Environmental Development 51 (2024) 101002

Contents lists available at ScienceDirect

Environmental Development

journal homepage: www.elsevier.com/locate/envdev

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

Utsav Bhattarai [a,b,*], Tek Maraseni [a,c,d], Laxmi Devkota [b,e], Armando Apan [a,f,g]

[a] Institute for Life Sciences and the Environment (ILSE), University of Southern Queensland, Toowoomba, Queensland, 4350, Australia
[b] Water Modeling Solutions Pvt. Ltd., Kathmandu, Nepal
[c] Centre for Sustainable Agricultural Systems (CSAS), University of Southern Queensland, Toowoomba, Queensland, 4350, Australia
[d] Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, Lanzhou, 730000, China
[e] Nepal Academy of Science and Technology (NAST), Kathmandu, Nepal
[f] School of Surveying and Built Environment, University of Southern Queensland, Toowoomba, Queensland, 4350, Australia
[g] Institute of Environmental Science and Meteorology, University of the Philippines Diliman, Quezon City, 1101, Philippines

ARTICLE INFO

Keywords:
Energy security
Principal Component Analysis (PCA)
Energy Security Composite Index of Nepal (ESCOIN)
Regional energy trade
South Asia

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 multi-collinearity, 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.

* Corresponding author.
E-mail address: Utsav.Bhattarai@unisq.edu.au (U. Bhattarai).

https://doi.org/10.1016/j.envdev.2024.101002
Received 5 June 2023; Received in revised form 7 May 2024; Accepted 8 May 2024
Available online 15 May 2024

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.

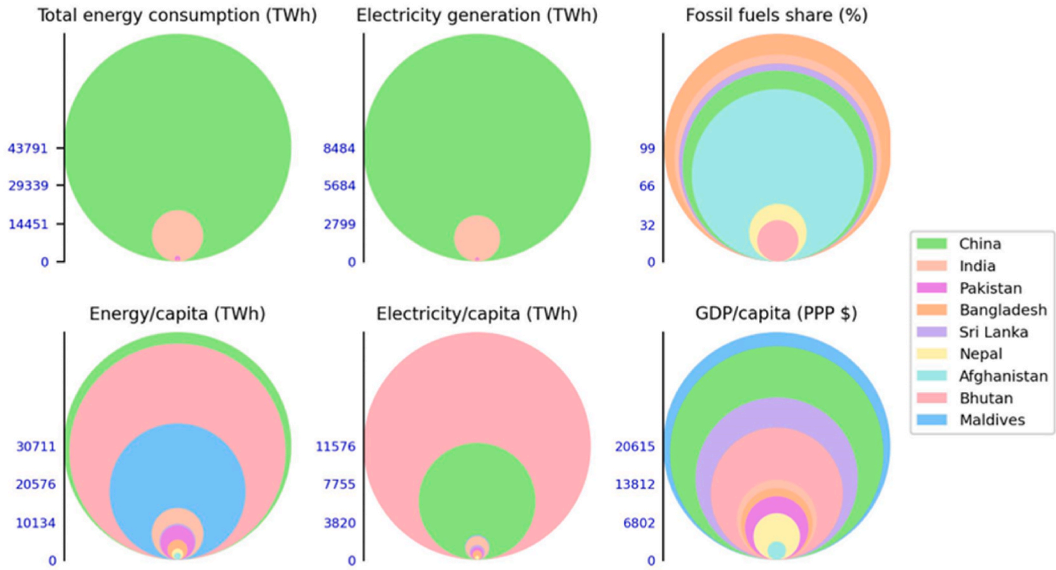

Fig. 1. Comparison of energy related indicators (total primary energy consumption in Tera-Watt-hours, TWh; total electricity generation in TWh; share of fossil fuels on the total energy (%), energy consumption per capita (TWh); electricity generation per capita (TWh); and GDP per capita in current US$) 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

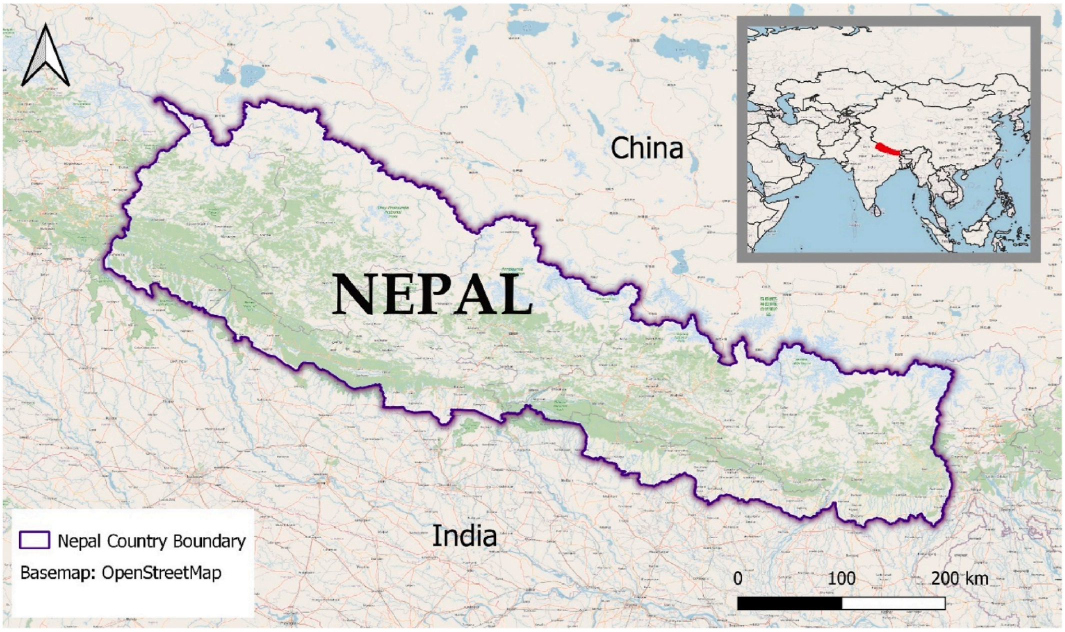

Fig. 2. Geographical setting of Nepal.

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

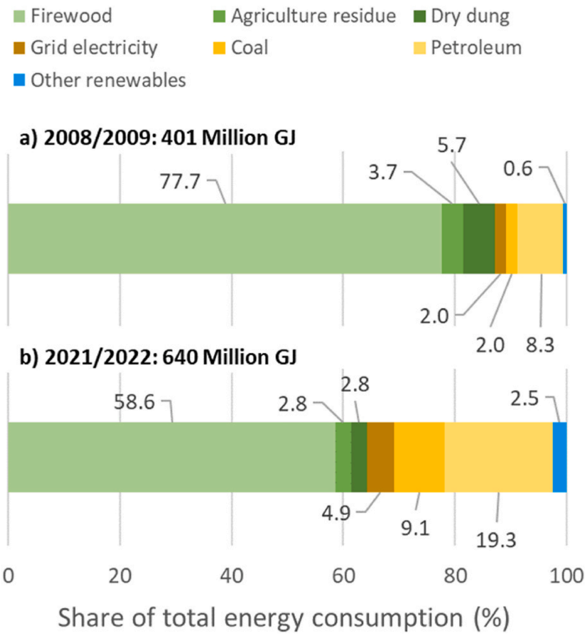

Fig. 3. Energy consumption of Nepal by fuel type for: a) 2008/2009 and b) 2021/2022; green, brown and blue shades indicate traditional, commercial and other small renewable sources respectively; magnitudes shown in bold at the top are the total annual energy consumptions in million GJ [Data source: WECS/GoN (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.)

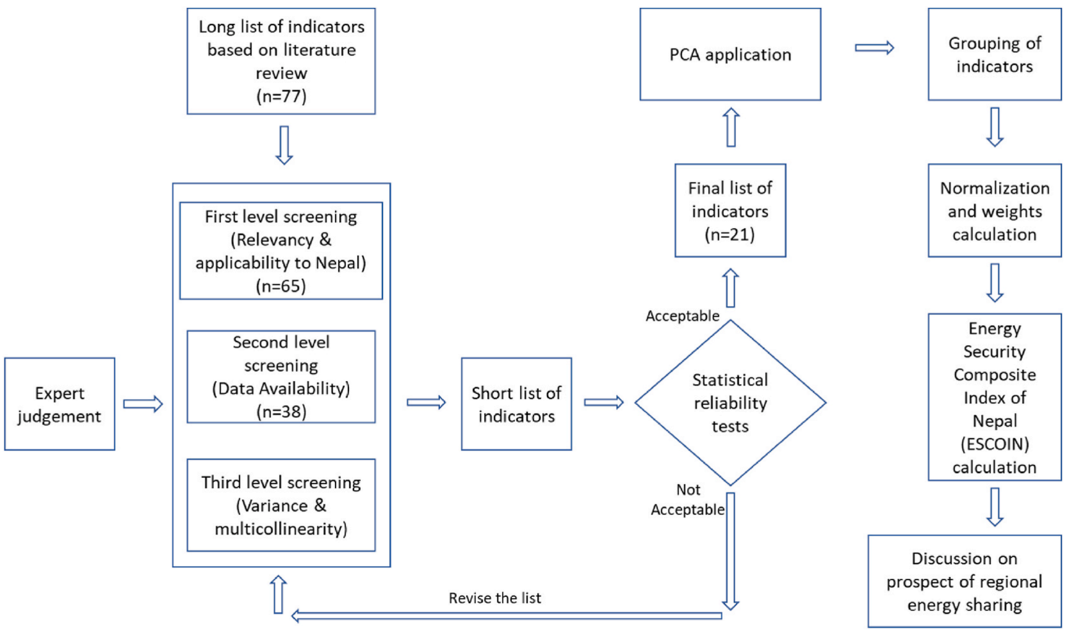

Fig. 4. Overall methodology adopted in this study.

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.

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

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

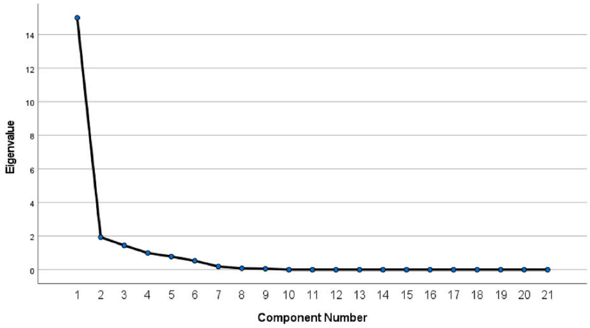

Fig. 5. Scree plot of the eigen values versus component number of PCA.

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.

$$w_k = \frac{V_k}{\sum V_k} \tag{4}$$

Where, w_k is the weighting factor of the kth component; V_k is the percentage variance of the kth 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,

$$y_{ij} = \frac{1}{y_{ij}} \text{ Else } y_{ij} = y_{ij} \tag{5}$$

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).

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

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).

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

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.

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

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

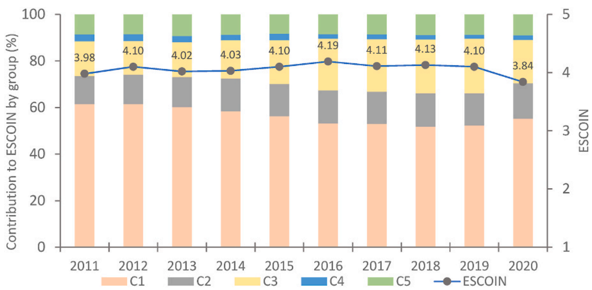

Fig. 6. Contribution of the respective components (C) on the *Energy Security Composite Index of Nepal (ESCOIN)* and its temporal trend during 2011–2020; contributions in % are plotted on the primary y-axis (left) while *ESCOIN* values (dimensionless) are plotted on the secondary y-axis (right).

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.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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.

Acknowledgements

The first author would like to thank the University of Southern Queensland (UniSQ), Australia for providing the UniSQ International PhD Scholarship to support him conduct this research. We are indebted to our colleague Dr. Thanveer Shaik for providing substantial inputs during the implementation of the PCA algorithm. We would also like to thank the anonymous reviewer for providing constructive feedback on our paper.

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

(*continued on next page*)

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	

(continued on next page)

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

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envdev.2024.101002.

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.