Techno-Economic Analysis of Hydrogen and Ammonia Production in Isolated Microgrids for Sustainable Development

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1 Introduction

Isolated grids with access to natural gas can produce grey and green hydrogen and ammonia. This study presents innovative frameworks for implementing hybrid renewable energy systems (HRESs) that produce hydrogen and ammonia in isolated grids. The motivation behind using HRESs that use renewable and non-renewable energy sources for producing green and grey hydrogen is that it provides more reliability and affordability to isolated grids compared to renewable energy sources (Koohi-Fayeghand Rosen, 2020). We suggested using natural gas in the HRES because it is a part of the solution for achieving sustainable development, particularly in the global south countries because it is an affordable energy source and has lower pollution compared to oil and coal (Hamel, 2023). The primary objective of our study is to achieve cost-effectiveness and emissions reduction while maintaining reliability, resilience, and affordability.

Our thesis is structured around two primary case studies, delineated as follows:

The first case study: **Techno-economic and environmental analysis of heat source for SMR in isolated grids.**

Q1*: *What is the impact of SMR heat source for grey hydrogen production on HREs isolated microgrids cost and emissions?

The steam methane reforming process is the main method for industrial-scale grey hydrogen production due to its efficiency and ability to utilize readily available natural gas feedstocks. However, it produces carbon dioxide as a byproduct, making it a source of greenhouse gas emissions. Although the end use of grey hydrogen is carbon emission-free, the SMR process requires a high temperature to separate hydrogen from methane products; which contributes significantly to greenhouse gas emissions (Alhamdani et al., 2017; Sun et al., 2019). Some studies have indicated that the heat source for SMR contributes between 72% and 80% of total process emissions (Cetinkaya et al., 2012; Hajjaji et al., 2013; Hajjaji et al., 2016).

Existing studies have extensively investigated the thermodynamic and thermochemical technologies of heating sources for SMR, e.g., CHP (Le Corre et al., 2011; Dubinin et al., 2018). Concentrated solar thermal (Petrasch and Steinfeld, 2007; Calisan et al., 2019). More recent studies have discussed the advancements in broad SMR technologies (Pashchenko 2023; Wójcik et al., 2024; Esfandiary et al, 2024; Sheu et al., 2023). However, economic aspects, particularly in terms of the total cost of the entire system, including operation and investment costs over the project lifetime, have received less attention**.**

Hydrogen has been investigated in microgrids through various approaches. Yazdani et al. (2019) analyzed Power-to-Gas (P2G) technology from economic and environmental perspectives. Obara et al. (2011) and Jaramillo and Weidlich (2016) explored optimal hybrid renewable energy systems (HRES) that incorporate electrolysis. Lim et al. (2020) examined optimal HRES configurations involving electrolyzers and reformers. To the best of our knowledge, different methods for supplying heat, which is crucial for the endothermic process of SMR, have not been fully studied in isolated microgrids with HRESs.

This study undertakes an isolated grid supported by HRES, comprising PV, wind power generation, battery storage, microturbines, and steam reformer for producing grey hydrogen. Typically, the required heat is supplied using gas boiler and electric boiler technology. However, in this study, we propose additional implementation of the CHP boiler system and Hybrid boiler system. The gas boiler operates independently, supported by an external gas source, and remains disconnected from the isolated grid components. The CHP boiler system relies on an external gas source and a surplus heat generated by the microturbines. It is considered an extension of the gas boiler accompanied by microturbines. The hybrid boiler system represents a fusion of the CHP boiler system and the electric boiler system. The rationale behind suggesting the hybrid boiler system lies in avoiding the trade-off between cost and emissions. Relying on renewable energy to support the electric boiler might increase the costs while diminishing emissions. Conversely, relying on gas or the CHP boiler potentially decreases costs but elevates CO2 emissions. We developed a thermodynamic model to determine the necessary heat for SMR, and subsequently, we studied the impact of supporting heat using different mechanisms on the isolated grid NPC, CO2 emissions, optimal dispatch, and LCOH.

Our study's motivation is to understand the economic feasibility of decarbonization strategies. The choice of heat source can impact the environmental footprint of SMR. By studying different heat sources, including renewable options, it's possible to minimize greenhouse gas emissions and other environmental impacts associated with SMR operations.

The second case study: Economic feasibility of producing ammonia in isolated microgrids considering Seasonal gas price flexibility.

Q2: *Given two gas prices, what is the best way operation and configuration to produce ammonia in HRES-isolated grids?*

The study aims to explore the feasibility of producing grey and green ammonia in hybrid renewables isolated grids, considering seasonal gas price fluctuation.

Recent studies have explored the advancement of blue ammonia, investigating various SMR technologies, aiming to contribute to CO2 emission reduction and economic feasibility enhancement (Cloete et al., 2021; Pereira et al., 2022; Mattisson et al., 2018). Despite the environmental advantages associated with blue ammonia, widespread adoption has been hindered by economic and technological challenges. Grey ammonia continues to dominate the market (Abu Hasan et al., 2012). However, it has received relatively little research attention, particularly in terms of an integrated SMR-HB process (Mayer et al., 2023). Oh et al. (2024) conducted an economic evaluation of the feasibility of transitioning from grey to blue ammonia at varying carbon tax levels. On the other hand, previous studies in green ammonia focused on: The economic viability of a) Ammonia production considering: HB flexibility (Armijo and Philibert, 2020) and HB inflexibility (Osman et al., 2020); b) The best locations for producing ammonia (Kakavand et al., 2023; Fasihi et al., 2021); c) Minimizing LCOA (Salmon et al. (2021); d) Replacing diesel fuel with ammonia (Morgan et al., 2014).

Several studies have investigated the optimization of the HRES dispatch in isolated grids for minimization of NPC, or explored methods for producing green and grey hydrogen (Jaramillo and Weidlich, 2016; Abdin et al., 2019). However, the economic feasibility of ammonia production in isolated microgrids and mini-grids powered by HRESs remains unexplored, whereas previous studies have focused mainly on ammonia production in the context of conventional stations.

We consider two gas price scenarios representing off-peak and peak gas demand and evaluate three systems that have different ammonia storage operations. These systems aim to reduce gas procurement during peak demand periods and increase production and use storage during the off-peak demand season. We examine the impact of seasonal gas price fluctuations on the grid systems NPC and LCOA. This approach is potentially crucial for motivating changing operational strategies to improve economic viability. Furthermore, it helps to understand how changes in gas prices affect ammonia production in isolated grids to provide valuable insights for decision-making for the planning process. Overall, the study aims to identify configurations and operational strategies that maximize economic benefits and sustainability within hybrid renewable isolated grids. It appears to be motivated by the need to align grid operations and resource utilization with real-world conditions, such as seasonal variations in gas prices.

Our primary targets are isolated microgrids with access to diverse onshore natural gas resources to produce grey and green hydrogen and ammonia. However, s natural gas resources is challenging in isolated grids, so, we confine our model to specific applications and regions such as:

- Remote grids that use diesel generators and changed to natural gas after discoveries, for example, Barbosa et al. (2023) examined the use of natural gas in isolated microgrids in the Amazonas state in Brazil, where many isolated grids changed to natural gas after discoveries (Peyerl et al., 2022).
- Microgrids in suburban areas where microgrids operate as independent systems although they can be connected to the main grid (Delfino et al., 2018). Such suburban microgrids have greater access to natural gas infrastructure, such as gas pipelines.
- Gas flaring locations: for example: Bishnoi and Chaturvedi (2021, 2022) studied HRESs that utilized waste flare gas from onshore natural gas fields in Assam, India. Previous studies focused on the electric power supply; however, we can extend the work to include hydrogen and ammonia.
- More broadly in Sub-Saharan Africa region, where more than 621 million people live. Most of the power generation depends on diesel generators. This region has many challenges, such as 1) Reliability and resilience issues, because of the weak generation, transmission, and distribution infrastructure, and 2) having a vast agriculture area and importing most of their ammonia needs from other countries. In this case, most of the population is regarded as living in isolation, so the intervention by the government to apply large scale microgrids that rely on HRESs could supporting reliability and resilience and produce ammonia at affordable prices.

2 Methodology

First study

To address the research gaps and to have an understanding of the impact of the heat source of SMR on HRES isolated grids. This study conducted a techno-economic and environmental analysis of a hybrid renewable isolated microgrid with a steam reformer that produces grey hydrogen, supported by heat generated by different approaches. We consider an HRES comprising PVs, wind units, battery storage systems, microturbines, and steam reformers. Based on the thermodynamic models, heat for SMR is provided by four different approaches:

CHP; gas, and electric boiler systems; and a hybrid of these components. In our study, the CHP boiler system combines waste heat from a microturbine with heat from a gas boiler using natural gas. The electric boiler uses electricity generated by a PV system, wind turbine, and microturbine in a microgrid. In the hybrid boiler system, the CHP and electric boilers supply heat in tandem. We evaluated the impact of different thermal sources of SMR on the optimal configuration and sizing, NPC and CO_2 emissions of a hybrid renewable microgrid. To evaluate the impact on emissions, NPCs are compared with and without considering the CO_2 penalty cost (e.g., carbon tax payment) in the optimization. Using the HOMER Pro software, our models are applied to an isolated microgrid in East Owienat, Egypt, as a case study.

Second study

To address the research gaps and understand the impact of seasonal gas price fluctuation on ammonia production in hybrid renewable isolated grids. We conduct a techno-economic analysis of an isolated grid powered by HRES to produce grey and green ammonia. We considered the gas price flexibility by applying two prices, representing the peak and off-peak demand seasons. We adopt three systems that increase production, use storage during the off-peak demand, and reduce production during the peak demand. The first system stores grey ammonia, the second stores green, and the third stores grey and green ammonia. Using various values of the two gas prices we examine whether we need to resort to an electrolyzer supported by surplus energy for storing ammonia or increase the reformer capacity. The analysis considered two electrolyzer sizes of 3.2 MW (Case A) and 1.6 MW (Case B) to examine the results consistency. Additionally, we examine the potential benefits of the grid consumers and the gas producers' after applying the three systems. Our study could help in achieving better resource allocation and management. Using the HOMER Pro software, our models are applied to an isolated microgrid in East Owienat, Egypt, as a case study.

3 Results/Discussion

First study

Our main findings are as follows: (1) The CHP boiler system outperforms the other types of boilers in terms of NPC. In particular, the NPCs of the CHP boiler are lower than those of the electric boiler by 16.2% and 13.6% without and with a CO_2 penalty cost in the optimization, respectively. (2) In contrast, the CO_2 emissions from the CHP boiler are greater than those from the electric boiler by 11.2% and 8.9% without and with a CO_2 penalty cost, respectively. (3)

The CO_2 penalty cost has an asymmetric impact on the sizes of the PV and wind units; that is, it incentivizes more PV units than wind units. (4) The LCOH ranges from 2.1 to 2.8 $/kg. Specifically, the LCOH is the lowest for the CHP boiler, whereas it is the highest for the electric boiler.

One may think that the CHP boiler system faces a trade-off between the NPC and CO_2 emissions. However, we emphasize that the overall NPC in our study considers the CO_2 penalty cost as a monetized environmental impact. Thus, the CHP boiler system for SMR in microgrids outperforms other boiler options, even when the impact of CO_2 emissions is considered. This study provides practical insights into the approaches for supplying heat to the SMR process in isolated microgrids. Furthermore, our approach is applicable to more general microgrids, spanning from rural to suburban areas that have access to diverse types of natural gas resources.

Finally, we mention the limitations of this study. Our focus was on SMR, while there are other emerging technologies for hydrogen production, such as electrolysis. The combination of SMR and electrolysis to produce hydrogen in a hybrid renewable isolated microgrid is another direction for future research. We investigated four available and representative heat source options for the SMR process. However, this study did not encompass all the aspects of boiler technologies and heat sources. Future work should aim to explore other heat sources, such as concentrated solar power.

Second study

Our key findings are as follows:

Using 3.2 MW electrolyzer (CaseA)

1) At a fixed gas price, relying on the reformer for ammonia production was more favorable than adding an electrolyzer.
2) At a low-price difference (0.3, 0.5) relying on the electrolyzer supported by excess energy in the system 2 for storing ammonia is better than increasing the reformer capacity.
3) As the gas price difference increased (0.2, 0.6) better to use an electrolyzer and increase the reformer capacity in system 3.
4) Further increases in price difference (0.1, 0.7) favored to increasing the reformer capacity and eliminating the electrolyzer in system 1.

Using 1.6 MW electrolyzer (CaseB)

1) Adding the electrolyzer was preferable at a fixed gas price.

2) For price differences of (0.3, 0.5) and (0.2, 0.6), similar results were observed as that with the 3.2 MW electrolyzer,
3) For a higher price difference (0.1, 0.7) favored System 3, with the electrolyzer's presence, while to eliminate the electrolyzer such as case A further increase in the price difference is required.

On the other hand, during peak demand, relying on System 1, System 2, and System 3 reduces gas volume by 2,022,160, 182,398, and 1,838,952 m3 for Case A, and by 2,022,160, 115,262, and 1,906,898 $/m3 for Case B.

All in all, adjusting the grid's seasonal systems in response to fluctuating gas prices appears to be a favorable approach. Lower gas prices during periods of low demand may encourage grid operators to increase production and use storage, taking advantage of cost savings. On the other hand, during peak periods when gas demand falls, this adaptive strategy may allow for more efficient resource allocation and management.

The limitation of this study is that considers two gas prices, but in certain regions, there may be multiple peak gas demand seasons. Therefore, future investigations should explore more than two gas prices so as to capture a broader range of market dynamics and variations in gas demand.

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