al., 2023), interconnected micro-grids (Gao et al., 2023), and floatavoltaics (Almelda et al., 2022), could ensure energy stability while addressing environmental and community vulnerabilities (Bhattarai et al., 2023a). Furthermore, the country could benefit from concentrating its efforts on building national capacity in the energy sector through cooperatives (Wagemans et al., 2019) and promoting community-centred off-grid renewable projects (WPalit and Bandyopadhyay, 2016).

The "Wish-for" (WIS) scenario in this study outlines a pathway for Nepal to achieve a clean energy transition by 2050, reducing reliance on energy imports and fossil fuels. This scenario combines the benefits of both the supply-side management of hydropower (HYD) and the demand-side management (DSM) strategies, showcasing the potential for a holistic approach to energy planning. Figure 9 is a Sankey diagram corresponding to the WIS scenario for the year 2050. Despite its vast renewable energy potential, Nepal has struggled to exploit it. Hydropower is projected to play a leading role in meeting the energy demands across all sectors, with biomass, including biogas, also having a significant share in the domestic sector. Other alternative renewables are likely to have lesser impacts.

Developing clean energy in Nepal could reduce the trade deficit and contribute to regional GHG emission reductions. Bhattarai et al. (2023) carried out a comprehensive assessment of different renewable energy technologies feasible for Nepal and emphasized the importance of hydropower for the country, which has also been the key focus of the Government of Nepal (WECS/GoN, 2013; NPC/GoN, 2017). IEA (2021) has also highlighted hydropower as the "forgotten giant of low carbon electricity", urging it to be one of the current leading clean and efficient renewable energy technologies for achieving net-zero emissions targets by mid-century.

Scholars assessed environmental, energy security and equity benefits of net zero emissions (Shakya et al., 2023) in relation to the well-being of a majority of Nepal's population in the near future (Aryal and Dhakal, 2022). Shakya et al. (2023) show promising results of reduced air pollutant emissions by up to 85% in 2050 from the reference scenario with suitable interventions in place, in addition to considerable improvement in the energy security and equity conditions of the country. However, setting ambitious targets without proper planning and development is unlikely to succeed. Hence, Nepal should refrain from 'bike shedding' in the energy sector realizing that the (past and) current efforts by the state have undergone a lot of distractions, focusing on other subsidiary activities rather than the main issue at hand (Bhattarai et al., 2024b). The country could significantly benefit from focusing on developing dedicated energy infrastructure, conducting awareness programs for energy efficiency, and investing in research and development of local energy technologies. Furthermore, it is recommended that energy planning and policy formulation be evidence-based, with pragmatic and achievable goals and further attract the private sector in energy generation.

The impressive contribution of the private sector (55% of the total installed capacity, NEA/GoN (2023)) in Nepal's hydropower development is an exemplary model for public-private collaboration in the energy sector. Studies on future cross-border electricity trade through hydropower development are promising, particularly in the Himalayan region (SARI/EI-IRADe, 2021; Hussain et al., 2019). However, challenges in policy implementation reflect a common struggle among developing nations, including Nepal, as highlighted in studies of Brazil (Ávila et al., 2021), Asia (Mohsin et al., 2021), Africa (Müller et al., 2021), and South Asia (Shakya et al., 2022).

Nepal is one of the least energy consuming (MoF/GoN, 2021) and carbon emitting countries in the world (WB, 2024). Due to such miniscule magnitudes compared to the world values, altered energy generation and use of Nepal will not have considerable impacts globally. However, information obtained from this study particularly on recapitulating past policies, sectoral demand management and diversification of energy generation mix considering local contexts could be useful references for other countries, particularly in the developing world.

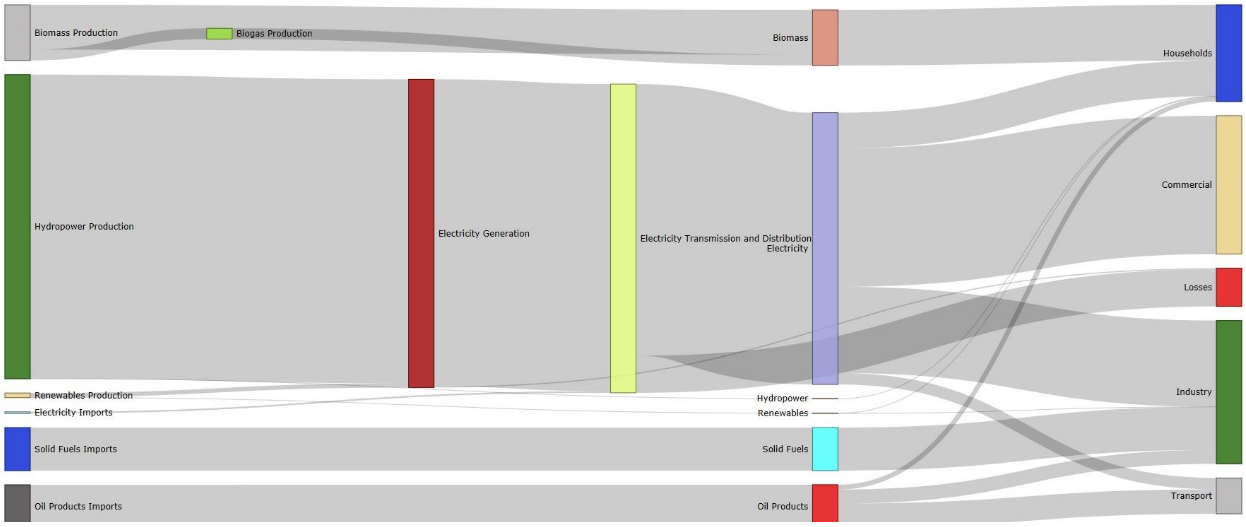

Figure 9: Sankey diagram for the WIS scenario (year 2050) showing the transformation of energy from multiple sources and their distribution across the different demand sectors.

4.3 Wider inferences

Current global debates in energy research and climate change revolve around balancing innovation with implementation while minimizing the adverse impacts (Cevik, 2024; Johnson and VanDeveer, 2024). A key dilemma is to whether focus on developing new technologies or scale up existing ones. Many developed countries such as Australia, New Zealand, Japan, Canada, and European nations, have adopted both measures in parallel (Bradford, 2022; Cetkovic and Buzogany, 2019; Child et al., 2019; Hurford et al., 2020; Ichimura and Kimura, 2019; Kelly-Richards et al., 2017; Wagner et al., 2019). But the developing nations, for example in Africa (Haldar et al., 2023), South-East Asia (Adha et al., 2024; Franco and Taeighagh, 2024), Central Asia (Karatayev et al., 2016), and South Asia (Tiwari et al., 2024), are financially constrained that prevents them from being benefitted from such choices for energy transition. Hence, expanding and modernizing energy systems in the developing world has been focused by the UN in its SDG-7 (UN, 2015).

The developing countries are undergoing a situation of carbon lock-in because of the large long-term investments made in carbon-intensive infrastructure, institutional inertia preventing changes, behavioural and social norms favouring carbon-intensive lifestyles, and a technology path dependent self-reinforcing cycle (Chen et al., 2023; Jewell et al., 2019; Robertson, 2022; Sovacool and Brisbois, 2019; Trencher er tal., 2020). Studies have highlighted the effectiveness of carbon pricing mechanisms and price elasticity of emissions reduction (Jan et al., 2021; Klenert et al., 2018), strategies for decarbonizing heavy industries (Verpoort et al., 2024; Zhang et al., 2024) and maintaining a balance between regulation and market-based approaches for renewable energy transitions to achieve net zero targets (Döbbeling-Hildebrandt, et al., 2024; Gasparini et al., 2024). However, scholars have also raised concerns about whether transitioning to renewables actually benefit decarbonization (Debnath and Mourshed, 2024; Johnstone et al., 2020; York and Bell, 2019). Additionally, the controversial role of nuclear power because of its low carbon benefits versus safety and waste concerns have gained much global attention recently. For instance, Chung and Kim (2018) showed that South Koreans are reluctant to transition to nuclear power as a solution to climate change mitigation. Similarly, Poortinga et al. (2013) demonstrate the hesitancy among the Japanese people to continue nuclear power plants for climate change mitigation after the Fukushima tragedy.

In the context of climate change, there is a persistent challenge in balancing adaptation strategies with mitigation efforts (Aboagye and Sharifi, 2024; Kyriakopoulos et al., 2023; Raihan, 2023). Moreover, climate (in)justice arising out of disparities particularly affecting poorer and less resourceful nations are rising areas of contemporary research (Osborne and Carlson, 2023; Morrison et al., 2023). The Intergovernmental Panel on Climate Change (IPCC) AR6 Working Group III report emphasizes the urgency of immediate climate action through detailed assessments of current and future emission trends, mitigation pathways to limit global warming within allowable limits, sectoral mitigation options and the roles of policies and measures (IPCC, 2023; Akpuokwe et al., 2024). Moreover, this urgency is influenced by technological innovations, socio-economic behavioural aspects, international cooperation, and co-benefits and trade-offs that vary by country, affecting their contributions to global mitigation efforts (Clabough, 2023; Caruso et al., 2024; Halsnaes et al., 2024; Sovacool and Griffiths, 2020). Furthermore, feasibility of net zero commitments (Sun et al., 2021; Tiwari et al., 2024), standardized emissions accounting and the role of negative emission technologies (Deng et al., 2024; Renforth, 2019) are also points of discussion in contemporary literature.

Hence, effectively managing the intermittency of renewable energy sources, investing in necessary infrastructure, and ensuring energy equity to avoid energy poverty have been crucial in transitioning to a renewable energy future.

As Vanegas Cantarero (2020) highlights, a large quantity of the remaining renewable energy potential yet to be harnessed is located in the developing countries which could be extremely valuable for the future. In the case of the US, Turner et al. (2024) show that only a fifth of the reduction in the country's hydropower generation is attributable to climate while the others are largely governed by deteriorating plant machinery and changes in dam operations requiring immediate attention. It is worth mentioning here that there are approximately 230,000 dams in 13 European countries, a considerable number of which are used for hydropower generation (Habel et al., 2020). Moreover, a recent study shows that two-thirds of the untapped global hydropower potential is in the Himalayas (Xu et al., 2023). Furthermore, global practices show that diversifying the energy mix is the most logical approach to energy transition (Nibedita and Irfan, 2024; Triguero-Ruiz et al., 2023). A strong government-society synergy with proper institutionalization and capacity strengthening of local enterprises are key to a successful transition (Bhattarai et al., 2023b).

4.4 Limitations

Some limitations are acknowledged in this research. The focus of this study was on synthesis of likely policy scenarios for the future followed by quantification of energy demand and supply conditions and energy-related emissions corresponding to these scenarios. On the use of models, both top-down and bottom-up methods are common in the scientific community for energy modelling. The top-down models are generally considered better in providing a wider overview of the problem at stake while the bottom-up methods are better in carrying out detailed assessment of sector-specific technologies mostly relying on primary data. As Li et al. (2020) and Yang et al. (2023) mention, the need for the approaches is mostly governed by the research objective and the spatial domain of coverage. Macroeconomic and other statistical data form the input dataset for the top-down methods while the bottom-up methods are more focused on individual components that can be aggregated to the stock level. As a result, analysts opt for bottom-up models for sector-level analysis such as in the residential buildings (Shimoda et al., 2021; Guo et al., 2021). On the other hand, national level or regional level studies are generally carried out in top-down models (Chen and Chen, 2019). Although the spatial coverage of this study was the whole of Nepal, a bottom-up approach was selected so that a detailed sectoral projection at the activity level could be modelled in order to closely examine how the activity level changes impact the overall the sectoral and national energy conditions of the country.

We have projected the past trends across the supply and demand sides leading to the baseline condition. However, the other cases (or scenarios) are projected, not only considering past trends but also future policy implications that we have identified from our review in this study. We acknowledge that there could be several other scenarios, for instance, impacts of climate change on energy generation and use behaviour, impacts of new development pathways and policy interventions, impacts of change in economic conditions (such as GDP) and geopolitical developments on the energy use, and impacts of increased education levels on the adoption of renewables (particularly in the household sector), among others. Hence, we do not claim our contribution in providing accurate information across this diverse spectrum of future energy conditions. We also understand that there are many uncertainties related to the data, assumptions, models, projections and the results. Moreover, the plausibility of each scenario, thus predicted, itself is one of the primary reasons for uncertainty. That is why, we have avoided generating future scenarios of development pathways or new technology policies that could further add to these uncertainties. Carrying out such quantitative scenarios analysis require inputs from multiple sectors, which was subject to resource implications. Rather, our analysis provides insights of how the energy conditions of the country could change should historic development trends continue, and the policy sphere does not vary much from its historical commitments. Although Nepal is an agricultural country, its share in the total energy consumption is less than 1% (WECS/GoN, 2023). Hence, this sector was clubbed with the Industrial sector in our analysis but can be treated separately, provided data is available. We assumed that the same hourly system load curve remains valid throughout our analysis duration; multiple options can be further tested. Energy assessment of public buildings have not been separately carried out because of lack of data. In addition, we have quantified the emissions in an aggregate. However, the impacts of the energy demand and supply changes can be assessed on the complete range of GHGs individually. These could be possible avenues for further research.

Conclusion

This study addressed the need to examine the historical development of energy policies, and model future energy generation, consumption, and emissions scenarios for Nepal, a developing country with significant renewable energy potential. By employing an integrated bottom-up approach using the Bottom-up Nepal LEAP (BU-NEP LEAP) model, this study synthesized scenarios that are indicative of the energy conditions of the country should historic development trends continue, and the policy sphere does not vary much from its historical commitments until mid-century. These scenarios were constructed through an extensive review of policies spanning the last four decades and consultations with experts, providing a comprehensive analysis of the energy trajectory Nepal might follow.

The results of this study show that Nepal has had a progressive policy development trajectory, but the implementation side has not been as expected. In addition, a ‘meet-with-import’ approach to fulfill current unmet energy demands across three major sectors: household (particularly urban) through the import of large amounts of LPG, and the transportation and industrial sectors through the import petrol and diesel could lead to sustainability issues. Furthermore, substantial potential for energy savings (up to 300 Mtoe until 2050) and emissions reductions (rom 66.6 $MtCO_2$-e in baseline to 10.5 $MtCO_2$-e by 2050) are seen across various sectors of Nepal. The residential sector, historically overlooked in energy planning despite its crucial role in energy demand management, could achieve a 38% reduction in energy consumption and a 48% reduction in emissions by 2050 through the adoption of cleaner and more efficient appliances. Similarly, while the transportation sector has the potential for energy savings and emissions reductions through the adoption of clean energy vehicles, the lack of clear policy implementation and necessary infrastructure remains a significant hurdle. Overall, comprehensive demand-side and supply-side interventions could achieve a 60% reduction in energy-related emissions across all sectors. This study underscores the importance of a diversified energy mix, emphasizing hydropower as the cornerstone of Nepal's energy future. However, despite the promising results, the study also highlights the persistent challenges of Nepal's reliance on petroleum imports and the underutilization of domestic renewable energy resources. Moreover, a resilient and self-sufficient energy future of Nepal warrants a balanced focus on domestic resource harnessing. The findings of this study are useful in guiding the identification and prioritization of areas for Nepal necessitating interventions augmenting effective sustainable energy management practices.

Wider inferences drawn from this study suggest that Nepal's energy transition could serve as a valuable reference for other developing countries facing similar challenges. The country's unique energy landscape, characterized by its heavy reliance on hydropower and significant untapped potential, offers insights into the complexities of balancing energy security, environmental sustainability and policy agility. The findings underscore the need for targeted sectoral strategies and robust policy frameworks to capitalize on the potential identified and overcome these challenges. Furthermore, a holistic approach combining both supply-side and demand-side management strategies is essential for achieving long-term energy goals. This study also recognizes the global context of energy transitions, and the importance of navigating critical issues such as financial constraints, institutional inertia, and the risks of carbon lock-in, among others, by developing nations such as Nepal, although detailed assessments of these issues were beyond the scope of this research. Furthermore, the study discusses the importance of government-society synergy and the role of private sector in energy generation. Other developing nations could benefit from these lessons from Nepal.

Finally, this research acknowledges certain limitations, including scenarios development, inherent uncertainties in long-term projections and the challenges of modelling in a dynamic socio-economic and geopolitical context. Further research could explore the economic impacts of additional development scenarios, the role of new technologies, and the potential for optimization algorithms in a constrained energy environment. Additionally, detailed studies on the impacts of climate change, policy interventions, and changes in economic conditions on energy futures would be valuable extensions of this work.

References

AEPC/GoN, 2009. Subsidy Policy for Renewable (Rural) Energy. Alternative Energy Promotion Centre, Government of Nepal, Kathmandu, Nepal

AEPC/MoEWRI/GoN, 2022a. Renewable Energy Subsidy Delivery Mechanism. Alternative Energy Promotion Centre, Ministry of Energy, Water Resources and Irrigation, Government of Nepal, Kathmandu, Nepal

AEPC/MoEWRI/GoN, 2022b. Renewable Energy Subsidy Policy. Alternative Energy Promotion Centre, Ministry of Energy, Water Resources and Irrigation, Government of Nepal, Kathmandu, Nepal

Ahmad, M., Dai, J., Mehmood, U., & Abou Houran, M. (2023). Renewable energy transition, resource richness, economic growth, and environmental quality: Assessing the role of financial globalization. Renewable Energy, 216, 119000.

Akpuokwe, C. U., Adeniyi, A. O., Bakare, S. S., & Eneh, N. E. (2024). Legislative responses to climate change: a global review of policies and their effectiveness. *International Journal of Applied Research in Social Sciences*, *6*(3), 225-239.

Almelda, R.M., Schmitt, R., Grodsky, S.M., Flecker, A.S., Gomes, C.P., Zhao, L., Liu, H., Barros, N., Kelman, R., McIntyre, P.B., 2022. Floating solar power: evaluate trade-offs. Nature 606, 246–249.

Amo-Aidoo, A., Kumi, E.N., Hensel, O., Korese, J.K., Sturm, B., 2022. Solar energy policy implementation in Ghana: A LEAP model analysis. Sci Afr. https://doi.org/10.1016/j.sciaf.2022.e01162

Andreas, J.J., Burns, C., Touza, J., 2018. Overcoming energy injustice? Bulgaria's renewable energy transition in times of crisis. Energy Res. Soc. Sci. 42, 44–52. https://doi.org/10.1016/j.erss.2018.02.020.

Aryal, S., Dhakal, S., 2022. Medium-term assessment of cross border trading potential of Nepal’s renewable energy using TIMES energy system optimization platform. Energy Policy 168. https://doi.org/10.1016/j.enpol.2022.113098

Aryal, S., Dhakal, S., KC, S., 2023. Integrated analysis of end-use electrification and cross-border electricity trade policies for hydropower enabled energy transformation in Nepal. Renew Energy 219. https://doi.org/10.1016/j.renene.2023.119467

Ates, S.A., 2015. Energy efficiency and CO2 mitigation potential of the Turkish iron and steel industry using the LEAP (long-range energy alternatives planning) system. Energy 90, 417–428. https://doi.org/10.1016/j.energy.2015.07.059

Ávila, L., Mine, M.R.M., Kaviski, E., Detzel, D.H.M., 2021. Evaluation of hydro-wind complementarity in the medium-term planning of electrical power systems by joint simulation of periodic streamflow and wind speed time series: A Brazilian case study. Renew Energy 167, 685–699. https://doi.org/10.1016/j.renene.2020.11.141

Azam, M., Othman, J., Begum, R.A., Abdullah, S.M.S., Nor, N.G.M., 2016. Energy consumption and emission projection for the road transport sector in Malaysia: an application of the LEAP model. Environ Dev Sustain 18, 1027–1047. https://doi.org/10.1007/s10668-015-9684-4

Baniya, R., Talchabhadel, R., Panthi, J., Ghimire, G.R., Sharma, S., Khadka, P.D., Shin, S., Pokhrel, Y., Bhattarai, U., Prajapati, R., Thapa, B.R., Maskey, R.K., 2023. Nepal Himalaya offers considerable potential for pumped storage hydropower. Sustainable Energy Technologies and Assessments 60. https://doi.org/10.1016/j.seta.2023.103423

Bashir, M. F., Pan, Y., Shahbaz, M., & Ghosh, S. (2023). How energy transition and environmental innovation ensure environmental sustainability? Contextual evidence from Top-10 manufacturing countries. Renewable Energy, 204, 697-709.

Bastola, U., Sapkota, P., 2015. Relationships among energy consumption, pollution emission, and economic growth in Nepal. Energy 80, 254–262. https://doi.org/10.1016/j.energy.2014.11.068

Bhandari, B., Lee, K.T., Chu, W.S., Lee, C.S., Song, C.K., Bhandari, P., Ahn, S.H., 2017. Socio-economic impact of renewable energy-based power system in mountainous villages of Nepal. International Journal of Precision Engineering and Manufacturing - Green Technology 4, 37–44. https://doi.org/10.1007/s40684-017-0005-2

Bhandari, R., Pandit, S., 2018. Electricity as a cooking means in Nepal-A modelling tool approach. Sustainability (Switzerland) 10. https://doi.org/10.3390/su10082841

Bhattarai, D., Somanathan, E., Nepal, M., 2018. Are renewable energy subsidies in Nepal reaching the poor? Energy for Sustainable Development 43, 114–122. https://doi.org/10.1016/j.esd.2018.01.001

Bhattarai, N., Bajracharya, I., 2016. Industrial Sector’s Energy Demand Projections and Analysis of Nepal for Sustainable National Energy Planning Process of the Country. Journal of the Institute of Engineering 11, 50–66. https://doi.org/10.3126/jie.v11i1.14695

Bhattarai, N., Kumar Jha, A., 2015. Commercial Sector Energy Demand Projections of Nepal for Sustainable Sectoral Energy Planning, Journal of Environment Protection and Sustainable Development.

Bhattarai, U., Devkota, L.P., Marahatta, S., Shrestha, D., Maraseni, T., 2022a. How will hydro-energy generation of the Nepalese Himalaya vary in the future? A climate change perspective. Environ Res 214, 113746. https://doi.org/10.1016/j.envres.2022.113746

Bhattarai, U., Devkota, R., Maraseni, T., Devkota, L., Marahatta, S., 2023a. Attaining multiple sustainable development goals through storage hydropower development amidst community vulnerabilities. Sustainable Development. https://doi.org/10.1002/sd.2634

Bhattarai, U., Maraseni, T., Apan, A., 2022b. Assay of renewable energy transition: A systematic literature review. Science of The Total Environment 833, 155159. https://doi.org/10.1016/j.scitotenv.2022.155159

Bhattarai, U., Maraseni, T., Apan, A., Devkota, L.P., 2023b. Rationalizing donations and subsidies: Energy ecosystem development for sustainable renewable energy transition in Nepal. Energy Policy 177, 113570. https://doi.org/10.1016/j.enpol.2023.113570

Bhattarai, U., Maraseni, T., Devkota, L.P., Apan, A., 2023c. Application of machine learning to assess people's perception of household energy in the developing world: A case of Nepal. Energy and AI 14. https://doi.org/10.1016/j.egyai.2023.100303

Bhattarai, U., Maraseni, T., Devkota, L.P., Apan, A., 2024a. A Composite Indicator-based Method to Assess the Energy Security of Nepal and prospects of Cross-border Electricity Sharing in South Asia. Environmental Development 51:101002. https://doi.org/10.1016/j.envdev.2024.101002

Bhattarai, U., Maraseni, T., Devkota, L.P., Apan, A., 2024b. Evaluating Four Decades of Energy Policy Evolution for Sustainable Development of a South Asian Country - Nepal: A Comprehensive Review. Sustainable Development. Sustainable Development, 1-29. https://doi.org/10.1002/sd.3053

Bigerna, S., Bollino, C.A., Polinori, P., 2021. Convergence in renewable energy sources diffusion worldwide. J. Environ. Manag. 292. https://doi.org/10.1016/j.jenvman.2021.112784.

Budhathoki, S., Yuangyai, C., Gyawali, S., Techato, K., 2021. Current Energy Scenario Of Nepal And Its Future Implication. International Journal of Energy, Environment, and Economics 29, 121–141.

Butchers, J., Williamson, S., Booker, J., Tran, A., Karki, B., Gautam, B., 2020. Understanding sustainable operation of micro-hydropower: a field study in Nepal. Energy for Sustainable Development 57, 12–21. https://doi.org/10.5523/bris.1k9cigxbcdiye22kuay4wbt5yu

Carrington, G., Stephenson, J., 2018. The politics of energy scenarios: Are International Energy Agency and other conservative projections hampering the renewable energy transition? Energy Res Soc Sci 46, 103–113. https://doi.org/10.1016/j.erss.2018.07.011

Caruso, G., de Marcos, I., & Noy, I. (2024). Climate changes affect human capital. *Economics of Disasters and Climate Change*, *8*(1), 157-196.

Castrejon-Campos, O., Aye, L., Hui, F.K.P., 2020. Making policy mixes more robust: an integrative and interdisciplinary approach for clean energy transitions. Energy Res. Soc. Sci. 64. https://doi.org/10.1016/j.erss.2020.101425

CBS, 2021. Nepal in Figures 2021. Central Bureau of Statistics, Government of Nepal.

Chen, H., & Chen, W. 2019. Carbon mitigation of China's building sector on city-level: Pathway and policy implications by a low-carbon province case study. Journal of Cleaner Production, 224, 207-217.

Chen, Y., Liu, K., Ni, L., & Chen, M. (2023). Impact of carbon lock-in on green economic efficiency: Evidence from Chinese provincial data. *Science of The Total Environment*, *892*, 164581.

Child, M., Bogdanov, D., Aghahosseini, A., Breyer, C., 2020. The role of energy prosumers in the transition of the Finnish energy system towards 100 % renewable energy by 2050. Futures 124. https://doi.org/10.1016/j.futures.2020.102644

Clabough, A. (2023). A transatlantic energy security strategy must also be a sustainable one. *Nat Energy* **8**, 1048. https://doi.org/10.1038/s41560-023-01357-x

Das, I., Rogers, B., Nepal, M., & Jeuland, M. 2022. Fuel stacking implications for willingness to pay for cooking fuels in peri-urban Kathmandu Valley, Nepal. Energy for Sustainable Development, 70, 482–496. https://doi.org/10.1016/j.esd.2022.08.017

Devkota, L.P., Bhattarai, U., Khatri, P., Marahatta, S., Shrestha, D., 2022. Resilience of hydropower plants to flow variation through the concept of flow elasticity of power: Theoretical development. Renew Energy 184, 920–932. https://doi.org/10.1016/j.renene.2021.11.051

Dhaubanjar, P., Nakarmi, A.M., Bajracharya, S.B., 2019. Energy Scenarios of Household Sector In Panauti Municipality For Sustainable Development and Energy Security. Journal of Advanced College of Engineering and Management 5, 89–100. https://doi.org/10.3126/jacem.v5i0.26692

Dhital, R.P., Ito, Y., Kaneko, S., Komatsu, S., Mihara, R., Yoshida, Y., 2016. Does institutional failure undermine the physical design performance of solar water pumping systems in rural Nepal? Sustainability (Switzerland) 8. https://doi.org/10.3390/su8080770

Di Sbroiavacca, N., Nadal, G., Lallana, F., Falzon, J., Calvin, K., 2016. Emissions reduction scenarios in the Argentinean Energy Sector. Energy Econ 56, 552–563. https://doi.org/10.1016/j.eneco.2015.03.021

Döbbeling-Hildebrandt, N., Miersch, K., Khanna, T.M. *et al.* (2024). Systematic review and meta-analysis of ex-post evaluations on the effectiveness of carbon pricing. *Nat Commun* **15**, 4147. https://doi.org/10.1038/s41467-024-48512-w

DoC/GoN, 2023. Nepal Foreign Trade Statistics Fiscal Year 2022/23 (2079/80). Department of Customs, Government of Nepal

Dulal, S., Shakya, S.R., 2020. Energy Security and Scenario Analysis of Province One of Federal Democratic Republic of Nepal. Journal of the Institute of Engineering 15, 104–121. https://doi.org/10.3126/jie.v15i3.32158

Durmanov, A., Saidaxmedova, N., Mamatkulov, M., Rakhimova, K., Askarov, N., Khamrayeva, S., Mukhtorov, A., Khodjimukhamedova, S., Madumarov, T. and Kurbanova, K., 2023. Sustainable growth of greenhouses: investigating key enablers and impacts. Emerging Science Journal, 7(5), pp.1674-1690.

El Alaoui, M., Chahidi, L.O., Rougui, M., Lemrani, A. and Mechaqrane, A., 2023. Prediction of energy consumption of an administrative building using machine learning and statistical methods. Civil Engineering Journal, 9(5), pp.1007-1022.

Fares, R.L., Webber, M.E., 2017. The impacts of storing solar energy in the home to reduce reliance on the utility. Nat Energy 2. https://doi.org/10.1038/nenergy.2017.1

Ferdoush, M. R., Al Aziz, R., Karmaker, C. L., Debnath, B., Limon, M. H., & Bari, A. M. 2024. Unraveling the challenges of waste-to-energy transition in emerging economies: Implications for sustainability. Innovation and Green Development, 3(2), 100121.

Gao, H., Hu, M., He, S. and Liu, J., 2023. Green electricity trading driven low-carbon sharing for interconnected microgrids. Journal of Cleaner Production, p.137618.

Gasparini, M., Ives, M.C., Carr, B. *et al.* (2024). Model-based financial regulations impair the transition to net-zero carbon emissions. *Nat. Clim. Chang.* **14**, 476–481. https://doi.org/10.1038/s41558-024-01972-w

Gebreslassie, M.G., Cuvilas, C., Zalengera, C., To, L.S., Baptista, I., Robin, E., Bekele, G., Howe, L., Shenga, C., Macucule, D.A., Kirshner, J., Mulugetta, Y., Power, M., Robinson, S., Jones, D., Castán Broto, V., 2022. Delivering an off-grid transition to sustainable energy in Ethiopia and Mozambique. Energy Sustain Soc 12. https://doi.org/10.1186/s13705-022-00348-2

GoN, 2012. National Renewable and Rural Energy Program (2012-2017). Government of Nepal, Singhadurbar, Kathmandu, Nepal

GoN, 2016. Renewable Energy Subsidy Policy, 2016. Government of Nepal, Kathmandu, Nepal

GoN, 2020. Second Nationally Determined Contribution (NDC), Government of Nepal Government of Nepal, Kathmandu, Nepal.

GoN, 2021. Nepal's Long-term Strategy for Net-zero Emissions. Government of Nepal, Kathmandu, Nepal.

Guo, S., Yan, D., Hu, S., & Zhang, Y. 2021. Modelling building energy consumption in China under different future scenarios. Energy, 214, 119063.

Gyanwali, K and Bajracharya,T.R., 2013. Demand side management in industrial sector of Nepal. Proceedings of IOE Graduate Conference, Vol. 1, November 2013, Kathmandu, Nepal

Halsnæs, K., Some, S., & Pathak, M. (2024). Beyond synergies: understanding SDG trade-offs, equity and implementation challenges of sectoral climate change mitigation options. *Sustainability Science*, *19*(1), 35-49.

Heaps, C., 2022. The Low Emissions Analysis Platform (LEAP) [software] version 2020.1.106. Stockholm Environment Institute, Somerville, MA, USA

Hilpert, S., Kaldemeyer, C., Krien, U., Günther, S., Wingenbach, C., Plessmann, G., 2018. The Open Energy Modelling Framework (oemof) - A new approach to facilitate open science in energy system modelling. Energy Strategy Reviews 22, 16–25. https://doi.org/10.1016/j.esr.2018.07.001

HMG/N, 1985. Seventh Plan (1985-1990). His Majesty's Government of Nepal, Singha Durbar, Kathmandu, Nepal

HMG/N, 1992a. Eighth Plan (1992-1997). His Majesty's Government of Nepal, Singha Durbar, Kathmandu, Nepal

HMG/N, 1992b. The Industrial Enterprises Act, 2049 (1992). His Majesty's Government of Nepal, Singha Durbar, Kathmandu, Nepal

HMG/N, 1992c. Water Resources Act, 2049 (1992). His Majesty's Government of Nepal, Kathmandu, Nepal

HMG/N, 1992d. Hydropower Development Policy, 1992. His Majesty's Government of Nepal, Kathmandu, Nepal

HMG/N, 1993a. Electricity Rules, 2050 (1993). His Majesty's Government of Nepal, Kathmandu, Nepal

HMG/N, 1993b. Nepal Environmental Policy and Action Plan. Environmental Protection Council, His Majesty's Government of Nepal, Singha Durbar, Kathmandu, Nepal

HMG/N, 1999a. Forest Sector Policy 2000. Ministry of Forests and Soil Conservation, His Majesty's Government of Nepal, Kathmandu, Nepal

HMG/N, 1999b. Local Self-Governance Act, 2055 (1999). His Majesty's Government of Nepal, Singha Durbar, Kathmandu, Nepal

HMG/N, 2001. Hydropower Development Policy, 2058 (2001). Government of Nepal, Kathmandu, Nepal

Huda, M.S., Ali, S.H., 2018. Environmental peacebuilding in South Asia: Establishing consensus on hydroelectric projects in the Ganges-Brahmaputra-Meghna (GBM) Basin. Geoforum 96, 160–171. https://doi.org/10.1016/j.geoforum.2018.08.015

Hussain, A., Sarangi, G.K., Pandit, A., Ishaq, S., Mamnun, N., Ahmad, B., Jamil, M.K., 2019. Hydropower development in the Hindu Kush Himalayan region: Issues, policies and opportunities. Renewable and Sustainable Energy Reviews. https://doi.org/10.1016/j.rser.2019.03.010

Hussain, S. A., Razi, F., Hewage, K., & Sadiq, R. (2023). The perspective of energy poverty and 1st energy crisis of green transition. Energy, 275, 127487.

Hvelplund, F., Djørup, S., 2017. Multilevel policies for radical transition: governance for a 100% renewable energy system. Environ.Plan.C Polit.Space 35, 1218–1241. https://doi.org/10.1177/2399654417710024

IEA, 2023a. CO2 Emissions in 2023, International Energy Agency, France. https://www.iea.org/reports/co2-emissions-in-2023.

IEA, 2023b. World Energy Outlook 2023, International Energy Agency, France. https://www.iea.org/data-and-statistics/data-product/world-energy-outlook-2023-free-dataset-2 (accessed 10 May 2024)

Indra Al Irsyad, M., Halog, A.B., Nepal, R., Koesrindartoto, D.P., 2017. Selecting tools for renewable energy analysis in developing countries: An expanded review. Front Energy Res. https://doi.org/10.3389/fenrg.2017.00034

Intergovernmental Panel on Climate Change (IPCC) (ed.) (2023) 'Summary for Policymakers', in Climate Change 2022 - Mitigation of Climate Change: Working Group III Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press, pp. 3–48.

Jewell, Jessica, Vadim Vinichenko, Lola Nacke, and Aleh Cherp. (2019). "Prospects for powering past coal." *Nature climate change* 9, no. 8: 592-597.

JICA/DOR/KVDA, 2017. Federal Democratic Republic of Nepal The Project on Urban Transport Improvement for Kathmandu Valley Master Plan and Pilot Project. Kathmandu, Nepal.

Johannsen, R. M., Prina, M. G., Østergaard, P. A., Mathiesen, B. V., & Sparber, W., 2023. Municipal energy system modelling–A practical comparison of optimisation and simulation approaches. Energy, 269, 126803.

Klenert, D., Mattauch, L., Combet, E. *et al.* (2018). Making carbon pricing work for citizens. *Nature Clim Change* **8**, 669–677. https://doi.org/10.1038/s41558-018-0201-2

Koirala, D. P., & Acharya, B. 2022. Households' fuel choices in the context of a decade-long load-shedding problem in Nepal. Energy Policy, 162, 112795. https://doi.org/10.1016/j.enpol.2022.112795

Kuldna, P., Peterson, K., Kuhi-Thalfeldt, R., 2015. Knowledge brokering on emissions modelling in Strategic Environmental Assessment of Estonian energy policy with special reference to the LEAP model. Environ Impact Assess Rev 54, 55–60. https://doi.org/10.1016/j.eiar.2015.06.001

Kurniawan, T.B., Dewi, D.A., Usman, F. and Fadly, F., 2023. Towards Energy Analysis and Efficiency for Sustainable Buildings. Emerging Science Journal, 7(6), pp.2226-2238.

Li, Z., Lin, B., Zheng, S., Liu, Y., Wang, Z., & Dai, J. (2020, August). A review of operational energy consumption calculation method for urban buildings. In Building Simulation (Vol. 13, pp. 739-751). Tsinghua University Press.

Liya, C., Jianfeng, G., 2018. Scenario analysis of CO 2 emission abatement effect based on LEAP, in: Energy Procedia. Elsevier Ltd, pp. 965–970. https://doi.org/10.1016/j.egypro.2018.09.101

Lohani, S.P., Blakers, A., 2021. 100% renewable energy with pumped-hydro-energy storage in Nepal. Clean Energy. https://doi.org/10.1093/ce/zkab011

Mali, B., Shrestha, A., Chapagain, A., Bishwokarma, R., Kumar, P., Gonzalez-Longatt, F., 2022. Challenges in the Penetration of Electric Vehicles in Developing Countries with a Focus on Nepal. Renewable Energy Focus. https://doi.org/10.1016/j.ref.2021.11.003.

Malla, S., 2013. Household energy consumption patterns and its environmental implications: Assessment of energy access and poverty in Nepal. Energy Policy 61, 990–1002. https://doi.org/10.1016/j.enpol.2013.06.023

Malla, S., 2022. An outlook of end-use energy demand based on a clean energy and technology transformation of the household sector in Nepal. Energy 238. https://doi.org/10.1016/j.energy.2021.121810

Marahatta, S., Aryal, D., Devkota, L.P., Bhattarai, U., Shrestha, D., 2021. Application of swat in hydrological simulation of complex mountainous river basin (Part ii: Climate change impact assessment). Water (Switzerland) 13. https://doi.org/10.3390/w13111548

Marahatta, S., Bhattarai, U., Devkota, L.P., Aryal, D., 2022. Unravelling the water-energy-economics-continuum of hydroelectricity in the face of climate change. International Journal of Energy and Water Resources. https://doi.org/10.1007/s42108-021-00174-w

Masson-Delmotte, V., Zhai, P., Chen, Y., Goldfarb, L., Gomis, M.I., Matthews, J.B.R., Berger, S., Huang, M., Yelekçi, O., Yu, R., Zhou, B., Lonnoy, E., Maycock, T.K., Waterfield, T., Leitzell, K., Caud, N., 2021. Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.

McPherson, M., Karney, B., 2014. Long-term scenario alternatives and their implications: LEAP model application of Panama's electricity sector. Energy Policy 68, 146–157. https://doi.org/10.1016/j.enpol.2014.01.028

Mirjat, N.H., Uqaili, M.A., Harijan, K., Walasai, G. Das, Mondal, M.A.H., Sahin, H., 2018. Long-term electricity demand forecast and supply side scenarios for Pakistan (2015–2050): A LEAP model application for policy analysis. Energy 165, 512–526. https://doi.org/10.1016/j.energy.2018.10.012

MoE/GoN, 2006. Rural Energy Policy, 2006. Ministry of Environment, Government of Nepal, Singhadurbar, Kathmandu, Nepal

MoE/GoN, 2009. Twenty Years Hydropower Development Plan. Ministry of Energy, Government of Nepal, Kathamndu, Nepal

MoE/GoN, 2010. National Adaptation Program of Action (NAPA) to Climate Change. Ministry of Environment, Government of Nepal, Kathmandu, Nepal

MoEWRI/GoN, 2018. Whitepaper on Energy, Water and Irrigation: Present Situation and Future Prospect. Ministry of Energy, Water Resources and Irrigation, Government of Nepal, Kathmandu, Nepal

MoF&E/GoN, 2021. Nepal's Third National Communication to the United Nations Framework Convention on Climate Change. Ministry of Forests and Environment, Government of Nepal, Kathmandu, Nepal

MoF&SC/GoN, 2016. Forest Sector Strategy (2016-25). Ministry of Forests and Soil Conservation, Government of Nepal, Babarmahal, Kathmandu, Nepal

MoF/GoN, 2020. Economic Survey 2019/20. Ministry of Finance, Government of Nepal, Singhadurbar Kathmandu, Nepal

MoF/GoN, 2021. Economic Survey 2020/21. Ministry of Finance, Government of Nepal, Singhadurbar Kathmandu, Nepal

MoF/GoN, 2022. Economic Survey 2021/22. Ministry of Finance, Government of Nepal, Singhadurbar Kathmandu, Nepal

MoFA&GM/GoN, 2021. Environment-friendly Local Governance Framework. Ministry of Federal Affairs and Generation Administration, Government of Nepal, Kathmandu, Nepal

MoFA&LD/GoN, 2013. Environment-friendly Local Governance Framework, 2013. Ministry of Federal Affairs and Local Development, Government of Nepal, Kathmandu, Nepal

MoFE/MoPIT/GGGI, 2018. National Action Plan for Electric Mobility. Ministry of Forests and Environment, Ministry of Physical Infrastructure and Transport, Government of Nepal and Global Green Growth Institute, Korea

Mohsin, M., Kamran, H.W., Atif Nawaz, M., Sajjad Hussain, M., Dahri, A.S., 2021. Assessing the impact of transition from nonrenewable to renewable energy consumption on economic growth-environmental nexus from developing Asian economies. J Environ Manage 284. https://doi.org/10.1016/j.jenvman.2021.111999

MoICS/GoN, 2022a. Industrial Statistics Fiscal Year 2078/79 (2021/2022). Ministry of Industry, Commerce and Supplies, Government of Nepal, Kathmandu, Nepal.

MoICS/GoN, 2022b. Foreign Investment in Nepal A synopsis 2022. Ministry of Industry, Commerce and Supplies, Government of Nepal, Kathmandu, Nepal.

MoP&E/GoN, 2016. First Nationally Determined Contribution. Ministry of Population and Environment, Government of Nepal, Kathmandu, Nepal

MoPIT/GoN, 2014. Environment-friendly Vehicle and Transport Policy, 2014. Ministry of Physical Infrastructure and Transport, Government of Nepal, Kathmandu, Nepal

MoPIT/GoN, 2022. Urban Public Transport Management Authority Act, 2022. Ministry of Physical Infrastructure and Transport, Government of Nepal, Kathmandu, Nepal

MoSTE/GoN, 2013. Renewable Energy Subsidy Policy. Ministry of Science, Technology and Environment, Government of Nepal, Kathmandu, Nepal

Mukelabai MD, Wijayantha KGU, Blanchard RE, 2023. Using machine learning to expound energy poverty in the global south: understanding and predicting access to cooking with clean energy. Energy AI 14:100290. https://doi.org/10.1016/j.egyai.2023.100290.

Müller, F., Neumann, M., Elsner, C., Claar, S., 2021. Assessing african energy transitions: Renewable energy policies, energy justice, and SDG 7. Politics and Governance 9, 119–130. https://doi.org/10.17645/pag.v9i1.3615

Munro, F.R., 2019. Renewable energy and transition-periphery dynamics in Scotland. Environ. Innov.Soc.Transit. 31, 273–281. https://doi.org/10.1016/j.eist.2018.09.001.

Murshed, M. (2023). Efficacies of technological progress and renewable energy transition in amplifying national electrification rates: contextual evidence from developing countries. Utilities Policy, 81, 101512.

Nakarmi, A.M., Mishra, T., Banerjee, R., 2016. Integrated MAED–MARKAL-based analysis of future energy scenarios of Nepal. International Journal of Sustainable Energy 35, 968–981. https://doi.org/10.1080/14786451.2014.966712

NEA/GoN, 2020. A Year in Review Fiscal Year 2019/20. Nepal Electricity Authority, Government of Nepal, Kathmandu, Nepal

NEA/GoN, 2021. A Year in Review Fiscal Year 2020/21. Nepal Electricity Authority, Government of Nepal, Kathmandu, Nepal

NEA/GoN, 2022. A Year in Review Fiscal Year 2021/22. Nepal Electricity Authority, Government of Nepal, Kathmandu, Nepal

NEA/GoN, 2023. A Year in Review Fiscal Year 2022/23. Nepal Electricity Authority, Government of Nepal, Kathmandu, Nepal

Ngcamu, B. S. (2023). Climate change effects on vulnerable populations in the Global South: a systematic review. *Natural Hazards*, *118*(2), 977-991.

Nijsse, Femke JMM, Jean-Francois Mercure, Nadia Ameli, Francesca Larosa, Sumit Kothari, Jamie Rickman, Pim Vercoulen, and Hector Pollitt. 2023. "The momentum of the solar energy transition." Nature Communications 14, no. 1: 6542.

NISS/GoN, 2024. Nepal Investment Summit 2024. Nepal Investment Summit 2024 Secretariat, Government of Nepal [Web source: https://investinnepal.gov.np/] (accessed on 10 May 2024)

Nižetić, S., Arıcı, M., & Hoang, A. T. (2023). Smart and Sustainable Technologies in energy transition. Journal of cleaner production, 389, 135944.

NPC/GoN, 2016a. Fourteenth Periodic Plan (2016-2019). National Planning Commission, Government of Nepal, Singha Durbar, Kathmandu, Nepal

NPC/GoN, 2016b. Sustainable Development Goals - Status and Roadmap: 2016-2030. National Planning Commission, Government of Nepal, Kathmandu, Nepal

NPC/GoN, 2019. Fifteenth Plan (2019-2024). National Planning Commission, Government of Nepal, Singha Durbar, Kathmandu, Nepal

Palit, D., Bandyopadhyay, K.R., 2016. Rural electricity access in South Asia: Is grid extension the remedy? A critical review. Renewable and Sustainable Energy Reviews. https://doi.org/10.1016/j.rser.2016.03.034

Parag, Y., Ainspan, M., 2019. Sustainable microgrids: Economic, environmental and social costs and benefits of microgrid deployment. Energy for Sustainable Development 52, 72–81. https://doi.org/10.1016/j.esd.2019.07.003

Parajuli, R., Østergaard, P.A., Dalgaard, T., Pokharel, G.R., 2014. Energy consumption projection of Nepal: An econometric approach. Renew Energy 63, 432–444. https://doi.org/10.1016/j.renene.2013.09.048

Paudel, D., Jeuland, M., Lohani, S.P., 2021. Cooking-energy transition in Nepal: Trend review. Clean Energy. https://doi.org/10.1093/ce/zkaa022

PIB/GoI, 2019. Inauguration of Motihari-Amlekhganj (Nepal) pipeline by PM and PM Oli of Nepal [WWW Document]. Press Information Bureau, Government of India. URL https://pib.gov.in/PressReleseDetail.aspx?PRID=1584627 (accessed 6.10.22).

Pokharel, R., Bertolini, L., te Brömmelstroet, M., Acharya, S.R., 2021. Spatio-temporal evolution of cities and regional economic development in Nepal: Does transport infrastructure matter? J Transp Geogr 90. https://doi.org/10.1016/j.jtrangeo.2020.102904

Poudyal, R., Loskot, P., Nepal, R., Parajuli, R., Khadka, S.K., 2019. Mitigating the current energy crisis in Nepal with renewable energy sources. Renewable and Sustainable Energy Reviews. https://doi.org/10.1016/j.rser.2019.109388

Pradhan, S., Ale, B.B., Amatya, V.B., 2006. Mitigation potential of greenhouse gas emission and implications on fuel consumption due to clean energy vehicles as public passenger transport in Kathmandu Valley of Nepal: A case study of trolley buses in Ring Road. Energy 31, 1748–1760. https://doi.org/10.1016/j.energy.2005.10.013

Rai, S.B., 2021. Biggest solar power plant in Nepal worth 250 MW in Banke and Kapilvastu | study and research goes underway. https://www.greenesa.com/news/biggest-solar-power-plant-in-nepal. (Accessed 5 February 2023) [WWW Document].

Raihan, A. (2023). A review of the global climate change impacts, adaptation strategies, and mitigation options in the socio-economic and environmental sectors. *Journal of Environmental Science and Economics*, *2*(3), 36-58.

REN21, 2024. Renewables 2021 Global Status Report Paris.

Robertson, A. M. (2022). Challenging carbon lock-in: insights from US governmental energy research and development expenditures with advocacy recommendations for the energy research community. *Frontiers in Climate*, *4*, 831805.

Salari, M., Javid, R.J., Noghanibehambari, H., 2021. The nexus between CO2 emissions, energy consumption, and economic growth in the U.S. Econ Anal Policy 69, 182–194. https://doi.org/10.1016/j.eap.2020.12.007

Sanjel, N., Baral, B., 2020. Technical investigation of Nepalese electricity market-A review, in: Journal of Physics: Conference Series. IOP Publishing Ltd. https://doi.org/10.1088/1742-6596/1608/1/012005

Sanjel, N., Baral, B., 2021. Modelling and analysis of decentralized energy systems with photovoltaic, micro-hydro, battery and diesel technology for remote areas of Nepal. Clean Energy 5, 690–703. https://doi.org/10.1093/ce/zkab042

SARI/EI, 2021. Prospects for Sustainable Energy Infrastructure Development and Role of Cross Border Energy Trade in South Asia Challenges, Opportunities and Way forward. South Asia Regional Initiative for Energy Integration (SARI/EI) and Integrated Research and Action for Development (IRADe)

SARI/EI-IRADe, 2021. Strategy paper for creation of South Asia Forum for Electricity Market (SAFEM). South Asia Regional Initiative for Energy Integration (SARI/EI) and Integrated Research and Action for Development (IRADe)

SEI, 2022. LEAP. Stockholm Environment Institute (SEI). [WWW Document] https://www.sei.org/tools/leap-long-range-energy-alternatives-planning-system/ (accessed 4 March 2023)

Shahzadi, I., Yaseen, M.R., Iqbal Khan, M.T., Amjad Makhdum, M.S., Ali, Q., 2021. The nexus between research and development, renewable energy and environmental quality: evidence from developed and developing countries. Renew. Energy https://doi.org/10.1016/j.renene.2021.10.050.

Shakya, S.R., Adhikari, R., Poudel, S., Rupakheti, M., 2022. Energy equity as a major driver of energy intensity in South Asia. Renewable and Sustainable Energy Reviews 170. https://doi.org/10.1016/j.rser.2022.112994

Shakya, S.R., Nakarmi, A.M., Prajapati, A., Pradhan, B.B., Rajbhandari, U.S., Rupakheti, M., Lawrence, M.G., 2023. Environmental, energy security, and energy equity (3E) benefits of net-zero emission strategy in a developing country: A case study of Nepal. Energy Reports 9, 2359–2371. https://doi.org/10.1016/j.egyr.2023.01.055

Sharma, R.H., Awal, R., 2013. Hydropower development in Nepal. Renewable and Sustainable Energy Reviews 21, 684–693. https://doi.org/10.1016/j.rser.2013.01.013

Shimoda, Y., Sugiyama, M., Nishimoto, R., & Momonoki, T. 2021. Evaluating decarbonization scenarios and energy management requirement for the residential sector in Japan through bottom-up simulations of energy end-use demand in 2050. Applied Energy, 303, 117510.

Shrestha, A., Shrestha, S., Tingsanchali, T., Budhathoki, A., Ninsawat, S., 2021. Adapting hydropower production to climate change: A case study of Kulekhani Hydropower Project in Nepal. J Clean Prod 279, 123483. https://doi.org/10.1016/J.JCLEPRO.2020.123483

Shrestha, M.E.I., Sartohadi, J., Ridwan, M.K., Hizbaron, D.R., 2017. Urban energy scenario: The case of Kathmandu valley. Journal of Engineering and Technological Sciences 49, 210–224. https://doi.org/10.5614/j.eng.technol.sci.2017.49.2.4

Shrestha, R.M., Rajbhandari, S., 2010. Energy and environmental implications of carbon emission reduction targets: Case of Kathmandu Valley, Nepal. Energy Policy 38, 4818–4827. https://doi.org/10.1016/j.enpol.2009.11.088

Singh, P., Shakya, S.R., 2016. Policy Intervention to Reduce Energy Consumption and Mitigate Environmental Emission in Cement Industries of Nepal. International Journal of Environmental Protection and Policy 4, 34. https://doi.org/10.11648/j.ijepp.20160402.12

Sinha, A., Bekiros, S., Hussain, N., Nguyen, D. K., & Khan, S. A. (2023). How social imbalance and governance quality shape policy directives for energy transition in the OECD countries?. Energy Economics, 120, 106642.

Sovacool, Benjamin K., and Marie-Claire Brisbois. "Elite power in low-carbon transitions: A critical and interdisciplinary review." *Energy Research & Social Science* 57 (2019): 101242.

Sovacool, Benjamin K., and Steve Griffiths. "Culture and low-carbon energy transitions." *Nature Sustainability* 3, no. 9 (2020): 685-693.

Steckel, J.C., Dorband, I.I., Montrone, L. *et al.* (2021). Distributional impacts of carbon pricing in developing Asia. *Nat Sustain* **4**, 1005–1014. https://doi.org/10.1038/s41893-021-00758-8

Subedi, P., Shakya, S.R., 2016. Energy Efficiency and Low Carbon Strategy on Rural Tourism Area: A Case of Mount Annapurna Trekking Route. International Journal of Environmental Protection and Policy 4, 133. https://doi.org/10.11648/j.ijepp.20160405.14

Tiwari, S., Bashir, S., Sarker, T. *et al.* (2024). Sustainable pathways for attaining net zero emissions in selected South Asian countries: role of green energy market and pricing. *Humanit Soc Sci Commun* **11**, 93. https://doi.org/10.1057/s41599-023-02552-7

Trencher, G., Rinscheid, A., Duygan, M., Truong, N., & Asuka, J. (2020). Revisiting carbon lock-in in energy systems: Explaining the perpetuation of coal power in Japan. *Energy Research & Social Science*, *69*, 101770.

Tripathi, D., 2020. Re-imagining Border Studies in South Asia, First. ed. Routledge.

Vakulchuk, R., Overland, I., & Suryadi, B. 2023. ASEAN's energy transition: How to attract more investment in renewable energy. Energy, Ecology and Environment, 8(1), 1-16.

Vanegas Cantarero, M.M., 2020. Of renewable energy, energy democracy, and sustainable development: A roadmap to accelerate the energy transition in developing countries. Energy Res Soc Sci. https://doi.org/10.1016/j.erss.2020.101716

Verpoort, P.C., Gast, L., Hofmann, A. *et al.* (2024). Impact of global heterogeneity of renewable energy supply on heavy industrial production and green value chains. *Nat Energy* **9**, 491–503. https://doi.org/10.1038/s41560-024-01492-z

VRock, 2021. Report on projection of emission associated with electricity trading as part of Nepal's long-term strategy (LTS) to achieve net zero emissions status by 2050. Nepal Renewable Energy Programme, Kathmandu, Nepal.

Wagemans, D., Scholl, C., Vasseur, V., 2019. Facilitating the energy transition-the governance role of local renewable energy cooperatives. Energies (Basel) 12. https://doi.org/10.3390/en12214171

WECS/GoN 2023. Nepal Energy Sector Synopsis Report-2023. Water and Energy Commission Secretariat, Government of Nepal, Singhadurbar, Kathmandu, Nepal

WECS/GoN, 2013. Nepal's energy sector vision 2050 A.D. Kathmandu.

WECS/GoN, 2013a. National Energy Strategy of Nepal. Water and Energy Commission Secretariat, Government of Nepal, Singhadurbar, Kathmandu, Nepal

WECS/GoN, 2013b. Nepal's Energy Sector Vision 2050 A.D. Water and Energy Commission Secretariat, Government of Nepal, Singhadurbar, Kathmandu, Nepal

WECS/GoN, 2017. Electricity Demand Forecast Report. Water and Energy Commission Secretariat, Government of Nepal, Singhadurbar, Kathmandu, Nepal

WECS/GoN, 2022. Energy Sector Synopsis Report 2021/22. Water and Energy Commission Secretariat, Government of Nepal, Singhadurbar, Kathmandu, Nepal

WECS/HMG/N, 2002. Water Resources Strategy. Water and Energy Commission Secretariat, His Majesty's Government of Nepal, Singhadurbar, Kathmandu, Nepal

Weko, S., Goldthau, A., 2022. Bridging the low-carbon technology gap? Assessing energy initiatives for the Global South. Energy Policy 169. https://doi.org/10.1016/j.enpol.2022.113192

Werner, D., & Lazaro, L. L. B., 2023. The policy dimension of energy transition: The Brazilian case in promoting renewable energies (2000–2022). Energy Policy, 175, 113480.

Windemer R., 2023. Acceptance should not be assumed. How the dynamics of social acceptance changes over time, impacting onshore wind repowering. Energy Policy 2023;173. https://doi.org/10.1016/j.enpol.2022.113363.

Wolfram, P., Wiedmann, T., 2017. Electrifying Australian transport: hybrid life cycle analysis of a transition to electric light-duty vehicles and renewable electricity. Appl. Energy 206, 531–540. https://doi.org/10.1016/j.apenergy.2017.08.219.

World Bank, 2022. World Bank Open Data [WWW Document]. [Dataset]. URL https://data.worldbank.org/indicator (accessed 12.18.22).

Xu, R., Zeng, Z., Pan, M., Ziegler, A.D., Holden, J., Spracklen, D. V., Brown, L.E., He, X., Chen, D., Ye, B., Xu, H., Jerez, S., Zheng, C., Liu, J., Lin, P., Yang, Y., Zou, J., Wang, D., Gu, M., Yang, Z., Li, D., Huang, J., Lakshmi, V., Wood, Eric.F., 2023. A global-scale framework for hydropower development incorporating strict environmental constraints. Nature Water 1, 113–122. https://doi.org/10.1038/s44221-022-00004-1

Yang, J., Deng, Z., Guo, S., & Chen, Y. 2023. Development of bottom-up model to estimate dynamic carbon emission for city-scale buildings. Applied Energy, 331, 120410.

Yao Z, Lum Y, Johnston A, Mejia-Mendoza LM, Zhou X, Wen Y, Aspuru-Guzik A, Sargent EH, Seh ZW, 2023. Machine learning for a sustainable energy future. Nat Rev Mater 8(3):202–15. https://doi.org/10.1038/s41578-022-00490-5.

Zhang, Z., Lei, Y., Liew, J.Y.R. *et al.* (2024). Embodied carbon saving potential of using recycled materials as cement substitute in Singapore’s buildings. *npj Mater. Sustain.* **2**, 27. https://doi.org/10.1038/s44296-024-00032-w

Annex

A1: Functioning of the BU-NEP LEAP model

Firstly, the LEAP model works from the bottom-up calculating the demands at the activity levels and accumulating them as it moves up the hierarchy. It then tries to meet the demands using the available supply sources. In doing so, it quantifies the contribution from all the sources of energy that has been built into the modelling system. Then, with the option of import allowed/not-allowed, it reports whether there is a deficit/surplus/equal condition between the supply and demand sides. Secondly, in our model, we have minutely examined the hydropower development trend of Nepal in the past, identified the existing projects (currently under operation, under construction, and the planned and proposed ones), all with different completion and operation dates, and retirement dates based on the annual reports published by the authorities. In this way, we have estimated the likely energy contribution of these projects with time in the national generation mix over our analysis time window. In addition, we have also studied and built in the trends of other renewable energy sources in Nepal currently being developed and planned. However, it is to be noted that the proportions of these additional renewable technologies are much lesser compared to hydropower in the national energy supply mix. Hence, our estimates of the supply and demand in the DSM scenario are not high which is different from the estimates adopted in other past studies. Most such studies have assumed that Nepal will be able to generate massive amounts of domestic energy in the near future. As a result, they imposed conditions of much larger supply than domestically demanded.

8.3 Links and implications

From this paper, I identify that the energy supply and demand sides of Nepal need to be managed collaboratively for effectively achieving future energy security and emissions reduction. On the supply side, I infer that domestically generated hydropower development should lead the future energy mix supplemented by other renewables. On the demand side, it is seen that Nepal should work towards electrification of all the demand sectors, particularly the household sector. However, with the increasing brunt of climate change, people's energy behaviour is expected to change. This issue has been examined in my next paper (Paper #7).

CHAPTER 9: PAPER 7 – FACILITATING SUSTAINABLE ENERGY TRANSITION OF NEPAL: A BEST-FIT MODEL TO PRIORITIZE INFLUENTIAL SOCIO-ECONOMIC AND CLIMATE PERCEPTION FACTORS ON HOUSEHOLD ENERGY BEHAVIOUR

9.1 Introduction

This paper (Paper #7) looks at the demand side (energy behaviour) of Nepalese households and is aimed at identifying the influential socio-economic factors and perception of climate change on people's energy use and their preference of clean energy transition using a best-fit econometric model. I applied a mixed-method approach, surveyed 323 households across 49 districts and three physiographic regions (high hills, mid hills and Terai plains) of Nepal. The explanatory and response variables were fixed through literature review and evaluated three ordinal logistic regression models. This paper directly contributes to the third objective of my research.

9.2 Published paper

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Facilitating sustainable energy transition of Nepal: A best-fit model to prioritize influential socio-economic and climate perception factors on household energy behaviour

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ABSTRACT

Our study investigates the relatively unexplored relationships between socio-economic factors and perceptions of climate change and their influence on household energy preferences in developing contexts, taking the case of Nepal. We aim to achieve two objectives: to create a robust model identifying key socio-economic and climate perception variables affecting household energy behaviour; and to compare the respective impacts of these factors. Applying a mixed-method approach, we surveyed 323 households across 49 districts and three physiographic regions (high hills, mid hills and Terai plains) of Nepal. We fixed the explanatory and response variables through literature review and evaluated three ordinal logistic regression models: one focused solely on socio-economic factors, the second only on climate perception and the third a composite model integrating both. Data statistics showed that 47 % of the respondents preferred no change to their existing energy status, 23 % opted to rely completely on grid-electricity, 14 % favoured switching to renewables, while 16 % preferred an optimal combination of grid-electricity and renewables for their household use. The *Composite-model* was found to be the best fit model for our dataset. The identified key socio-economic factors include urbanization, education levels, and the availability of energy alternatives indicating a wide disparity in the energy access and use across the different socio-economic categories of Nepal. Likewise, magnitude and timing of summer and winter rainfall, changes in the household energy demands and community level subsidies were found to be the significant climate change perception variables. Hence, our findings highlight the need for better access to modern energy and financial incentives, mostly to the rural remote areas, and community-awareness initiatives throughout the country supported by comprehensive energy policies for sustainable renewable energy transition at the household level as well as in mitigation of the impacts of climate change. By enhancing this policy-science-society interface, our research contributes valuable insights for developing effective strategies to promote renewable energy adoption in similar developing contexts.

Introduction

The Intergovernmental Panel on Climate Change (IPCC) has reported that it would be difficult to achieve the pre-industrial warming levels of 1.5 °C globally unless immediate steps, primarily pertaining to energy consumption, are strictly implemented to reduce the impacts of climate change (Masson-Delmotte et al., 2019). Adoption of energy technologies by a country is directly dependent on its infrastructural, environmental, and technical conditions (Baniya et al., 2023; Manasi & Mukhopadhyay, 2024). Moreover, the energy consumption landscape is governed by its socio-economic settings, people's awareness, and capacity to adopt modern technologies (Franco & Taeighagh, 2024; Israel & Jehling, 2019; Liao et al., 2021; Mukhtarov et al., 2020). For instance, the energy consumption of China was 40,207 TWh in 2019, which was considerably

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higher than US (26,575 TWh) – the largest economy in the world, and India at 9,311 TWh; smaller economies recorded much lower figures (Ritchie et al., 2022). However, there are distinct North-South disparities in energy consumption patterns globally (Lin & Omoju, 2017; Weko & Goldthau, 2022). Energy consumption of the Global North is more concentrated in the transportation and industrial sectors (McGreevy et al., 2021). But the household energy consumption contributes considerably to the total energy use of the Global South (Nepal et al., 2018).

Making the transition to renewables has been a high priority worldwide. For instance, the climate and energy framework adopted by the European Commission (EC) targeting at 27 % share of renewables by 2030 is an important commitment (EC, 2014). Sustainable development in line with SDG 7, European Green Deal, Agenda 2030 and other global efforts have provided some impetus to renewable energy transition (Borozan, 2022). Studies have shown that Europe is leading the transition while the rest of the world is following its lead in terms of technological development (Bhattarai et al., 2022; Bigerna et al., 2021). Moreover, it is established that countries with larger investment in research and development of energy systems are able to promote renewable sources, meet the energy demands sustainably, improve the living standards of the people and enhance economic growth (Adedoyin et al., 2020; Gümüş, 2015). Interestingly, studies have shown that renewable energy transition will not occur instantaneously (Johnstone et al., 2020). In fact, the global diffusion of renewables in the energy mix is more of an addition to the conventional generation systems rather than transitioning from it (York & Bell, 2019). Some energy scholars are doubtful whether the current renewable energy transition efforts are enough to sustain the growing demands (Johnstone et al., 2020). Studies have even raised concerns whether transitioning to renewables actually benefit decarbonization (Debnath & Mourshed, 2024). Due to these reasons, researchers have highlighted the need for a more radical and urgent change in the energy behaviour promoting transition to renewables globally in order to mitigate the impacts of climate change (Johnstone et al., 2020; Millot et al., 2020). Moreover, expanding and modernizing energy systems in the global south has been the focus of the Sustainable Development Goal (SDG-7) (UN, 2015).

Energy plays an indispensable role in supporting the overall development of a nation, more importantly in the case of developing countries. Furthermore, energy transition and economic growth have a bidirectional relationship (Mohsin et al., 2021). As a result, researchers highlight the need to focus on increasing the accessibility to energy and efficiency considering the variations in the supply and demand sides (Verma et al., 2024). Abbas et al. (2022) identified common key socio-economic determinants of multidimensional energy poverty among a panel of developing countries. People tend to switch to modern and efficient technologies as well as increase the energy consumption as they climb up the energy ladder (Dominguez et al., 2021) and renewable sources become more desirable (Shahzadi et al., 2022). Adha et al. (2024) demonstrate that the current high levels of energy inefficiencies in the ASEAN countries are hindering their economic growth. Franco and Taeighagh (2024) assessed the interlinkages between the renewable energy technology adoption process and how they are perceived by the community in the Philippines. Shakya et al. (2022) show that diesel generated electricity still plays a critical role in substantiating the supply of national grid electricity in Nepal. Haldar et al. (2023) show the dynamic roles of rising renewable-energy share in the energy mix directly impacting energy poverty taking the case of sub-Saharan Africa. Karatayev et al. (2016) underscore the importance of policy as drivers of renewable energy adoption in Kazakhstan.

On a positive role, studies have identified ways to overcome the energy related challenges in the Global South. For instance, Raza et al. (2022) highlights the need for increased renewables in the energy mix for a sustainable energy future in Pakistan. Gautam and Bolia (2024) demonstrate the adoption of electric vehicles as a promising intervention for sustainable transportation development in India. Likewise, Kapoor and Garg (2021) present the use of solar panels over irrigation canals in India as a feasible co-benefit of technologies to increase clean energy generation. Floating solar power station has been studied with scaling up possibilities in Azerbaijan (Mukhtarov et al., 2020). Nshimiyimana et al. (2024) highlight the importance of cooking-related awareness, behaviour change and marketing campaigns for switching to cleaner cooking energy technologies in Rwanda. Shakya et al. (2022) identified possible co-benefits of demand side energy management combining microgrids of diesel generators and solar PV for achieving energy security in Nepal. Bhattarai et al. (2022) focus on developing an 'energy ecosystem' for sustainable use of energy while Bhattarai et al. (2024a) recommend increasing the 'suppressed demand' by strengthening the domestic renewable energy generation capacity of Nepal in the near future. Hussain et al. (2019) demonstrate how hydropower remains an important option for achieving renewable energy goals in the Hindu Kush Himalayan region by promoting micro-hydropower and fostering regional energy development and sharing programs. Likewise, Huda and McDonald (2016) underscore the importance of regional energy sharing in South Asia. Moreover, studies highlight the potential of the developing Asian economies in mitigation of greenhouse gas emissions and climate change impact minimization provided public awareness on the availability and adoption of renewable technologies is effectively created (Mohsin et al., 2021).

People's energy use behaviour and climate change are inter-related. Therefore, understanding people's views and managing household energy consumption as an adaptation strategy to minimize the impacts of climate change is a major challenge for policy makers, especially in the developing world (Amrutha et al., 2018; Bahn et al., 2019; Bhat et al., 2019; Ramagoma & Adendorff, 2016; Raza et al., 2022). This requires a proper understanding of the people's energy use perceptions and preferences holistically (Sovacool, 2014). However, Windemer (2023) warns against assuming uniform energy use behaviours among people while Shrestha et al. (2019) cautions about the likely mismatch between science and people's perceptions.

Numerous studies have investigated socio-economic factors influencing people's energy perceptions. For instance, Koirala and Acharya (2022), Paravantis et al. (2018) and Dominguez et al. (2021) show how people's choice of fuel varied at the household level in Nepal, Greece, and Kenya, respectively. Taking the case of Canada, Hurlbert et al. (2020) underscore how the existing energy technologies and people's energy behaviour are not likely to be substituted by renewables until strong actors surface. Andreas et al. (2018) demonstrates how disproportionate burdening of the energy consumers in Bulgaria undermined its renewable energy transition. Across many Asian countries, energy security is largely dependent on common socioeconomic determinants (Abbas et al., 2022). Li et al. (2021) highlight the importance of renewable energy policy-relevant treatments in household fuel saving in China. Hess and Mai (2014) point out the reluctance of developing countries to formulate policies which are supportive of renewable energy transition. Studies such as Proka et al. (2018) and Martinez and Komendantova (2020) analyze various aspects of social resistance to renewable energy transition in different parts of the world.

A wide range of literature have examined how people perceive climate change and the consequent impacts on different socio-economic sectors. Recent studies have focused on agriculture (Chhogyel et al., 2020; Paudel et al., 2020), hazards and adaptation (Devkota et al., 2020; Ghosh & Ghosal, 2020), forest management (Acharya et al., 2019; Dhungana et al., 2020) and socio-psychological assessments (Ballantyne et al. , 2016; Bremer & Linnenluecke, 2017), among others. Additionally, researchers have attempted to standardize public opinions of climate change and their adaptations across different contexts and scales (van Valkengoed et al., 2021).

Contemporary literature presents perception-focused studies on energy and climate change often aimed at specific energy technologies. For instance, Chung and Kim (2018) demonstrate that South Koreans do not support transitioning to nuclear power as a solution to climate change reduction. Likewise, Poortinga et al. (2013) present an interesting case which showed that the Japanese people are reluctant to continue nuclear power plants for climate change mitigation compared to the British after the Fukushima tragedy. Moreover, a diverse set of factors have been found to influence energy use behaviour. For example, Tanti and Yena (2023) show that access to energy sources for irrigation is one of the major determinants of adoption of climate smart agriculture by the local farmers in an Indian state to mitigate climate change issues. Likewise, awareness and existing norms were found to be the most influential factors on the adoption of biofuels for climate change mitigation in the rural context of Iran (Yaghoubi et al., 2019). Interestingly, Karlstrøm and Ryghaug (2014) present political inclination of the people as a governing factor for adoption of renewable energy technologies in Norway in the wake of climate change. Moreover, it was found that the preference of development of new hydropower in Norway as a clean energy source was less impacted by people's pre-existing beliefs and more influenced by the direct benefits and the involvement of the stakeholders in the development process (Saha & Idsø, 2016). Evensen and Brown-Steiner (2018) report that people in the US do not believe that unconventional gas development (as an energy source) will have a considerable impact on global climate change. Moreover, attitudes of the people of Finland were found to be different for the national and global level climate policies underscoring the need for societal context-specific interventions (Sivonen, 2023). Likewise, Cho et al. (2024) mentions that achieving carbon neutrality in the building energy sector of South Korea is largely dependent on the occupants' behavioural characteristics in addition to the proper implementation of building codes. Debnath and Mourshed (2024) identify ensuring tangible outcomes by implementing carbon pricing and removing energy subsidies while maintaining equitable socio-economic impact for all income category people as two important recommendations for decarbonization of Bangladesh's energy sector. Similarly, energy conservation and demand-side management have also been of interest in recent studies in the face of climate change (Han et al., 2022; He et al., 2023; Lacroix & Gifford, 2018). Thus, meticulous assessment of people's behaviours for minimizing energy consumption and the impacts of climate change is seen necessary.

Moreover, studies comprehensively exploring the influential social and climate change-perception related factors on people's current and future energy preferences are scarcer in the developing world, particularly South Asia and almost none in Nepal. In addition to developing a better understanding of the people's views, the findings of this study will be instrumental to the decision makers in identifying the areas of the society that need more attention while devising and implementing energy and climate change policies. Hence, we aim to contribute to this important policy-science-society interface in the energy sector. We take the case of a developing country – Nepal. More specifically, this study aims:

1. to fit an optimal model for identifying the determinant socio-economic and climate change perception parameters impacting people's energy use behaviour at the household level; and
2. to compare the respective influences of the parameters on people's energy transition preferences.

The next section (*Materials and Methods*) explains about the geographical location and the current energy status of Nepal (*Study Area*). The subsequent section is on the adopted methodology in which the different steps are sequentially explained in the respective subsections. *Household Questionnaire Survey* explains the sampling strategy and provides additional details of the administration of the household questionnaire survey. Likewise, *Data pre-processing* provides information on data cleaning, basic statistical checks and multicollinearity analysis. *Application of ordinal logistic regression model* is on the categorization of the response variable and the modelling details. This is followed by the results of the data spread, collinearity and the three models. In the Discussion section, we discuss about the socio-economic variables, climate change perception variables and analyse the people's preference of energy transition based on the modelling results. We then conclude with key takeaway messages and policy recommendations in the *Conclusion* section.

Materials and methods

Study area

Nepal lies in the central Hindu Kush Himalayan region landlocked between India and China (Fig. 1). Nepal can be roughly categorized into four distinct physiographic regions: mountains, high hills, mid hills, and Terai plains.

In the fiscal year 2022/2023, Nepal's total energy consumption was 14.943 million tons of oil equivalent (toe) (WECS/GoN, 2023). The country's energy mix comprises three primary sources: traditional (firewood, agricultural residue, and dry dung for direct combustion, 64.2 %); commercial (petroleum, coal, and grid electricity, 33.3 %); and other off-grid renewable sources (micro-hydro, solar and biogas, 2.5 %) (WECS/GoN, 2023). Although overall access to electricity has increased from 29 % in 2000 to 92 % of the population in 2023 (NEA/GoN, 2023), 51 % of the rural population still rely on firewood for cooking, 2.9 % use dried dung while only 1.2 % use bio-gas and <1 % use kerosene or other sources (CBS, 2021). Likewise, electricity, solar, kerosene, biogas and other sources are used by 92.1 %, 6.6 %, 0.6 %, 0.03 % and 0.62 % of the total population, respectively for household lighting (CBS, 2021).

The annual electricity consumption of Nepal was 6789 GWh with a peak demand of 1870 MW in 2022/2023 (MoF/GoN, 2023; NEA/GoN, 2023). Nepal's total installed power capacity was 2666 MW in the end of the FY 2022/2023, out of which large hydropower projects, solar, thermal, smaller renewable technologies and co-generation technologies from sugar mills contributed 2499 MW, 75 MW, 53.4 MW, 82 MW and 6 MW, respectively (MoF/GoN, 2023). Moreover, the private sector contributes significantly (55 %) to the total power installed capacity of Nepal (NEA/GoN, 2023). Nepal faces a loss (due to theft and transmission losses) of about 13.5 % in the power sector (NEA/GoN, 2023). The total installed capacity of rooftop solar PV is 10.1 MW, that of micro- and mini-hydropower is 38.8 MW and local hybrid grids is 2.7 MW (AEPC/GoN, 2023). In the FY 2022/2023, Nepal purchased 1855 GWh year-round from India and exported 1333 GWh (~72 % of imported electricity) during June to October (NEA/GoN, 2023).

Methodology

This study adopted a mixed-method approach in which we implemented a series of steps: household survey, data pre-processing, and application of three ordinal logistic regression models to examine people's preferences of energy transition in the household sector of Nepal (Fig. 2).

Household questionnaire survey

Household questionnaire survery was the first step of our research. A cross-sectional questionnaire survey was undertaken in 49 districts of Nepal encompassing 350 households over three physiographic regions, namely, high hills, mid hills and Terai plains. However, there is almost no human habitat in the mountain region (around above 3000 metres above sea level, masl) largely owing to its rugged terrain and harsh climatic conditions. Regions above 4000 masl have permanent snowline where the temperature is below freezing throughout the year, making it almost impossible for human settlement. Moreover, access to these areas is extremely difficult. As a result, our survey was confined to the remaining three regions.

We made sure that the sampled households are representative of certain attributes related to our study aims (Table 1). Thus, capturing the diversity in the household energy use was the major adopted criteria

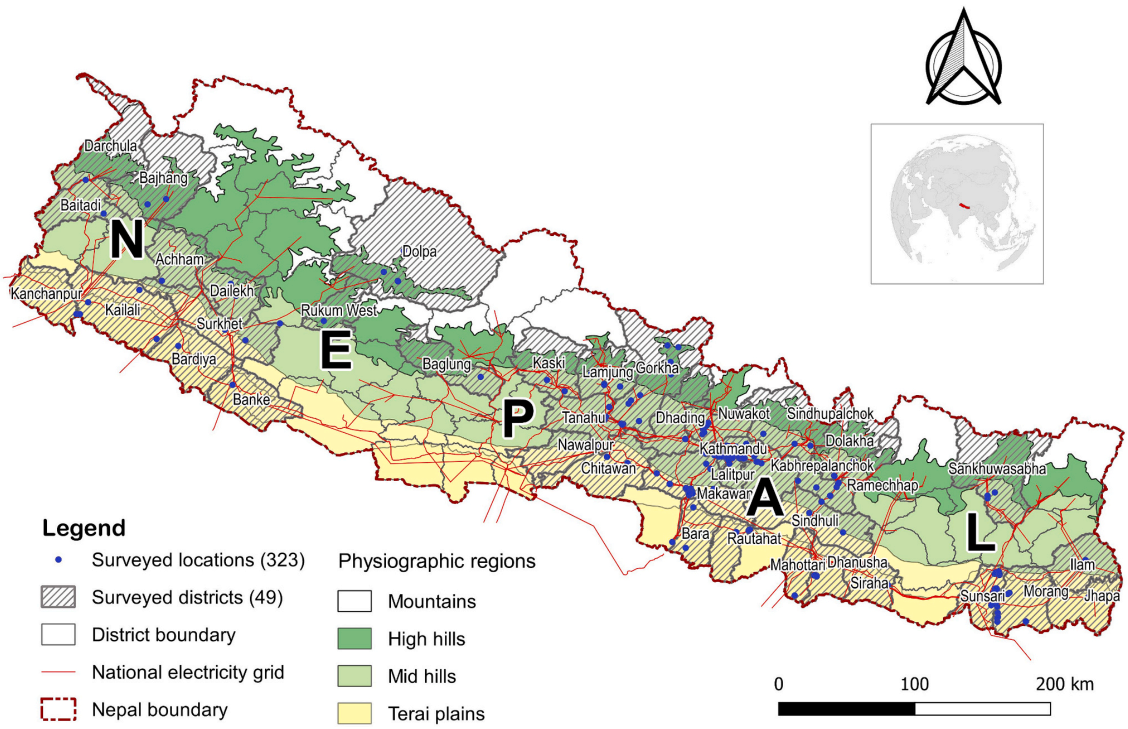

Fig. 1. Geographical setting of Nepal. Dots indicate the locations where household questionnaire survey ($n = 323$) was carried out.

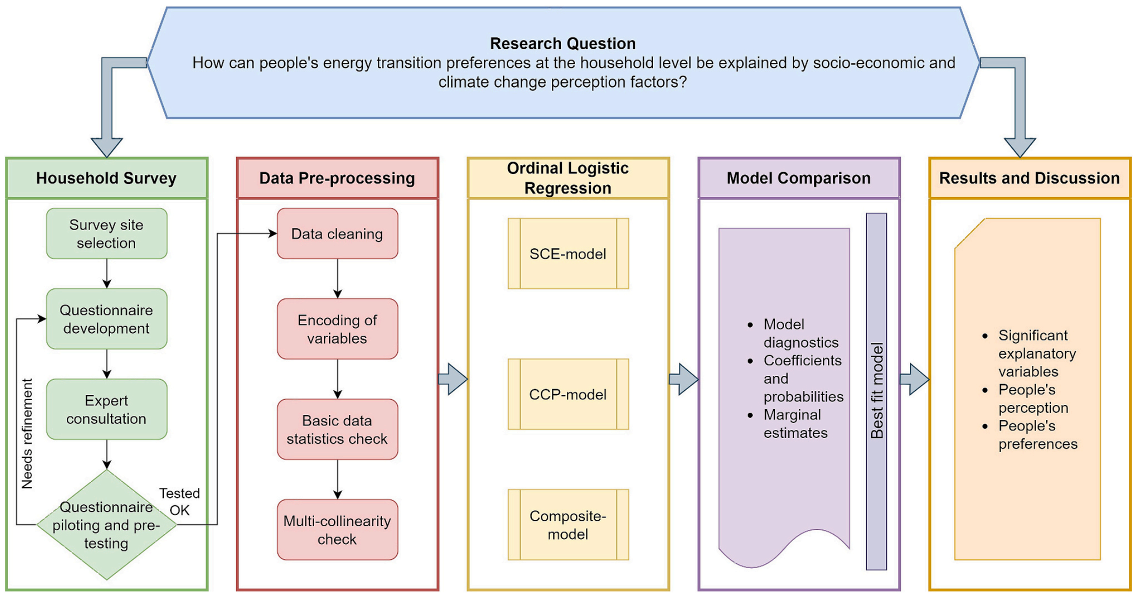

Fig. 2. Research methodology implemented in the study.

during survey site selection. Energy supply and usage varies considerably across the different physiographic regions of Nepal. In addition, the rural, semi-urban and urban areas have varying energy consumption patterns. Therefore, these attributes were chosen as important factors in sites selection. Furthermore, the energy (mainly electricity) generation technologies vary according to different locations. Hence, survey locations were chosen such that the residents would be able to provide information about the industrial areas, major hydropower projects, representative micro-hydropower, solar and other off-grid renewable energy projects and how these projects would impact their energy

Table 1
Survey districts selection criteria.

S. N	Survey districts	Sample size	Physio-graphy	Urbanization	Electri-fication status	Alternate electricity	Remarks
1	Kathmandu/ Bhaktapur / Lalitpur	60	Mid hills	Urban/ semi-urban	Electrified	HH-solar	Core city/ semi-urban areas
2	Makwanpur/ Chitwan / Nawalpur	30	Mid hills / Terai	Semi-urban	Electrified/ non-electrified	HH-/ local grid solar/ micro hydro/ diesel	Kulekhani cascade, Lower Bagmati hydropower and diesel plant areas
3	Gorkha/ Lamjung/ Tanahu/ Kaski/ Baglung	45	High hills/ Mid hills	Semi-urban/ rural	Electrified/ non-electrified	HH-/ local grid solar/ micro hydro	Budhigandaki, Marsyangdi and Tanahu hydropower project areas
4	Rautahat/ Bara / Dhanusha / Siraha/ Mahottari	45	Terai	Semi-urban/ rural	Electrified/ non-electrified	HH-/ local grid solar/ micro hydro	Bagmati multipurpose project & Chandranighapur Solar project areas
5	Dolakha/ Ramechhap/ Kabhrepalanchok/ Sindhupalchok	45	Mid hills/ High hills	Urban/ semi-urban/ rural	Electrified/ non-electrified	HH-/ local grid solar /micro hydro	Upper Tamakoshi, Khimti hydropower & Sunkoshi cascade project areas
6	Sankhuwasabha/ Illam/ Jhapa	30	High hills/ Mid hills/ Terai	Semi-urban/ rural	Electrified/ non-electrified	HH-/ local grid solar/ micro hydro	Arun III/ Kimathanka and many other hydropower project areas
7	Morang/ Sunsari	30	Terai	Urban/ semi-urban	Electrified	HH-/ local grid solar/ diesel	Duhabi industrial corridor/ Biratnagar/ Dharan
8	Dolpa/ Rukum West/ Dailekh / Surkhet / Achham/ Bajhang / Baitadi / Darchula	35	High hills	Rural	Electrified/ non-electrified	HH-/ local grid solar/ micro hydro	
9	Banke/ Bardiya/ Kailali/ Kanchanpur	30	Terai	Urban/ semi-urban/ rural	Electrified/ non-electrified	HH-/ local grid solar/ micro hydro	Biggest solar project, Bhalubang, Naumure & other project areas
	Total	**350**					

Note - HH: Household.

availability choices.

The high hills are less populated (in terms of population density as well as total population) compared to the mid hills while the Terai plains have the largest population. It can be seen from CBS (2021) that each Terai district has a contribution of >1.5 % to the total national population while that of the mid hills range from 0.5 to 1 %. The contribution of each high hill district is <0.5 % in the national population. It has to be noted that 7 % of Nepal's population live in the Kathmandu district where the capital city Kathmandu is situated. We have tried to maintain this proportion in our sample size distribution for the survey. We sampled the 49 surveyed districts such that 14 districts (29 %) were selected from Terai, 11 districts (22 %) from mid hills and 24 (49 %) districts from high hills. More districts were chosen for the high hills to account for their fewer population compared to the other two regions. Moreover, 23 samples (7 % of our total sample size) were chosen from Kathmandu district which lies in the mid hills region. Similarly, CBS (2021) and WB (2024) report that about 22 % of the country's population is located in urban areas, about 46 % in semi-urban areas while 33 % are in rural areas. We have tried to partly maintain this proportion in our sample size distribution as well such that there are 87 samples (27 %) from the urban areas, 63 samples (20 %) from semi-urban areas and 173 samples (53 %) from rural areas. As with the high hill districts, more samples were chosen for the rural and semi-urban areas for two reasons. Firstly, it is to account for their fewer population compared to the urban areas. Secondly, there is a much larger variation in the use of household energy sources across the rural areas (Table 1:) compared to the urban areas which are mostly confined to grid electricity and LPG.

Moreover, our classification was based on the homogeneity within the classes of each explanatory variable as well as the diversity across the classes. Therefore, based on the homogeneity of the sample clusters, the sample size utilized in this study is deemed adequate. Careful measures have been undertaken to ensure at least 30 samples for each group among the variables are maintained, confirming a robust sampling representation. Readers are referred to Bhattarai, Maraseni, Devkota, and Apan (2023) for additional details of the sampling strategy and survey. Hence, 350 was an optimum sample size that we could achieve within our time and other research resource constraints.

Furthermore, randomization is an effective way to remove bias. Hence, the sampling strategy was so designed that first, the population was divided into strata, and then each household was randomly selected from each strata so that each household had an equal chance of being selected. The household database was collected and collated from local government offices. All households were numbered and randomly selected. Moreover, we did not select specific respondents from each household. Rather, selection of the respondents was done such that they were knowledgeable about their household energy related matters and are able to communicate their perceptions about local climatic context. In most cases, it was the household head who fell in this criterion but in other cases, other family members were more aware of the energy and climate contexts and had a stronger say in the household energy related decisions. We strongly believe that adopting these measures are indicative of the reliability of the questionnaire as an instrument and the survey methods as a whole.

Questionnaire was meticulously devised through an extensive review of literature, notably referenced from scholarly works such as Bhandari et al. (2018), Bhattarai, Devkota, Maraseni, et al. (2023), Braito et al. (2017), Cloke et al. (2017), Das et al. (2022), Ghimire and Kim (2018), Jacksohn et al. (2019), Liao et al. (2021), Matavel et al. (2023), Munro (2019), Roberts (2020), Salari et al. (2021), Strazzera and Statzu (2017), Tsvetanov (2019), Wiehe et al. (2021), and Winkler et al. (2018). After undergoing expert consultation and pre-testing, household surveys were conducted during December 2022 to February 2023. The ethical requirements of Human Research Ethical Clearance HREC ID H22REA258 issued by the University of Southern Queensland, Australia were strictly followed by trained enumerators while conducting the surveys. It was made sure that only local enumerators were selected who were well acquainted with the socio-economic, energy and climatic contexts of Nepal. For this, at least undergraduate level educated enumerators were selected for the survey. Moreover, the survey was conducted in Nepali language so as to facilitate easy communication between the enumerators and the respondents throughout the survey locations. The respondents were well-informed about their voluntary contribution to this research through the survey. They were also assured that anonymity would be maintained by coding the responses and that the respondents had no direct or indirect risk of anything beyond their day-to-day activities by participating in this survey. In addition, they were also informed that they could withdraw from the survey at any time without any implications.

Data pre-processing

We collected 350 household questionnaire survey samples based on the distribution shown in Table 1. During data cleaning, 27 samples were found to be incomplete or had irrelevant responses; they were excluded. In this way, a final sample size of 323 was maintained for further analysis. A total of twenty-four predictor variables and one response variable were chosen. The independent explanatory variables were of mixed data types (continuous, binary and categorical) which were converted into logical classes. Detailed description of the variables, their classes and justification of the categorization are given in Annex Table A1. The response (dependent) variable was classified into a logical order. Basic statistics of the surveyed data was checked. Furthermore, we checked the correlation among the 24 explanatory variables (12 socio-economic and 12 climate change perception) and ensured that issues of multi-collinearity did not impact our analysis (Fig. 3). Additionally, the spread for each predictor variable in the different classes was assessed. All the explanatory variables are either binary or categorical. Therefore, Chi-squared test is appropriate for finding the

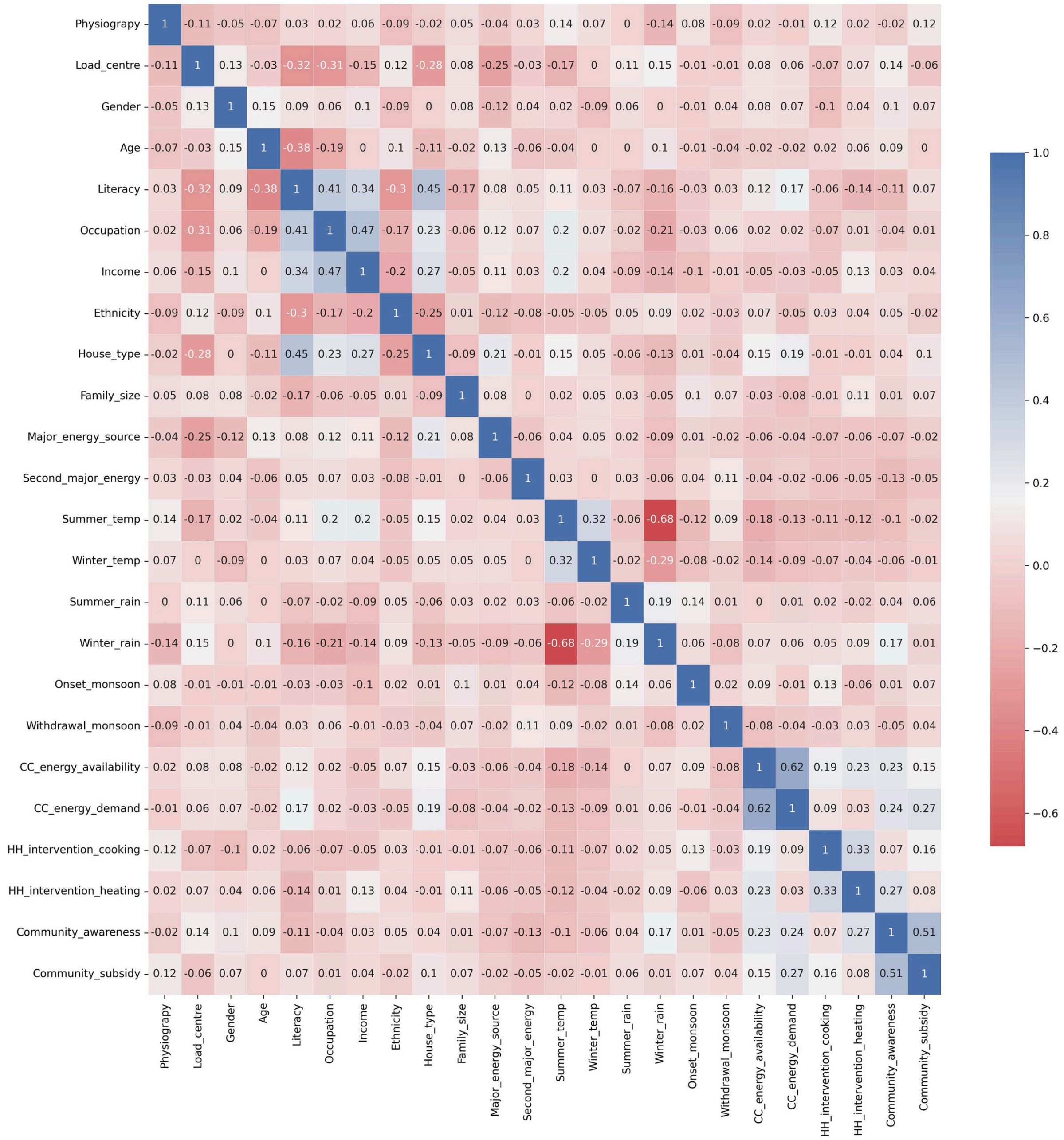

Fig. 3. Correlation matrix of the explanatory variables. The first twelve are the socio-economic variables while the remaining twelve are climate change perception variables.

variation between categorical data (Hamilton, 2012; Sharna et al., 2024).

Application of ordinal logistic regression model

Econometric models are popular among researchers in identifying the determinants of the choices people make. Scholars generally adopt a collection of explanatory independent variables through literature review, consultations with informants and expert evaluations, followed by regression analysis with respect to the reliant variables (Anik et al., 2022; Storm et al., 2020). For instance, He et al. (2023) used a combination of binary probit model and ordered probit model; Das et al. (2022) and Koirala and Acharya (2022) applied multinomial logit and multinomial probit models; Acosta et al. (2021) applied a quantile regression model; Park et al. (2023) applied multinomial logistic regression model while Sivonen (2023) and Sharna et al. (2024) applied ordinal logistic regression. Moreover, ordinal logistic regression is the common choice when the responses are categorical and can be ordered in a logical way related to people's opinions (Deisenroth et al., 2020; Sivonen, 2023; Storm et al., 2020).

The dependent/response variable in our research is ordinal. The lowest order (first category) of the preference variable has been assigned to the respondents who are either unaware of the available energy options or they are financially and technologically not capable to change their household energy choice or both. In (mostly urban) areas with access to grid electricity as well as the non-electrified (semi-urban and most rural) areas, the behaviour of the people to avoid transitioning to better alternatives is characterized by this class. The second category refers to the people's preference of being able to connect to grid electricity for household use, particularly in the non-electrified rural areas. In the case of already electrified urban areas, this category is indicative of people's desire of increasing their reliance on the grid electricity (for example by connecting to higher capacity lines) so that they can use more household electric appliances, without any contribution from other renewable sources. This category is indicative of complete dependency on the government with very limited initiatives for the energy transition from the users' side. The third category pertains to the people's preference to completely switch to other off-grid renewables for meeting their household energy demands. This indicates the households' desire to take the initiative from their side and decrease dependency on the state. Moreover, this category also denotes a condition in which the users have the ownership and more control over the energy generation and use in their houses. The fourth category is a condition which shows the households' access to both grid electricity and renewable energy sources such that the combination leads to an optimum use of energy for household purposes. Responses willing to opt for technological advancements (such as net metering) in the electricity sector of the electrified urban areas also come under this category. As a result, it was categorized as the highest ordinal (fourth) category.

Hence, an ordered logistic regression model has been used. The assumptions for application of this model such as proportional effect of independent variables on the outcome, independence of observations, linearity in log-odds of the response categories, no multicollinearity, homoscedasticity, sufficiently large sample size, no outliers and adoption of valid and meaningful categories have been satisfied (Deisenroth et al., 2020). Through model diagnostics, regression coefficients and marginal values of the explanatory variables, we explored how the people appraised the energy transition preferences using three models i) socio-economic parameters only (*SCE-model*), ii) climate change perception parameters only (*CCP-model*) and iii) combination of both parameters (*Composite-model*). In the first model, *ceteris paribus*, we assume that only the socio-economic variables affect people's energy preference. Likewise, in the second model, we assume that only the climate perception variables affect people's energy preference, holding all other socio-economic factors remain constant. However, in the third model, we consider the cumulative impact of both types of explanatory variables on the household energy preferences. The best performing model was chosen among these based on the above-mentioned metrics.

Mathematically, the energy transition preference behaviour can be represented as shown in Eq. 1 to Eq. 3.

$$\text{SCE}-\text{model}: Y_m(Preference) = a_1 + \sum_{i=1}^{12} X_i\alpha + \varepsilon_i \quad (1)$$

$$\text{CCP}-\text{model}: Y_m(Preference) = a_2 + \sum_{j=1}^{12} X_j\beta + \varepsilon_j \quad (2)$$

$$\text{Composite}-\text{model}: Y_m(Preference) = a_3 + \sum_{i=1}^{12} X_i\alpha + \sum_{j=1}^{12} X_j\beta + \varepsilon_k \quad (3)$$

where, $Y_m(Preference)$ denotes the status of energy transition preference with four possible values of m (1 denoting Preference 1: no change from current energy conditions; 2 representing Preference 2: transitioning to grid electricity only; 3 denoting Preference 3: transitioning to other renewables only; and 4 representing Preference 4: transitioning to a combination of grid electricity and renewables). X is a vector of the explanatory variables with subscript i for the socio-economic variables while j for the climate change perception variables and a, α and β are the regression coefficients. ε denotes identically distributed error terms for the respective models with variance one and mean zero. The probability associated with people's preferences can be written as Eq. 4.

$$\pi\left(y_i \leq \frac{j}{x_i}\right) = \Delta\left(\gamma_j - X\alpha\right) - \Delta\left(\gamma_{j-1} - X\alpha\right) \quad (4)$$

where, j is the observed variable and γ is the threshold parameter. Hence, the generic ordered logistic regression model is written as in Eq. (5).

$$Logit(Y_m) = Log_e\left(\frac{\pi}{1-\pi}\right) = a_0 + X_i\alpha_i + \varepsilon \quad (5)$$

The ordered logit model was implemented in STATA 16 and the descriptive analyses was carried out using Chi-square test to assess the statistically significant differences among the people's preference categories (StataCorp, 2023; Williams, 2006; Williams, 2018).

Results

Correlation

Fig. 3 depicts a correlation matrix of our dataset. The heatmap shows that the value of the Pearson correlation coefficient ($|r| < 0.3$) for majority of the variables. Only a few variables, for example *Occupation* and *Income*, *Literacy* and *Occupation* have r values in the range of 0.4 indicating weak correlation while only *Winter_rain* and *Summer_temp* demonstrate a moderate correlation of 0.68. Readers are referred to Annex Table A1 for details of the variables.

Descriptive statistics

Socio-economic variables

A considerable heterogeneity was seen among the four energy transition preference groups (Table 2). Out of the 323 respondents, 151 (47 %) were either unaware or chose no transition – preference 1; 74 (23 %) opted for transitioning to grid electricity only – preference 2; 47 (14 %) preferred changing to other renewables only – preference 3; and 51 (16 %) chose to transition to a combination of grid electricity and renewables – preference 4. The frequency (and percentage) of people's responses according to the classes of the explanatory variables are presented columnwise which add up to 323 (100 %) for each variable.

Results of the Chi-square test show that, among the 12 socio-economic variables, the differences were significant at 1 % ($p \leq 0.01$) for four variables of urbanization status, level of education, living

Table 2
Descriptive statistics of the socio-economic variables with respect to the energy preferences.

Description of explanatory factors (*variables*) and classes	Energy transition preference								Chi-square (*p*-value)
	Preference 1: No change/ I do not know		Preference 2: To grid electricity only		Preference 3: To other renewables only		Preference 4: To electricity and renewables		
	Frequency	%	Frequency	%	Frequency	%	Frequency	%	
Type of terrain *(Physiography)*									10.0368 (0.123)
High hills (1)	51	34	19	26	8	17	17	33	
Mid hills (2)	65	43	41	55	23	49	26	51	
Terai Plains (3)	35	23	14	19	16	34	8	16	
Level of urbanization *(Load_centre)*									25.150*** (0.000)
Kathmandu Valley (1)	23	15	28	38	14	30	22	43	
Other towns (2)	30	20	11	15	12	26	10	20	
Rural areas (3)	98	65	35	47	21	45	19	37	
Gender of the respondent *(Gender)*									0.6897 (0.876)
Female (1)	34	23	15	20	8	17	11	22	
Male (2)	117	77	59	80	39	83	40	78	
Age of the respondent *(Age)*									9.2045 (0.162)
≤ 35 years (1)	54	36	32	43	28	60	23	46	
35–50 years (2)	56	37	23	31	9	19	15	29	
> 50 years (3)	41	27	19	26	10	21	13	25	
Education level of the respondent *(Literacy)*									60.308*** (0.000)
Illiterate (1)	34	23	4	5	1	2	4	8	
Primary school/informal education (2)	33	22	9	12	3	6	1	2	
Secondary/high school (3)	50	33	24	32	13	28	28	55	
University (4)	34	23	37	50	30	64	18	35	
Type of employment of the respondent *(Occupation)*									25.493** (0.013)
Unemployed/retired (1)	15	10	12	16	2	4	4	8	
Farming/livestock rearing (2)	51	34	14	19	10	21	8	16	
Self-employed (3)	43	28	17	23	10	21	15	29	
Academic/government service (4)	16	11	13	18	10	21	5	10	
Private organization (5)	26	17	18	24	15	33	19	37	
Annual household income in US$ *(Income)*									11.9103 (0.218)
< 692 (1)	51	34	14	19	9	19	11	22	
692–1154 (2)	16	11	9	12	6	13	6	12	
1154–1961 (3)	22	15	14	19	5	11	12	24	
> 1961 (4)	62	40	37	50	27	57	22	42	
Ethnic background of the household *(Ethnicity)*									15.875** (0.014)
Marginalized/underprivileged (1)	9	6	0	0	0	0	3	6	
Indigenous (2)	70	46	33	45	12	26	20	39	
Brahmin/Chhetri (3)	72	48	41	55	35	74	28	55	
Living standard of the household *(House_type)*									32.276*** (0.000)
Mud hut/cottage (1)	18	12	3	4	1	2	2	4	
Bamboo/wood (2)	15	10	1	1	0	0	0	0	
Bricks and mud mortar (3)	20	13	8	11	2	4	3	6	
Bricks and cement (4)	98	65	62	84	44	94	46	90	
Household size and type of family *(Family_size)*									2.6390 (0.853)
≤ 4: Nuclear (1)	62	41	34	46	25	53	23	45	
5–6: Extended (2)	65	43	29	39	15	32	19	37	
>6: Joint (3)	24	16	11	15	7	15	9	18	
Domestic energy options *(Major_energy_source)*									27.360*** (0.007)
Agriculture residue (1)	21	14	6	8	4	9	8	16	
Petroleum (2)	11	7	6	8	7	15	1	2	
LPG (3)	90	60	34	46	30	64	27	53	
Grid-electricity (4)	25	17	28	38	5	11	15	29	
Renewables (5)	4	3	0	0	1	2	0	0	
Alternate household energy options *(Second_major_energy)*									20.648** (0.014)
Petroleum (1)	13	9	4	5	6	13	1	2	
LPG (2)	35	23	32	44	11	23	19	37	
Grid-electricity (3)	91	60	34	46	30	64	30	59	
Renewables (4)	12	8	4	5	0	0	1	2	
Total	**151**	**100**	**74**	**100**	**47**	**100**	**51**	**100**	

Note: Numbers in parenthesis alongside the variable classes in the first column indicate the numeric classes used for modelling. ** and *** in the last column refer to significance level of 5 % ($p \leq 0.05$) and 1 % ($p \leq 0.01$), respectively.

standard, and the availability of household energy options (Table 2). A majority (65 %) of the respondents not aware of the energy transition or reluctant to make any changes were from the rural areas. However, most respondents preferring to transition to grid-electricity and renewables (43 %) were from Kathmandu Valley, the capital city of the country. A considerable number of people preferring transitioning to renewables had university education (64 %), while those preferring to change to electricity and renewables were mostly (55 %) secondary or high school educated. Additionally, people living in houses made of bricks and cement were dominant in the response categories (no change in energy: 65 % and transition to renewables only: 94 %). People using LPG as their major source of household energy were sizable in number across all the preference categories ranging from 46 % (to grid electricity only) to 64 % (to other renewables only).

Similarly, the differences were significant at 5 % ($p \leq 0.05$) for three other variables: type of employment, ethnic background, and the availability of alternate sources of energy (Table 2). A large faction of the people working in private organizations (37 %) preferred to transition to grid electricity and renewables, whereas those unaware of the transition or choosing no change were mostly farmers (34 %). Similarly, 74 % of the respondents from the Brahmin/Chhetri (the privileged group in Nepal's context) ethnic group preferred transitioning to grid electricity only. Additionally, most of the people with grid electricity as their second major energy source opted either no change from the current conditions (60 %), use more electricity (64 %) or transition to grid electricity and renewables (59 %). Hence, a distinct pattern of people's energy transition preferences depending on the different socio-economic determinants was not observed.

Climate change perception variables

Results of the Chi-square test for the climate change perception variables showed four significant parameters: change in the average summer temperature, withdrawal of monsoon season, impact of climate change on energy availability, and the importance of community level subsidies at 1 % ($p \leq 0.01$) (Table 3). Most of the people (70 %) preferring to change to electricity and renewables and 64 % of the respondents preferring to change to grid electricity only perceived summer being hotter compared to twenty years ago. Similarly, a majority of the people who are not willing to make any energy transition (76 %) and choosing to change to grid electricity only (73 %) perceived no change in monsoon withdrawal. People perceiving high (45 %) and very high (39 %) impacts of climate change on energy availability respectively prefer transitioning to grid electricity only and a combination of grid electricity and renewables. Provision of community-level subsidies in energy efficient devices was considered highly effective measures for reduction of climate change impacts on household energy by people who chose transitioning to grid electricity and renewables (76 %) and those (65 %) who chose changing to grid electricity only.

Likewise, significant differences at 5 % ($p < 0.05$) were observed for four variables pertaining to the perceptions of change in the amount of summer rainfall, timing of monsoon start, impact of climate change on energy demand and energy consumption behaviour for space heating to reduce the impact of climate change on household energy (Table 3). A sizeable percentage of the respondents (47 to 74 %) choosing to transition to either of the four preference options did not perceive any change in the summer rainfall amount compared to two decades ago. Similarly, a major share of the people (77 to 86 %) did not perceive any change in the starting time of monsoon compared to the last twenty years. Additionally, people perceiving very high impacts of climate change on household energy demand preferred transitioning to grid electricity only (43 %) and grid electricity and renewables (37 %). Moreover, a considerable percentage of the respondents willing to make no changes in energy behaviour (44 %) perceived interventions in household heating could be beneficial for reduction of climate change impacts on the energy sector. As with socio-economic variables, no distinct pattern of people's preferences can be deduced with the climate change perception variables.

Socio-economic and climate change perception factors impacting people's energy transition preferences

Results of the ordinal logistic regression models show that the log likelihood values are comparable across the three models with the *Composite-model* having a relatively higher value (−365.56) (Table 4). The *p*-values are very close for all the three models. In addition, 10.5 % of the variance in the outcome is explained by the predictors in the *Composite-model* as shown by the McFadden's R2 which implies a reasonable fit of the model to the socio-economic and cross-section data (Hensher & Johnson, 2018; Ozili, 2023; Salam et al., 2023). Hence, the *Composite-model* is more representative of the data in explaining the response based on the explanatory variables.

For the *SCE-model*, variables related to the urbanization status, level of education, living standard, and the availability of alternate household energy sources are statistically significant predictors of the responses at 5 % level of significance (Table 4). In the case of *CCP-model*, variables linked to the perceptions regarding changes in winter rainfall, withdrawal of monsoon season, household energy demand, notably cooking and space heating, and the importance of community level subsidies for minimizing the climate change-induced effects on household energy patterns were found to be statistically significant (Table 4).

Similarly, for the *Composite-model*, variables associated to the urbanization status, level of education, living standard, the role of changing the energy consumption behaviour for cooking, and the importance of community level subsidies for minimizing the climate change-induced effects on household energy patterns were found to be statistically significant at 5 % (Table 4). The values of the coefficients within this model closely resemble those of the corresponding predictor variables within the *SCE-* and *CCP-models* (with some exceptions such as timing of start of monsoon, *Onset_monsoon*).

Table 5 presents the marginal effect estimates (coefficients) for the predictor variables for the four energy transition preferences (labelled as preference 1 (P1) to preference 4 (P4)) across three models: *SCE*, *CCP* and *Composite*. In the *SCE-model*, urbanization status, level of education, living standard and alternate household energy source were significant across all the response categories. For example, the marginal estimate is 0.080 for the first preference (no change to existing household energy behaviour) when considering the urbanization status variable (*Load_centre*). This indicates that as the value of this variable increases by one category (say, urban to semi-urban areas), the odds of preferring to transition to better energy technologies also increases by 8 %. On the other hand, the level of education (*Literacy*) depicts that it has a marginal coefficient of −0.118 for not preferring to make any energy changes. This shows that as the education level increases, people are more likely to prefer transitioning to better energy technologies. Interestingly, the probabilities continuously increase as we progress up the preference level from P1 to P4. Likewise, the marginal estimate of the respondents for their living standard (*House_type* variable) for being in the no change category (P1) is −0.103 indicating the probability of transitioning to higher options continuously increases with better living standards.

In the case of *CCP-model*, the marginal effects of people's perception of changes in winter rainfall, withdrawal of monsoon season, household energy demand, including cooking and space heating energy behaviour, and community level subsidies were found to be significant across all the response preferences (Table 5). For example, as the value of the winter rainfall perception variable (*Winter_rain*) increases by one category (say, from 'increased' to 'no change'), the odds of preferring to transition to better energy technologies also increases by 10 %. Conversely, marginal estimate (−0.110) in the 'no change' category in energy transition preference category (P1) for the community level subsidies (*Comm_interv_subsidy*) indicates that more the people start realizing the importance of community subsidies for energy efficiency, the odds of moving

Table 3
Descriptive statistics of the climate change perception variables with respect to the four energy transition preferences.

Description of perception based explanatory factors (*variables*) and classes	Energy transition preference								Chi-square (p-value)
	Preference 1: No change/ I do not know		Preference 2: To grid electricity only		Preference 3: To other renewables only		Preference 4: To electricity and renewables		
	Frequency	%	Frequency	%	Frequency	%	Frequency	%	
Change in the summer temperature on an average *(Summer_temp)*									17.827*** (0.007)
Increased (1)	93	62	47	64	18	38	36	70	
No change (2)	47	31	18	24	26	56	11	22	
Decreased (3)	11	7	9	12	3	6	4	8	
Change in the winter temperature on an average *(Winter_temp)*									2.7493 (0.840)
Increased (1)	72	48	39	53	25	53	27	53	
No change (2)	68	45	30	41	17	36	22	43	
Decreased (3)	11	7	5	7	5	11	2	4	
Change in the amount of rainfall during summer *(Summer_rain)*									16.414** (0.012)
Increased (1)	33	22	23	31	20	43	16	31	
No change (2)	112	74	50	68	22	47	31	61	
Decreased (3)	6	4	1	1	5	11	4	8	
Change in the amount of rainfall during winter *(Winter_rain)*									5.8477 (0.440)
Increased (1)	35	23	22	30	16	34	16	31	
No change (2)	78	52	38	51	25	53	27	53	
Decreased (3)	38	25	14	19	6	13	8	16	
Change in the timing of monsoon start *(Onset_monsoon)*									13.976** (0.030)
Delayed (1)	19	13	17	23	6	13	6	12	
No change (2)	130	86	57	77	39	83	41	80	
Ahead (3)	2	1	0	0	2	4	4	8	
Change in the timing of monsoon end *(Withdrawal_monsoon)*									23.752*** (0.001)
Delayed (1)	33	22	18	24	18	38	24	47	
No change (2)	115	76	54	73	25	53	23	45	
Ahead (3)	3	2	2	3	4	9	4	8	
Impact of climate change on household energy availability *(climate change_energy_availability)*									26.375*** (0.009)
Very Low (1)	2	1	4	5	0	0	0	0	
Low (2)	13	9	3	4	5	11	3	6	
Moderate (3)	56	37	13	18	17	36	10	20	
High (4)	40	26	33	45	15	32	18	35	
Very high (5)	40	26	21	28	10	21	20	39	
Impact of climate change on household energy demand *(climate change_energy_demand)*									24.411** (0.018)
Very Low (1)	8	5	0	0	0	0	0	0	
Low (2)	15	10	6	8	4	9	1	2	
Moderate (3)	45	30	11	15	17	36	14	27	
High (4)	44	29	25	34	11	23	17	33	
Very high (5)	39	26	32	43	15	32	19	37	
Impact of change in cooking behaviour for reduction of climate change impacts on the household energy sector *(HH_intervention_cooking)*									9.4470 (0.664)
Very Low (1)	22	15	9	12	7	15	1	2	
Low (2)	13	9	4	5	3	6	3	6	
Moderate (3)	17	11	12	16	7	15	6	12	
High (4)	39	26	21	28	13	28	15	29	
Very high (5)	60	40	28	38	17	36	26	51	
Impact of change in space heating behaviour for reduction of climate change impacts on the household energy sector *(HH_intervention_heating)*									20.468** (0.059)
Very Low (1)	2	1	5	7	3	6	2	4	
Low (2)	7	5	4	5	2	4	2	4	
Moderate (3)	35	23	16	22	17	36	9	18	
High (4)	41	27	25	34	18	38	20	39	
Very high (5)	66	44	24	32	7	15	18	35	
Effectiveness of raising community level awareness for reduction of climate change impacts on household energy *(Community_awareness)*									18.9755* (0.089)
Very Low (1)	1	1	1	1	0	0	0	0	
Low (2)	2	1	0	0	1	2	0	0	
Moderate (3)	6	4	1	1	7	15	3	6	
High (4)	40	26	14	19	11	23	8	16	
Very high (5)	102	68	58	78	28	60	40	78	
Effectiveness of providing community level subsidies in energy efficient devices for reduction of climate change impacts on household energy *(Community_subsidy)*									36.737*** (0.000)

(*continued on next page*)

Table 3 (*continued*)

Description of perception based explanatory factors (*variables*) and classes	Energy transition preference								Chi-square (p-value)
	Preference 1: No change/ I do not know		Preference 2: To grid electricity only		Preference 3: To other renewables only		Preference 4: To electricity and renewables		
	Frequency	%	Frequency	%	Frequency	%	Frequency	%	
Very Low (1)	1	1	1	1	2	4	0	0	
Low (2)	2	1	0	0	2	4	0	0	
Moderate (3)	20	13	1	1	6	13	2	4	
High (4)	59	39	24	32	7	15	10	20	
Very high (5)	69	46	48	65	30	64	39	76	
Total	**151**	**100**	**74**	**100**	**47**	**100**	**51**	**100**	

Note: Numbers in parenthesis alongside the variable classes in the first column indicate the numeric classes used for modelling. *, ** and *** in the last column refer to significance level of 10 % ($p \leq 0.1$), 5 % ($p \leq 0.05$) and 1 % ($p \leq 0.01$), respectively.

Table 4

Estimation of the impact that explanatory variables have on the response (preference) variable obtained by a) socio-economic (SCE) model ; b) climate change perception (CCP) model and c) combined socio-economic and climate change perception (Composite) model.

Variables	a) SCE-model			b) CCP-model			c) Composite-model		
	Coefficient	Std. Error	p-Value	Coefficient	Std. Error	p-Value	Coefficient	Std. Error	p-Value
Physiography	0.077	0.156	0.621				−0.037	0.165	0.822
Load Centre	−0.319**	0.142	0.025				−0.319**	0.156	0.041
Gender	0.130	0.287	0.650				0.124	0.297	0.675
Age	0.016	0.158	0.921				0.017	0.163	0.917
Literacy	0.474***	0.155	0.002				0.432***	0.165	0.009
Occupation	0.097	0.098	0.321				0.108	0.103	0.292
Income	−0.071	0.101	0.481				0.010	0.108	0.929
Ethnicity	−0.063	0.212	0.767				−0.095	0.219	0.663
House_type	0.413**	0.173	0.017				0.342**	0.175	0.050
Family_size	0.098	0.154	0.522				0.068	0.158	0.667
Major_energy_source	−0.118	0.130	0.365				−0.101	0.138	0.463
Second_major_energy	−0.309**	0.160	0.050				−0.317*	0.167	0.058
Summer_temp				−0.105	0.207	0.612	−0.235	0.219	0.283
Winter_temp				−0.083	0.183	0.651	−0.053	0.191	0.782
Summer_rain				−0.173	0.206	0.401	−0.013	0.219	0.954
Winter_rain				−0.411**	0.191	0.032	−0.271	0.202	0.181
Onset_monsoon				0.284	0.276	0.303	0.504*	0.288	0.080
Withdrawal_monsoon				−0.393*	0.212	0.063	−0.372*	0.219	0.090
CC_energy_availability				0.047	0.138	0.732	−0.001	0.146	0.995
CC_energy_demand				0.245*	0.128	0.056	0.184	0.132	0.164
HH_interv_cooking				0.176**	0.087	0.044	0.164*	0.093	0.077
HH_interv_heating				−0.278**	0.115	0.016	−0.273**	0.124	0.028
Comm_interv_awareness				−0.215	0.196	0.273	−0.127	0.211	0.548
Comm_interv_subsidy				0.442***	0.169	0.009	0.403**	0.179	0.024
Model diagnostics									
Log likelihood	−379.08			−388.94			−365.56		
LR chi2(12)	59.02			39.30			86.05		
Prob > chi2	0.000			0.0001			0.000		
McFadden's R2	0.0722			0.0481			0.105		
Number of obs.	323			323			323		

Note: Ordinal logistic regression was carried out separately for the three cases *a* , b, and c. *, ** and *** in the "Coefficeint" columns refer to significance level of 10 % ($p \leq 0.1$), 5 % ($p \leq 0.05$) and 1 % ($p \leq 0.01$), respectively.

up the preference category increases substantially. The same set of variables as in the individual *SCE-model* and *CCP-model* were found to be significant for the *Composite-model* except people's perception of changes in winter rainfall and influence of CC on household energy demand.

Discussion

Socio-economic data

Our choice of the socio-economic variables was based on literature review. As suggested by Butchers et al. (2020), careful attention has been given to capture the local energy context of Nepal. Most of the household energy is used for cooking in Nepal followed by lighting and other uses (MoF/GoN, 2023). People mostly use traditional fuels such as firewood, hay and dung cakes in the rural areas with very limited use of LPG and electric stoves whereas people in the urban areas mostly use LPG stoves with some electric appliances (CBS, 2021).

One of our respondents explained that 'guitha' (dried cow/buffalo dung cakes for direct combustion) is the only available option to her family for cooking and heating. Although her village is connected to the national electricity grid, but her family cannot afford to use electricity because of their poor financial condition. She reported a similar reluctance in the use of LPG stoves due to the same reason. Her family rears cows and buffalos and they prepare 'guitha' for free. She was not aware of the health issues that would arise due to extended use of 'guitha' for household use and did not believe that it would be harmful because she has seen the same thing in her kitchen from generations without anyone complaining (a mid-aged housewife from Laxminiya Rural Municipality of Dhanusha district in the Terai plains).

Unlike the developed countries, refrigerators and modern room heating/cooling technologies such as air conditioners, coolers and heaters are mostly limited to the upper-class people of urban areas only.

Table 5
Marginal effect estimates across the four preference values derived from a) socio-economic (*SCE*) model ; b) climate change perception (*CCP*) model and c) combined socio-economic and climate change perception (*Composite*) model.

Variables	a) SCE-Model				b) CCP-Model				c) Composite-Model			
	P1	P2	P3	P4	P1	P2	P3	P4	P1	P2	P3	P4
Physiograpy	−0.019	0.004	0.006	0.008					0.009	−0.002	−0.003	−0.004
Load_centre	0.080*	−0.018**	−0.027**	−0.035**					0.080**	−0.020*	−0.028**	−0.032**
Gender	−0.033	0.007	0.011	0.014					−0.031	0.008	0.011	0.013
Age	−0.004	0.001	0.001	0.002					−0.004	0.001	0.001	0.002
Literacy	−0.118***	0.026**	0.040***	0.052***					−0.108***	0.027**	0.038**	0.043***
Occupation	−0.024	0.005	0.008	0.011					−0.027	0.007	0.009	0.011
Income	0.018	−0.004	−0.006	−0.008					−0.002	0.001	0.001	0.001
Ethnicity	0.016	−0.004	−0.005	−0.007					0.024	−0.006	−0.008	−0.010
House_type	−0.103**	0.023**	0.035**	0.045**					−0.085*	0.021*	0.030*	0.034**
Family_size	−0.025	0.005	0.008	0.011					−0.017	0.004	0.006	0.007
Major_energy_source	0.029	−0.007	−0.010	−0.013					0.025	−0.006	−0.009	−0.010
Second_major_energy	0.077**	−0.017*	−0.026*	−0.034**					0.079*	−0.020*	−0.028*	−0.032*
Summer_temp					0.026	−0.005	−0.009	−0.012	0.059	−0.015	−0.021	−0.024
Winter_temp					0.021	−0.004	−0.007	−0.010	0.013	−0.003	−0.005	−0.005
Summer_rain					0.043	−0.008	−0.014	−0.021	0.003	−0.001	−0.001	−0.001
Winter_rain					0.102**	−0.019*	−0.034**	−0.049**	0.068	−0.017	−0.024	−0.027
Onset_monsoon					−0.071	0.013	0.024	0.034	−0.126*	0.031	0.044*	0.051*
Withdrawal_monsoon					0.098*	−0.018*	−0.033*	−0.047*	0.093*	−0.023	−0.032	−0.037*
CC_energy_availability					−0.012	0.002	0.004	0.006	0.000	0.000	0.000	0.000
CC_energy_demand					−0.061**	0.011	0.021*	0.029*	−0.046	0.011	0.016	0.018
HH_interv_cooking					−0.044**	0.008*	0.015**	0.021**	−0.041*	0.010*	0.014*	0.016*
HH_interv_heating					0.069**	−0.013**	−0.023	−0.033**	0.068**	−0.017*	−0.024**	−0.027**
Comm_interv_awareness					0.053	−0.010	−0.018	−0.026	0.032	−0.008	−0.011	−0.013
Comm_interv_subsidy					−0.110***	0.020**	0.037**	0.053***	−0.100**	0.025*	0.035**	0.040**

Note: *P1* denotes people's first preference responses “I don't know” or “No change”; *P2* denotes people's second preference responses “Transition to grid electricity only”; *P3* denotes people's third preference response “Transition to other renewables only”; *P4* denotes people's fourth preference responses “Transition to electricity and renewables”. *, ** and *** refer to significance level of 10 % ($p \leq 0.1$), 5 % ($p \leq 0.05$) and 1 % ($p \leq 0.01$), respectively.

The hilly regions are mostly cooler compared to the southern plains. Hence, cooling devices are generally not necessary. Traditional room heating (bonfires, charcoal fire in pans, *etc.*) are common in these areas. These days, some people with a strong financial status in the hilly areas have started using electric or LPG heaters. Hybrid solar water heating systems have also been piloted in some areas of Nepal recently (Thapa et al., 2022) but their sustainability is a big issue. On the other hand, the Terai plains are mostly hot throughout the year but only those households that can afford use table/ceiling fans mostly during summer.

It can be seen from Table 2 that the spread of the data across the different categories as well as across the different response classes is relatively well distributed. It is also evident that variables related to urbanization status, level of education, employment condition, ethnicity, living standards and availability of household energy sources are statistically significant as depicted by the *p*-values of Chi-square test. These results are as expected because the preferences of the local people are mostly governed by their level of awareness (which is explained by education), and financial capacity to move to better energy alternatives (which is explained by the level of urbanization, employment and living standards). Moreover, the underprivileged ethic groups do not have access to multiple energy options in Nepal as compared to the privileged classes (Lin & Kaewkhunok, 2021). As a result, the use of household energy, availability of modern and efficient energy technologies and willingness to adopt better options are rather limited in such underprivileged groups. These results are concurrent with other recent studies on household energy behaviour of Nepal such as Das et al. (2022) and Koirala and Acharya (2022). Moreover, Bhattarai et al. (2018) show doubt over whether the government subsidies and donations targeted at the rural poor and marginalized people are actually reaching them.

Climate change perception data

Similar to the socio-economic variables, the climate change perception variables have also been carefully chosen so that they depict the true context of Nepal encompassing the perceived changes in temperature, magnitude and timing of rainfall, impacts on the household energy use and the role of possible interventions at the household and community levels. It is to be noted that the climate of Nepal varies from subtropical to arctic over a short north-south span of <200 km (DHM/CCAFS, 2013). Because of the rugged terrain and hilly and mountainous topography, rainfall is largely influenced by factors such as orography, aspect (windward/leeward) and other micro-climatic conditions. Therefore, people living in such diverse climatic conditions have different perceptions of climate change and its impact on the household energy behaviour.

From a climate change perspective, change in summer temperature, timing and volume of monsoon, effectiveness of household interventions and community level interventions for reducing the climate-related impacts on household energy demand and availability have been identified as statistically significant variables across the classes (Table 3). Most people are aware that almost 100 % of Nepal's domestic electricity production is from hydropower which relies on the monsoon. As a result, people perceive the change in timing and volume of monsoon to have a considerable impact on the availability of energy (mostly electricity) in grid connected areas. The rural remote areas are also supplied with electricity generated by micro-hydropower supplied though local grids (AEPC/GoN, 2023). Hence, these smaller rivers are even more sensitive to the changes in monsoon. In addition, increased monsoon causes cloud cover for a longer period of time which could possibly impact the local rooftop solar power generation mainly for lighting the rural households.

One respondent during our field survey mentioned that his family has been cooking in LPG stoves since a long time. They find LPG stoves convenient because it does not produce smoke, the food is cooked relatively faster, the gas cylinders are conveniently available for refilling and they can easily afford one cylinder per month. Although being in an urban area with access to grid electricity, his family is hesitant to switch to electric stoves due to frequent power cuts. Interestingly, he is not aware of the impacts that climate change could have on (hydro) electricity generation and felt that the government is intentionally not generating enough electricity in the dry season despite the availability of tremendous volume of water in the rivers of Nepal (a mid-aged university graduate from Lalitpur Metropolitan in Kathmandu Valley).

People's energy transition preferences

Our results show that the same set of explanatory variables are statistically significant for the individual models as well as the combined model. Moreover, the model diagnostics show that the *Composite-model* is more appropriate in explaining people's energy transition preferences at the household level in Nepal.

Table 4 and Table 5 show that the statistically significant socio-economic variables related to urbanization status, level of education, living standard, availability of household energy sources, and employment status are indicative of two key points: the level of awareness and financial condition for transitioning to better energy forms (similar to the findings of Matavel et al. (2023) in Mozambique). People living in the urban areas (for instance, Kathmandu City of Nepal and other towns) have a general tendency to prefer switching to better renewable forms of energy. This is because, in most of the cases, these households are already connected to the national electricity grid. Additionally, they are in a relatively better financial condition and are used to fuel stacking as a result of the chaotic and disintegrated energy landscape of energy that Nepal had to go through (Das et al., 2022; Movik & Allouche, 2020).

However, people in the semi-urban and rural areas of the country have a lower level of literacy. Rural households are still largely dependent on conventional fuels (CBS, 2021). Additionally, they are either already reliant on off-grid energy technologies such as rooftop solar PVs (Gautam et al., 2015) or micro-hydropower projects (Yadoo & Cruickshank, 2012) or they are not in a financially stable position to make these changes. Moreover, studies have demonstrated that off-grid electricity systems in South Asia typically lack systematic distribution models and are mostly reliant on community-centred projects without proper linkage to income generating opportunities, sustainable market and poor technological management (Palit & Bandyopadhyay, 2016). National electricity grid has a limited reach in the remote areas of Nepal which are difficult to access (AEPC/GoN, 2023). Some studies have recommended increasing electricity tariffs to increase the efficiency of Nepal's electricity sector (Sovacool et al., 2013). However, such an intervention could prove counter-productive especially among the rural poor who are already in a difficult financial situation to afford electricity at the current price. A similar finding has been reported by Navarro-Espinosa and Thomas-Galán (2023) considering people in the lowest socio-economic category of Chile. Besides, people refrain from diverting their existing energy beliefs and practices and do not want to step out of their comfort zones (Chung & Kim, 2018; Nshimiyimana et al., 2024).

One of our survey respondents mentioned that he is unaware of the available renewable energy technologies applicable for daily household use. He also expressed his happiness that he took part in the survey with our team because he got to learn many new things about renewable energy. He further seemed willing to progress to clean renewable technologies at the household level that he could afford to build a better and sustainable energy future for Nepal (a resident from Banepa Municipality in Kavrepalanchowk district in mid hills region).

On the climate change end, the timing and volume of monsoon have been identified as statistically significant variables for people's energy transition preference (Table 4 and Table 5). Hence, people perceive hydropower to be the most impacted due to climate change in the future. Studies in the Hindu Kush Himalayan (HKH) region have shown that the performance of hydropower projects are likely to be adversely impacted by climate change (Shrestha et al., 2021). Conversely, some studies such as Bhattarai et al. (2022), Marahatta, Devkota, and Aryal (2021) and Marahatta et al. (2022) have projected increased hydropower generation possibilities as a result of climate change in the future addressing due challenges. Moreover, a recent study has shown that two-thirds of the untapped hydropower potential lies in the HKH region (Xu et al., 2023) among which Nepal has a possibility to contribute significantly. Nepal has a unique Himalayan climate with a massive economically feasible hydropower potential of 50,000 MW (Jha, 2010; Sharma & Awal, 2013). But the country has been able to harness only a miniscule fraction of the potential because of its poor economic condition (MoF/GoN, 2023; NEA/GoN, 2023). Recent studies have even quantified energy security of Nepal to find that it is in a 'pseudo energy-secure' condition (Bhattarai et al., 2024b). Such a resource-underutilized situation is common across many developing countries of Africa, Latin America and Asia (Hamududu & Killingtveit, 2016; Mtilatila et al., 2020; Uamusse et al., 2020).

Additionally, climate change studies such as Devkota and Bhattarai (2018) and (Lutz et al., 2022) have reported increasing extremes in temperature in Nepal and the entire HKH region. Identification of summer temperature as a significant variable in determining people's energy preferences could be linked to people's perception of summers becoming hotter (Marahatta, Aryal, et al., 2021). Because of the apprehension of changing monsoon and temperature, people also consider that climate change is likely to impact the household energy demand which can be addressed by regulated subsidies. Many instances of past failures of subsidies in the renewable energy sector have been reported in Nepal (Balachandra, 2015; Bhandari et al., 2017; Dhital et al., 2016). However, the effectiveness can be considerably enhanced by investing in awareness building on the benefits of using renewable energy at the community level.

Another survey respondent admitted not knowing about the household sector being the largest energy consuming sector of Nepal. She was aware of the health and environmental impacts of cooking using traditional fuels and LPG. She also showed concern about their impacts on climate change in the long run. But, to our surprise, she denied her willingness to completely switch to renewables for household energy because they were expensive and there were not enough and convincing awareness campaigns conducted at the community level (a university student from Lalitpur Metropolitan of Lalitpur District in the mid hills region).

Studies have shown that the energy policy trajectory of Nepal has been progressive over the last few decades (Bhattarai et al., 2024a). The rural energy policies of Nepal are more inclined towards increasing the penetration of off-grid renewable energy technologies in rural and remote areas whereas the other policies and strategies are centerd towards increasing access to quality grid hydroelectricity in Nepal. The rural energy policies of Nepal have undergone many revisions (2006, 2009, 2013 , 2016 and 2022) over the last couple of decades (AEPC/GoN, 2023; MoPE/GoN, 2016). The Seventh National Plan 1985 and Eight National Plan 1992 envisioned hydropower development and alternative renewable energy while the Hydropower Development Policy 1992 and 2001 and Water Resources Strategy 2002 promoted (large and small) hydropower development for meeting industrial, domestic and transportation demands (AEPC/GoN, 2023; HMG/N, 1992a; HMG/N, 1992b; HMG/N, 2001; HMG/N, 2002; Sanjel & Baral, 2020). Furthermore, the Second and Third Nationally Determined Contribution to UNFCC (MoFE/GoN, 2021) and the Nepal's Long-term Strategy for Net Zero Emissions (GoN, 2021) have strongly focused on the increment of renewables in the energy generation mix in the future. However, the effectiveness of such policies has been limited in Nepal, mainly due to administrative hassles in the implementation side and lack of proper 'energy ecosystem' development in the generation and use of renewables (Bhattarai, Maraseni, Apan, & Devkota, 2023). Moreover, we agree with the recommendations set out by Bhattarai et al. (2024a) on improving supply-side management, demand-side management, multi-sector collaboration, and political stability and good governance for a sustainable energy future of Nepal.

A well-educated self-employed businessman (one of the survey respondents) from Kathmandu Metropolitan city felt great pride in mentioning that he had installed two sets of electric wiring in his house: one for the use of grid electricity (alternating current) while the second for the use of solar electricity from his rooftop solar PV panel (direct current). He further mentioned that it was quite expensive from his end and did not get any rebates for the installation. Nevertheless, he felt a great deal of satisfaction in being able to generate electricity at his house through solar energy and rely less on the state-supplied grid electricity. However, he showed his frustration over the government of Nepal in not supporting him to install net metering systems in his house despite a lot of effort from his side. But he is hopeful that the state will soon implement supportive policies for such technological advancements to increase the share of renewables in the household energy sector of Nepal.

García-Gusano et al. (2017) highlights that energy transition comes with structural changes – rearrangement in policies, economies and societies leading to redistribution of power, resources and risks. Zhou et al. (2023) recommend strengthening renewable energy outputs, green technological innovation and financial development for reducing sectoral risks to a sustainable carbon-neutral society in Asia. Taking the case of South Korea, Cho et al. (2024) show that only technological advancements might not be adequate to attain future carbon-neutrality targets. The current trend of reduction in the use of traditional fuels for cooking at the cost of increased use of imported LPG at high prices in Nepal (MoF/GoN, 2023) should be discouraged at the policy and implementation levels. In addition, scholars have stressed regular revisions of the policies following a bottom-up pathway incorporating conflict sensitivity assessment to minimize disproportionate impacts on the stakeholders (Lomax et al., 2023; Pandey et al., 2021; Wu, 2020). Hence, Nepal needs to learn from the past mistakes and focus more on strengthening the energy policies to create a conducive environment encouraging generation of domestic renewable energy. The Government of Nepal has identified hydropower as the lead renewable energy technology in Nepal (WECS/GoN, 2013) which needs to be supplemented by other off-grid alternative renewables. Extension of the national electricity grid to the rural remote areas need to be the prime focus of the government to provide impetus to the renewable energy transition in Nepal. Moreover, proper check and balance mechanisms need to be in place to ensure that community level energy subsidies reach the actual needy. Likewise, effective energy credit measures and mass interventions of energy efficient devices not only for lighting but also for cooking to completely displace the usage of traditional fuels is seen as an utmost necessity for achieving economic as well as environmental well-being of the country sustainably.

There were some limitations in our study. Firstly, increasing the sample size could provide a more comprehensive coverage of the study area. Additionally, utmost care has been taken to collect data from different locations occupying diverse socio-economic respondents and implemented randomization to avoid sample bias. Moreover, perception and preferences are qualitative data which are relative in nature. Therefore, respondents belonging to similar socio-economic categories and climatic contexts can also have different perceptions and preferences. Furthermore, the perceptions and preferences of the same respondent can vary over time. We consider this as the measurement error that we might have in this study which could be overcome by longitudinal survey across different times. Additionally, we acknowledge that considering confounding variables could provide a more nuanced understanding of the relationships between the predictor-response variables. However, assessing the impacts of potential confounding variables (such as specific local environmental conditions, in−/out-migration, regional economic policies, and other socio-demographic factors, among others) on the household energy behaviour is beyond the scope of this work. They could be plausible areas of future research.

Conclusion

Realizing the need for research into the assessment of the combined effects of socio-economic factors and climate change perception on energy preferences in developing nations, we carried out this study taking the case of a South Asian developing country – Nepal – focusing on household level energy use behaviour.

Results show that 151 (47 %) respondents preferred no change from their existing conditions; 74 (23 %) opted solely to rely on grid electricity; 47 (14 %) chose transitioning to renewables only while 51 (16 %) preferred changing to a mix of grid-electricity and renewables. Moreover, the *Composite-model* outperformed the others two (socio-economic, *SCE* and climate change perception, *CCP*) models with relatively better model diagnostics. Most of the identified influencing parameters were common across the three models. The socio-economic factors pertaining mainly to urbanization status, education level, and availability of energy choices for households were found to be statistically significant with relatively higher marginal estimates. This indicated that creating awareness among the people and building economic motivation play key roles in energy transition preference of Nepalese households. Similarly, climate change perception determinants related to timing of monsoon, amount of winter rainfall, alterations in cooking and space heating energy demands, and community level energy subsidies were found to be statistically significant.

Hence, we infer that the socio-economic and climate change perception parameters need to be dealt with holistically to drive the renewable energy transition of Nepal effectively. Moreover, our research suggests that the combination of socioeconomic and climate perception factors yields comprehensive, meaningful, and adoptable outcomes for decision makers at all levels. The current energy prices are still unaffordable to a major share of the national population. Current fossil-fuel based technologies are not sustainable leading to increased trade deficits and have long-term environmental implications. The renewable energy potential of Nepal needs to be harnessed to help the country transition to a cleaner and sustainable energy future. However, the country does not possess adequate technical and financial capacity to adapt to changing energy conditions. Furthermore, there are high chances that subsidies for renewable energy may increase the disparity among the rich and poor. These issues act as barriers to the renewable energy transition of Nepal.

We conclude that, at the state level, Nepal should continuously update its energy policies to create a conducive environment for sustainable renewable energy transition. Promotion of domestic hydropower generation should lead the way with the addition of other renewable technologies in the generation mix. Relying on off-grid smaller energy technologies could be a temporary measure but the country should focus on extending the national electricity grid to the rural remote areas to penetrate the rural household energy sector of Nepal. In addition, it is seen that Nepal needs to focus on providing impetus to building community awareness and maximizing effectiveness of subsidies and other financial incentives. Hence, our contribution lies in this important policy-science-society interface which will be insightful to the decision makers in the energy sector of developing countries in general and Nepal in particular.

Longitudinal survey could be an extension of this research to examine the time-varying parameters and their likely influence on people's energy use behaviour. In addition, there are a number of unanswered questions in our study, such as those related to energy democracy and justice, bottom-up approaches in policy formulation, stakeholder involvement in development of energy generation projects, public concerns related to good governance and their impacts on the household energy sector. Furthermore, assessing the influence of other confounding variables could provide a better understanding of the predictor-response relationship. Addressing these concerns could serve as future research avenues.

CRediT authorship contribution statement

Utsav Bhattarai: Writing – original draft, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Tek Maraseni:** Writing – review & editing, Supervision, Resources, Methodology, Conceptualization. **Laxmi Prasad Devkota:** Writing – review & editing, Validation, Supervision, Methodology. **Armando Apan:** Writing – review & editing, Validation, Supervision.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

Table A1
Independent explanatory and response variables and their classification adopted in this study.

S·N	Description	Variables	Classes	Code	Justification
a) Explanatory socio-economic variables					
1	Type of terrain	*Physiography*	High hills Mid hills Terai (plains)	1 2 3	We excluded High Mountains among the four physiographic zones of Nepal as it is almost inhabited. Each of these regions showcases distinct patterns of energy generation and consumption. Therefore, this classification has been adopted

(*continued on next page*)

Table A1 (*continued*)

S-N	Description	Variables	Classes	Code	Justification
					to encompass the diverse energy dynamics across the country.
2	Level of urbanization	*Load_centre*	Kathmandu Other towns Others	1 2 3	This variable primarily represents the accessibility and utilization of grid electricity in Nepal. Kathmandu (the capital city) is characterized by a significantly high population density, extensive electricity infrastructure and large energy consumption. In contrast, other towns have lower population densities and smaller electricity consumption rates. The remaining areas (Others) are considered less significant for electricity use.
3	Gender of the respondent	*Gender*	Female Male	1 2	These are obvious natural categories.
4	Age of the respondent	*Age*	20–35 years 35–50 years > 50 years	1 2 3	This variable pertains not to the age of the household head, but to the age of the individuals who possess greater awareness of energy-related matters within the household. Category '1' encompasses young individuals, including students and those in the early stages of their careers. Likewise, the second category '2' represents middle-aged people who have established careers and exhibit maturity in household decision-making. The third category '3' pertains to retirees or those who work less in comparison to the other two groups.
5	Education level of the respondent	*Literacy*	Illiterate Primary school/ informal education Secondary / high school University	1 2 3 4	These categories are selected to examine people's awareness level based on their education.
6	Type of employment of the respondent	*Occupation*	Unemployed/ retired Farming/ livestock rearing Self-employed Academic/ government service Private organization	1 2 3 4 5	Socioeconomic circumstances and occupation shape individual's perspectives, lifestyles and household behaviours. People with stable occupations are more likely to make deliberate and sustainable household choices whereas those unemployed or engaging in unstable professions are more inclined towards to temporary decisions. Our classification scheme for this variable aims to capture the responses of these distinct groups.
7	Annual household income (US$)	*Income*	< 692 692–1154 1154–1961 > 1961	1 2 3 4	We have considered the income thresholds aligning them with the World Bank's categorization of: (category 1) the international poverty line (US$ 1.90 per day), and the income brackets of (category 2) lower middle-income (US$ 3.20 per day) and (category 3) upper-middle income countries (US$ 5.50 per day). Considering the foreign exchange rate of US$ 1 ≈ NRs 130 during the time this research was conducted for Nepal, an annual income of NRs 90,000 which is equivalent to US$ 692 per year corresponds to category 1; NRs 150,000 which is equivalent to US$1154 per year corresponds to category 2; and NRs 255,000 is equivalent to US$ 1961 per year corresponds to category 3.
8	Ethnic background of the household	*Ethnicity*	Marginalized/ Underprivileged Indigenous Brahmin/ Chhetri	1 2 3	These categories correspond to the caste/ethnicity structure prevalent in Nepal in which the distinction is made between the privileged, indigenous and underprivileged communities of the society. Such a segregation have led to disparities in access to amenities, services, information and household behaviours between these groups which we aim to consider in our analysis.
9	Living standard of the household	*House_type*	Mud hut/ cottage Bamboo/ wood Bricks and mud mortar Bricks and cement	1 2 3 4	The type of house reflects the overall economic condition of the family. A well-to-do family generally have their houses made of bricks and cement while the extremely poor ones live in temporary structures such as mud huts and cottages. Moreover, the energy use pattern is also highly dependent on the type of houses people have. The bricks and cement houses are generally located in the urban areas which are electrified whereas the poor people rely on traditional fuels for meeting their domestic energy needs.
10	Household size and type of family	*Family_size*	Nuclear (≤4 members) Extended (4–6 members) Joint (> 6 members)	1 2 3	The extended family structure (including grandparents) is prevalent in most semi-urban and rural areas of Nepal whereas the nuclear family model has lately become predominant in urban settings. Nevertheless, joint family setups, including grandparents, uncles, aunts, nephews, and nieces living together are still very common in the rural and remote areas of the country. Size of the family is likely to impact the household energy behaviour and we aim to incorporate this phenomenon into our analysis through this classification.
11	Availability of household energy options	*Major_energy_source*	Firewood/ dung/ agriculture residue	1	These categories have been devised based on the most common types of household fuels in Nepal. The accessibility,

(*continued on next page*)

Table A1 (*continued*)

S-N	Description	Variables	Classes	Code	Justification
			Petroleum (kerosene)	2	cost, health impacts, environmental implications and individual preferences considerably differ among the households utilizing various energy sources. We aim to consider such a variation into our analysis through information segregated for these classes.
			Liquified petroleum gas (LPG)	3	
			Grid-electricity	4	
			Renewables	5	
12	Availability of alternate household energy options	*Second_major_energy*	Petroleum (kerosene)	1	These categories have been devised based on the most common types of household fuels in Nepal. The accessibility, cost, health impacts, environmental implications and individual preferences considerably differ among the households utilizing various energy sources. We aim to consider such a variation into our analysis through information segregated for these classes.
			Liquified petroleum gas (LPG)	2	
			Grid-electricity	3	
			Renewables	4	
b) Explanatory climate change perception variables					
1	Change in the summer temperature on an average	*Summer_temp*	Increased	1	Temperature and rainfall are two of the most important climatic variables that are used for climate change assessments. Moreover, Nepal has a diverse climate ranging from sub-tropical to alpine. There are distinct summers (which are mostly hot) and winters (which are mostly cold). High temperatures during the summer and low temperatures during the winter are of special importance in Nepal's climatic system. Moreover, temperature has a great contribution mostly in agriculture and in the overall availability of natural resources. Hence, people's perception of whether they have felt any change in the summer and winter temperatures lately compared to twenty years ago is an important factor for this study which is expected to largely influence the people's preferences of energy transition.
			No change	2	
			Decreased	3	
2	Change in the winter temperature on an average	*Winter_temp*	Increased	1	
			No change	2	
			Decreased	3	
3	Change in the amount of rainfall during summer	*Summer_rain*	Increased	1	Similarly, the rainfall pattern is also quite distinct in Nepal with very wet monsoons (June to September) and dry during the rest of the year. As Nepal's electricity is completely reliant on hydropower, the amount of monsoon and its timing is very important. Most of the hydropower projects of Nepal are run-of-river types which are completely reliant on the monsoon water. Therefore, people's perception of whether they have felt any change in the rainfall compared to twenty years ago is an important factor for this study which is expected to largely influence the people's preferences of energy transition.
			No change	2	
			Decreased	3	
4	Change in the amount of rainfall during winter	*Winter_rain*	Increased	1	
			No change	2	
			Decreased	3	
5	Change in the timing of monsoon start	*Onset_monsoon*	Increased	1	
			No change	2	
			Decreased	3	
6	Change in the timing of monsoon end	*Withdrawal_monsoon*	Increased	1	
			No change	2	
			Decreased	3	
7	Impact of climate change on household energy availability	*CC_energy_availability*	Very Low	1	These variables are important because there is a large variation in how people perceive climate change across the different socio-economic categories in Nepal. Moreover, most people are aware of the country's dependency of electricity on hydropower, which in turn is impacted by the change in the overall hydrology. Additionally, change in climatic conditions could lead to altered availabilities of traditional fuels such as firewood and agricultural residue which form the major energy source for the rural domestic sector. Furthermore, impact of climate change on the energy requirement for different domestic purposes is an important aspect for this study.
			Low	2	
			Moderate	3	
			High	4	
			Very high	5	
8	Impact of climate change on energy demand	*CC_energy_demand*	Very Low	1	
			Low	2	
			Moderate	3	
			High	4	
			Very high	5	
9	Effectiveness of household level intervention in cooking to reduce the impact of climate change	*HH_interv_cooking*	Very Low	1	People's perceptions of their existing energy behaviour in cooking is a major factor in deciding their household energy transition preferences. Additionally, it is also interesting to understand how people have related their energy sources and technologies for cooking and whether making any interventions at the household level will make any contribution to reduce the impact of climate change.
			Low	2	
			Moderate	3	
			High	4	
			Very high	5	
10	Effectiveness of household level intervention in space heating to reduce the impact of climate change	*HH_interv_heating*	Very Low	1	People's perception of their existing energy behaviour in space heating is another major factor in deciding their household energy transition preferences. In addition, a better understanding of the relation between energy sources and technologies for space heating will help identify the necessary interventions required to contribute in reduction of the impact of climate change.
			Low	2	
			Moderate	3	
			High	4	
			Very high	5	
11	Effectiveness of increasing energy awareness at the community level to reduce the impact of climate change on household energy	*Comm_interv_awareness*	Very Low	1	In addition to household level energy technologies, off-grid systems at the community level also play a major role in people's energy transition preference. Raising awareness at the community level has high impacts on promoting such locally gridded technologies which reduce the reliance on the central (electricity) grid as well as motivate people to use clean and renewable energy. Community level efforts have
			Low	2	
			Moderate	3	
			High	4	
			Very high	5	

(*continued on next page*)

Table A1 (*continued*)

S-N	Description	Variables	Classes	Code	Justification
					been lagging behind in Nepal despite tremendous government efforts. Therefore, raising awareness has been considered an important intervention which direct impacts on the reduction of the impacts of climate change.
12	Effectiveness of increasing subsidy for energy efficiency at the community level to reduce the impact of climate change on household energy	*Comm_interv_subsidy*	Very Low	1	Additionally, many studies in the past have shown that subsidies for the household and community level energy systems have not been as effective as anticipated. Various
			Low	2	reasons have been identified for this ineffectiveness.
			Moderate	3	Moreover, if such subsidies can be effectively implemented,
			High	4	they would contribute largely towards the development of
			Very high	5	efficient clean energy systems which leads to mitigation of the climate change impacts. This perspective of the local people has been addressed by this variable which would govern their energy transition preference.
	Response variable				This is the dependent variable which has been
1	People's preference of transitioning to improved household energy options	*Preference*	Not aware/no change	1	conceptualized to be determined by a number of explanatory
			To grid-electricity only	2	variables discussed above. The people's responses indicate the variation in choice of transitioning to better energy
			To other renewables only	3	alternatives for domestic consumption. Moreover, such a categorization is able to capture people's willingness to
			To grid-electricity and other renewables	4	choose the best option for their socio-economic condition as well as future energy scenario due to climate change. In addition, segregation of the responses by different socio-economic categories provides insight into which areas need to be attended to by the state for a sustainable energy transition in Nepal. As studies have shown that large hydropower (grid-electricity) and other renewables (micro-hydro, solar, wind and hybrid systems) are the possible feasible energy options in Nepal, these have been selected as the response categories of this variable.

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.esd.2024.101505.

References

Abbas, K., Butt, K. M., Xu, D., Ali, M., Baz, K., Kharl, S. H., & Ahmed, M. (2022). Measurements and determinants of extreme multidimensional energy poverty using machine learning. *Energy, 251*, Article 123977. https://doi.org/10.1016/j.energy.2022.123977

Acharya, R., Maraseni, T. N., & Cockfield, G. (2019). Local users and other stakeholders' perceptions on the identification and prioritization of ecosystem services in fragile mountains: A case study of Chure region of Nepal. *Forests, 10*, 421. https://doi.org/10.3390/f10050421

Acosta, A., Nicolli, F., & Karfakis, P. (2021). Coping with climate shocks: The complex role of livestock portfolios. *World Development, 146*. https://doi.org/10.1016/j.worlddev.2021.105546

Adedoyin, F. F., Bekun, F. V., & Alola, A. A. (2020). Growth impact of transition from non-renewable to renewable energy in the EU: The role of research and development expenditure. *Renewable Energy, 159*, 1139–1145. https://doi.org/10.1016/j.renene.2020.06.015

Adha, R., Hong, C., Yang, S., & Muzayyanah, S. (2024). Re-Unveiling the energy efficiency impact: Paving the way for sustainable growth in ASEAN countries. *Sustainable Development. Portico*. https://doi.org/10.1002/sd.3005

AEPC/GoN. (2023). *Progress at a Glance: Year in Review FY 2079/80 (2022/23)*. Kathmandu, Nepal: Alternative Energy Promotion Centre. www.aepc.gov.np.

Amrutha, A. A., Balachandra, P., & Mathirajan, M. (2018). Model-based approach for planning renewable energy transition in a resource-constrained electricity system—A case study from India. *International Journal of Energy Research, 42*(3), 1023–1039. https://doi.org/10.1002/er.3892

Andreas, J. J., Burns, C., & Touza, J. (2018). Overcoming energy injustice? Bulgaria's renewable energy transition in times of crisis. *Energy Research & Social Science, 42*, 44–52. https://doi.org/10.1016/j.erss.2018.02.020

Anik, A. R., Begho, T., Sharna, S. C., Eory, V., & Rahman, M. M. (2022). Toward improving nitrogen use efficiency in rice production: The socio-economic, climatic and technological determinants of briquette urea adoption. *Renewable Agriculture and Food Systems, 37*(5), 417–428.

Bahn, O., De Bruin, K., & Fertel, C. (2019). Will adaptation delay the transition to clean energy systems? An analysis with ad-merge. *Energy Journal, 40*(4), 235–253. https://doi.org/10.5547/01956574.40.4.obah

Balachandra, P. (2015). Review of energy access, poverty, and development: The governance of small-scale renewable energy in developing Asia. *The Energy Journal, 360*.

Ballantyne, A. G., Wibeck, V., & Neset, T. S. (2016). Images of climate change – A pilot study of young people's perceptions of ICT-based climate visualization. *Climatic Change, 134*(1–2), 73–85. https://doi.org/10.1007/s10584-015-1533-9

Baniya, R., Talchabhadel, R., Panthi, J., Ghimire, G. R., Sharma, S., Khadka, P. D., Shin, S., Pokhrel, Y., Bhattarai, U., Prajapati, R., & Thapa, B. R. (2023). Nepal Himalaya offers considerable potential for pumped storage hydropower. *Sustainable Energy Technologies and Assessments, 60*, Article 103423. https://doi.org/10.1016/j.seta.2023.103423

Bhandari, B., Lee, K. T., Chu, W. S., Lee, C. S., Song, C. K., Bhandari, P., & Ahn, S. H. (2017). Socio-economic impact of renewable energy-based power system in mountainous villages of Nepal. *International Journal of Precision Engineering and Manufacturing - Green Technology, 4*(1), 37–44. https://doi.org/10.1007/s40684-017-0005-2

Bhandari, R., Saptalena, L. G., & Kusch, W. (2018). Sustainability assessment of a micro hydropower plant in Nepal. *Energy, Sustainability and Society, 8*(3). https://doi.org/10.1186/s13705-018-0147-2

Bhat, K. S., Bachhiesl, U., Feichtinger, G., & Stigler, H. (2019). A techno-economic model-based analysis of the renewable energy transition in the Indian subcontinent region. *Elektrotechnik und Informationstechnik, 136*(8), 361–367. https://doi.org/10.1007/s00502-019-00773-w

Bhattarai, D., Somanathan, E., & Nepal, M. (2018). Are renewable energy subsidies in Nepal reaching the poor? *Energy for Sustainable Development, 43*, 114–122. https://doi.org/10.1016/j.esd.2018.01.001

Bhattarai, U., Devkota, L. P., Marahatta, S., Shrestha, D., & Maraseni, T. (2022). How will hydro-energy generation of the Nepalese Himalaya vary in the future? A climate change perspective. *Environmental Research, 214*, Article 113746. https://doi.org/10.1016/j.envres.2022.113746

Bhattarai, U., Devkota, R., Maraseni, T., Devkota, L., & Marahatta, S. (2023). Attaining multiple sustainable development goals through storage hydropower development amidst community vulnerabilities. *Sustainable Development*. https://doi.org/10.1002/sd.2634

Bhattarai, U., Maraseni, T., Apan, A., & Devkota, L. P. (2023). Rationalizing donations and subsidies: Energy ecosystem development for sustainable renewable energy transition in Nepal. *Energy Policy, 177*, Article 113570. https://doi.org/10.1016/j.enpol.2023.113570

Bhattarai, U., Maraseni, T., Devkota, L., & Apan, A. (2024b). A Composite Indicator-based Method to Assess the Energy Security of Nepal and prospects of Cross-border Electricity sharing in South Asia. *Environment and Development*. https://doi.org/10.1016/j.envdev.2024.101002

Bhattarai, U., Maraseni, T., Devkota, L. P., & Apan, A. (2023). Application of machine learning to assess people's perception of household energy in the developing world: A case of Nepal. *Energy and AI, 14*, Article 100303. https://doi.org/10.1016/j.egyai.2023.100303

Bhattarai, U., Maraseni, T., Devkota, L. P., & Apan, A. (2024a). Evaluating four decades of energy policy evolution of a south asian country – Nepal: a comprehensive review. *Sustainable Development*. https://doi.org/10.1002/SD.3053

Bigerna, S., Bollino, C. A., & Polinori, P. (2021). Convergence in renewable energy sources diffusion worldwide. *Journal of Environmental Management, 292*. https://doi.org/10.1016/j.jenvman.2021.112784

Borozan, D. (2022). Asymmetric effects of policy uncertainty on renewable energy consumption in G7 countries. *Renewable Energy, 189*, 412–420. https://doi.org/10.1016/j.renene.2022.02.055

Braito, M., Flint, C., Muhar, A., Penker, M., & Vogel, S. (2017). Individual and collective socio-psychological patterns of photovoltaic investment under diverging policy regimes of Austria and Italy. *Energy Policy, 109*, 141–153. https://doi.org/10.1016/j.enpol.2017.06.063

Bremer, J., & Linnenluecke, M. K. (2017). Determinants of the perceived importance of organisational adaptation to climate change in the Australian energy industry. *Australian Journal of Management, 42*(3), 502–521. https://doi.org/10.1177/0312896216672273

Butchers, J., Williamson, S., Booker, J., Tran, A., Karki, B., & Gautam, B. (2020). *Understanding sustainable operation of micro-hydropower: A field study in Nepal*. https://doi.org/10.5523/bris.1k9cigxbcdiye22kuay4wbt5yu

CBS. (2021). *Nepal in figures 2021*. Kathmandu, Nepal: Central Bureau of Statistics. www.cbs.gov.np.

Chhogyel, N., Kumar, L., Bajgai, Y., & Hasan, M. K. (2020). Perception of farmers on climate change and its impacts on agriculture across various altitudinal zones of Bhutan Himalayas. *International journal of Environmental Science and Technology, 17* (8), 3607–3620. https://doi.org/10.1007/s13762-020-02662-8

Cho, S., Jeong, Y. S., & Huh, J. H. (2024). Is South Korea's 2050 Carbon-Neutral scenario sufficient for meeting greenhouse gas emissions reduction goal? *Energy for Sustainable Development, 80*, Article 101447. https://doi.org/10.1016/j.esd.2024.101447

Chung, J. B., & Kim, E. S. (2018). Public perception of energy transition in Korea: Nuclear power, climate change, and party preference. *Energy Policy, 116*, 137–144. https://doi.org/10.1016/j.enpol.2018.02.007

Cloke, J., Mohr, A., & Brown, E. (2017). Imagining renewable energy: Towards a Social Energy Systems approach to community renewable energy projects in the Global South. *Energy Research and Social Science, 31*, 263–272. https://doi.org/10.1016/j.erss.2017.06.023

Das, I., Rogers, B., Nepal, M., & Jeuland, M. (2022). Fuel stacking implications for willingness to pay for cooking fuels in peri-urban Kathmandu Valley, Nepal. *Energy for Sustainable Development, 70*, 482–496. https://doi.org/10.1016/j.esd.2022.08.017

Debnath, K. B., & Mourshed, M. (2024). Although feasible, falling renewables costs might not benefit Bangladesh's energy sector's decarbonisation: Is this another 'debt-fossil fuel production trap'? *Energy for Sustainable Development, 79*, Article 101416. https://doi.org/10.1016/j.esd.2024.101416

Deisenroth, M. P., Faisal, A. A., Ong, C., & Soon.. (2020). *Mathematics for machine learning* (1st ed.) (1st ed., Vol. 1). Cambridge University Press https://mml-book.com.

Devkota, R., Bhattarai, U., Devkota, L., & Maraseni, T. N. (2020). Assessing the past and adapting to future floods: A hydro-social analysis. *Climatic Change, 163*(2), 1065–1082. https://doi.org/10.1007/s10584-020-02909-w

Devkota, R. P., & Bhattarai, U. (2018). Assessment of climate change impact on floods from a techno-social perspective. *Journal of Flood Risk Management, 11*, S186–S196. https://doi.org/10.1111/jfr3.12192

Dhital, R. P., Ito, Y., Kaneko, S., Komatsu, S., Mihara, R., & Yoshida, Y. (2016). Does institutional failure undermine the physical design performance of solar water pumping systems in rural Nepal? *Sustainability (Switzerland), 8*(8). https://doi.org/10.3390/su8080770

DHM/CCAFS. (2013). Agroclimatic atlas of Nepal. In *Department of Hydrology and Meteorology (DHM), Ministry of Science, Technology and Environment, Government of Nepal and Climate Change Agriculture and Food Security CGIAR-CCAFS Regional (IGP) Program Unit*.

Dhungana, N., Silwal, N., Upadhaya, S., Khadka, C., Regmi, S. K., Joshi, D., & Adhikari, S. (2020). Rural coping and adaptation strategies for climate change by Himalayan communities in Nepal. *Journal of Mountain Science, 17*(6), 1462–1474. https://doi.org/10.1007/s11629-019-5616-3

Dominguez, C., Orehounig, K., & Carmeliet, J. (2021). Understanding the path towards a clean energy transition and post-electrification patterns of rural households. *Energy for Sustainable Development, 61*, 46–64. https://doi.org/10.1016/j.esd.2021.01.002

EC. (2014). 2030 climate and energy policy framework – Conclusions. *European Council, Brussels*, (24 October 2014).

Evensen, D., & Brown-Steiner, B. (2018). Public perception of the relationship between climate change and unconventional gas development ('fracking') in the US. *Climate Policy, 18*(5), 556–567. https://doi.org/10.1080/14693062.2017.1389686

Franco, M. A. J. Q., & Taeighagh, A. (2024). Sustainable energy adoption in poor rural areas: A comparative case perspective from the Philippines. *Energy for Sustainable Development, 79*, Article 101389. https://doi.org/10.1016/j.esd.2024.101389

García-Gusano, D., Iribarren, D., & Garraín, D. (2017). Prospective analysis of energy security: A practical life-cycle approach focused on renewable power generation and oriented towards policy-makers. *Applied Energy, 190*, 891–901. https://doi.org/10.1016/j.apenergy.2017.01.011

Gautam, B. R., Li, F., & Ru, G. (2015). Assessment of urban roof top solar photovoltaic potential to solve power shortage problem in Nepal. *Energy and Buildings, 86*, 735–744. https://doi.org/10.1016/j.enbuild.2014.10.038

Gautam, D., & Bolia, N. (2024). Understanding consumer choices and attitudes toward electric vehicles: A study of purchasing behavior and policy implications. *Sustainable Development, 1–21*. https://doi.org/10.1002/sd.2939

Ghimire, L. P., & Kim, Y. (2018). An analysis on barriers to renewable energy development in the context of Nepal using AHP. *Renewable Energy, 129*, 446–456. https://doi.org/10.1016/j.renene.2018.06.011

Ghosh, M., & Ghosal, S. (2020). Determinants of household livelihood vulnerabilities to climate change in the himalayan foothills of West Bengal, India. *International Journal of Disaster Risk Reduction, 50*. https://doi.org/10.1016/j.ijdrr.2020.101706

GoN. (2021). *Nepal's Long-term Strategy for Net-zero Emissions*. Government of Nepal.

Gümüş, Y. K. (2015). How secure is the EU energy policy after the Ukraine crisis? *International Journal of Energy Economics and Policy, 5*(4), 1016–1021.

Haldar, A., Sethi, N., Jena, P. K., & Pradhan, P. C. (2023). Towards achieving sustainable development goal 7 in sub-Saharan Africa: Role of governance and renewable energy. *Sustainable Development, 31*, 2446–2463. https://doi.org/10.1002/sd.2521

Hamilton, L. C. (2012). *Statistics with Stata: Version 12*. Cengage Learning.

Hamududu, B. H., & Killingtveit, Å. (2016). Hydropower production in future climate scenarios; the case for the Zambezi River. *Energies, 9*(7). https://doi.org/10.3390/en9070502

Han, P., Tong, Z., Sun, Y., & Chen, X. (2022). Impact of climate Change Beliefs on Youths' Engagement in Energy-Conservation Behavior: The Mediating Mechanism of Environmental concerns. *International Journal of Environmental Research and Public Health, 19*(12). https://doi.org/10.3390/ijerph19127222

He, R., Jin, J., Qiu, X., Zhang, C., & Yan, J. (2023). Rural residents' climate change perceptions, personal experiences, and purchase intention–behavior gap in energy-saving refrigeration appliances in Southwest China. *Environmental Impact Assessment Review, 98*. https://doi.org/10.1016/j.eiar.2022.106967

Hensher, D. A., & Johnson, L. W. (2018). *Applied discrete-choice modelling*. Routledge.

Hess, D. J., & Mai, Q. D. (2014). Renewable electricity policy in Asia: A qualitative comparative analysis of factors affecting sustainability transitions. *Environmental Innovation and Societal Transitions, 12*, 31–46. https://doi.org/10.1016/j.eist.2014.04.001

HMG/N. (1992a). *Water Resources Act, 2049 (1992). His Majesty's Government of Nepal*.

HMG/N. (1992b). *Hydropower Development Policy, 1992. His Majesty's Government of Nepal*.

HMG/N. (2001). *Hydropower Development Policy, 2058 (2001). His Majesty's Government of Nepal*.

HMG/N. (2002). *Water Resources Strategy Nepal. Water and Energy Commission Secretariat, his Majesty's Government of Nepal. Singha Durbar, Kathmandu, Nepal*.

Huda, M. S., & McDonald, M. (2016). Regional cooperation on energy in South Asia: Unraveling the political challenges in implementing transnational pipelines and electricity grids. *Energy Policy, 98*, 73–83. https://doi.org/10.1016/j.enpol.2016.07.046

Hurlbert, M., Osazuwa-Peters, M., McNutt, K., & Rayner, J. (2020). Transitioning from coal: Toward a renewables-based socio-technical regime in Saskatchewan. *Environmental Innovation and Societal Transitions, 36*, 321–330. https://doi.org/10.1016/j.eist.2019.11.005

Hussain, A., Sarangi, G. K., Pandit, A., Ishaq, S., Mamnun, N., Ahmad, B., & Jamil, M. K. (2019). Hydropower development in the Hindu Kush Himalayan region: Issues, policies and opportunities. *Renewable and Sustainable Energy Reviews, 107*, 446–461. https://doi.org/10.1016/j.rser.2019.03.010

Israel, A., & Jehling, M. (2019). How modern are renewables? The misrecognition of traditional solar thermal energy in Peru's energy transition. *Energy Policy, 133*. https://doi.org/10.1016/j.enpol.2019.110905

Jacksohn, A., Grösche, P., Rehdanz, K., & Schröder, C. (2019). Drivers of renewable technology adoption in the household sector. *Energy Economics, 81*, 216–226. https://doi.org/10.1016/j.eneco.2019.04.001

Jha, R. (2010). Total Run-of-river type hydropower potential of Nepal. *Hydro Nepal: Journal of Water, Energy and Environment, 7*, 8–13. https://doi.org/10.3126/hn.v7i0.4226

Johnstone, P., Rogge, K. S., Kivimaa, P., Fratini, C. F., Primmer, E., & Stirling, A. (2020). Waves of disruption in clean energy transitions: Sociotechnical dimensions of system disruption in Germany and the United Kingdom. *Energy Research and Social Science, 59*. https://doi.org/10.1016/j.erss.2019.101287

Kapoor, M., & Garg, R. D. (2021). Solar potential assessment over canal-top using geospatial techniques. *Arabian Journal of Geosciences, 14*(254), 1–13. https://doi.org/10.1007/s12517-021-06674-7/Published

Karatayev, M., Hall, S., Kalyuzhnova, Y., & Clarke, M. L. (2016). Renewable energy technology uptake in Kazakhstan: Policy drivers and barriers in a transitional economy. *Renewable and Sustainable Energy Reviews, 66*, 120–136. https://doi.org/10.1016/j.rser.2016.07.057

Karlstrøm, H., & Ryghaug, M. (2014). Public attitudes towards renewable energy technologies in Norway. The role of party preferences. *Energy Policy, 67*, 656–663. https://doi.org/10.1016/j.enpol.2013.11.049

Koirala, D. P., & Acharya, B. (2022). Households' fuel choices in the context of a decade-long load-shedding problem in Nepal. *Energy Policy, 162*. https://doi.org/10.1016/j.enpol.2022.112795

Lacroix, K., & Gifford, R. (2018). Psychological Barriers to Energy Conservation Behavior: The Role of Worldviews and climate Change Risk perception. *Environment and Behavior, 50*(7), 749–780. https://doi.org/10.1177/0013916517715296

Li, Y., Wang, G., Shen, B., Zhang, Q., Liu, B., & Xu, R. (2021). Conception and policy implications of photovoltaic modules end-of-life management in China. *Wiley*

Interdisciplinary Reviews. Energy and Environment, 10(1). https://doi.org/10.1002/wene.387
Liao, C., Erbaugh, J. T., Kelly, A. C., & Agrawal, A. (2021). Clean energy transitions and human well-being outcomes in lower and Middle Income Countries: A systematic review. In *, 145*. *Renewable and Sustainable Energy Reviews*. Elsevier Ltd. https://doi.org/10.1016/j.rser.2021.111063.
Lin, B., & Kaewkhunok, S. (2021). The role of socio-culture in the solar power adoption: The inability to reach government policies of marginalized groups. *Renewable and Sustainable Energy Reviews, 144*, Article 111035. https://doi.org/10.1016/j.rser.2021.111035
Lin, B., & Omoju, O. E. (2017). Focusing on the right targets: Economic factors driving non-hydro renewable energy transition. *Renewable Energy, 113*, 52–63. https://doi.org/10.1016/j.renene.2017.05.067
Lomax, J., Mirumachi, N., & Hautsch, M. (2023). Does renewable energy affect violent conflict? Exploring social opposition and injustice in the struggle over the Lake Turkana Wind Farm, Kenya. *Energy Research and Social Science, 100*. https://doi.org/10.1016/j.erss.2023.103089
Lutz, A. F., Immerzeel, W. W., Siderius, C., et al. (2022). South Asian agriculture increasingly dependent on meltwater and groundwater. *Nat. Clim. Chang., 12*, 566–573. https://doi.org/10.1038/s41558-022-01355-z
Manasi, B., & Mukhopadhyay, J. P. (2024). Definition, measurement and determinants of energy poverty: Empirical evidence from Indian households. *Energy for Sustainable Development, 79*, Article 101383. https://doi.org/10.1016/j.esd.2024.101383
Marahatta, S., Aryal, D., Devkota, L. P., Bhattarai, U., & Shrestha, D. (2021). Application of swat in hydrological simulation of complex mountainous river basin (part ii: Climate change impact assessment). *Water (Switzerland), 13*(11). https://doi.org/10.3390/w13111548
Marahatta, S., Bhattarai, U., Devkota, L. P., & Aryal, D. (2022). Unravelling the water-energy-economics-continuum of hydroelectricity in the face of climate change. *International Journal of Energy and Water Resources*. https://doi.org/10.1007/s42108-021-00174-w
Marahatta, S., Devkota, L. P., & Aryal, D. (2021). Application of swat in hydrological simulation of complex mountainous river basin (Part i: Model development). *Water (Switzerland), 13*(11). https://doi.org/10.3390/w13111546
Martinez, N., & Komendantova, N. (2020). The effectiveness of the social impact assessment (SIA) in energy transition management: Stakeholders' insights from renewable energy projects in Mexico. *Energy Policy, 145*. https://doi.org/10.1016/j.enpol.2020.111744
Masson-Delmotte, V., Zhai, P., Pörtner, H.-O., Roberts, D., Skea, J., Shukla, P. R., Pirani, A., Moufouma-Okia, W., Péan, C., Pidcock, R., Connors, S., Matthews, J. B. R., Chen, Y., Zhou, X., Gomis, M. I., Lonnoy, E., Maycock, T., Tignor, M., & Waterfield, T. (2019). Global warming of 1.5°C An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty Edited by Science Officer Science Assistant Graphics Officer Working Group I Technical Support Unit. www.environmentalgraphiti.org.
Matavel, C. E., Kächele, H., Hafner, J. M., Rybak, C., Uckert, G., Hoffmann, H., … Sieber, S. (2023). How to increase cookstove adoption? Exploring cost-effective dissemination techniques in Central Mozambique. *Energy Research and Social Science, 100*. https://doi.org/10.1016/j.erss.2023.103082
McGreevy, D. M., MacDougall, C., Fisher, D. M., Henley, M., & Baum, F. (2021). Expediting a renewable energy transition in a privatised market via public policy: the case of south Australia 2004-18. *Energy Policy, 148*. https://doi.org/10.1016/j.enpol. 2020.111940
Millot, A., Krook-Riekkola, A., & Maïzi, N. (2020). Guiding the future energy transition to net-zero emissions: Lessons from exploring the differences between France and Sweden. *Energy Policy, 139*. https://doi.org/10.1016/j.enpol.2020.111358
MoF/GoN. (2023). *Economic survey 2022/23*. Government of Nepal: Ministry of Finance.
MoFE/GoN. (2021). *Nepal's Third National Communication to the United Nations Framework Convention on climate Change (UNFCC)*. Singha Durbar, Kathmandu, Nepal: Ministry of Forests and Environment, Government of Nepal.
Mohsin, M., Kamran, H. W., Atif Nawaz, M., Sajjad Hussain, M., & Dahri, A. S. (2021). Assessing the impact of transition from nonrenewable to renewable energy consumption on economic growth-environmental nexus from developing Asian economies. *Journal of Environmental Management, 284*, Article 111999. https://doi.org/10.1016/j.jenvman.2021.111999
MoPE/GoN. (2016). *Renewable Energy Subsidy Policy, 2073 BS*. Singha Durbar, Government of Nepal: Ministry of Population and Environment.
Movik, S., & Allouche, J. (2020). States of Power: Energy Imaginaries and Transnational Assemblages in Norway, Nepal and Tanzania. *Energy Research and Social Science, 67*. https://doi.org/10.1016/j.erss.2020.101548
Mtilatila, L., Bronstert, A., Shrestha, P., Kadewere, P., & Vormoor, K. (2020). Susceptibility of water resources and hydropower production to climate change in the tropics: The case of Lake Malawi and Shire River Basins, SE Africa. *Hydrology, 7*(3). https://doi.org/10.3390/HYDROLOGY7030054
Mukhtarov, S., Mikayilov, J. I., Humbatova, S., & Muradov, V. (2020). Do high oil prices obstruct the transition to renewable energy consumption? *Sustainability (Switzerland), 12*(11). https://doi.org/10.3390/su12114689
Munro, F. R. (2019). Renewable energy and transition-periphery dynamics in Scotland. *Environmental Innovation and Societal Transitions, 31*, 273–281. https://doi.org/10.1016/j.eist.2018.09.001
Navarro-Espinosa, A., & Thomas-Galán, M. (2023). Firewood electrification in Chile: Effects on household expenditure and energy poverty. *Energy Policy, 173*, Article 113337. https://doi.org/10.1016/j.enpol.2022.113337
NEA/GoN. (2023). *A year in review fiscal year 2022/23*. Government of Nepal: Nepal Electricity Authority.
Nepal, R., Jamasb, T., & Sen, A. (2018). Small systems, big targets: Power sector reforms and renewable energy in small systems. *Energy Policy, 116*, 19–29. https://doi.org/10.1016/j.enpol.2018.01.013
Nshimiyimana, J. P., Mukeshimana, M. C., & Nshimiyimana, E. (2024). Tracking the progress towards adopting LPG as a clean cooking fuel in Rwanda: User's perspective. *Energy for Sustainable Development, 80*, Article 101441. https://doi.org/10.1016/j.esd.2024.101441
Ozili, P. K. (2023). The acceptable R-square in empirical modelling for social science research. In *Social research methodology and publishing results: A guide to non-native English speakers* (pp. 134–143). IGI global.
Palit, D., & Bandyopadhyay, K. R. (2016). Rural electricity access in South Asia: Is grid extension the remedy? A critical review. In *, 60*. *Renewable and Sustainable Energy Reviews* (pp. 1505–1515). Elsevier Ltd. https://doi.org/10.1016/j.rser.2016.03.034.
Pandey, A., Prakash, A., & Werners, S. E. (2021). Matches, mismatches and priorities of pathways from a climate-resilient development perspective in the mountains of Nepal. *Environmental Science and Policy, 125*, 135–145. https://doi.org/10.1016/j.envsci.2021.08.013
Paravantis, J. A., Stigka, E., Mihalakakou, G., Michalena, E., Hills, J. M., & Dourmas, V. (2018). Social acceptance of renewable energy projects: A contingent valuation investigation in Western Greece. *Renewable Energy, 123*, 639–651. https://doi.org/10.1016/j.renene.2018.02.068
Park, J., Namkung, O. S., & Ko, J. (2023). Changes in public bike usage after the COVID-19 outbreak: A survey of Seoul public bike sharing users. *Sustainable Cities and Society, 96*, 104716.
Paudel, B., Zhang, Y., Yan, J., Rai, R., Li, L., Wu, X., … Khanal, N. R. (2020). Farmers' understanding of climate change in Nepal Himalayas: Important determinants and implications for developing adaptation strategies. *Climatic Change, 158*(3–4), 485–502. https://doi.org/10.1007/s10584-019-02607-2
Poortinga, W., Aoyagi, M., & Pidgeon, N. F. (2013). Public perceptions of climate change and energy futures before and after the Fukushima accident: A comparison between Britain and Japan. *Energy Policy, 62*, 1204–1211. https://doi.org/10.1016/j.enpol.2013.08.015
Proka, A., Hisschemöller, M., & Loorbach, D. (2018). Transition without conflict? Renewable energy initiatives in the dutch energy transition. *Sustainability (Switzerland), 10*(6). https://doi.org/10.3390/su10061721
Ramagoma, J., & Adendorff, C. (2016). Managing a transition to green energy sources: The perspectives of energy practitioners in the Southern African Development Community region. *Journal of Energy in Southern Africa, 27*(4), 77–90. https://doi.org/10.17159/2413-3051/2016/v27i4a1638
Raza, M. A., Khatri, K. L., & Hussain, A. (2022). Transition from fossilized to defossilized energy system in Pakistan. *Renewable Energy, 190*, 19–29. https://doi.org/10.1016/j.renene.2022.03.059
Ritchie, H., Roser, M., & Rosado, P. (2022). Energy. https://ourworldindata.org/energy.
Roberts, J. (2020). Power to the people? Implications of the Clean Energy Package for the role of community ownership in Europe's energy transition. *Review of European, Comparative & International Environmental Law, 29*(2), 232–244. https://doi.org/10.1111/reel.12346
Saha, P., & Idsø, J. (2016). New hydropower development in Norway: Municipalities' attitude, involvement and perceived barriers. In *, 61*. *Renewable and Sustainable Energy Reviews* (pp. 235–244). Elsevier Ltd. https://doi.org/10.1016/j.rser.2016.03.050.
Salam, M. A., Rahman, S., Anik, A. R., & Sharna, S. C. (2023). Exploring competitiveness of surface water versus ground water irrigation and their impacts on rice productivity and efficiency: An empirical analysis from Bangladesh. *Agricultural Water Management, 283*, Article 108298.
Salari, M., Javid, R. J., & Noghanibehambari, H. (2021). The nexus between CO2 emissions, energy consumption, and economic growth in the U.S. *Economic Analysis and Policy, 69*, 182–194. https://doi.org/10.1016/j.eap.2020.12.007
Sanjel, N., & Baral, B. (2020). Technical investigation of Nepalese electricity market-a review. *Journal of Physics: Conference Series, 1608*(1). https://doi.org/10.1088/1742-6596/1608/1/012005
Shahzadi, I., Yaseen, M. R., Khan, M. T. I., Makhdum, M. S. A., & Ali, Q. (2022). The nexus between research and development, renewable energy and environmental quality: Evidence from developed and developing countries. *Renewable Energy, 190*, 1089–1099. https://doi.org/10.1016/j.renene.2021.10.050
Shakya, S. R., Bajracharya, I., Vaidya, R. A., Bhave, P., Sharma, A., Rupakheti, M., & Bajracharya, T. R. (2022). Estimation of air pollutant emissions from captive diesel generators and its mitigation potential through microgrid and solar energy. *Energy Reports, 8*, 3251–3262. https://doi.org/10.1016/j.egyr.2022.02.084
Sharma, R. H., & Awal, R. (2013). Hydropower development in Nepal. *Renewable and Sustainable Energy Reviews, 21*, 684–693. https://doi.org/10.1016/j.rser.2013.01.013
Sharna, S. C., Maraseni, T., & Radanielson, A. M. (2024). Determinants of organic soil fertilization methods use over time and in the face of climate vulnerability. *Soil and Tillage Research, 240*, Article 106066.
Shrestha, A., Shrestha, S., Tingsanchali, T., Budhathoki, A., & Ninsawat, S. (2021). Adapting hydropower production to climate change: A case study of Kulekhani Hydropower Project in Nepal. *Journal of Cleaner Production, 279*, Article 123483. https://doi.org/10.1016/J.JCLEPRO.2020.123483
Shrestha, U. B., Shrestha, A. M., Aryal, S., Shrestha, S., Gautam, M. S., & Ojha, H. (2019). Climate change in Nepal: A comprehensive analysis of instrumental data and people's perceptions. *Climatic Change*. https://doi.org/10.1007/s10584-019-02418-5

Sivonen, J. (2023). Attitudes toward global and national climate policies in Finland – The significance of climate change risk perception and urban/rural-domicile. *GeoJournal, 88*(2), 2247–2262. https://doi.org/10.1007/s10708-022-10750-0

Sovacool, B. K. (2014). Energy studies need social science. *Nature, 511*, 529–530.

Sovacool, B. K., Dhakal, S., Gippner, O., & Jain Bambawale, M. (2013). Peeling the energy pickle: Expert perceptions on overcoming Nepal's electricity crisis. *South Asia: Journal of South Asia Studies, 36*(4), 496–519. https://doi.org/10.1080/00856401.2013.788469

StataCorp. (2023). *Stata: Release 18. Statistical Software*. College Station, TX: StataCorp LLC.

Storm, H., Baylis, K., & Heckelei, T. (2020). Machine learning in agricultural and applied economics. *European Review of Agricultural Economics, 47*(3), 849–892. https://doi.org/10.1093/erae/jbz033

Strazzera, E., & Statzu, V. (2017). Fostering photovoltaic technologies in Mediterranean cities: Consumers' demand and social acceptance. *Renewable Energy, 102*, 361–371. https://doi.org/10.1016/j.renene.2016.10.056

Tanti, P. C., & Jena, P. R. (2023). Perception on climate change, access to extension service and energy sources determining adoption of climate-smart practices: A multivariate approach. *Journal of Arid Environments, 212*. https://doi.org/10.1016/j.jaridenv.2023.104961

Thapa, B., Wang, W., & Williams, W. (2022). Life-cycle cost optimization of a solar combisystem for residential buildings in Nepal. *Journal of Asian Architecture and Building Engineering, 21*(3), 1137–1148. https://doi.org/10.1080/13467581.2021.1928502

Tsvetanov, T. (2019). When the carrot goes bad: The effect of solar rebate uncertainty. *Energy Economics, 81*, 886–898. https://doi.org/10.1016/j.eneco.2019.05.028

Uamusse, M. M., Tussupova, K., & Persson, K. M. (2020). Climate change effects on hydropower in Mozambique. *Applied Sciences (Switzerland), 10*(14). https://doi.org/10.3390/app10144842

UN. (2015). *Transforming our world: The 2030 agenda for Sustainable Development, Resolution Adopted by the General Assembly on 21 October 2015, a/RES/70/1*. United Nations General Assembly.

van Valkengoed, A. M., Steg, L., & Perlaviciute, G. (2021). Development and validation of a climate change perceptions scale. *Journal of Environmental Psychology, 76*. https://doi.org/10.1016/j.jenvp.2021.101652

Verma, P., Chodkowska-Miszczuk, J., & Raghubanshi, A. S. (2024). Are cities ready for low-carbon inclusive strategies? Household energy management under heterogeneous socioeconomic conditions. *Sustainable Development*, 1–17. https://doi.org/10.1002/sd.2922

WB. (2024). World Bank national accounts data, and OECD National Accounts data files. Webpage. https://data.worldbank.org/indicator/NY.GDP.MKTP.CD?locations=NP&msclkid=c583c33ad00811ec9a96c3a8dce184bf accessed on 29 March, 2024.

WECS/GoN. (2013). Nepal's energy sector vision 2050 A.D. In *Water and Energy Commission Secretariat*. Singhadurbar, Kathmandu, Nepal: Government of Nepal.

WECS/GoN. (2023). *Nepal energy sector synopsis report-2023. Water and Energy Commission Secretariat*. Singhadurbar, Kathmandu, Nepal: Government of Nepal.

Weko, S., & Goldthau, A. (2022). Bridging the low-carbon technology gap? Assessing energy initiatives for the Global South. *Energy Policy, 169*. https://doi.org/10.1016/j.enpol.2022.113192

Wiehe, J., Thiele, J., Walter, A., Hashemifarzad, A., Zum Hingst, J., & von Haaren, C. (2021). Nothing to regret: Reconciling renewable energies with human wellbeing and nature in the German Energy transition. *International Journal of Energy Research, 45*(1), 745–758. https://doi.org/10.1002/er.5870

Williams, R. (2006). Generalized ordered logit/partial proportional odds models for ordinal dependent variables. *The Stata Journal, 6*(1), 58–82.

Williams, R. (2018). *Ordered logit models–basic & intermediate topics*. University of Notre Dame.

Windemer, R. (2023). Acceptance should not be assumed. How the dynamics of social acceptance changes over time, impacting onshore wind repowering. *Energy Policy, 173*. https://doi.org/10.1016/j.enpol.2022.113363

Winkler, B., Lewandowski, I., Voss, A., & Lemke, S. (2018). Transition towards renewable energy production? Potential in smallholder agricultural systems in West Bengal, India. *Sustainability (Switzerland), 10*(3). https://doi.org/10.3390/su10030801

Wu, S. (2020). The evolution of rural energy policies in China: A review. In *, 119*. *Renewable and Sustainable Energy Reviews*. Elsevier Ltd. https://doi.org/10.1016/j.rser.2019.109584.

Xu, R., Zeng, Z., Pan, M., Ziegler, A. D., Holden, J., Spracklen, D. V., … F.. (2023). A global-scale framework for hydropower development incorporating strict environmental constraints. *Nature Water, 1*(1), 113–122. https://doi.org/10.1038/s44221-022-00004-1

Yadoo, A., & Cruickshank, H. (2012). The role for low carbon electrification technologies in poverty reduction and climate change strategies: A focus on renewable energy mini-grids with case studies in Nepal, Peru and Kenya. *Energy Policy, 42*, 591–602. https://doi.org/10.1016/j.enpol.2011.12.029

Yaghoubi, J., Yazdanpanah, M., & Komendantova, N. (2019). Iranian agriculture advisors' perception and intention toward biofuel: Green way toward energy security, rural development and climate change mitigation. *Renewable Energy, 130*, 452–459. https://doi.org/10.1016/j.renene.2018.06.081

York, R., & Bell, S. E. (2019). Energy transitions or additions? Why a transition from fossil fuels requires more than the growth of renewable energy. *Energy Research and Social Science, 51*, 40–43. https://doi.org/10.1016/j.erss.2019.01.008

Zhou, P., Abbas, J., Najam, H., & Alvarez-Otero, S. (2023). Nexus of renewable energy output, green technological innovation, and financial development for carbon neutrality of Asian emerging economies. *Sustainable Energy Technologies and Assessments, 58*, Article 103371. https://doi.org/10.1016/j.seta.2023.103371

9.3 Links and implications

This paper has highlighted the differences across the urban, semi-urban and rural areas with regards to their access to energy, level of awareness and financial conditions. Additionally, it was observed that conjointly analysing the socio-economic and climate change perception factors would be more representative of their current energy behaviour and preference of transitioning to renewables in the future. As most people were found to be aware that electricity produced in Nepal is from hydropower, there is a strong enthusiasm among the local people as to how hydropower will most likely be impacted by climate change in the future. This aspect has been addressed by my next paper (Paper #8).

CHAPTER 10: PAPER 8 – HYDROPOWER AND CLIMATE RESILIENCE OF NEPAL HIMALAYA: A BOTTOM-UP HYDROLOGICAL APPROACH

10.1 Introduction

This paper (Paper #8) examines the impacts of climate change on run-of-river (ROR) hydropower projects in Nepal, where over 90% of electricity is generated by hydropower. Using robust hydrological models and extensive climate data, the study simulates future hydrological responses across various basins of Nepal. This paper contributes to the third objective of my research.

10.2 Published paper

(*Earth Systems and Environment*, [Accepted; In Press] Manuscript ID: ESEV-D-24-00523)

10.3 Links and implications

The implications of this study are significant for the future of hydropower in Nepal, highlighting the need for adaptive strategies to address regional variations in hydrological responses to climate change. I suggest that policy frameworks must be developed prioritizing projects resilient to climate change. Moreover, this research underscores the urgency of developing sustainable hydropower strategies to ensure reliable energy generation amidst changing climatic conditions. The findings of this study offer important contributions to the field of hydropower and climate change research not only for Nepal but for the Himalayan region.

CHAPTER 11: DISCUSSION AND CONCLUSION

11.1 Global review of renewable energy transition

My review shows that there is a global awareness to accelerate the rate of renewable energy transition so that the world can be a cleaner and safer place in the future (Borozan, 2022; UN, 2015). But the current efforts are not found to be enough. Europe is leading energy research, as shown by a large number of publications (Bhattarai et al., 2022b), while China is leading the implementation of multiple renewable energy technologies in recent times (Bigerna et al., 2021; IEA, 2023). However, there is large disparity among the rich and poor countries in relation to their capabilities of technological advancement and implementation potentials of clean energy technologies, and their efficient use (Bhattarai et al., 2022b; Weko and Goldthau, 2022). As a result, developing countries are still highly reliant on traditional and fossil fuels (IEA, 2023). There is a consensus among recent studies on the prospects of renewable energy in the electricity sector; however, some scepticism still exists regarding other high energy demanding areas (Johnstone et al., 2020). Additionally, studies have identified disproportionate distribution of resources with a vast untapped potential of renewable energy sources in the developing countries (Xu et al., 2023). These could play an important role in tackling the burgeoning rise of global energy insecurity through fair global north-south cooperation (Vanegas Cantarero, 2020). Furthermore, I infer that developing countries, such as Nepal, should duly plan their energy strategies carefully taking into account different factors such as technology, investment, market, environment, governance and institutionalization, policy instruments and regulatory mechanisms, and social acceptance at the national level as well considering contemporary regional and global geo-political developments.

11.2 Renewable energy transition modelling framework

The renewable energy transition modelling framework developed in this study is an integrated multi-layered approach to advancing renewable energy from the grass-roots to the national level (Figure 11.1). The framework employs a comprehensive participatory approach, recognizing that effective energy transition must consider the socio-eocnomic contexts and start at the local activity level (Usman et al., 2024). The key components of the framework that I have identified are demand assessment, resources accounting and infrastructure development. At the foundational level, various activities leading to energy demand needs to be carefully evaluated (D1, D2,..., Dn denote the activity level demands in Figure 11.1). The next step is the identification and quantification of local renewable resources such as water for hydropower, sunlight for solar PV, wind for wind power, etc. (R1, R2,..., Rn denote the locally available renewable resources). Realization of these resources is made possible through the necessary infrastructure development. These sources (supply side) need to be compared against the demands to identify a condition of deficit or surplus at the sectoral level where they are aggregated (Hvelplund and Djørup, 2017; Marczinkowski and Barros, 2020) with a focus on optimizing energy usage and increasing renewable energy adoption.

Furthermore, sectoral demands and renewable energy supply are consolidated at the national level. Demand assessment needs to ensure that the energy needs are accurately projected. Resources accounting considers the actual potential of the available resources while infrastructures are developed in concurrency with the energy management plans. These components collectively maintain the energy balance of the country which is likely to be supplemented by energy imports (in case of deficits), or exports (in the case of surplus). Economic analysis of the possible planning strategies needs to be carried out for ascertaining the feasibility of such strategies (Dominguez et al., 2021).

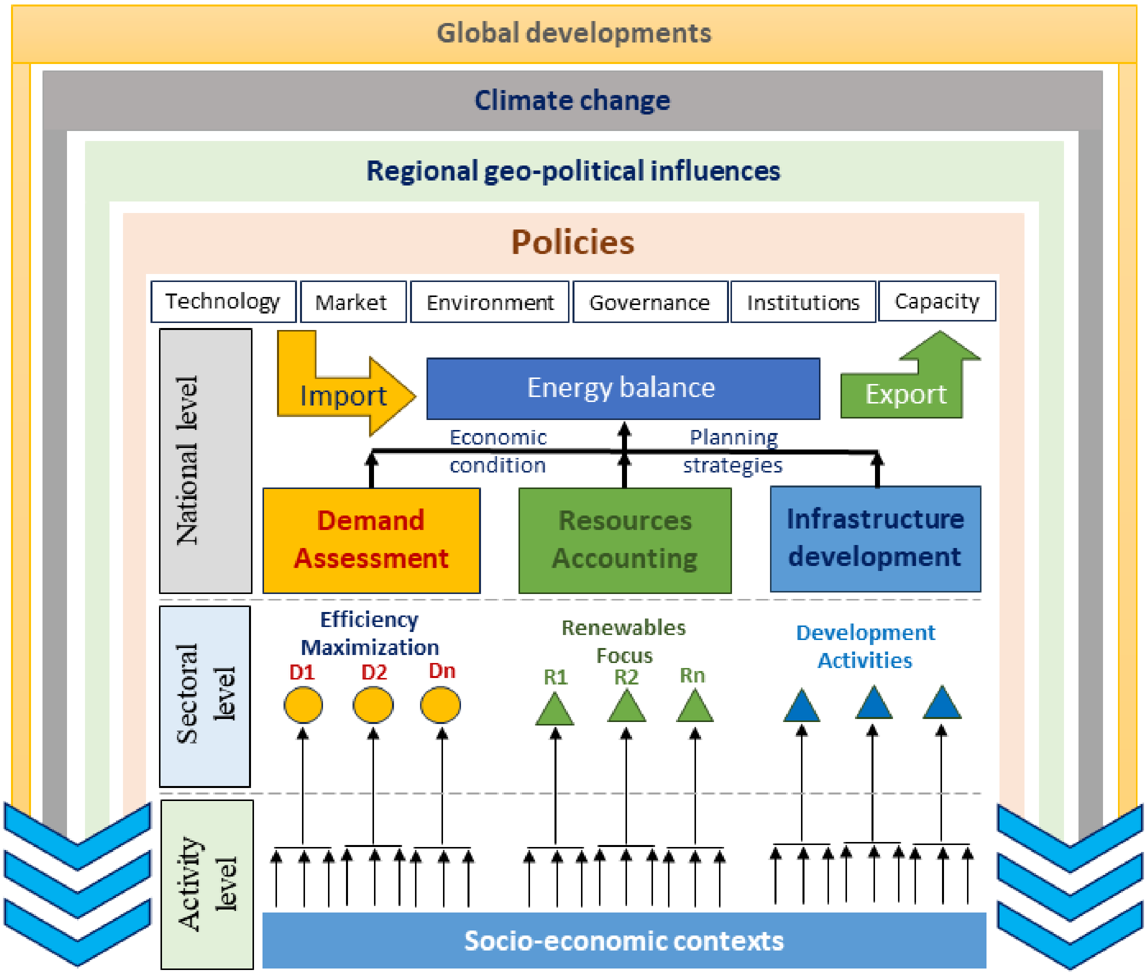

Figure 11.1: Renewable energy transition modelling framework developed in this study.

Note: D1, D2,... Dn denote the activity level demands;R1, R2,... Rn denote the locally available renewable resources.

Policies play a pivotal role in this framework shaping and guiding the actions at all levels through technological advancements, market dynamics, environmental considerations, governance, institutional frameworks and capacity building (Bhattarai et al., 2024b; Bell, 2020). Policies are not created in isolation but are influenced by broader regional geo-political factors and global developments. Climate change is likely to impact energy-supply and demand at all levels (Mohsin et al., 2021). Hence, it needs special consideration and quantification.

The framework's emphasis on a comprehensive participatory approach underscores the importance of local-level initiatives and the socio-economic contexts that drive them. It highlights the interconnectedness of activities across different levels and sectors, demonstrating that effective and sustainable energy transition requires coordination and integration across all layers of governance and activity. This interconnected approach ensures that policy decisions at the national level are informed by ground realities and sectoral needs, while aligning them with the broader regional and global conditions (Aryal et al., 2021). By integrating these multiple layers of influence and action, the framework provides a holistic view of how renewable energy transition can be systematically achieved, ensuring that local activities and sectoral developments are aligned with national strategies and policies (Ram et al., 2022). Furthermore, this integrated framework provides a robust model adaptable to local specificities for transitioning to renewable energy, addressing the complexities and interdependencies that characterize the energy sector.

This research has adopted the above-mentioned framework to model its various components in Nepal.

11.3 Research summary for Nepal

In the case of Nepal, a high dependence on traditional energy is evident, despite tremendous renewable energy potential, particularly in the hydropower sector (Gyanwali et al., 2020; MoF/GoN, 2023). I find that the country is going through a pseudo-energy-secure state with an 'import-as-needed modality' applied to the energy sector. Recent developments show that the domestic sector is decreasing its dependency on the traditional fuels but at the cost of increasing use of fossil fuels (MoF/GoN, 2023; WECS/GoN, 2023). The transportation sector is unmanageably growing and is completely reliant on imported petroleum products from neighbouring countries (Mali et al., 2022). Moreover, Nepal faces a problem of suppressed demand in the absence of energy-intensive development activities in other productive sectors of the economy (NEA/GoN, 2023; WECS/GoN, 2023). Sadly, growth in the energy demand is met only marginally by domestic hydropower and other renewables, and largely by increasing imports (DoC/GoN, 2023). This approach is on the one hand, increasing the trade deficit of the already poor country, while on the other hand, undermining the country's immense clean renewable energy potential. I further infer that without immediate and intensive pragmatic interventions to address current energy-related issues, Nepal's state of energy security is not likely to change in the near future (Bhattarai et al., 2024a).

A progressive energy policy development trajectory can be seen over the last several decades in Nepal. Although difficult to demarcate exactly, the country has gone through many stages of energy policies development and their implementation (Movik and Allouche, 2020). In addition, there has been a distinct concentration of the rural energy policies on off-grid renewable technologies at the household or community levels while the central level policies are concentrated mostly on hydropower development and electrification. Nepal is currently focused on diversifying the energy generation mix and increasing energy efficiencies across the different demand sectors (NEA/GoN, 2023; WECS/GoN, 2023). However, I find that policies are still not completely supportive for the renewable energy transition necessary for the country. Research and development is limited and the ever-changing political settings are not able to demonstrate tangible progress in this area, as suggested by Ruan et al. (2023). Moreover, as with most developing countries (Pandey and Sharma, 2021; Wu, 2020), community level engagements and voices of the general Nepalese people need to be incorporated adequately into policies and action (Bhattarai et al., 2024b).

Additionally, my research shows that the effectiveness of international donations and government subsidies in the energy sector have not been as desired in the past (Alex et al., 2014; Ha and Kumar, 2021). Many energy development projects (especially for off-grid renewable energy technologies) have been found to be unsuccessful immediately after the donations/subsidies ended (ADB, 2017; Bhattarai et al., 2018). This raises a serious concern on the sustainable use of such funds. Technology transfers without creating a proper techno-social base has been identified as the major reason for such failures in the developing world, including Nepal (Palit and Bandyopadhyay, 2016; Muller et al, 2021). In addition, corruption and misuse/mismanagement of funds is a common problem across the global south which need to be minimized for the overall prosperity of the nation, including the renewable energy sector (Aryanpur et al., 2022). Hence, I conclude that an 'energy ecosystem' is to be developed with an inclusive and participatory approach addressing context-specific needs, particularly for the renewable energy systems. Technological development, awareness raising, capacity strengthening, institution building, and supportive policy reforms need to go hand-in-hand for a sustainable energy future (Bhattarai et al., 2023a).

Furthermore, local contexts can be better comprehended and managed by identifying the influential socio-economic factors on the energy behaviour of the end-users (Conradie et al., 2023; Teckler et al., 2022). Being the largest energy consumer, currently and anticipated in the near future, the residential sector has a major stake in Nepal's energy landscape (Bhattarai et al., 2024a; WECS/GoN, 2023). Moreover, I find that data driven machine learning models perform well in classifying non-linear social responses reflecting people's perceptions and energy behaviour at the household level. I also find that rural and semi-urban areas of Nepal tend to resist changes to their current energy sources and consumption pattern due to economic constraints and lack of awareness. Contrary to my expectation, even the urban residents of Nepal with access to better energy options were found against switching to modern and improved alternatives. They rather resorted to fuel-stacking due to a lack of trust in the government's commitments and efforts, which are concurrent with the findings of other studies such as Das et al. (2022) and Koirala and Acharya (2022). The marginalized and the most disadvantages are still the largest sufferers in terms of inclusiveness in energy access and use. Hence, I believe that, while promoting small off-grid renewable energy technologies could be a temporary rural measure, the country should aggressively promote domestic hydropower supplemented by other renewables to cater to the household energy demands of both urban and rural areas of Nepal (Bhattarai et al., 2023b).

In addition, I surmise that Nepal has not been able to meet most of its ambitious energy targets that was set in the past (Bhattarai and Bajracharya, 2016; Poudyal et al., 2019; WECS/GoN, 2013). Hence, understanding the past and current development trends across all sectors of the economy to project plausible and realistic future targets is seen necessary. Modelling the energy system of Nepal applying a bottom-up framework in LEAP (BU-NEP) shows that the residential sector can be expected to continue bieng the largest energy consuming sector of the country unless leap-frogging advancements are made in the industrial and commercial sectors, which are less likely under current trends. The recent tendency of increasing reliance on fossil fuels, mainly liquified petroleum gas (LPG) for residential purposes, is counter-productive in the long run. Furthermore, I find that the household energy demands in Nepal necessitate a transition to modern, clean electricity to replace traditional fuels. The commercial/service sector, particularly information technology (IT), has tremendous potential to grow and contribute to the economy of Nepal. However, it is completely dependent on reliable electricity supply and related infrastructure which need to be guaranteed by the government. As with the household sector, the required electricity needs to be domestically generated by hydropower leading the way and supplemented by other renewables. Furthermore, the country can be expected to still rely on (imported) fossil fuels until the mid of this century, primarily because of lack of domestic resources to replace them. These findings are similar to other recent studies modelling the energy scenarios of Nepal (Shakya et al., 2023; Aryal and Dhakal, 2022). Hence, Nepal should focus on setting plausible and achievable targets within the nation's abilities paying due attention to its resources availability, sectoral demands, current development efforts, future needs and adaptive capacity to external shocks such as geopolitics and climate change (Bhattarai et al., 2023c).

Further, I find that socio-economic factors and climate change perceptions of the local people influences the preferential energy behaviour, particularly at the household level (Amrutha et al., 2018; Raza et al., 2022). From my research, urbanization status, education level and availability of energy choices for households were identified to be the significant socio-economic factors in this regard. Likewise, perceptions on timing of monsoon, magnitude of winter rainfall, alterations in cooking and space heating energy demands and effective community level energy subsides for change in the energy behaviour were found to be the most influential climate change perception parameters. Hence, I infer that the socio-economic and climate change perception parameters need to be dealt with holistically to drive the renewable energy transition of Nepal effectively. These findings are comparable to those from other similar recent studies in other developing contexts (He et al., 2023; Tanti and Yena, 2023; Yaghoubi et al., 2019). I also find that the current energy prices are still unaffordable to a major share of the national population. Current fossil-fuel based technologies are not sustainable leading to increased trade deficits and have long-term environmental implications (Bhattarai et al., 2022a). Hence, the renewable energy potential of Nepal needs to be harnessed to help the country transition to a cleaner and sustainable energy future.

Finally, carrying out hydrological simulation of Nepal to assess the impacts of future climate change on hydropower generation, I find that the response of stream flows to different climate scenarios vary across locations. As a result, hydropower projects in the eastern basins of Nepal are likely to experience more increases in monsoon flows compared to the other areas of the country. Dry season flows are expected to increase all over the country but to a lesser extent in comparison to the changes in the monsoon flows. Likewise, energy generation changes to varying climatic conditions are different across the basins. A majority of the hydropower projects are likely to meet only a fraction of their energy targets under future climatic conditions. More importantly, large projects can be expected to often meet their energy targets unlike the smaller projects.

These results imply the need for developing an effective framework for assessing and prioritizing planned and proposed hydropower projects based on their abilities to generate the committed energy under anticipated climatic changes. Additionally, prioritizing high-discharge over high-head hydropower projects is found necessary for climate resilience. The government needs to plan and allow the implementation of hydropower projects based on an integrated river basin planning approach. Moreover, immediate construction of storage type projects is felt necessary at strategic locations to harness multipurpose benefits as well as better utilization of regulated flows in downstream areas. Pumped storage hydropower projects could prove to be particularly beneficial (Baniya et al., 2023). These findings are concurrent with similar other studies exploring the impacts of climate change on the hydropower sector of Nepal (Bhattarai et al., 2022a; Marahatta et al, 2022; Shrestha et al., 2021). Furthermore, emerging concepts such as floatavoltaics (Almeida et al., 2022) can be possible areas of research for obtaining co-benefits in the renewable energy sector of Nepal.

Overall, I conclude that, at the state level, Nepal should continuously update its energy policies to create a conducive environment for sustainable renewable energy transition. Promotion of domestic hydropower generation should lead the way with the addition of other renewable technologies in the generation mix. Relying on off-grid smaller energy technologies could be a temporary measure but the country should focus on extending the national electricity grid to the rural remote areas to penetrate the rural household energy sector of Nepal. Electricity prices should be made affordable to the majority of the (particularly rural) population. In addition, it is seen that Nepal needs to focus on providing impetus to building community awareness and maximizing effectiveness of subsidies and other financial incentives. Hence, my contribution lies in this important policy-science-society interface which will be insightful to the decision makers in the energy sector of developing countries in general and Nepal in particular.

11.4 Contribution of the research

My research contributes to multiple aspects of the energy domain by providing comprehensive insights into Nepal's energy sector, addressing broader regional and global implications, and advancing methodological frameworks for sustainable energy planning and climate resilience.

First, the study assesses the baseline energy status of Nepal, considering its energy security, policy development and socio-economic conditions. By incorporating global and national reviews, social perception assessments, and modelling, my study offers an integrated framework tailored to Nepal's unique context. Through the development of the *Energy Security Composite Index of Nepal (ESCOIN)* for the first time, my work delivers a valuable advancement in the evaluation of the current and future energy status of the country. Moreover, a key contribution of this research is the identification of socio-economic and climate perception factors influencing household energy behaviour, the largest energy-consuming sector of Nepal.

Second, by applying a comprehensive modelling framework, the study evaluates Nepal's likely energy supply- and demand-side scenarios until mid-century, providing crucial insights for sustainable energy planning. This includes the development of an integrated energy planning model, which is capable of being conveniently updated with new inputs as data becomes available. The customizable model-base can assist authorities at national or provincial levels in testing technological and policy options, supporting robust and sustainable energy pathways for Nepal.

Third, my research quantifies the likely impact of climate change on the hydropower sector of Nepal. The results of this assessment emphasize the need for a project evaluation framework that incorporates climate resilience into project prioritization. The findings of this research are not only valuable for Nepal but the entire Himalayan region with similar biophysical contexts.

Fourth, the evidence-based policy implications and policy-to-practice recommendations made here are tangible outputs of this research. These serve as a guide for policymakers and practitioners in Nepal, ensuring a sustainable and inclusive shaping of future energy policies, with long-term energy security in mind.

Furthermore, through multiple peer-reviewed publications in top-tier D1 and Q1 journals, my research has broader implications for the renewable energy transition, especially for developing countries whose perspectives are often less represented in global research. The framework and the methodologies of its components can be replicated, customized, and scaled to other developing countries with similar contexts, providing a blueprint for sustainable energy planning and policy formulation.

The advancements presented here, particularly in the model-base including the use of machine learning to assess social perceptions and the application of hydrological and energy modelling, are significant contributions to energy studies in the global south. Additionally, this study has made a valuable contribution by demonstrating how energy research can be effectively conducted in resource and data-constrained environments through careful research design and planning. The study's findings related to climate change impacts on hydropower generation are valuable for the Himalayan region and global climate change studies. The new insights from my research add to the current scholarship in the energy domain of South Asia in general, and Nepal in particular. Moreover, my findings and recommendations will be an important input for the countries of this region in devising their future plans for cross border energy sharing. Overall, my research makes direct contributions to three UN Sustainable Development Goals (SDGs): 7 (affordable and clean energy), 13 (climate action), and 11 (sustainable cities and communities).

11.5 Limitations and recommendations

11.5.1 Limitations

I acknowledge several limitations in this study. Firstly, my review of the energy policies of Nepal was limited until 2022, which could have missed out on recent developments. On the technical aspects, I was not able to consider the storage-type hydropower projects and their energy generation conditions in my energy model. Moreover, I was not able to carry out optimization of all the proposed hydropower projects individually for Nepal at the basin level.

On the social side, several questions still remain unanswered in my study, such as what are the conditions of energy democracy and justice, community participation in policy formulation, stakeholder involvement in the development of energy generation projects, and public concerns related to good governance and their impacts on the various energy demand sectors?

In addition, while carrying out the household survey, randomization was implemented to avoid sample bias and utmost care was taken to collect data from different locations occupying diverse socio-economic respondents. However, perception and preferences are qualitative data, which are highly subjective in nature. Therefore, respondents belonging to similar socio-economic categories and climatic contexts can also have different perceptions and preferences. Furthermore, the perceptions and preferences of the same respondent can vary over time. This can be considered a measurement error in my study.

Based on the global review of literature, it is seen that renewable energy transition should duly consider local specificities, which differ considerably across the developed and developing worlds.

11.5.2 Technical recommendations

Based on the findings of my research, I have made some technical recommendations for the energy sector of Nepal.

At the implementation level, integrated management of the demand- and supply-sides of energy is needed to achieve sustainable energy security for Nepal. Efficient resource accounting and utilization can be achieved only through well-established assessment methods, including reinforcing currents means and methods of data observations. Several recent studies have attempted to assess the renewable energy potential of Nepal considering multiple types of technologies. However, it is essential to apply robust scientific assessments to timely validate and update these potentials in response to dynamic climatic, geopolitical, regional, and local developments. In concurrence with recommendations from past studies and current government efforts, this research further stresses that hydropower must lead Nepal's renewable energy transition, supplemented by solar, wind, and biogas technologies, among others. However, special care needs to be taken to minimize the socio-economic and environmental impacts of the future hydropower and other renewable energy projects.

Energy planning in Nepal needs to be carried out adopting a basin level approach, rather than the currently implemented isolated project-approach, largely owing to the major contribution of hydropower in the current energy mix as well as in the future. Such a way of planning helps optimize energy generation, harness benefits from cascading projects, foresee upstream-downstream linkages of the river basins and adequately discuss and plan for possible issues related to riparian water rights among the different water-users beforehand. The model-base and the renewable energy transition framework developed in this study could be useful in contributing to future energy planning of Nepal.

Furthermore, an urgent development of and adherence to an assessment framework for hydropower projects are recommended, which, not only considers the technical and economic feasibilities, but also appropriately ranks and prioritizes the planned projects based on their resiliency to anticipated future climatic shocks. Moreover, high-discharge hydropower projects need to be prioritized over the high-head ones because of the lesser impacts on energy generation of the former for a unit change in the water availability due to altered future climatic conditions. In addition to the ROR hydropower projects, the Government of Nepal should intensify construction of storage type projects (with possibilities of pumped storage options) at strategic locations of the country. Because of the large generation capacities and multipurpose use of such storage projects, other downstream projects are highly likely to benefit from the regulated flows. The private sector, already having a large contribution, should be encouraged to contribute more to generation of renewable energy in Nepal.

Moreover, Nepal needs to set achievable targets, both in the supply- and demand-sides. It must strengthen its efforts in extending the national electricity grid to the rural and remote areas of the country and expand its current electricity transportation capacity to meet future supply and demands, accounting for anticipated imports and exports. Planning strategies need to be tailored and updated regularly as per the changing sectoral demands, particularly the residential sector.

On the demand side, there is high potential of transitioning to modern, clean electricity to replace traditional fuels in the largest energy consuming residential sector. Government efforts need to concentrate on increasing the financial capacity of the rural areas with the necessity of community-level awareness building in parallel. In the case of urban areas, impactful intervention is needed to raise awareness on the use and benefits of clean renewable energy as well as to gain trust of the energy users to rely on clean electricity supplied by the government. The largely growing transportation sector needs to be managed focusing on renewables and the use of electric vehicles for mass public transport. Promoting small individual private electric vehicles is not sustainable in the long run. Additionally, converting existing petrol/diesel vehicles to electric could be researched in the Nepalese context. The service sector, particularly information technology, carries a large scope for Nepal provided the electric supply from the government is reliable. Moreover, other economic sectors need to be developed in parallel evaluating their economic benefits and trade-offs.

11.5.3 Policy recommendations

Based on global literature review and the findings of this research, several policy recommendations are proposed for Nepal.

The Government of Nepal should focus on transitioning from traditional and fossil fuels to cleaner energy sources at the policy level for a sustainable energy future. All economic sectors need to be developed in parallel, with careful evaluation of their benefits, to reduce reliance on traditional and fossil fuels, decrease national trade deficits, and minimize adverse environmental impacts. Nepal should set achievable energy targets for the future rather than being overly ambitious, which are mostly driven by political intentions. Moreover, the country needs to give special attention to the largest energy consuming residential sector. Differentiated strategies are necessary for urban and rural residential sectors of Nepal in terms of energy management because of their differences in energy behaviours.

Expanding off-grid technologies can provide short-term relief, but extending national grid access, particularly to the rural remote areas, is a much-needed long-term solution. This could also have considerable positive impacts on the reduction of emissions in the long run. Additionally, socio-economic and climate change perception factors influence the energy behaviour of end-users. Hence, they need to be holistically assessed in order to identify the most influential parameters and appropriately factored in while making future energy plans and policies for a successful energy transition in the face of climate change.

Policymaking should involve increased community-level participation. Local government authorities need to be better capacitated for effective resource management locally. This could considerably reduce the associated burden on the central government. Furthermore, international donations and government subsidies must be better managed to reach those in need and support the development of a comprehensive ’energy ecosystem’ fostering new technologies to be a part of the energy mix as well as reduction in and efficient management of the demands. The private sector’s role is vital in renewable energy generation of Nepal, including hydropower development. Hence, the government should focus on formulating and updating energy policies (such as one-door policy) that create a conducive environment for encouraging private investment in this national venture.

An effective science-policy synergy is envisioned by this study for the sustainable implementation of renewable energy and low-carbon transition in Nepal. For this to occur effectively, key stakeholders—including the government, private sector, academia, and local communities—must collaborate effectively. The Government of Nepal should create an enabling environment through policy frameworks and incentives, while the private sector plays a pivotal role in investments and technology deployment. Academia contributes through research and development, and local communities should be empowered to participate in decision-making processes to ensure an inclusive and just energy transition.

11.5.4 Recommendations for future research

To overcome the limitations encountered in this research, the following recommendations are made for future improvement:

- The policy review time window could be extended to date in order to include insights from policies introduced after 2022 to reflect more recent developments.
- Future studies could incorporate the impacts of regulated releases from reser-

voir type hydropower projects on existing and planned downstream ROR projects using a river-basin allocation model.

- Further research could adequately consider multiple combinations of reservoir operating rules for individual hydropower schemes to optimize energy generation across different load centres in addition to other renewable energy sources.
- In terms of primary data survey design, future studies could benefit considerably by increasing the sample size and ensuring a more comprehensive coverage of the socio-economic contexts, thus minimizing sample bias.
- In addition, the measurement error of data collection could be overcome by longitudinal survey across different times. Assessing the influence of other confounding variables could provide a better understanding of the predictor-response relationship in explaining the household energy behaviour of Nepal.
- Future studies could explore social aspects in detail to ensure that energy development prioritizes people during planning, implementation, and operational stages. Specifically, in the case of hydropower development in Nepal, assessing how energy developers, local people directly impacted by the projects, end-users of the generated electricity, and the state can be benefitted equitably through the lens of energy democracy and justice serves as a promising research avenue.
- From a broader perspective, building on the energy planning model developed in this research, impacts of external geopolitical factors, particularly related to the energy futures of the neighbouring countries — India and China — could be examined to develop inclusive future energy pathways for Nepal.

Finally, a comprehensive economic analysis of the anticipated changes in the energy supply and demand conditions of Nepal including the impacts of climate change can be an extension of this PhD research.

REFERENCES

Adachi, S. A., Tomita, H. 2020. Methodology of the constraint condition in dynamical downscaling for regional climate evaluation: A review. *Journal of Geophysical Research: Atmospheres, 125*(11), e2019JD032166. https://doi.org/10.1029/2019JD032166

ADB, 2017. Nepal Energy Sector Assessment, Strategy, and Roadmap. The Asian Development Bank, Manila, Philippines. https://doi.org/10.22617/TCS178936-2

Adesanya, A.A., Sidortsov, R. v., Schelly, C. 2020. Act locally, transition globally: Grassroots resilience, local politics, and five municipalities in the United States with 100

Ahmad, M., Dai, J., Mehmood, U., Abou Houran, M. 2023. Renewable energy transition, resource richness, economic growth, and environmental quality: Assessing the role of financial globalization. *Renewable Energy, 216*, 119000. https://doi.org/10.1016/j.renene.2023.119000

Ahrens, C.D. 2017. Transition to very high share of renewables in Germany. *CSEE J. PowerEnergy Syst. 3*, 17-25. https://doi.org/10.17775/CSEEJPES.2017.0004

Alex, Z., Clark, A., Cheung, W., Zou, L., Kleissl, J. 2014. Minimizing the lead-acid battery bank capacity through a solar PV - Wind turbine hybrid system for a high-altitude village in the Nepal Himalayas. *Energy Procedia, 57*, 1516–1525. https://doi.org/10.1016/j.egypro.2014.10.144

Ali Raza, S., Shah, N., Asif Qureshi, M., Qaiser, S., Ali, R., Ahmed, F. 2020. Nonlinear threshold effect of financial development on renewable energy consumption: Evidence from panel smooth transition regression approach. *Environmental Science and Pollution Research, 27*, 32034–32047. https://doi.org/10.1007/s11356-020-09520-7

Alimi, M., Rhif, A., Rebai, A. 2017. Nonlinear dynamic of the renewable energy cycle transition in Tunisia: Evidence from smooth transition autoregressive models. *International Journal of Hydrogen Energy, 42*, 8670–8679. https://doi.org/10.1016/j.ijhydene.2016.07.131

Almeida, R.M., Schmitt, R., Grodsky, S.M., Flecker, A.S., Gomes, C.P., Zhoa, L., Liu, H., Barros, N., Kelman, R., McIntyre, P.B. Floating solar power: evaluate trade-offs. *Nature 606*, 246-249. https://doi.org/10.1038/d41586-022-01525-1

Alonso-Fradejas, A. 2021. 'Leaving no one unscathed' in sustainability transitions: The life purging agro-extractivism of corporate renewables. *Journal of Rural Studies, 81*, 127–138. https://doi.org/10.1016/j.jrurstud.2020.10.00

Amin, A., Yusoff, N. Y. B. M., Peng, S., Işık, C., Ullah, A., Akbar, M. 2024. The influence of energy transition, and natural resources on carbon emissions in China: An augmented ARDL application. *Environment, Development and Sustainability*, 1-19. https://doi.org/10.1007/s10668-023-04398-0

Amo-Aidoo, A., Kumi, E.N., Hensel, O., Korese, J.K., Sturm, B. 2022. Solar energy policy implementation in Ghana: A LEAP model analysis. *Scientific African, 16*, e01162. https://doi.org/10.1016/j.sciaf.2022.e01162

Amrutha, A.A, Balachandra, P., Mathirajan, M. 2018. Model-based approach for planning renewable energy transition in a resource-constrained electricity system—A case study from India. *International Journal of Energy Research, 42*, 1023–1039. https://doi.org/10.1002/er.3892

Aniello, G., Többen, J., Kuckshinrichs, W. 2019. The transition to renewable energy technologies-Impact on economic performance of North Rhine-Westphalia. *Applied Sciences (Switzerland), 9*. https://doi.org/10.3390/app9183783

Aryal, K., Laudari, H. K., Neupane, P. R., Maraseni, T. 2021. Who shapes the environmental policy in the global south? Unpacking the reality of Nepal. *Environmental Science and Policy, 121*, 78–88. https://doi.org/10.1016/j.envsci.2021.04.008

Aryal, K., Maraseni, T., Apan, A. 2022. How much do we know about trade-offs in ecosystem services? A systematic review of empirical research observations. *Science of the Total Environment, 806*. https://doi.org/10.1016/j.scitotenv.2021.151229

Aryal, S., Dhakal, S. 2022. Medium-term assessment of cross border trading potential of Nepal's renewable energy using TIMES energy system optimization platform. *Energy Policy, 168*. https://doi.org/10.1016/j.enpol.2022.113098

Aryanpur, V., Fattahi, M., Mamipour, S., Ghahremani, M., Gallachóir, B., Bazilian, M.D., Glynn, J. 2022. How energy subsidy reform can drive the Iranian power sector towards a low-carbon future. *Energy Policy, 169*. https://doi.org/10.1016/j.enpol.2022.113190

Azhgaliyeva, D., Mishra, R. 2022. Feed-in tariffs for financing renewable energy in Southeast Asia. *Wiley Interdisciplinary Reviews: Energy and Environment, 11*(3). https://doi.org/10.1002/wene.425

Bahn, O., de Bruin, K., Fertel, C. 2019. Will adaptation delay the transition to clean energy systems? An analysis with Ad-Merge. *Energy Journal, 40*, 235–253. https://doi.org/10.5547/01956574.40.4.obah

Baniya, R., Talchabhadel, R., Panthi, J., Ghimire, G.R., Sharma, S., Khadka, P.D., Shin, S., Pokhrel, Y., Bhattarai, U., Prajapati, R., Thapa, B.R., Maskey, R.K. 2023. Nepal Himalaya offers considerable potential for pumped storage hydropower. *Sustainable Energy Technologies and Assessments, 60*. https://doi.org/10.1016/j.seta.2023.103423

Barbir, F. 2009. Transition to renewable energy systems with hydrogen as an energy carrier. *Energy, 34*, 308–312. https://doi.org/10.1016/j.energy.2008.07.007

Bashir, M.F., Inglesi-Lotz, R., Razi, U., Shahzad, L. 2024. Economic complexity, greenfield investments, and energy innovation: policy implications for sustainable development goals in newly industrialised economies. *Environmental Science and Pollution Research, 31*, 36013–36027.
https://doi.org/10.1007/s11356-024-33433-4

Bayulgen, O. 2020. Localizing the energy transition: Town-level political and socio-economic drivers of clean energy in the United States. *Energy Research & Social Science, 62*. https://doi.org/10.1016/j.erss.2019.101376

Bell, S. 2020. The Renewable Energy Transition Energy Path Divergence, Increasing Returns and Mutually Reinforcing Leads in the State-Market Symbiosis. *New Political Economy, 25*, 57–71. https://doi.org/10.1080/13563467.2018.1562430

Best, R. 2017. Switching towards coal or renewable energy? The effects of financial capital on energy transitions. *Energy Economics, 63*, 75–83. https://doi.org/10.1016/j.eneco.2017.01.019

Bhattarai, D., Somanathan, E., Nepal, M. 2018. Are renewable energy subsidies in Nepal reaching the poor? *Energy for Sustainable Development, 43*, 114–122. https://doi.org/10.1016/j.esd.2018.01.001

Bhattarai, N., Bajracharya, I. 2016. Industrial Sector's Energy Demand Projections and Analysis of Nepal for Sustainable National Energy Planning Process of the Country. *Journal of the Institute of Engineering, 11*, 50–66. https://doi.org/10.3126/jie.v11i1.14695

Bhattarai, U., Devkota, L. P., Marahatta, S., Shrestha, D., Maraseni, T. 2022a. How will hydro-energy generation of the Nepalese Himalaya vary in the future? A climate change perspective. *Environmental Research, 214*, 113746. https://doi.org/10.1016/j.envres.2022.113746

Bhattarai, U., Devkota, R., Maraseni, T., Devkota, L., Marahatta, S. 2023c. Attaining multiple sustainable development goals through storage hydropower development amidst community vulnerabilities. *Sustainable Development, 31*(5), 3913–3929. https://doi.org/10.1002/sd.2634

Bhattarai, U., Maraseni, T., Apan, A. 2022b. Assay of renewable energy transition: A systematic literature review. *Science of The Total Environment, 833*, 155159. https://doi.org/10.1016/j.scitotenv.2022.155159

Bhattarai, U., Maraseni, T., Apan, A., Devkota, L. P. 2023a. Rationalizing donations and subsidies: Energy ecosystem development for sustainable renewable energy transition in Nepal. *Energy Policy, 177*, 113570. https://doi.org/10.1016/j.enpol.2023.113570

Bhattarai, U., Maraseni, T., Devkota, L.P., Apan, A. 2023b. Application of machine learning to assess people's perception of household energy in the developing world: A case of Nepal. *Energy and AI, 14*, 100303. https://doi.org/10.1016/j.egyai.2023.100303

Bhattarai, U., Maraseni, T., Devkota, L.P., Apan, A. 2024a. A Composite Indicator-based Method to Assess the Energy Security of Nepal and prospects of Cross-border Electricity Sharing in South Asia. *Environmental Development, 51*, 101002. https://doi.org/10.1016/j.envdev.2024.101002

Bhattarai, U., Maraseni, T., Devkota, L.P., Apan, A. 2024b. Evaluating Four Decades of Energy Policy Evolution for Sustainable Development of a South Asian Country - Nepal: A Comprehensive Review. *Sustainable Development*, 1-29. https://doi.org/10.1002/sd.3053

Bigerna, S., Bollino, C.A., Polinori, P. 2021. Convergence in renewable energy sources diffusion worldwide. *Journal of Environmental Management, 292*. https://doi.org/10.1016/j.jenvman.2021.112784

Bogdanov, D., Gulagi, A., Fasihi, M., Breyer, C. 2021. Full energy sector transition towards 100% renewable energy supply: Integrating power, heat, transport and industry sectors including desalination. *Applied Energy, 283*. https://doi.org/10.1016/j.apenergy.2020.116273

Bointner, R., Pezzutto, S., Grilli, G., Sparber, W. 2016. Financing innovations for the renewable energy transition in Europe. *Energies (Basel), 9*. https://doi.org/10.3390/en9120990

Borozan, D. 2022. Asymmetric effects of policy uncertainty on renewable energy consumption in G7 countries. *Renewable Energy, 189*, 412–420. https://doi.org/10.1016/j.renene.2022.02.055

Brown, C., Steinschneider, S., Ray, P., Wi, S., Basdekas, L., Yates, D. 2019. Decision Scaling (DS): Decision Support for Climate Change, in: Decision Making under Deep Uncertainty. Springer International Publishing, pp. 255–287. https://doi.org/10.1007/978-3-030-05252-2_12

Bryant, S. T., Straker, K., Wrigley, C. 2019. The discourses of power – governmental approaches to business models in the renewable energy transition. *Energy Policy, 130*, 41–59. https://doi.org/10.1016/j.enpol.2019.03.050

Butchers, J., Williamson, S., Booker, J., Tran, A., Karki, B., Gautam, B. 2020. Understanding sustainable operation of micro-hydropower: a field study in Nepal. *Energy for Sustainable Development, 57*, 12–21. https://doi.org/10.5523/bris.1k9cigxbcdiye22kuay4wbt5yu

Cantarero, M. M. V. 2020. Of renewable energy, energy democracy, and sustainable development: A roadmap to accelerate the energy transition in developing countries. *Energy Research and Social Science, 70*. https://doi.org/10.1016/j.erss.2020.101716

Carrington, G., Stephenson, J. 2018. The politics of energy scenarios: Are International Energy Agency and other conservative projections hampering the renewable energy transition? *Energy Research and Social Science, 46*, 103–113. https://doi.org/10.1016/j.erss.2018.07.011

Carrosio, G., Scotti, I. 2019. The 'patchy' spread of renewables: A socio-territorial perspective on the energy transition process. *Energy Policy, 129*, 684–692. https://doi.org/10.1016/j.enpol.2019.02.057

CBS. 2021. Nepal in figures 2021. Central Bureau of Statistics, Government of Nepal, Kathmandu, Nepal. www.cbs.gov.np

Ćetković, S., Buzogány, A. 2019. The political economy of EU climate and energy policies in central and eastern Europe revisited: Shifting coalitions and prospects for clean energy transitions. *Politics and Governance, 7*, 124–138. https://doi.org/10.17645/pag.v7i1.1786

Chauhan, H. K., Gallacher, D., Bhatt, A., Bisht, A. K. 2023. The Himalayas: A climate change laboratory. *Environmental Development, 45*, 100814. https://doi.org/10.1016/j.envdev.2023.100814

Chen, C., Kalra, A., Ahmad, S. 2019. Hydrologic responses to climate change using downscaled GCM data on a watershed scale. *Journal of Water and Climate Change, 10*(1), 63–77.

Chen, R., Xu, P., Yao, H., Ding, Y. 2023a. How will China achieve net-zero? A policy text analysis of Chinese decarbonization policies. *Energy Research and Social Science, 99*. https://doi.org/10.1016/j.erss.2023.103051

Chen, Y., Mamon, R., Spagnolo, F., Spagnolo, N. 2023b. Sustainable developments, renewable energy, and economic growth in Canada. *Sustainable Development, 31*, 2950–2966. https://doi.org/10.1002/sd.2561

Child, M., Kemfert, C., Bogdanov, D., Breyer, C. 2019. Flexible electricity generation, grid exchange and storage for the transition to a 100% renewable energy system in Europe. *Renewable Energy, 139*, 80–101. https://doi.org/10.1016/j.renene.2019.02.077

Coleman, N., Esmalian, A., Lee, C. C., Gonzales, E., Koirala, P., Mostafavi, A. 2023. Energy inequality in climate hazards: empirical evidence of social and spatial disparities in managed and hazard-induced power outages. *Sustainable Cities and Society, 92*, 104491. https://doi.org/10.1016/j.scs.2023.104491

Conradie, P., Van Hove, S., Pelka, S., Karaliopoulos, M., Anagnostopoulos, F., Brugger, H., Ponnet, K. 2023. Why do people turn down the heat? Applying behavioural theories to assess reductions in space heating and energy consumption in Europe. *Energy Research and Social Science, 100*, 103059. https://doi.org/10.1016/j.erss.2023.103059

Creutzig, F., Goldschmidt, J. C., Lehmann, P., Schmid, E., von Blücher, F., Breyer, C., Fernandez, B., Jakob, M., Knopf, B., Lohrey, S., Susca, T., Wiegandt, K. 2014. Catching two European birds with one renewable stone: Mitigating climate change and Eurozone crisis by an energy transition. *Renewable and Sustainable Energy Reviews, 38*, 1015–1028. https://doi.org/10.1016/j.rser.2014.07.028

Das, I., Rogers, B., Nepal, M., Jeuland, M. 2022. Fuel stacking implications for willingness to pay for cooking fuels in peri-urban Kathmandu Valley, Nepal. *Energy for Sustainable Development, 70*, 482–496. https://doi.org/10.1016/j.esd.2022.08.017

Dhaubanjar, P., Nakarmi, A. M., Bajracharya, S. B. 2019. Energy Scenarios of Household Sector in Panauti Municipality For Sustainable Development and Energy Security. *Journal of Advanced College of Engineering and Management, 5*, 89–100. https://doi.org/10.3126/jacem.v5i0.26692

Dhaubanjar, S., Pandey, V. P., Bharati, L. 2020. Climate futures for Western Nepal based on regional climate models in the CORDEX-SA. *International Journal of Climatology, 40*(4), 2201–2225. https://doi.org/10.1002/JOC.6327

DHM/CCAFS. 2013. Agro-climatic atlas of Nepal. Department of Hydrology and Meteorology (DHM), Ministry of Science, Technology and Environment, Government of Nepal and Climate Change Agriculture and Food Security CGIAR-CCAFS Regional Program Unit

DHM/GoN, 2017. Observed Climate Trend Analysis in the Districts and Physiographic Regions of Nepal. Kathmandu

Diezmartínez, C. V. 2021. Clean energy transition in Mexico: Policy recommendations for the deployment of energy storage technologies. *Renewable and Sustainable Energy Reviews, 135*. https://doi.org/10.1016/j.rser.2020.110407

DoC/GoN, 2023. Nepal Foreign Trade Statistics Fiscal Year 2022/23 (2079/80). Department of Customs, Government of Nepal

Dominguez, C., Orehounig, K., Carmeliet, J. 2021. Understanding the path towards a clean energy transition and post-electrification patterns of rural households. *Energy for Sustainable Development, 61*, 46–64. https://doi.org/10.1016/j.esd.2021.01.002

EC. 2015. Roadmap for the Energy Union: A Framework Strategy for a Resilient Energy Union with a Forward-Looking Climate Change Policy. European Commission, Brussels.

EI. 2023. Statistical Review of World Energy 2023. Energy Institute (EI), London. 72nd edition.

Feng, Y., Hu, J., Afshan, S., Irfan, M., Hu, M., Abbas, S. 2023. Bridging resource disparities for sustainable development: A comparative analysis of resource-rich and resource-scarce countries. *Resources Policy, 85*, 103981. https://doi.org/10.1016/j.resourpol.2023.103981

Franco, M. A. J. Q., Taeighagh, A. 2024. Sustainable energy adoption in poor rural areas: A comparative case perspective from the Philippines. *Energy for Sustainable Development, 79*, 101389. https://doi.org/10.1016/j.esd.2024.101389

Furlong, K., 2020. EmPower the Yukon. Using community renewable energy in the transition to energy resilience: a social enterprise approach. *The Northern Review*. https://doi.org/10.22584/nr49.2020.016

Gasser, P. 2020. A review on energy security indices to compare country performances. *Energy Policy*. https://doi.org/10.1016/j.enpol.2020.111339

Gebreslassie, M. G., Cuvilas, C., Zalengera, C., To, L. S., Baptista, I., Robin, E., Bekele, G., Howe, L., Shenga, C., Macucule, D. A., Kirshner, J., Mulugetta, Y., Power, M., Robinson, S., Jones, D., Castán Broto, V. 2022. Delivering an off-grid transition to sustainable energy in Ethiopia and Mozambique. *Energy Sustainability and Society, 12*. https://doi.org/10.1186/s13705-022-00348-2

GoN, 2019. Climate Change Policy of Nepal, 2076 (in Nepali). Government of Nepal, Kathmandu, Nepal.

Gottschamer, L., Zhang, Q. 2020. The dynamics of political power: the socio-technical transition of California electricity system to renewable energy. *Energy Res. Soc. Sci. 70*, 899–920. https://doi.org/10.1016/j.erss.2020.101618

Gulagi, A., Ram, M., Solomon, A. A., Khan, M., Breyer, C. 2020. Current energy policies and possible transition scenarios adopting renewable energy: A case study for Bangladesh. *Renewable Energy, 155*, 899–920. https://doi.org/10.1016/j.renene.2020.03.119

Guo, Z., Zhang, X., Feng, S., Zhang, H. 2020. The Impacts of Reducing Renewable Energy Subsidies on China's Energy Transition by Using a Hybrid Dynamic Computable General Equilibrium Model. *Frontiers in Energy Research 8*. https://doi.org/10.3389/fenrg.2020.00025

Gyanwali, K., Komiyama, R., Fujii, Y. 2020. Representing hydropower in the dynamic power sector model and assessing clean energy deployment in the power generation mix of Nepal. *Energy, 202*. https://doi.org/10.1016/j.energy.2020.117795

Ha, Y. H., Kumar, S. S. 2021. Investigating decentralized renewable energy systems under different governance approaches in Nepal and Indonesia: How does governance fail? *Energy Research & Social Science, 80*. https://doi.org/10.1016/j.erss.2021.102214

Hashemi, M. 2021. The economic value of unsupplied electricity: Evidence from Nepal. *Energy Economics, 95*. https://doi.org/10.1016/j.eneco.2021.105124

He, R., Jin, J., Qiu, X., Zhang, C., Yan, J. 2023. Rural residents' climate change perceptions, personal experiences, and purchase intention–behavior gap in energy-saving refrigeration appliances in Southwest China. *Environmental Impact Assessment Review, 98*. https://doi.org/10.1016/j.eiar.2022.106967

Hill, D., Connelly, S. 2018. Community energies: Exploring the socio-political spatiality of energy transitions through the Clean Energy for Eternity campaign in New South Wales Australia. *Energy Research and Social Science, 36*, 138–145. https://doi.org/10.1016/j.erss.2017.11.021

Hunt, J., Riley, B., O'Neill, L., Maynard, G. 2021. Transition to Renewable Energy and Indigenous People in Northern Australia: Enhancing or Inhibiting Capabilities? *Journal of Human Development and Capabilities, 22*, 360–378. https://doi.org/10.1080/19452829.2021.1901670

Hurlbert, M., Osazuwa-Peters, M., McNutt, K., Rayner, J. 2020. Transitioning from coal: Toward a renewables-based socio-technical regime in Saskatchewan. *Environmental Innovation and Societal Transitions, 36*, 321–330. https://doi.org/10.1016/j.eist.2019.11.005

Hussain, M., Bashir, A., Wang, C., Wang, Y. 2023. World uncertainty, natural resources, consumer prices, and financial development in high-income countries. *Resources Policy, 81*, 103302. https://doi.org/10.1016/j.resourpol.2023.103302

Hvelplund, F., Djørup, S. 2017. Multilevel policies for radical transition: governance for a 100% renewable energy system. *Environmental Planning C: Politics and Space, 35*, 1218–1241. https://doi.org/10.1177/2399654417710024

IEA, 2023a. CO2 Emissions in 2023. International Energy Agency, France. https://www.iea.org/reports/co2-emissions-in-2023

IEA, 2023b. World Energy Outlook 2023. International Energy Agency. OECD Publishing, Paris, France. https://www.iea.org/data-and-statistics/data-product/world-energy-outlook-2023-free-dataset-2 (accessed 10 May 2024)

Indra Al Irsyad, M., Halog, A. B., Nepal, R., Koesrindartoto, D. P. 2017. Selecting tools for renewable energy analysis in developing countries: An expanded review. *Frontiers in Energy Research*. https://doi.org/10.3389/fenrg.2017.00034

IPCC, 2021. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M.I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J.B.R., Maycock, T.K., Waterfield, T., Yelekçi, O., Yu, R., Zhou, B. (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2391 pp. https://doi.org/10.1017/9781009157896

IRENA, 2024. Renewable Energy Statistics 2024. International Renewable Energy Agency, Abu Dhabi.

Israel, A., Jehling, M. 2019. How modern are renewables? The misrecognition of traditional solar thermal energy in Peru's energy transition. *Energy Policy, 133*. https://doi.org/10.1016/j.enpol.2019.110905

Jiang, Y., Khaskheli, A., Ali Raza, S., Qureshi, M. A., Ahmed, M. 2021. Threshold non-linear relationship between globalization, renewable energy consumption, and environmental degradation: evidence from smooth transition models. *Environmental Science and Pollution Research, 28*, 13323–39. https://doi.org/10.1007/s11356-020-11537-x

Johnstone, P., Rogge, K. S., Kivimaa, P., Fratini, C. F., Primmer, E., Stirling, A. 2020. Waves of disruption in clean energy transitions: Sociotechnical dimensions of system disruption in Germany and the United Kingdom. *Energy Research and Social Science, 59*. https://doi.org/10.1016/j.erss.2019.101287

Jones, A., Nock, D., Samaras, C., Qiu, Y. L., Xing, B. 2023. Climate change impacts on future residential electricity consumption and energy burden: A case study in Phoenix, Arizona. *Energy Policy, 183*, 113811. https://doi.org/10.1016/j.enpol.2023.113811

Kaini, S., Nepal, S., Pradhananga, S., Gardner, T., Sharma, A. K. 2020. Impacts of climate change on the flow of the transboundary Koshi River, with implications for local irrigation. *International Journal of Water Resources Development, 37*, 929-954. https://doi.org/10.1080/07900627.2020.1826292

Keller, A. A., Garner, K. L., Rao, N., Knipping, E., Thomas, J. 2022. Downscaling approaches of climate change projections for watershed modeling: Review of theoretical and practical considerations. *PLoS Water, 1(9)*, e0000046. https://doi.org/10.1371/journal.pwat.0000046

Kelly, A. M., Radler, R. D. N. N. 2024. Does energy consumption matter for climate change in Africa? New insights from panel data analysis. *Innovation and Green Development, 3(3)*, 100132. https://doi.org/10.1016/j.igd.2024.100132

Khan, Y., Hassan, T. 2024. Promoting sustainable development: Evaluating the influence of natural resources, high-tech export and corruption on CO2 emissions in developing economies. *Resources Policy, 88*, 104511. https://doi.org/10.1016/j.resourpol.2023.104511

Kim, E.S., Chung, J.B., Seo, Y. 2018. Korean traditional beliefs and renewable energy transitions: pungsu, shamanism, and the local perception of wind turbines. *Energy Research and Social Science, 46*, 262-273. https://doi.org/10.1016/j.erss.2018.07.024

Ko, I. 2023. Rural opposition to landscape change from solar energy: explaining the diffusion of setback restrictions on solar farms across South Korean counties. *Energy Research and Social Science, 99*. https://doi.org/10.1016/j.erss.2023.103073

Koçak, E., Çelik, B. 2022. The nexus between access to energy, poverty reduction and PM2.5 in Sub-Saharan Africa: New evidence from the generalized method of moments estimators. *Science of The Total Environment, 827*, 154377. https://doi.org/10.1016/j.scitotenv.2022.154377

Koengkan, M., Fuinhas, J. A. 2020. Exploring the effect of the renewable energy transition on CO2 emissions of Latin American & Caribbean countries. *International Journal of Sustainable Energy, 39*, 515–538. https://doi.org/10.1080/14786451.2020.1731511

Koirala, D. P., Acharya, B. 2022. Households' fuel choices in the context of a decade-long load-shedding problem in Nepal. *Energy Policy, 162*. https://doi.org/10.1016/j.enpol.2022.112795

Kurniawan, T. B., Dewi, D. A., Usman, F., Fadly, F. 2023. Towards Energy Analysis and Efficiency for Sustainable Buildings. *Emerging Science Journal, 7(6)*, 2226–2238.

Li, M., Jin, T., Liu, S., Zhou, S. 2021. The cost of clean energy transition in rural China: Evidence based on marginal treatment effects. *Energy Economics, 97* https://doi.org/10.1016/j.eneco.2021.105167

Liao, C., Erbaugh, J. T., Kelly, A. C., Agrawal, A. 2021. Clean energy transitions and human well-being outcomes in Lower and Middle Income Countries: A systematic review. *Renewable and Sustainable Energy Reviews*. https://doi.org/10.1016/j.rser.2021.111063

Lin, B., Omoju, O. E. 2017. Focusing on the right targets: Economic factors driving non-hydro renewable energy transition. *Renewable Energy, 113*, 52–63. https://doi.org/10.1016/j.renene.2017.05.067

Liya, C., Jianfeng, G. 2018. Scenario analysis of CO2 emission abatement effect based on LEAP. *Energy Procedia*, 965–970. https://doi.org/10.1016/j.egypro.2018.09.101

Liu, Y., Zhu, J., Li, E. Y., Meng, Z., Song, Y. 2020. Environmental regulation, green technological innovation, and eco-efficiency: The case of Yangtze river economic belt in China. *Technological Forecasting and Social Change, 155*, 119993. https://doi.org/10.1016/j.techfore.2020.119993

Lohani, S. P., Gurung, P., Gautam, B., Kafle, U., Fulford, D., Jeuland, M. 2022. Current status, prospects, and implications of renewable energy for achieving sustainable development goals in Nepal. *Sustainable Development*. https://doi.org/10.1002/sd.2392

Lutz, A. F., Immerzeel, W. W., Siderius, C., Wijngaard, R. R., Shrestha, A. B., Wester, P., Biemans, H. 2022. On meltwater and groundwater. *Nature Climate Change*. https://doi.org/10.1038/s41558-022-01355-z

Maennel, A., Kim, H. G. 2018. Comparison of greenhouse gas reduction potential through renewable energy transition in South Korea and Germany. *Energies (Basel), 11*. https://doi.org/10.3390/en11010206

Mali, B., Shrestha, A., Chapagain, A., Bishwokarma, R., Kumar, P., Gonzalez-Longatt, F. 2022. Challenges in the Penetration of Electric Vehicles in Developing Countries with a Focus on Nepal. *Renewable Energy Focus*. https://doi.org/10.1016/j.ref.2021.11.003

Marahatta, S., Bhattarai, U., Devkota, L. P., Aryal, D. 2022. Unravelling the water-energy-economics-continuum of hydroelectricity in the face of climate change. *International Journal of Energy and Water Resources*. https://doi.org/10.1007/s42108-021-00174-w

Marczinkowski, H. M., Barros, L. 2020. Technical approaches and institutional alignment to 100% renewable energy system transition of Madeira Island - electrification, smart energy and the required flexible market conditions. *Energies (Basel), 13*. https://doi.org/10.3390/en13174434

Martinez, N., Komendantova, N. 2020. The effectiveness of the social impact assessment (SIA) in energy transition management: Stakeholders' insights from renewable energy projects in Mexico. *Energy Policy, 145*. https://doi.org/10.1016/j.enpol.2020.111744

Masson-Delmotte, V., Zhai, P., Pörtner, H.-O., Roberts, D., Skea, J., Shukla, P. R., Pirani, A., Moufouma-Okia, W., Péan, C., Pidcock, R., Connors, S., Matthews, J. B. R., Chen, Y., Zhou, X., Gomis, M. I., Lonnoy, E., Maycock, T., Tignor, M., Waterfield, T. 2019. Global warming of 1.5°C An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. Edited by Science Officer Science Assistant Graphics Officer Working Group I Technical Support Unit. https://www.environmentalgraphiti.org

Matavel, C. E., Kächele, H., Hafner, J. M., Rybak, C., Uckert, G., Hoffmann, H., Kipkulei, H. K., Massuque, J., Steinke, J., Sieber, S. 2023. How to increase cookstove adoption? Exploring cost-effective dissemination techniques in Central Mozambique. *Energy Research and Social Science, 100*. https://doi.org/10.1016/j.erss.2023.103082

McEwan, C. 2017. Spatial processes and politics of renewable energy transition: Land, zones and frictions in South Africa. *Political Geography, 56*, 1–12. https://doi.org/10.1016/j.polgeo.2016.10.001

McGreevy, D. M., MacDougall, C., Fisher, D. M., Henley, M., Baum, F. 2021. Expediting a renewable energy transition in a privatised market via public policy: The case of South Australia 2004-18. *Energy Policy, 148*. https://doi.org/10.1016/j.enpol.2020.111940

McPherson, M., Karney, B. 2014. Long-term scenario alternatives and their implications: LEAP model application of Panama's electricity sector. *Energy Policy, 68*, 146–157. https://doi.org/10.1016/j.enpol.2014.01.028

Millot, A., Krook-Riekkola, A., Maïzi, N. 2020. Guiding the future energy transition to net-zero emissions: Lessons from exploring the differences between France and Sweden. *Energy Policy, 139*. https://doi.org/10.1016/j.enpol.2020.111358

Mirjat, N. H., Uqaili, M. A., Harijan, K., Walasai, G., Das, M., Mondal, M. A. H., Sahin, H. 2018. Long-term electricity demand forecast and supply side scenarios for Pakistan (2015–2050): A LEAP model application for policy analysis. *Energy, 165*, 512–526. https://doi.org/10.1016/j.energy.2018.10.012

MoF/GoN. 2023. Economic Survey 2022/23. Ministry of Finance, Government of Nepal, Singh Durbar, Kathmandu, Nepal.

MoFE/GoN, 2019. Climate Change Scenarios for Nepal National Adaptation Plan. Ministry of Forests and Environment, Government of Nepal, Singh Durbar, Kathmandu, Nepal.

Mohsin, M., Kamran, H. W., Atif Nawaz, M., Sajjad Hussain, M., Dahri, A. S. 2021. Assessing the impact of transition from nonrenewable to renewable energy consumption on economic growth-environmental nexus from developing Asian economies. *Journal of Environmental Management, 284*. https://doi.org/10.1016/j.jenvman.2021.111999

Mool, P. K., Wangda, D., Bajracharya, S. R., Kunzang, K., Raj Gurung, D., Joshi, S. P. 2001. Inventory of Glaciers, Glacial Lakes and Glacial Lake Outburst Floods Monitoring and Early Warning Systems in the Hindu Kush-Himalayan Region Bhutan In cooperation with United Nations Environment Programme Regional Resource Centre-Asia and the Pacific.

Movik, S., & Allouche, J. 2020. States of Power: Energy Imaginaries and Transnational Assemblages in Norway, Nepal and Tanzania. *Energy Research and Social Science, 67*. https://doi.org/10.1016/j.erss.2020.101548

Mukelabai, M.D., Wijayantha, K.G.U., Blanchard, R.E. 2023. Using machine learning to expound energy poverty in the global south: understanding and predicting access to cooking with clean energy. *Energy and AI, 14*, 100290. https://doi.org/10.1016/j.egyai.2023.100290

Müller, F., Neumann, M., Elsner, C., Claar, S. 2021. Assessing african energy transitions: Renewable energy policies, energy justice, and SDG 7. *Politics and Governance, 9*, 119–130. https://doi.org/10.17645/pag.v9i1.3615

Munro, F.R. 2019. Renewable energy and transition-periphery dynamics in Scotland. *Environmental Innovation and Societal Transitions, 31*, 273–281. https://doi.org/10.1016/j.eist.2018.09.001

Murshed, M. 2021. Can regional trade integration facilitate renewable energy transition to ensure energy sustainability in South Asia? *Energy Reports, 7*, 808–821. https://doi.org/10.1016/j.egyr.2021.01.038

Nakarmi, A.M., Mishra, T., Banerjee, R. 2016. Integrated MAED–MARKAL-based analysis of future energy scenarios of Nepal. *International Journal of Sustainable Energy, 35*, 968–981. https://doi.org/10.1080/14786451.2014.966712

NEA/GoN, 2023. A Year in Review Fiscal Year 2022/23. Nepal Electricity Authority, Government of Nepal, Kathmandu, Nepal.

Nie, Y., Zhang, G., Zhong, L., Su, B., Xi, X. 2024. Urban–rural disparities in household energy and electricity consumption under the influence of electricity price reform policies. *Energy Policy, 184*, 113868. https://doi.org/10.1016/j.enpol.2023.113868

Nijsse, F.J., Mercure, J.F., Ameli, N., Larosa, F., Kothari, S., Rickman, J., Vercoulen, P., Pollitt, H. 2023. The momentum of the solar energy transition. *Nature Communications, 14*(1), 6542. https://doi.org/10.1038/s41467-023-41971-7

Palit, D., Bandyopadhyay, K.R. 2016. Rural electricity access in South Asia: Is grid extension the remedy? A critical review. *Renewable and Sustainable Energy Reviews*. https://doi.org/10.1016/j.rser.2016.03.034

Pandey, A., Prakash, A., Werners, S. E. 2021. Matches, mismatches and priorities of pathways from a climate-resilient development perspective in the mountains of Nepal. *Environmental Science and Policy, 125*, 135–145. https://doi.org/10.1016/j.envsci.2021.08.013

Pandey, P., Sharma, A. 2021. Knowledge politics, vulnerability and recognition-based justice: Public participation in renewable energy transitions in India. *Energy Research and Social Science, 71*. https://doi.org/10.1016/j.erss.2020.101824

Parag, Y., Ainspan, M. 2019. Sustainable microgrids: Economic, environmental and social costs and benefits of microgrid deployment. *Energy for Sustainable Development, 52*, 72-81. https://doi.org/10.1016/j.esd.2019.07.003

Pokharel, R., Bertolini, L., te Brömmelstroet, M., Acharya, S.R. 2021. Spatio-temporal evolution of cities and regional economic development in Nepal: Does transport infrastructure matter? *Journal of Transport Geography, 90*. https://doi.org/10.1016/j.jtrangeo.2020.102904

Pi, K., Khan, S., Raza, S.A., Shahzadi, I. 2024. Sustainable energy efficiency, greener energy and energy-related emissions nexus: Sustainability-related implications for G7 economies. *Geological Journal, 59(1)* https://doi.org/10.1002/gj.4864

Pons-Seres de Brauwer, C., Cohen, J.J. 2020. Analysing the potential of citizen-financed community renewable energy to drive Europe's low-carbon energy transition. *Renewable and Sustainable Energy Reviews, 133*. https://doi.org/10.1016/j.rser.2020.110300

Poudyal, R., Loskot, P., Nepal, R., Parajuli, R., Khadka, S.K. 2019. Mitigating the current energy crisis in Nepal with renewable energy sources. *Renewable and Sustainable Energy Reviews*. https://doi.org/10.1016/j.rser.2019.109388

Proka, A., Hisschemöller, M., Loorbach, D. 2018. Transition without conflict? Renewable energy initiatives in the Dutch energy transition. *Sustainability (Switzerland), 10*. https://doi.org/10.3390/su10061721

Ram, M., Bogdanov, D., Aghahosseini, A., Gulagi, A., Oyewo, A.S., Mensah, T.N.O., Child, M., Caldera, U., Sadovskaia, K., Barbosa, L.D.S.N.S., Fasihi, M. 2022. Global energy transition to 100% renewables by 2050: Not fiction, but much needed impetus for developing economies to leapfrog into a sustainable future. *Energy, 246*, 123419. https://doi.org/10.1016/j.energy.2022.123419

Ray, P.A., Bonzanigo, L., Wi, S., Yang, Y.C.E., Karki, P., García, L.E., Rodriguez, D.J., Brown, C.M. 2018a. Multidimensional stress test for hydropower investments facing climate, geophysical and financial uncertainty. *Global Environmental Change, 48*, 168–181. https://doi.org/10.1016/j.gloenvcha.2017.11.013

Ray, P.A., Brown, C.M. 2015. Confronting Climate Uncertainty in Water Resources Planning and Project Design: The Decision Tree Framework.

Ray, P.A., Taner, M.U., Schlef, K.E., Wi, S., Khan, H.F., Freeman, S.S.G., Brown, C.M. 2018b. Growth of the Decision Tree: Advances in Bottom-Up Climate Change Risk Management. *Journal of the American Water Resources Association*.

Raza, M.A., Khatri, K.L., Hussain, A. 2022. Transition from fossilized to defossilized energy system in Pakistan. *Renewable Energy, 190*, 19–29. https://doi.org/10.1016/j.renene.2022.03.059

REN21, 2024. Renewables 2021 Global Status Report. Paris.

Ringkjøb, H.K., Haugan, P.M., Nybø, A. 2020. Transitioning remote Arctic settlements to renewable energy systems – A modelling study of Longyearbyen, Svalbard. *Applied Energy, 258*. https://doi.org/10.1016/j.apenergy.2019.114079

Roberts, J. 2020. Power to the people? Implications of the Clean Energy Package for the role of community ownership in Europe's energy transition. *Review of European, Comparative and International Environmental Law, 29*, 232–244. https://doi.org/10.1111/reel.12346

Salari, M., Javid, R.J., Noghanibehambari, H. 2021. The nexus between CO2 emissions, energy consumption, and economic growth in the U.S. *Economic Analysis and Policy, 69*, 182–194. https://doi.org/10.1016/j.eap.2020.12.007

Sanjel, N., Baral, B. 2021. Modelling and analysis of decentralized energy systems with photovoltaic, micro-hydro, battery and diesel technology for remote areas of Nepal. *Clean Energy, 5*(4), 690–703. https://doi.org/10.1093/ce/zkab042

SEI, 2022. LEAP. Stockholm Environment Institute (SEI). [WWW Document] https://www.sei.org/tools/leap-long-range-energy-alternatives-planning-system/ (accessed 4 March 2023)

Shahzadi, I., Yaseen, M.R., Iqbal Khan, M.T., Amjad Makhdum, M.S., Ali, Q. 2022. The nexus between research and development, renewable energy and environmental quality: evidence from developed and developing countries. *Renewable Energy*. https://doi.org/10.1016/j.renene.2021.10.050

Shakya, S.R., Adhikari, R., Poudel, S., Rupakheti, M. 2022a. Energy equity as a major driver of energy intensity in South Asia. *Renewable and Sustainable Energy Reviews, 170*. https://doi.org/10.1016/j.rser.2022.112994

Shakya, S.R., Bajracharya, I., Vaidya, R.A., Bhave, P., Sharma, A., Rupakheti, M., Bajracharya, T.R. 2022b. Estimation of air pollutant emissions from captive diesel generators and its mitigation potential through microgrid and solar energy. *Energy Reports, 8*, 3251-3262. https://doi.org/10.1016/j.egyr.2022.02.084

Shakya, S.R., Nakarmi, A.M., Prajapati, A., Pradhan, B.B., Rajbhandari, U.S., Rupakheti, M., Lawrence, M.G. 2023. Environmental, energy security, and energy equity (3E) benefits of net-zero emission strategy in a developing country: A case study of Nepal. *Energy Reports, 9*, 2359–2371. https://doi.org/10.1016/j.egyr.2023.01.055

Sharma, T., Balachandra, P. 2019. Model based approach for planning dynamic integration of renewable energy in a transitioning electricity system. *International Journal of Electrical Power and Energy Systems, 105*, 642–659. https://doi.org/10.1016/j.ijepes.2018.09.007

Shrestha, A., Shrestha, S., Tingsanchali, T., Budhathoki, A., Ninsawat, S. 2021. Adapting hydropower production to climate change: A case study of Kulekhani Hydropower Project in Nepal. *Journal of Cleaner Production, 279*, 123483. https://doi.org/10.1016/j.jclepro.2020.123483

Shrestha, D., Basnyat, D. 2019. Weather Generator and Climate Change Scenario Generator for Climate Risk Assessment Technical Documentation. Kathmandu, Nepal.

Shrestha, M.E.I., Sartohadi, J., Ridwan, M.K., Hizbaron, D.R. 2017. Urban energy scenario: The case of Kathmandu valley. *Journal of Engineering and Technological Sciences, 49*, 210–224. https://doi.org/10.5614/j.eng.technol.sci.2017.49.2.4

Solaun, K., Cerdá, E. 2019. Climate change impacts on renewable energy generation. A review of quantitative projections. *Renewable and Sustainable Energy Reviews, 116*. https://doi.org/10.1016/j.rser.2019.109415

Solé, J., García-Olivares, A., Turiel, A., Ballabrera-Poy, J. 2018. Renewable transitions and the net energy from oil liquids: a scenarios study. *Renewable Energy, 116*, 258–271. https://doi.org/10.1016/j.renene.2017.09.035

Solé, J., Samsó, R., García-Ladona, E., García-Olivares, A., Ballabrera-Poy, J., Madurell, T., Turiel, A., Osychenko, O., Álvarez, D., Bardi, U., Baumann, M., Buchmann, K., Capellán-Pérez, Černý, M., Carpintero, de Blas, I., de Castro, C., de Lathouwer, J.D., Duce, C., Eggler, L., Enríquez, J.M., Falsini, S., Feng, K., Ferreras, N., Frechoso, F., Hubacek, K., Jones, A., Kaclíková, R., Kerschner, C., Kimmich, C., Lobejón, L.F., Lomas, P.L., Martelloni, G., Mediavilla, M., Miguel, L.J., Natalini, D., Nieto, J., Nikolaev, A., Parrado, G., Papagianni, S., Perissi, I., Ploiner, C., Radulov, L., Rodrigo, P., Sun, L., Theofilidi, M. 2020. Modelling the renewable transition: Scenarios and pathways for a decarbonized future using pymedeas, a new open-source energy systems model. *Renewable and Sustainable Energy Reviews, 132*. https://doi.org/10.1016/j.rser.2020.110105

Sovacool, B.K., Axsen, J., Sorrell, S. 2018. Promoting novelty, rigor, and style in energy social science: Towards codes of practice for appropriate methods and research design. *Energy Research and Social Science, 45*, 12-42. https://doi.org/10.1016/j.erss.2018.07.007

Sovacool, B.K., Hess, D.J., Amir, S., Geels, F.W., Hirsh, R., Medina, L.R., Miller, C., Palavicino, C.A., Phadke, R., Ryghaug, M., Schot, J. 2020. Sociotechnical agendas: Reviewing future directions for energy and climate research. *Energy Research and Social Science, 70*, 101617. https://doi.org/10.1016/j.erss.2020.101617

Steinschneider, S., Ray, P., Rahat, S.H., Kucharski, J. 2019. A weather regime based stochastic weather generator for climate vulnerability assessments of water systems in the western United States. *Water Resources Research, 55*(8), 6923-6945. https://doi.org/10.1029/2018WR024446

Steinschneider, S., Brown, C. 2013. A semiparametric multivariate, multisite weather generator with low□frequency variability for use in climate risk assessments. *Water Resources Research, 49*(11), 7205-7220. https://doi.org/10.1002/wrcr.20528

Su, C., Urban, F. 2021. Circular economy for clean energy transitions: A new opportunity under the COVID-19 pandemic. *Applied Energy, 289*. https://doi.org/10.1016/j.apenergy.2021.116666

Tanti, P. C., Jena, P. R. 2023. Perception on climate change, access to extension service and energy sources determining adoption of climate-smart practices: A multivariate approach. *Journal of Arid Environments, 212*. https://doi.org/10.1016/j.jaridenv.2023.104961

Tapiador, F. J., Navarro, A., Moreno, R., Sánchez, J. L., García-Ortega, E. 2020. Regional climate models: 30 years of dynamical downscaling. *Atmospheric Research, 235*, 104785. https://doi.org/10.1016/j.atmosres.2019.104785

Tekler, Z. D., Low, R., Blessing, L. 2022. User perceptions on the adoption of smart energy management systems in the workplace: Design and policy implications. *Energy Research and Social Science, 88*. https://doi.org/10.1016/j.erss.2022.102505

Tsvetanov, T. 2019. When the carrot goes bad: The effect of solar rebate uncertainty. *Energy Economics, 81*, 886-898. https://doi.org/10.1016/j.eneco.2019.05.028

UN. 2020. The Sustainable Development Goals Report. United Nations, New York.

UN. 2015. Transforming our world: the 2030 Agenda for Sustainable Development, Resolution Adopted by the General Assembly on 21 October 2015, A/RES/70/1. United Nations General Assembly.

Usman, O., Nwani, C., Ozkan, O. 2024. Role of household energy efficiency in shaping policy directives toward clean electricity transition in the United States: A nonparametric multivariate QQR approach. *Sustainable Energy Technologies and Assessments, 64*, 103741. https://doi.org/10.1016/j.seta.2024.103741

WB. 2015. South Asia investment decision making in hydropower. Decision tree case study of the Upper Arun Hydropower Project and Koshi Basin hydropower development in Nepal. International Bank for Reconstruction and Development, The World Bank, Washington DC, USA.

WB. 2024. World Bank national accounts data, and OECD National Accounts data files. Webpage. https://data.worldbank.org/indicator/NY.GDP.MKTP.CD?locations=NP&msclkid=c583c33ad00811ec9a96c3a8dce184bf (accessed on 29 March, 2024)

WECS/GoN 2023. Nepal Energy Sector Synopsis Report-2023. Water and Energy Commission Secretariat, Government of Nepal, Singhadurbar, Kathmandu, Nepal.

WECS/GoN, 2013a. National Energy Strategy of Nepal. Water and Energy Commission Secretariat, Government of Nepal, Singhadurbar, Kathmandu, Nepal.

WECS/GoN, 2013b. Nepal's Energy Sector Vision 2050 A.D. Water and Energy Commission Secretariat, Government of Nepal, Singhadurbar, Kathmandu, Nepal.

Weko, S., Goldthau, A. 2022. Bridging the low-carbon technology gap? Assessing energy initiatives for the Global South. *Energy Policy, 169*. https://doi.org/10.1016/j.enpol.2022.113192

Windemer, R. 2023. Acceptance should not be assumed. How the dynamics of social acceptance changes over time, impacting onshore wind repowering. *Energy Policy, 173*. https://doi.org/10.1016/j.enpol.2022.113363

Winkler, B., Lewandowski, I., Voss, A., Lemke, S. 2018. Transition towards renewable energy production? Potential in smallholder agricultural systems in West Bengal, India. *Sustainability (Switzerland), 10*. https://doi.org/10.3390/su10030801

Wittmayer, J. M., Hielscher, S., Fraaije, M., Avelino, F., Rogge, K. 2022. A typology for unpacking the diversity of social innovation in energy transitions. *Energy Research and Social Science, 88*, 102513. https://doi.org/10.1016/j.erss.2022.102513

Wu, S. 2020. The evolution of rural energy policies in China: A review. *Renewable and Sustainable Energy Reviews, 119*. https://doi.org/10.1016/j.rser.2019.109584

Xu, R., Zeng, Z., Pan, M., Ziegler, A.D., Holden, J., Spracklen, D. V., Brown, L.E., He, X., Chen, D., Ye, B., Xu, H., Jerez, S., Zheng, C., Liu, J., Lin, P., Yang, Y., Zou, J., Wang, D., Gu, M., Yang, Z., Li, D., Huang, J., Lakshmi, V., Wood, Eric. F. 2023. A global-scale framework for hydropower development incorporating strict environmental constraints. *Nature Water, 1*, 113–122. https://doi.org/10.1038/s44221-022-00004-1

Yao, Z., Lum, Y., Johnston, A., Mejia-Mendoza, L.M., Zhou, X., Wen, Y., Aspuru-Guzik, A., Sargent, E.H., She, Z.W. 2023. Machine learning for a sustainable energy future. *Nature Reviews Materials, 8*(3):202–215. https://doi.org/10.1038/s41578-022-00490-5

Yawale, S. K., Hanaoka, T., Kapshe, M., Pandey, R. 2023. End-use energy projections: Future regional disparity and energy poverty at the household level in rural and urban areas of India. *Energy Policy, 182*, 113772. https://doi.org/10.1016/j.enpol.2023.113772

York, R., Bell, S.E. 2019. Energy transitions or additions?: Why a transition from fossil fuels requires more than the growth of renewable energy. *Energy Research and Social Science, 51*, 40–43. https://doi.org/10.1016/j.erss.2019.01.008

Yaghoubi, J., Yazdanpanah, M., Komendantova, N. 2019. Iranian agriculture advisors' perception and intention toward biofuel: Green way toward energy security, rural development and climate change mitigation. *Renewable Energy, 130*, 452–459. https://doi.org/10.1016/j.renene.2018.06.081

Yunzhao, L. 2022. Modelling the role of ecoinnovation, renewable energy, and environmental taxes in carbon emissions reduction in E−7 economies: Evidence from advance panel estimations. *Renewable Energy, 190*, 309-318. https://doi.org/10.1016/j.renene.2022.03.119

Zhao, N., You, F. 2021. New York State's 100% renewable electricity transition planning under uncertainty using a data-driven multistage adaptive robust optimization approach with machine-learning. *Advances in Applied Energy, 2*, 100019. https://doi.org/10.1016/j.adapen.2021.100019

Zhang, C., Zhao, X., Shi, C. 2024. Efficiency assessment and scenario simulation of the Water-Energy-Food system in the Yellow River Basin, China. *Energy*, 132279. https://doi.org/10.1016/j.energy.2024.132279