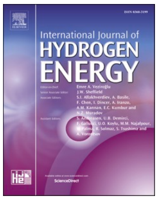
International Journal of Hydrogen Energy 71 (2024) 964–971

Contents lists available at ScienceDirect

International Journal of Hydrogen Energy

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



Unlocking potential in renewable energy curtailment for green ammonia production

M. Laimon [a], S. Goh [b,*]

[a] Department of Mechanical Engineering, Al-Hussein Bin Talal University, Ma'an, 71111, Jordan
[b] School of Engineering, University of Southern Queensland, Toowoomba, QLD, 4350, Australia

ARTICLE INFO

Handling Editor: Prof I Tolj

Keywords:
Solar power
Wind power
Capacity factor
Green hydrogen
Oxygen
Rare gases
Levelized cost
Hydrogen energy release optimizer

ABSTRACT

Renewable energy stands as a cornerstone for a sustainable future, yet it grapples with a significant obstacle: curtailment—deliberate energy generation reduction to avert grid overload. Curtailment not only squanders clean energy but also poses economic and environmental challenges. This study seeks to enhance the value of renewable energy by proposing a comprehensive methodology to evaluate and mitigate curtailment, with a particular focus on repurposing curtailed energy for ammonia production in Jordan, a pioneering nation in renewable energy adoption. The study unfolds several pivotal contributions to the field: (1) Incorporating curtailment in the capacity factor equation for the first time. (2) Exploring green ammonia potential in Jordan for the first time. (3) Investigating, for the first time, the effects of by-products (specifically oxygen and rare gases) on the investment in green hydrogen and ammonia, utilizing system dynamics (4) Outlining hydrogen applications and highlighting the breakthrough hydrogen energy release optimizer for combustion-free hydrogen extraction. In a scenario where curtailment is restrained (514.1 GWh/year), our findings unveil promising prospects: hydrogen and ammonia can be produced at levelized costs of 2.4 USD/kg and 600 USD/ton, respectively. More significantly, the integration of free energy (curtailed energy) and the synergistic utilization of oxygen and rare gases, notably argon, precipitate a remarkable cost reduction to 1.5 USD/kg and 401 USD/ton for hydrogen and ammonia production, respectively. This remarkable cost reduction underscores a substantial improvement, with the cost of ammonia being USD 219 lower than the average market price (USD 620). We advocate for the adoption of the hydrogen energy release optimizer and strategic utilization of by-products as pivotal strategies to significantly mitigate the costs associated with hydrogen and ammonia production, thereby amplifying the value and viability of renewable energy initiatives.

1. Introduction

In recent years, the global community has increasingly recognized the imperative of transitioning towards sustainable energy sources to mitigate climate change and ensure long-term environmental and economic viability [1,2]. At the forefront of this transition are renewable energy (RE) technologies. Integrating renewable energies into the existing energy infrastructure is crucial for achieving energy security, curbing greenhouse gas emissions, and stimulating economic development [3,4]. Many studies have explored the optimal design of RE systems integration, particularly focusing on wind and solar technologies [5–7]. However, transitioning to a RE-based system poses challenges, necessitating the resolution of intricate technical, economic, and policy considerations [8]. One of the key challenges in the integration of renewable energies is RE curtailment [9–11]. RE curtailment refers to the intentional reduction or elimination of RE generation to prevent overloading or damaging the power grid [12]. Understanding the background and significance of RE curtailment is essential in the context of transitioning to a sustainable and low-carbon future. RE sources, such as solar and wind power, play a crucial role in reducing greenhouse gas emissions and combating climate change. They offer the potential for clean and abundant energy generation. However, to ensure grid stability and reliability, energy grid operators sometimes curtail RE generation when there is excess supply or when the grid is unable to accommodate the fluctuating output. As a result, RE is being wasted or discarded. For instance, in Jordan, approximately 17% of wind energy alone goes to waste [13], and investors in RE do not receive compensation for such curtailments. This curtailment of RE not only results in wasted clean

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* Corresponding author.
E-mail address: Steven.Goh@unisq.edu.au (S. Goh).

https://doi.org/10.1016/j.ijhydene.2024.05.022
Received 14 January 2024; Received in revised form 3 April 2024; Accepted 3 May 2024
Available online 24 May 2024

energy resources but also poses economic and environmental challenges.

The economic impact of curtailment includes lost revenue for RE project owners and developers, as well as potential financial risks for investors. Curtailment also undermines the cost-effectiveness of RE systems, as the wasted energy reduces the overall efficiency and returns on investment. From an environmental perspective, curtailment hampers efforts to reduce carbon emissions. When RE generation is curtailed, it results in a higher dependence on conventional fossil fuel-based power plants, which in turn leads to an increase in the use of non-RE sources and the associated greenhouse gas emissions. Moreover, the curtailed energy represents a missed opportunity to replace electricity generation from fossil fuels.

The reasons for energy curtailment are complex and influenced by multiple factors [14] and stakeholders, such as grid constraints and transmission limitations [15,16], demand fluctuations [17,18], RE intermittency, regulatory requirements, and market dynamics [19]. Quantifying the specific causes and their contributions to curtailment requires coordination among various stakeholders. Accurately measuring and monitoring curtailed energy is technically challenging, often requiring specialized equipment and systems. Distinguishing between planned and unplanned curtailment and attributing curtailed energy to specific causes can be complex. Energy systems' intricacies, with their multiple generation sources, transmission lines, substations, and consumers, make it challenging to isolate and quantify curtailed energy accurately. System modeling and simulations may be necessary. Overall, accurate calculation of energy curtailment necessitates a comprehensive understanding of the energy system, access to relevant data, collaboration among stakeholders, and robust analytical techniques.

Recognizing the significance of RE curtailment, researchers and policymakers are actively exploring innovative strategies to minimize curtailment and maximize the utilization of RE resources. Previous efforts have primarily focused on demand-side management and conventional energy storage solutions, such as thermal storage, pumped hydro storage, and battery energy storage [13,20–22]. However, these solutions may not be suitable for certain countries, including Jordan, due to technical, economic, and energy density considerations, particularly concerning batteries. This is compounded by the high demand for batteries, especially in the context of electric vehicles. Moreover, there is a dearth of studies specifically investigating RE curtailment in Jordan. For example [13], conducted a study on wind energy curtailment in a single wind farm, uncovering a curtailment rate of 17% at that particular location. On the contrary, several studies [23–25] opt for intricate methodologies when evaluating RE curtailment. Additionally, the majority of these studies [13,26,27] focus on individual farms or specific types of RE, such as wind or solar, separately.

Given this research gap, the aim of the current study is to evaluate the total RE curtailment in Jordan by incorporating energy curtailment into the capacity factor equation for the first time. The study also aims to devise effective strategies to mitigate curtailment challenges. The focal point of the research is to explore the conversion of curtailed energy into hydrogen and ammonia, representing a notable area of study.

1.1. Hydrogen: a promising alternative

Hydrogen energy plays a pivotal role in bolstering energy security and facilitating the transition to RE, offering a zero-emission pathway while stimulating economic growth. It proves particularly advantageous for energy-intensive manufacturing sectors, power grids, long-distance transportation, gas networks, and chemical production, including ammonia [28]. Noteworthy is hydrogen's status as the most abundant element in the universe, characterized by efficiency, reliability, cleanliness, non-toxicity, and renewability. Boasting an exceptionally high-energy content, hydrogen provides nearly three times the energy of gasoline and natural gas, and almost seven times that of coal [29–31]. Hydrogen fuel cells exhibit significantly higher effective energy density compared to conventional energy sources. Compressed hydrogen, with an energy capacity of 40 kWh/kg, far surpasses the capabilities of lithium-ion batteries, currently considered the best for electric vehicle (EV) batteries, which achieve only 0.26 kWh/kg [32].

In Fig. 1, we delineate the applications of hydrogen, categorizing them into four main sections: H2E (hydrogen to electricity), H2H (hydrogen to heat), H2C (hydrogen to chemicals), and H2HC (hydrogen to hydrocarbon). The green color indicates that there is no practical alternative for hydrogen, while yellow indicates the presence of an alternative. One intriguing application for H2H is the Hydrogen Energy Release Optimizer (HERO). This marks a transformative juncture in hydrogen energy, as HERO attains temperatures exceeding 700 °C within minutes of hydrogen interacting with the catalyst, all achieved without combustion [33].

In recent years, the global focus on green hydrogen production has surged, driven by the pressing need to decarbonize energy systems and combat climate change [28,34,35]. Numerous green hydrogen production plants worldwide have emerged, showcasing innovative technologies to harness RE sources for hydrogen generation. For instance, the US government has introduced various incentives to expedite the transition to clean energy projects, including green hydrogen initiatives. Notably, a $7 billion grant in 2023 accelerated the deployment of green hydrogen technologies across seven regional hubs. Additionally, the 2022 Inflation Reduction Act (IRA) allocated approximately $369 billion to reduce costs associated with clean energy endeavors, with $9.5 billion specifically earmarked for clean hydrogen initiatives under the Bipartisan Infrastructure Law enacted in 2021. The Department of Energy's Hydrogen Program Plan, established in 2020, further supports these efforts by guiding research, development, and demonstration projects aimed at advancing hydrogen utilization across various sectors of the economy [36]. Similarly, in Europe, initiatives such as the European Hydrogen Backbone aim to connect hydrogen supply and demand across the region, integrating renewable energy sources and hydrogen imports [37]. As green hydrogen production costs decrease globally, exemplified by countries like Saudi Arabia, Chile, and Australia [36], these developments underscore the growing momentum towards a sustainable energy future.

1.2. Green hydrogen and ammonia production

Green hydrogen and ammonia are fundamental elements in sustainable energy, and their production plays a pivotal role in shaping the trajectory of clean and efficient energy systems. With growing demand for environmentally friendly alternatives, the methods and technologies employed in synthesizing hydrogen and ammonia have garnered heightened attention [38]. The conversion of hydrogen to ammonia is a well-established technology, and the rising interest in green ammonia as a stable and cost-effective means of storing and transporting hydrogen positions it as an effective driver for advancing the hydrogen economy [39–41]. Fig. 2 provides an illustrative overview of the processes involved in the production of hydrogen and ammonia.

Eighty percent of globally generated ammonia is utilized in fertilizer production, supporting approximately 50% of the world's food production [42]. Ammonia finds extensive applications in the chemical industry and various other industrial sectors [43]. Moreover, it plays a significant role in the energy sector, primarily as a key energy vector for hydrogen [40,44,45].

Many studies have investigated mitigating RE curtailment through hydrogen conversion, as evident in Refs. [46–50]. However, none of these studies have explored leveraging green ammonia production to alleviate power curtailment. While a few tangentially related studies have explored utilizing RE curtailment for ammonia production, as seen in Refs. [51,52], they have overlooked the potential impact of byproduct gases such as oxygen and rare gases (argon, neon, krypton and xenon) on the cost reduction of hydrogen and ammonia. A singular study [53] has

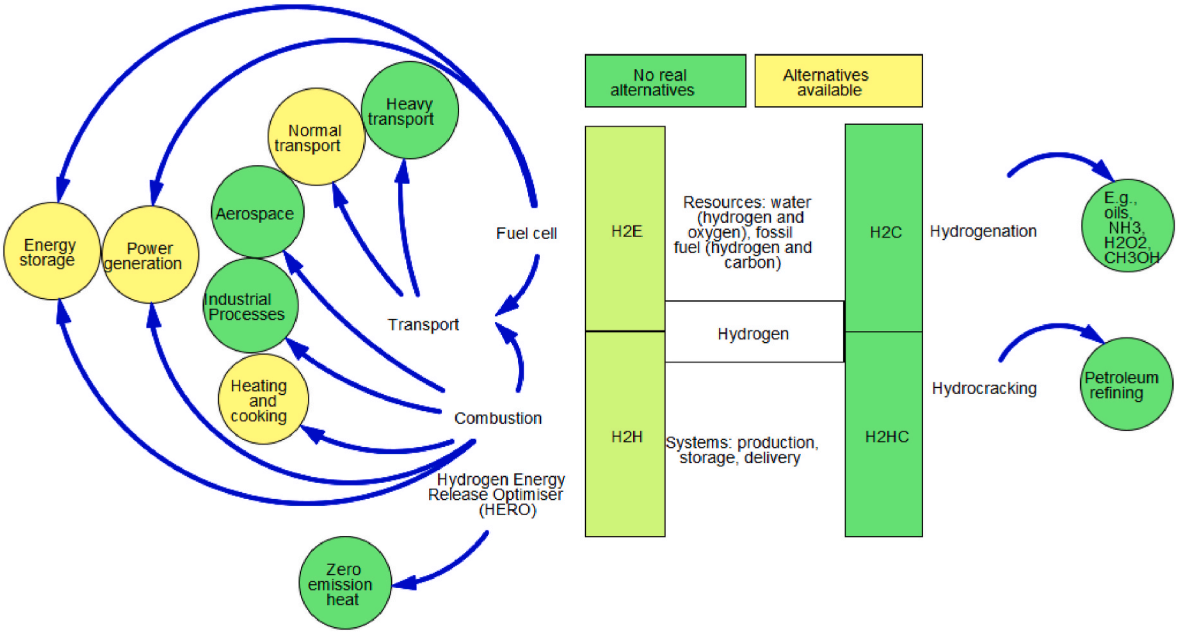

Fig. 1. Applications of hydrogen.

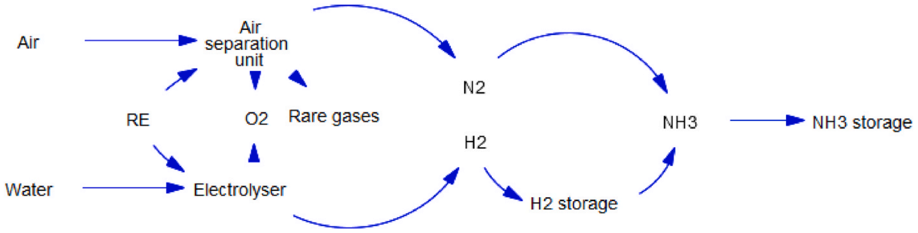

Fig. 2. The processes involved in hydrogen and ammonia production.

examined the impact on ammonia investment, focusing solely on oxygen and disregarding the consideration of rare gases. While widely used and in high demand, gases like oxygen find extensive applications, and argon, for instance, is crucially employed in substantial quantities for steel production, welding, laser technology, insulating windows, and various other sectors. Argon emerges as a viable substitute for helium [54]. Oxygen, indispensable across diverse industries, serves purposes ranging from medical support (e.g., breathing assistance) to industrial applications (e.g., metallurgy, welding, chemical production) and energy production [55]. Both oxygen and argon consistently face high demand, a trend not replicated by other gases like neon, krypton, and xenon. Furthermore, the supply of these rare gases may become critical [54].

2. Energy sector in Jordan

Jordan heavily depends on imported energy sources to meet its energy needs, with more than 95% of its energy coming from abroad [56]. The country possesses limited domestic fossil fuel resources, which necessitates significant imports of oil and natural gas. Despite this reliance on energy imports, the Jordanian government has demonstrated a strong commitment to achieving greater energy independence by focusing on RE development, energy efficiency measures, and diversification strategies. In line with these objectives, Jordan has actively promoted the development of RE sources as part of its efforts to diversify its energy mix, reduce reliance on fossil fuels, and mitigate climate change. As of 2022, RE accounts for approximately 29% of the country's electricity generation, mainly sourced from solar and wind power [57]. Fig. 3 provides a visual representation of RE projects in Jordan, showcasing the locations and distribution of these initiatives. Table 1 presents the capacity figures for wind and solar power installations in Jordan from 2018 to 2022, reflecting the growth and progress in the RE sector during that period. Overall, while Jordan remains dependent on energy imports, its strategic focus on RE development reflects a commitment to enhancing energy independence and reducing reliance on external sources.

3. Research method

The analysis methodology is structured into five primary sections: data, evaluation of curtailed energy, the proposed application, model validating, and policy design and evaluation. The first section focuses on discussing the data, followed by the calculation of RE curtailment using a new formula to include curtailed energy into the capacity factor formula. In the subsequent stage, the methodology presents a framework for converting the curtailed energy into hydrogen and explores its potential applications.

3.1. Data

The primary data utilized in this study has been obtained from the National Electric Power Company (NEPCO) [57]. Table 2 presents the electrical energy utilized by the company.

Net metering and wheeling have been excluded from the calculation due to their perceived minimal impact, falling beyond the study's scope, which concentrates primarily on large-scale projects rather than small

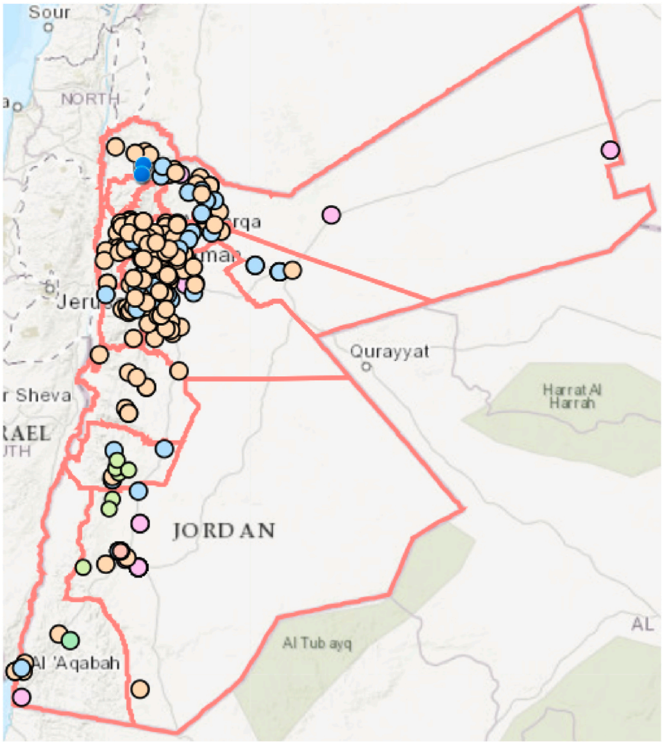

Fig. 3. RE projects map in Jordan [58].

Table 1
RE projects capacities [57].

Year	Wind Power (MW)	Solar Power (MW)	Total (MW)	Traditional	% to traditional
2018	280	449	729	4242	17.2
2019	369	637	1006	4242	23.7
2020	518	887	1405	4000	35.1
2021	622	938	1560	3977	39.2
2022	622	958	1580	4212	37.5

Table 2
RE electrical energy utilized.

	2018	2019	2020	2021	2022
Wind energy (GWh)	707	874.9	1378.8	1595.5	1748.2
Wind energy (MW)	280	369	518	622	622
Solar energy (GWh)	836.2	1341.2	1645.2	2162.6	2222.3
Solar energy (MW)	449	637	887	938	958

household units utilizing net metering systems. Moreover, a significant disparity exists in the capacity factors between household and large photovoltaic solar installations, influenced by various factors. Large-scale projects capitalize on economies of scale, advanced technologies, and strategic site selection to enhance sunlight exposure, resulting in higher capacity factors, reaching 36% in certain countries [59] and 32.2% in Jordan [60]. Conversely, household installations often depend on standard or less efficient solar panels, grapple with site-specific constraints like shading, and lack the professional maintenance and grid integration evident in utility-scale projects. Discrepancies in regulatory environments and incentives further accentuate this difference, with large-scale projects frequently benefiting from favorable policies and economic viability that may not be as pronounced at the residential level.

3.2. *Curtailment evaluation*

Curtailment plays a crucial role in influencing the capacity factor. However, in the calculation of the capacity factor, curtailed energy is not taken into account [61,62]. This omission stems from the fact that capacity factor calculations usually emphasize the energy delivered to the grid, excluding the total potential energy that could be generated but might face curtailment due to grid conditions or other factors. In order to tackle this problem, we suggest using the following formula.

$$\text{Capacity factor} = (\text{Actual energy output utilized} + \text{Curtailed energy})/\text{Maximum energy output} \quad (1)$$

Where “Actual energy output utilized” refers to the electricity successfully delivered to the grid or utilized. “Curtailed energy” refers to the amount of electricity intentionally reduced or not utilized due to grid constraints or other factors. “Maximum energy output” is the theoretical value that represents the upper limit of the power plant’s generation potential. A capacity factor of 36.1% is applied to wind energy based on the minimum and maximum capacity factors observed in Jordan’s wind turbines (ranging from 33.1% to 39.1%) [63]. For solar energy, a capacity factor of 30% is utilized for large PV systems.

3.3. *The proposed application: utilizing curtailment for ammonia production*

This section outlines an innovative approach to repurpose curtailed energy for ammonia production, transforming surplus energy— which would otherwise go underutilized— into a valuable resource for sustainable energy carriers like hydrogen and ammonia. By adopting this approach, we aim to contribute to a cleaner and more sustainable energy landscape, utilizing curtailment as a valuable asset in the pursuit of hydrogen and ammonia production as a clean and versatile fuel source. We use system dynamics (SD) approach to achieve the aims of the study. The SD approach is indispensable for understanding and addressing complex challenges. By modeling dynamic interactions and feedback loops within a system, this methodology enhances decision-making and policy formulation, with the ultimate goal of achieving sustainable and effective solutions [64].

The hydrogen requirement for the ammonia production plant is determined through stoichiometric calculations, as outlined in Equation (2) [65].

$$3H_2 + N_2 \rightarrow 2NH_3 \quad (2)$$

According to the balanced equation, 3 mol of hydrogen react to yield 2 mol of ammonia. The moles of ammonia produced from 1 kg of hydrogen can be calculated as follows: (1000 g)/(2 g/mol) = 500 mol. To adjust for the stoichiometric ratio specified in equation (2), we multiply by 2/3, resulting in approximately 333.33 mol of ammonia. Subsequently, the mass of ammonia produced is determined by multiplying the moles of ammonia by the molar mass (17 g/mol), resulting in approximately 5.67 kg. Therefore, from 1 kg of hydrogen, approximately 5.67 kg of ammonia is produced. A comprehensive set of details, including equations, units for all the model parameters, and references ([41,54,65,67,71–75]), is provided in Appendix A.

3.4. *Model validating*

The validation process SD models typically entails thorough assessments of both structure and behavior. Structural tests aim to guarantee the model accurately mirrors the real system, involving evaluations such as dependency and unit consistency tests, laws of conservation and accumulation tests, and negative stock tests. The confirmation of dependency and unit consistency relied on the software’s “dependency tracking” feature (Silico) [66], which scrutinizes relationships between parameters and their unit consistency. The laws of conservation and accumulation test requires that the stock's value equals the sum of inflows minus the sum of outflows, while the negative stock test ensures the stock cannot drop below zero. In terms of behavioral tests, the model should incorporate real or historical values for comparison with simulated values generated by the model. Unfortunately, actual historical values are unavailable as hydrogen and ammonia remain untapped in the Jordanian context.

3.5. Policy design and evaluation

Three possible scenarios for RE curtailment in Jordan have been developed for the period 2023–2030. These are (1) a no-change scenario, (2) a base case scenario, and (3) a likely-to-happen scenario. The no-change scenario envisions a situation where no alterations or interventions are made in the current conditions. The base case scenario represents a standard or reference situation against which other scenarios are evaluated. It often incorporates existing conditions and practices (current growth), providing a starting point for assessing the impact of changes or interventions. The likely-to-happen scenario anticipates a future state based on trends over the last five years (from 2018 to 2022).

3.6. Main parameters utilized in the model

Key parameters and variables crucial for the case study and model are listed in Table 3. A comprehensive set of details, encompassing equations and units for all the model parameters, is provided in Appendix A.

The acid polymer/proton exchange membrane (PEM) has been chosen for several compelling reasons: it is highly compatible with intermittent RE sources, showcases superior efficiency compared to alkaline electrolysers, requires minimal maintenance, ensures high hydrogen purity, exhibits remarkable durability, boasts a compact design, and is estimated to have the longest system lifetime, ranging from 20 to 30 years [41].

4. Results and discussion

The findings underscore a substantial level of curtailment, as illustrated in Table 4 and Fig. 4. In 2019, wind energy experienced the highest curtailment at 33%, reaching a low of 12.5% in 2022. Meanwhile, solar energy saw its peak curtailment at 42% in 2020, decreasing to a minimum of 13% in 2022. Cumulatively, these curtailments amount to a wasted energy total of 3280 GWh from 2018 to 2022. To provide context, this energy quantity would be sufficient to supply nearly 900,000 homes with free electricity, based on the average electricity consumption range of Jordanian households at around 10 kWh/day.

We have explored three scenarios for RE curtailment spanning from 2023 to 2030: the first scenario represents a “no-change” scenario, the second is the “base case” scenario, and the third is the “likely to happen” scenario. Our analysis indicates that under the first scenario, RE curtailment would reach 3085 GWh by 2030; for the second scenario, it would be 4834 GWh; and for the third scenario, it would be 6680 GWh, as depicted in Fig. 5. We adopt the first scenario as a conservative estimate.

Table 3
Parameters under consideration for the case study.

Parameter	Value	Unit	Ref.
Ammonia production cost	386	USD/ton	[41]
Transport cost	0.21	USD/ton-km	[41]
Distance	300	Km	
Storage cost	150	USD/ton	[41]
Ammonia production capacity	895	ton/day	
Average price of Ammonia	620	$	[41]
Electrolyzer capacity	58.69	MW	
Stack	635	USD/kW	[67]
Power electronics	159	USD/kW	[67]
Gas conditioning	107	USD/kW	[67]
Balance of plant	159	USD/kW	[67]
H_2 production energy consumption	50	kWh/kg	[67]
Efficiency	80	%	[67]

Table 4
RE capacities and curtailment from 2018 to 2022 in Jordan.

	2018	2019	2020	2021	2022
Wind energy (GWh)	707	874.9	1378.8	1595.5	1748.2
Wind energy (MW)	280	369	518	622	622
Curtailment for wind (GWh)	178.5	292	259	371	219
Curtailment for wind energy %	25	33	19	23	12.5
Solar energy (GWh)	836.2	1341.2	1645.2	2162.6	2222.3
Solar energy (MW)	449	637	887	938	958
Curtailment for solar energy (GWh)	344	333	686	302	295
Curtailment for solar energy %	40	25	42	14	13
Total curtailment (GWh)	522.5	625	945	673	514
Total curtailment %	34	28	31	18	13

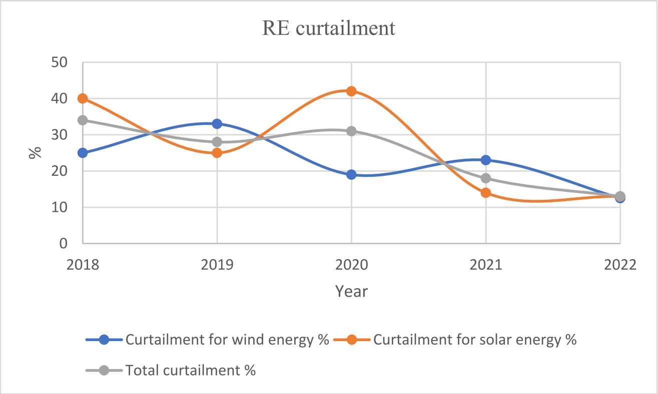

Fig. 4. RE curtailment percentages from 2018 to 2022 in Jordan.

In this scenario, with the given curtailment, the system dynamics model (Fig. 6) reveals that the levelized cost of ammonia (LCOA) and hydrogen (LCOH) is projected at 599 USD/ton and 2.4 USD/kg, respectively. These findings are in accordance with a recent study examining the feasibility of green hydrogen production in the Jordanian context [68]. Additionally align with [69] who investigated the production of green hydrogen and ammonia from solar and wind energy in various countries.

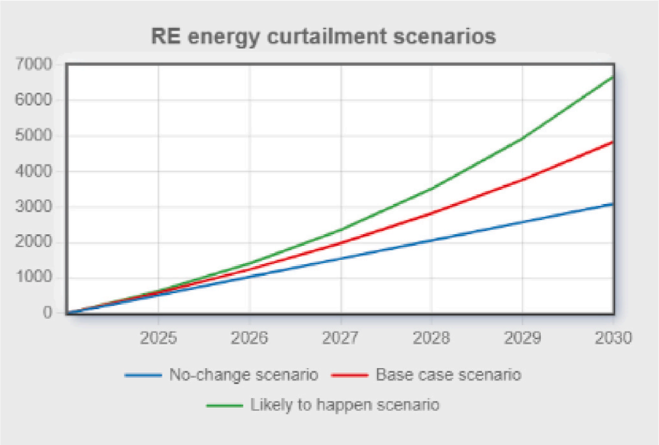

Fig. 5. RE energy curtailment scenarios.

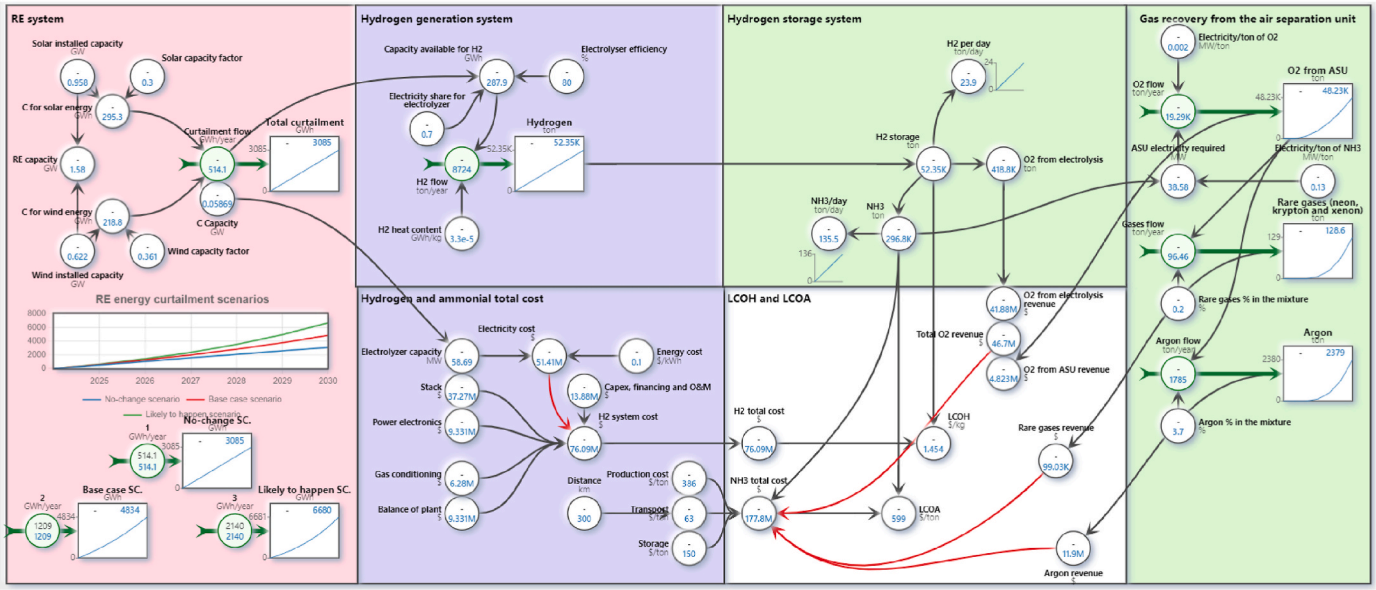

Fig. 6. Findings of the system dynamics model.

In the model, red lines denote variables not yet factored into the calculations. When considering free energy (curtailed energy) for the electrolyzer, the LCOH reduces to 1.5 USD/kg. The model also reveals intriguing findings for ammonia. Considering O_2 generated by the electrolyzer and the Air Separation Unit (ASU) reduces LCOA to 452 USD/ton [53]. found that incorporating oxygen could reduce the ammonia production price by 100 USD/ton; however, it was not clear whether the oxygen was generated by the electrolyzer or the ASU. Incorporating Argon further lowers it to 401 USD/ton. This represents a substantial decrease compared to the average ammonia price of 620 USD/ton. We have found that rare gases have nearly no effect. All these findings are summarized in Fig. 7.

The system dynamics model consists of six sections. The first section addresses RE systems to determine RE curtailment under different scenarios. The second section focuses on the hydrogen energy system to calculate the amount of hydrogen generated based on the capacity available from RE. The third section pertains to the hydrogen storage system, determining the quantity of hydrogen utilized for generating ammonia and oxygen through the electrolyzer. The fourth section is dedicated to gases recovery from the ASU, encompassing oxygen, argon, and rare gases (neon, krypton, and xenon). The fifth section assesses hydrogen and ammonia costs. Finally, the sixth section computes the LCOH and the LCOA. The model integrates all these sections along with their respective variables to provide a comprehensive overview. The model can also unveil several other significant findings. For instance, it indicates that the daily production of hydrogen and ammonia could potentially reach 24 tons/day and 136 tons/day, respectively, through the utilization of RE curtailment.

To achieve further cost reductions, alternative approaches can be considered to potentially replace gas turbines. Gas turbines play a pivotal role in ammonia production by facilitating the Haber-Bosch process, which is integral to ammonia synthesis. This process requires high temperatures, typically ranging between 300 and 500° ^{O}C, and high pressure [70], and it addresses the intermittency associated with RE sources. One viable alternative we propose is the implementation of the Hydrogen Energy Release Optimizer (HERO). This innovative solution utilizes on-site fuel, reaching temperatures of up to 700° ^{O}C within minutes without emissions or combustion. Adopting HERO offers the advantage of cost reduction by eliminating the reliance on fossil fuels and the need for pollution control measures [33].

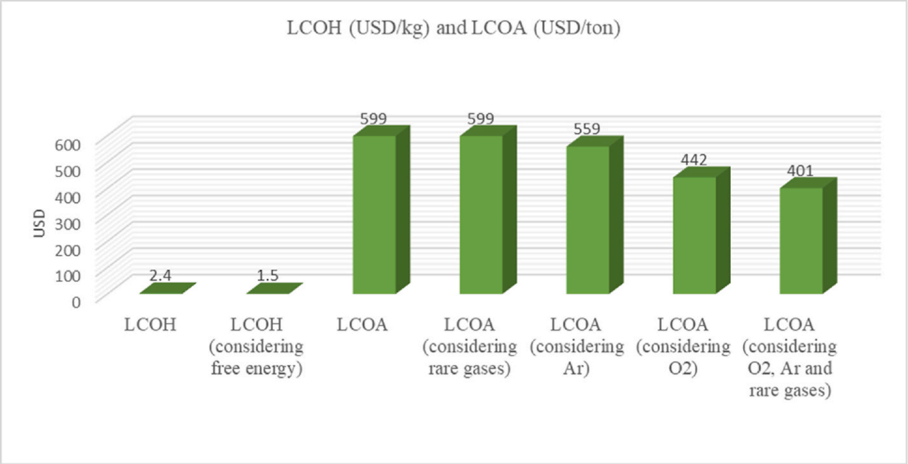

Fig. 7. LCOH and LCOA with different assumptions.

5. Conclusion

In summary, this study explored the pivotal domain of RE curtailment, presenting a novel methodology for assessment and mitigation with a specific focus on harnessing curtailed energy for ammonia production in Jordan, a country leading the way in the adoption of RE. Noteworthy contributions of this research include the pioneering incorporation of curtailment into the capacity factor equation, the exploration of Jordan's green ammonia potential, and the groundbreaking investigation into the impact of by-products, such as oxygen and rare gases, on green hydrogen and ammonia investments using a dynamic systems approach.

The findings from our conservative scenario, with RE curtailment capped at 514.1 GWh/year, provide valuable insights. The levelized costs for hydrogen and ammonia were estimated at 2.4 USD/kg and 600 USD/ton, respectively. More significantly, our study revealed that by integrating free energy (curtailed energy) and leveraging oxygen and rare gases, particularly argon, these costs could be dramatically reduced to 1.5 USD/kg and 401 USD/ton. This represents a substantial enhancement, with the cost of ammonia being USD 204 lower than the average market price of USD 620/ton.

Green hydrogen-derived ammonia production in Jordan offers numerous advantages. It has the potential to significantly reduce carbon emissions, bolstering efforts to combat climate change. Moreover, it enhances energy security by diversifying energy sources and promotes economic growth by nurturing a sustainable energy sector. However, there are important limitations to consider. This includes the need for substantial initial investment in infrastructure and technology, as well as potential intermittency issues with renewable energy sources. Additionally, robust policy frameworks and regulatory support are essential to incentivize private sector participation and ensure long-term viability. Despite these challenges, the development of green hydrogen-derived ammonia presents a promising opportunity for Jordan to align with global sustainability goals and transition towards a greener and more resilient energy future. In light of these findings and limitations, our recommendations advocate for the adoption of the hydrogen energy release optimizer over conventional gas turbines. Furthermore, the strategic utilization of by-products emerges as a pivotal strategy to substantially alleviate the economic and environmental burdens associated with hydrogen and ammonia production. By embracing these innovative approaches, we envision a transformative pathway toward sustainable and cost-effective green ammonia production, unlocking the untapped potential within RE curtailment.

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

M. Laimon: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Writing – original draft, Writing – review & editing. **S. Goh:** Writing – review & editing.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT in order to improve readability and language. After using this service, the authors reviewed and edited the content as needed and takes full responsibility for the content of the publication.

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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijhydene.2024.05.022.

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