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Discussion Paper

The Cost of Green Hydrogen Production in Saudi Arabia and Germany: A Model-Based Approach

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Summary

With over seventy countries setting net-zero commitments by or around mid-century, low-carbon hydrogen is expected to play a pivotal role in the decarbonization of the global economy, especially in sectors that are less dependent on electricity, often termed hard-to-abate industries. Unlike most fossil fuels, H_2 does not produce greenhouse gas emissions when burned. Instead, it yields water, making it a suitable substitute for fossil fuels, especially in hard-to-abate sectors such as steel and cement. However, to effectively decarbonize end uses, the source of H_2 production must also be free from any associated carbon footprint. H_2 produced from water electrolysis using renewable energy (RE) can fulfill this criterion, thereby earning it the name "green H_2."

This paper assesses the competitiveness of producing green H_2 in Saudi Arabia and Germany using a power-to-carrier modeling framework in PLEXOS. The only constraint provided in the model is the amount of green H_2 to be produced annually. The model, running on an hourly temporal resolution, then (i) optimizes for the electrolyzer technology (alkaline, proton exchange membrane (PEM) or solid oxide electrolyzer cell (SOEC)), (ii) the capacity of the electrolyzer to be built and (iii) the optimal carbon-free energy mix. The significant findings from the analysis are highlighted below:

- To produce 600 tons of green hydrogen per day in 2030, solar-based hydrogen production in Saudi Arabia will require ~25% fewer investments than wind-based H_2 production in Germany. The need for fewer investments is influenced by the higher values of solar radiation observed in most parts of Saudi Arabia, making solar photovoltaics (PVs) a more cost-effective option for H_2 production than wind.
- Despite the high efficiency of solid oxide electrolyzers, alkaline electrolyzers dominate the production process due to their lower capital expenditure (CAPEX) requirements. Similarly, building battery storage to fully utilize the available RE generation will increase the overall investment needs without any meaningful gains in H_2 production. As a result, whenever RE generation is more than needed to produce the required quality of green H_2, the model chooses to dump energy rather than build battery storage in Saudi Arabia and Germany.
- The levelized cost of hydrogen (LCOH) produced from locally available RE resources is lower in Saudi Arabia. It ranges from $2.34 to $3.08 per kilogram in Saudi Arabia, compared to $3.06-$3.69 per kilogram in Germany. Assuming that the shipping and reconversion cost of $1/kg of H_2 equivalent in the form of ammonia is achieved by 2030, green H_2 from Saudi Arabia could still be delivered to Germany with relative competitiveness.
- Increasing electrolyzer efficiencies decreased costs between $0.40 and $0.60/kgH$_2$. These findings underscore the pivotal role that advancing electrolyzer technologies will play in cost reduction in the years to come.
- Variations in the cost of financing assumptions can significantly alter the economics of green H_2 production and trade. The findings suggest that the financing costs in Saudi Arabia are lower by at least 200 basis points than those in Germany. Even when considering shipping costs, Saudi Arabia will have a lower LCOH than Germany in all scenarios.

1. Introduction

In recent years, low-carbon H_2, including green H_2, has emerged as a strong contender for reaching climate neutrality goals. With the growing acceptance of the role of H_2 role in the energy transition toward a more sustainable future, 44 countries have rolled out an H_2 strategy, and 11 aim to produce ~20 million tons per year of H_2 by 2030 (Bloomberg NEF 2023). Moreover, the European Union has targeted the production of 10 Mt of green H_2 by 2030 and the import of another 10 Mt (European Commission 2022).

H_2 energy is also actively pursued by several countries in the Gulf Cooperation Council (GCC) or the Middle East and North Africa region. The following are the three common drivers for the adoption of H_2 energy by these countries:

1. Diversification of the energy supply: As countries in the region have vast solar and wind potential, there is a growing desire to diversify the energy supply using nonhydrocarbon resources.
2. Decarbonization of energy and industrial systems: H_2 energy is an important enabler for accelerating energy and industry transitions.
3. Monetization of the energy transition: With the attractive low-cost and low-carbon potential of H_2, several countries aim to develop a local H_2 industry for exporting green and blue H_2 to other potential markets.

Saudi Arabia ranks sixth in solar energy potential and 13th in onshore wind energy resources worldwide (Shell Global 2023). Therefore, it is uniquely situated to produce renewable H_2 for local use and export. As the country is aiming to tap into the emerging opportunities for the export of H_2 (or its derivatives) to other potential markets, it is important to accurately assess the cost of producing and exporting green H_2 to target destinations. This study examines the cost competitiveness of Saudi Arabia's green H_2 for a potential market, Germany, compared with H_2 produced locally in Germany.

The cost of H_2 production from renewables is higher than that of H_2 production from fossil fuels. A recent IEA (2021) study found that, at present, producing H_2 from fossil fuels is the most cost-effective option in most parts of the world. Depending on regional gas prices, the levelized cost of hydrogen (LCOH) from natural gas ranges from \$0.50 to \$1.70 per kilogram. In contrast, renewable electricity-based green H_2 will cost more, often \$3 to \$8 per kilogram. Growing aspirations to achieve net-zero policy goals will create opportunities for green H_2 production and transport from renewable resource-rich countries to countries with a high green H_2 demand.

The following three sections are organized as follows. Section 2 provides an overview of the growing literature on hydrogen production cost modeling. The methodological approach, model boundaries and parameters used to determine the LCOH and investment needs are discussed in Section 3, and the assumptions are explained and described in Section 4. The model results are presented in Section 5. Finally, Section 6 presents the key conclusions and policy recommendations.

2. Literature Review

Studies on the economic feasibility of producing green H_2 often consider renewables coupled with proton exchange membrane (PEM) electrolyzers. Rezaei et al. (2022) examined a generalized case in which a photovoltaic (PV) array directly linked to a PEM. By varying the sensitivity of different factors, the study estimated the LCOH at approximately $5.27/kg. Atlam et al. (2011), Barbir (2005) and Sayedin et al. (2016) employed a similar PV-electrolyzer approach, where the PV array's maximum power point closely followed the electrolyzer's polarization curve. Atlam et al. (2011) reported that optimizing an electrolyzer system for a higher operating temperature of the PV system results in improved overall system efficiency and a greater rate of H_2 generation.

An electrolyzer can be dimensioned to absorb all the power generated by a PV array. However, doing so would result in it functioning with the same capacity factor as the PV array, which is contingent upon sunlight availability. A more cost-effective alternative proposed by Barbir (2005) involves sizing the electrolyzer for a lower power output than the maximum capacity of the PV system. In such a scenario, some PV-generated power may remain unused or be stored in batteries, but the electrolyzer would operate with a higher capacity factor.

Nasser and Hassan (2023) examined the H_2 yield in Assiut, Egypt, using multiple scenarios, including one involving solar and wind-based H_2 systems to drive the PEM and solid oxide electrolyzer cells (SOECs). Utilizing solar power coupled with a PEM electrolyzer resulted in an LCOH of $4.19/kg$H_2$, which increased to $6.45/kg$H_2$ when the SOEC electrolyzer was selected. The figures for wind-power-based H_2 production are twice as high for both electrolyzers.

Touili et al. (2018) conducted a techno-economic analysis of H_2 production from solar energy at 76 sites in Morocco. Using mathematical modeling, the study estimated that the cost of H_2 production is between $4.64 and $5.79/kg$H_2$.

Fragiacomo and Genovese (2020) conducted a techno-economic assessment of green H_2 production at three sites in Italy with three different renewable sources (solar, wind and geothermal). The chosen simulated PEM electrolyzer exhibited a different specific power consumption at each site. The facility powered by wind energy resulted in the best business case, with an LCOH of $7.40/kg$H_2$.

Burdack et al. (2023) conducted a techno-economic assessment of H_2 production and export from Colombia to Europe and Asia, employing open-source Python tools. The projected prices are $1.50 and $1.02/kg$H_2$ for 2030 and 2050, respectively, when utilizing wind power, while solar energy may yield prices of $3.24 and $1.65/kg$H_2$ for 2030 and 2050, respectively. Accounting for transportation costs, the landed LCOH from Colombia to Europe is approximately $3.10/kg$H_2$, while it is $3.40/kg$H_2$ to Japan and $3.50/kg$H_2$ to China by 2030.

Kakavand et al. (2023) performed a comprehensive technical and economic assessment of potential green H_2 and ammonia production plants located in various regions of Iran. They developed a model for a large-scale H_2 production plant utilizing PEM electrolyzers using the HOMER Pro simulation platform. Their findings showed that when surplus electricity can be sold to the national grid, the LCOH becomes 5%-12% more cost effective. In such a scenario, the LCOH is estimated to be between $2.94 and $5.16/kg$H_2$.

Hinkley et al. (2022) explored exporting H_2 from New Zealand, emphasizing the advantages of ammonia as an energy transport due to its comparable energy content on a lower heating value basis than liquid H_2. However, the case for ammonia becomes less compelling if it must be reconverted into H_2. Similarly, Borsboom-Hanson et al. (2022) developed a model capable of calculating transportation costs for various methods, encompassing both land and sea scenarios. Their findings revealed that for large-scale and long-distance H_2 transport, pipelines prove to be the most efficient option for gaseous H_2 transport.

Ishimoto et al. (2020) examined and compared liquefied H_2 and ammonia as H_2-based energy carriers in terms of energy efficiency, the CO_2 footprint and cost. The analysis showed that the levelized H_2 costs are comparable between liquefied H_2 and ammonia when they are transported from Norway to Tokyo, covering a distance of 23,407 km. However, in the case involving transport to Rotterdam, covering a distance of 2,539 km, liquefied H_2 proves to have a lower LCOH than ammonia. Notably, there is no commercial-scale liquefied H_2 carrier on the market.

Zhang et al. (2022) evaluated blue and green H_2 imports from Saudi Arabia to Huizhou, China, utilizing methyl cyclohexane-toluene (MCH-TOL) H_2 storage technology. Blue H_2 is produced from natural gas in combination with carbon capture and storage and green H_2 from RE sources. The findings indicate that the costs associated with dehydrogenation and purification post-landing are challenging in terms of competitiveness, amounting to \$3.78/kgH_2 and \$4.48/kgH_2, respectively. Consequently, these authors recommended an active approach to developing the H_2 import business within their country. Interestingly, they found that scale has a significant impact on the cost of H_2 imports. For example, when importing 100,000 tons per year, the costs can be reduced by more than 60% compared to importing 10,000 tons per year. This finding highlights the potential for increased competitiveness in large-scale and commercial H_2 imports.

Gandhi et al. (2022) conducted a study exploring the potential of green H_2 in the United Arab Emirates by employing an integrated adoption model. They evaluated various scenarios, including global trends and local capabilities. Their analysis yielded an estimated LCOH ranging from \$0.79/kgH_2 to \$1.94/kgH_2 in 2030.

One of the most significant challenges in achieving green H_2 production is the financial burden linked to electrolyzer investments. Reksten et al. (2022) presented a comprehensive technology cost assessment and provided an outlook for 2030, encompassing both alkaline and PEM electrolyzers. Their analysis forecasts a substantial reduction in the capital expenditure (CAPEX) gap between these technologies, particularly within the 1-10 megawatt range. However, anticipations suggest only modest cost reductions beyond this range, with CAPEX values converging at \$320-\$400/kW for large-scale plants by 2030. The study estimates the learning rates for both alkaline and PEM electrolyzers at 25%-30%.

While many studies have focused primarily on H_2 production, storage, transport and utilization, they have often overlooked the crucial role of ports as key hubs in supply chains. Chen et al. (2023) focused on assessing the preparedness of ports for the impending H_2 international trade. Their analysis identified 20 potential early ports that could serve as pioneers in the emerging H_2 trade landscape. Among them, 12 are designated as exporting ports, which include the Port of Yanbu in Saudi Arabia, while eight are categorized as importing ports, including the Port of Wilhelmshaven in Germany. The authors observe that the preparedness of ports for H_2 international trade is still at an early stage of development and that there is a need for further efforts in infrastructure construction or renovation, risk management strategies, the establishment of regulations and standards, and education and training. Importantly, in our analysis, we specifically designated the northwestern region of Saudi Arabia as the exporting port and the Port of Wilhelmshaven in Germany as the importing port.

Finally, the literature review reveals several key gaps in existing research. First, the majority of papers in this field have focused predominantly on PEM technology. To address this limitation, our study broadens its scope by considering a more comprehensive range of H_2 production technologies. Additionally, while many papers have primarily emphasized the use of PV systems, this study incorporates concentrating solar power (CSP), wind power and battery storage. Moreover, we encompass a range of variations related to RE resources, electrolyzer technologies and the weighted average cost of capital (WACC). Finally, an examination of transport and export dynamics has been notably lacking in most prior works. To provide a comprehensive analysis, this aspect is a vital component of our research.

3. Methodology

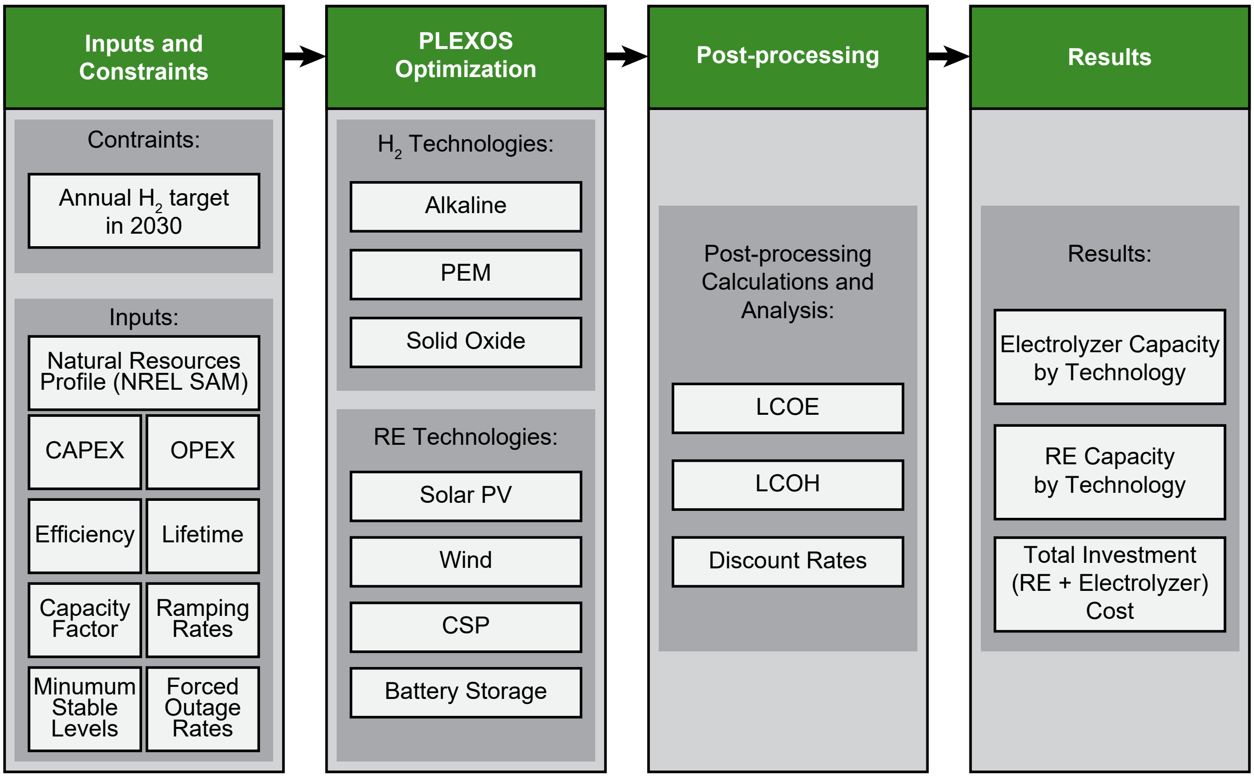
In this study, the production of green H_2 is analyzed through a capacity expansion optimization modeling exercise for two locations: Saudi Arabia and Germany. The capacity expansion model used in this study considers various factors to suggest the most cost-effective combination of H_2 production technologies and RE sources. While the hydrogen demand target and the generation profile of renewable resources are provided as exogenous inputs to the model, the cost of H_2 production is computed externally from the model run results.

This study considers a localized RE portfolio for the production of green H_2 in Saudi Arabia and Germany. Solar PVs, wind and CSP are included as potential RE sources for producing green electricity. Electricity storage batteries are considered an option in the generation mix. The model considered three types of electrolyzers: PEM, alkaline and solid oxide. The results of the model provide insight into the LCOH production in Saudi Arabia and Germany. Considering the likely H_2 shipping costs, these results are then compared to estimate the competitiveness of green H_2 exported from Saudi Arabia to Germany. The analysis assumes that production will occur in 2030.

The optimization model was built in the commercially available software PLEXOS, which can simulate power system operations to meet a predetermined load. The load in this study is the amount of green H_2 required, which serves as an input to the model and as our only constraint. For our purposes, we choose an annual H_2 production target of 0.213 million tons of H_2 per year by 2030. This number is considered reasonable because it aligns with the announced production capacity of NEOM, which is ~600 tons per day (ACWA Power 2022). While the required builds will scale higher (lower) with an increased (decreased) target, the overall insights provided by this paper would still apply without loss of generality.

The natural resource profiles were chosen for the northwestern region of Saudi Arabia and Wilhelmshaven, a port city on the North Sea coast of Germany. Wilhelmshaven is considered a major hub for trade and a potential hub for the import of H_2. The modeling flow is summarized in Figure 1.

Figure 1. Model boundaries and parameters.



Source: Authors.

The model outputs are in the form of total investments required for electrolyzers, RE and battery storage to support the assumed hydrogen needs in 2030 (i.e., 0.213 Mt). Based on these results, a discounted cashflow method is used to determine the LCOH (including renewable supply) via post-processing.

4. Study Assumptions

In this study, we established certain characteristics of electrolyzers and renewables as fixed assumptions while allowing others to vary for 2030 in all the scenarios. The cost and technical assumptions associated with the power generation technologies used in this study are summarized in Table 1; the electrolyzer assumptions are included in Table 2. We vary the natural resource profile (high and low with a 10% difference), the efficiency of the electrolyzers (high and low) and the minimum stable levels (MSLs) (high and low), as shown in Table 3, and simulate eight scenarios for each country, resulting in a total of sixteen scenarios (Table 4).

Table 1. PV, wind, CSP and battery assumptions.

Parameter*	Technology				
	PV	Wind	CSP	1-hour battery	4-hour battery
CAPEX in 2030 ($/kW)	555	992	3,159	340	1,360
O&M charge ($/kW/year)	10	40	30	20	80
WACC (%)	5	5	5	5	5
Economic life (Year)	25	25	25	10	10
Forced outage rate (FOR) (%)	15	50	15	–	–

Notes:

** Note that the assumptions are for 2030.*

Sources: Authors, based on Elshurafa et al. (2021), IEA (2022c), IRENA (2021) and Bloomberg NEF (2023).

To estimate the LCOH, this study uses CAPEX values of $700/kW, $1,450/kW and $3,000/kW for alkaline, PEM and solid oxide electrolyzers, respectively, as projected by the International Energy Agency/ International Renewable Energy Agency (IEA/IRENA) for 2030. Additionally, an annual operation and maintenance (O&M) cost of 1.5% of the total project cost is considered for alkaline and solid oxide electrolyzers, while 2.5% is considered for PEM electrolyzers (U.S. DOE 2014b).

A specific water consumption rate of 9 liters per kilogram of H_2 production is assumed for all the electrolyzer technologies, in line with the IEA/IRENA assumptions.

A FOR of 10% is assumed for PEM electrolyzers, and 15% is assumed for alkaline and solid oxide electrolyzers. Furthermore, the unit size for each alkaline electrolyzer is restricted to a maximum capacity of 10 MW (Asahi Kasei 2018) or 20 MW for PEM electrolyzers (Collins 2021). Finally, solid oxide electrolyzer units have a capacity of 4 MW (Hydrogen Tech World 2023), as shown in Table 2.

Table 2. Alkaline, PEM and solid oxide assumptions.

Parameter*	Technology		
	Alkaline	PEM	Solid oxide
CAPEX in 2030 ($/kW)	700	1,450	3,000
O&M charge (% of CAPEX)	1.5	2.5	1.5
Water consumption (L/kg)	9	9	9
One unit capacity (MW)	10	20	4
Forced outage rate (%)	15	10	15

Notes:

** Note that the assumptions are for 2030.*

Sources: Authors, based on IEA 2022c, IRENA 2021, U.S. DOE 2014b, Nel ASA 2023, Hydrogen Tech World 2023, Guan et al. 2014, Asahi Kasei 2018 and Collins 2021.

The efficiency and MSLs[1] of electrolyzers and the generation profile of renewable sources further vary within lower and higher values to make our results more accurate and to make them better reflect local conditions. While the first value represents the normal case, the second value represents the best case (or the optimistic case). Therefore, we have a total of eight different scenarios based on these three variables (Table 3).

The efficiency varies between 65% and 75% for alkaline electrolyzers and 80% to 85% for PEM electrolyzers based on the 2030 projections of the IEA (2022) and IRENA. Solid oxide electrolyzers can operate at higher temperatures, making them more efficient than other types. German steel group Salzgitter AG reached an efficiency of 84% for its H_2 project using solid oxide electrolysis technology (Hydrogen Tech World 2022). Therefore, the efficiency of solid oxide electrolyzers varies between 84% and 90% (Guan et al. 2014; U.S. DOE 2014a) in our scenarios. For the MSL, the percentages range between 12% and 15% for alkaline and solid oxide electrolyzers and between 8% and 10% for PEM electrolyzers (Nel ASA 2023; Wulf et al. 2020), as shown in Table 3.

[1] The minimum stable level (MSL) refers to the minimum operating level of an electrolyzer required to maintain stable and efficient electrolysis processes. This level is expressed as a percentage of the electrolyzer's capacity.

Table 3. The variable assumptions.

Parameter	Technology				
	Alkaline	PEM	Solid oxide	Solar resource	Wind resource
Efficiency (%)	65–75	80–85	84–90	–	–
Minimum stable level (%)	12–15	8–10	12–15	–	–
Generation profile	–	–	–	Low and high	Low and high

Notes:

Source: Authors, based on IEA 2022c, IRENA 2021, Hydrogen Tech World 2022, U.S. DOE 2014a and Wulf et al. 2020.

The variable parameters in Table 3 above create eight different scenarios for each country, as shown in Table 4, beginning with the first scenario, which presents a pessimistic outlook for all three variables: generation profiles, efficiencies and the MSL. The second scenario adopts an optimistic view of only the generation profiles, while the third scenario is optimistic about only efficiency. The fourth scenario combines optimistic assumptions for both efficiency and generation profiles. The fifth scenario is optimistic about only the MSL, while the sixth scenario incorporates optimistic assumptions for both the MSL and generation profiles. The seventh scenario explores the MSL-efficiency combination. Finally, the last scenario encompasses an optimistic outlook for all three variables.

In addition to the capital costs, fuel costs, fixed and variable O&M costs and the assumed utilization rate for each plant type (in this case, electrolyzers and RE power), financing costs form an important input for calculating the levelized cost of energy (LCOE)/LCOH. This study assumes a discount rate of 5% as a representative WACC for both Germany and Saudi Arabia throughout the cost calculations and analysis (Elshurafa et al. 2021). This assumption enables a fair comparison between the costs of H_2 production in both countries over the entire project period. However, to examine the impact of the discount rate on the competitiveness of H_2, we conduct a sensitivity analysis with the discount rate varying from 1% to 10%, in steps of 1%.

Table 4. All eight scenarios for Saudi Arabia and Germany.

Scenario	Natural resource	Electrolyzer technology*	Electrolyzer efficiency (%)	Electrolyzer minimum stable level (%)
1	Low	ALK	65	15
		PEM	80	10
		OXD	84	15
2	High	ALK	65	15
		PEM	80	10
		OXD	84	15
3	Low	ALK	75	15
		PEM	85	10
		OXD	90	15
4	High	ALK	75	15
		PEM	85	10
		OXD	90	15
5	Low	ALK	65	12
		PEM	80	8
		OXD	84	12
6	High	ALK	65	12
		PEM	80	8
		OXD	84	12
7	Low	ALK	75	12
		PEM	85	8
		OXD	90	12
8	High	ALK	75	12
		PEM	85	8
		OXD	90	12

Notes:

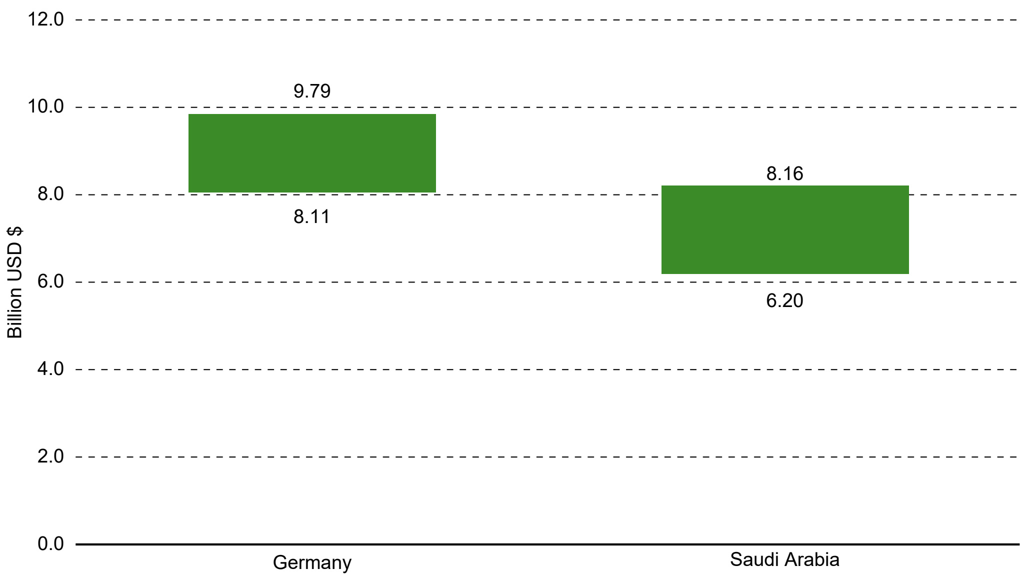
Source: Authors.

5. Results and Discussion

5.1. The Investment Needs in Saudi Arabia Are ~25% Lower Than Those in Germany

For all simulated scenarios, the total investment required in Germany to produce 0.213 Mt of green H_2 ranges from $8.11 billion to $9.79 billion. On the other hand, the total investment needs for Saudi Arabia vary from $6.20 billion to $8.16 billion, thus making the overall investment requirement, on average, 24.7% less than that for Germany (Figure 2). As shown in Figure 2, the best-case scenario for producing 0.213 Mt of green H_2 would cost a net present value of $6.20 billion in Saudi Arabia and $8.11 billion in Germany. In net present value terms, the best-case scenario is 31.6% in Saudi Arabia and 19.6% in Germany. The investment cost includes the CAPEX of the RE generation mix and the electrolyzer mix (Figure 2).

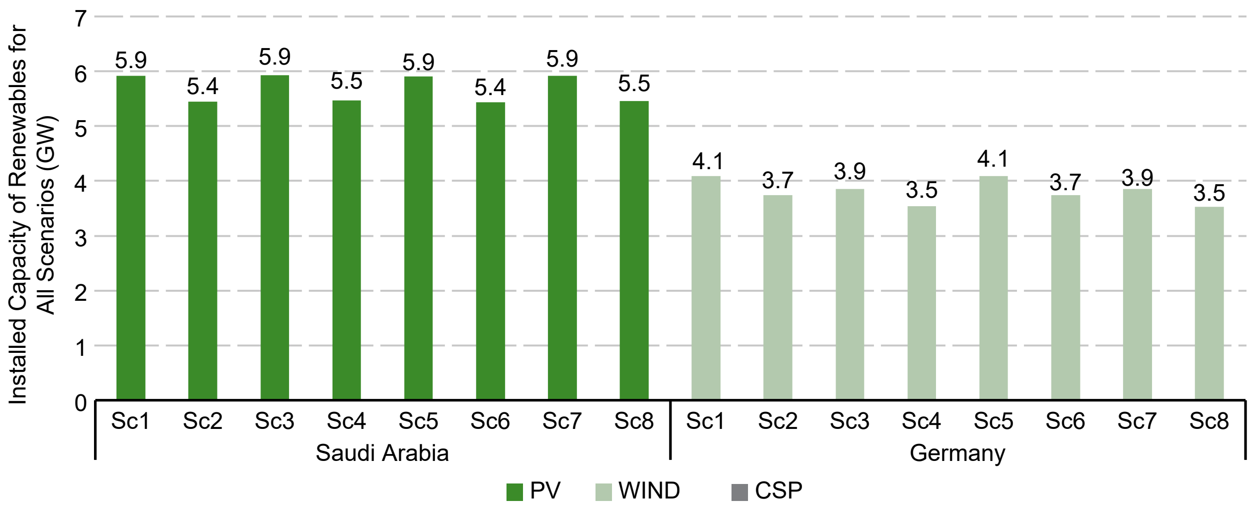
Figure 2. The total net present value of investments, including electrolyzers and renewables.



Source: Authors.

As power generation constitutes a significant part of the H_2 production cost via water electrolysis, the low cost of solar PVs in Saudi Arabia results in a lower overall cost of producing the targeted volume of H_2 compared to Germany (Figure 3). For Germany, the model chooses to build wind turbines instead of PVs, which increases the investment. A better wind profile than that of solar PVs also supports a higher capacity factor of electrolyzers and lower wind capacity needs in Germany. Changes in the input parameters in the different scenarios do not change the electrolyzer technology choice but lead to changes in electrolyzer capacity, as shown in Figure 3.

Figure 3. The required capacity to achieve the green H_2 target in 2030.



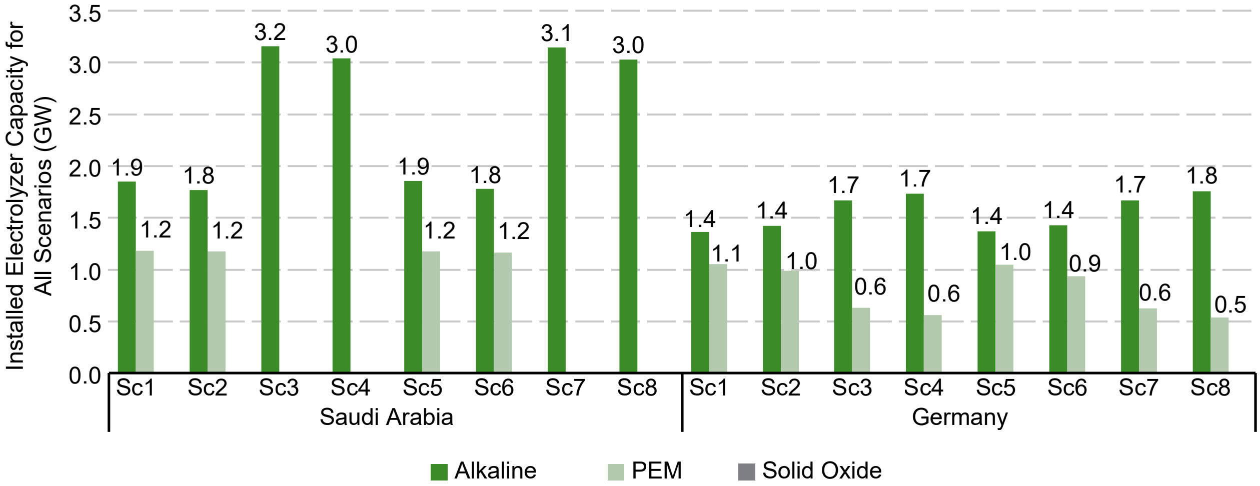
Source: Authors.

5.2. The Model Favors a Low-Cost Alkaline Electrolyzer over Other Electrolyzers, Despite Their Higher Efficiencies

For lower-bound efficiency numbers (Scenarios 1, 2, 5 and 6), the model chooses to build a mix of PEM and alkaline electrolyzers in Saudi Arabia (Figure 4). However, in scenarios with optimistic efficiency advancements, the model chooses to build alkaline electrolyzers only. Despite the high efficiency of solid oxide electrolyzers, their high CAPEX offsets the potential gains from higher efficiency.

Similarly, for Germany, a mix of alkaline and PEM electrolyzers is selected by the model. As efficiency increases, the share of deployed alkaline electrolyzers increases but only with the presence of PEM electrolyzers in the system. The reason is that the capacity utilization factor of the electrolyzers in a renewable-based H_2 production model will primarily depend on the availability of RE resources. In the case of Germany, as mentioned above, the model chooses to build wind power only, which translates to a greater availability of natural resources both day and night.

Figure 4. The installed electrolyzer capacity in Saudi Arabia and Germany.



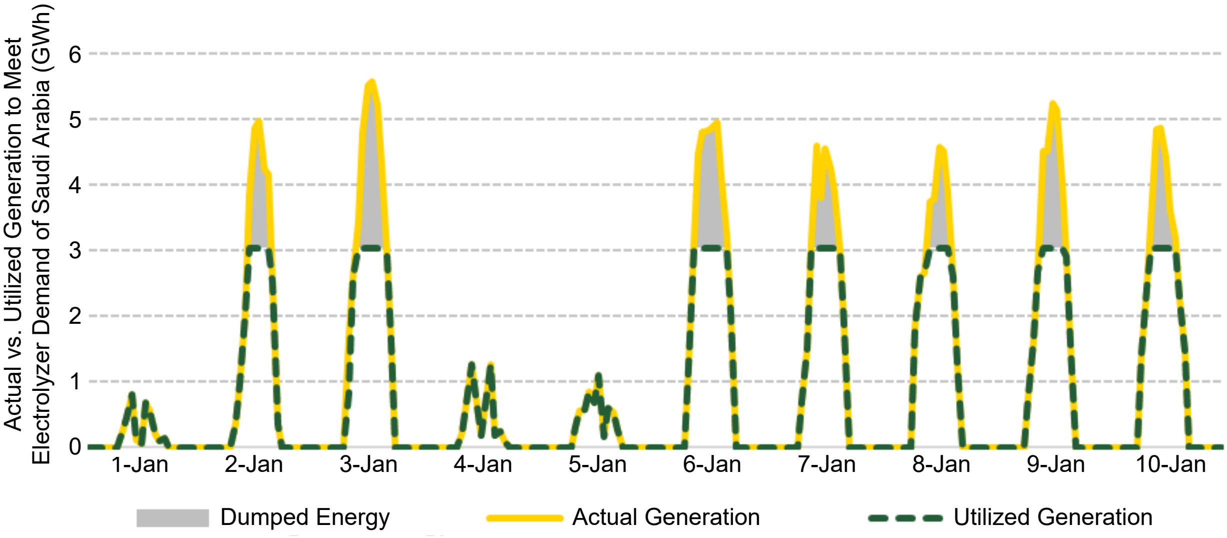
Source: Authors.

Regarding the MSL variable, the adjustments made based on the literature review have minimal discernible effects. In turn, this finding leads to negligible impacts on the installed capacity for both renewables and electrolyzers, as illustrated in Figures 3 and 4 when comparing Scenarios 1-4 with Scenarios 5-8 in both countries. For example, in Saudi Arabia, when we consider the difference between Scenarios 1 and 5, where the only variation is the MSL for the electrolyzers, Scenario 4 has an installed capacity for renewables of 5.47 MW, with the electrolyzers at 3.04 MW. On the other hand, in Scenario 5, characterized by a lower MSL, the values are 5.46 MW for renewables and 3.03 MW for electrolyzers.

5.3. Dumping Energy Is Favored Over Adding Battery Storage

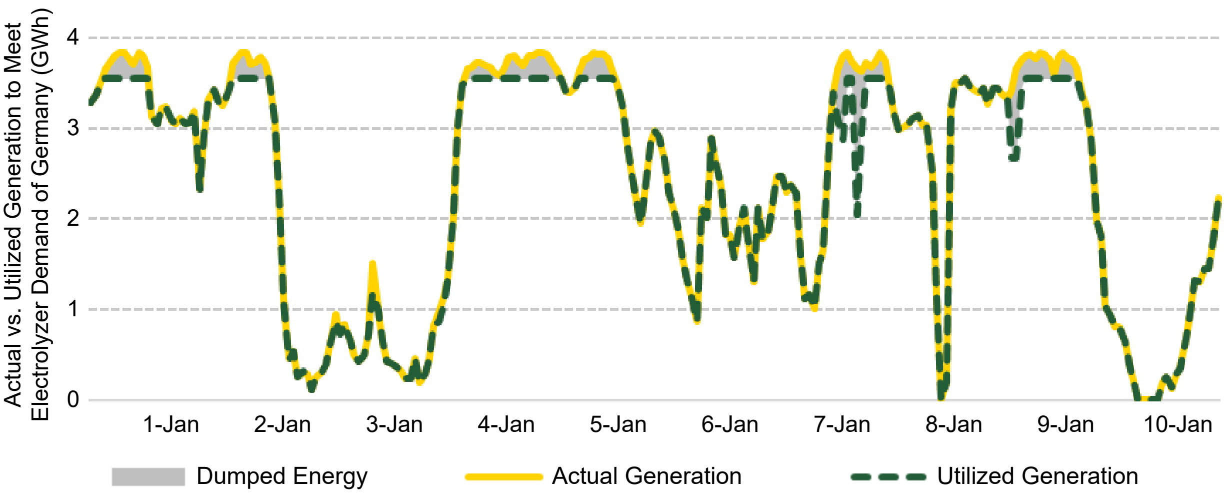
The model builds the optimal electrolyzer technology capacity along with the type and capacity of generation to meet the H_2 production target. Although battery storage is available as a candidate technology, the model does not find value in building battery storage. Instead, dumping surplus energy is found by the model to be more economical. This finding is illustrated in Figure 5, which illustrates the generation profile of the PV system built in Saudi Arabia for one week in January 2030. The total PV capacity built is 5.9 GW, and the electrolyzer capacity built is 3.03 GW. There are several hours during which the PV output is greater than the electrolyzer capacity. In such a case, the additional generated energy is dumped (curtailed). In other words, the model dumps the energy rather than building storage for this additional generation for later use. The same applies to Germany, as shown in Figure 6. Note that the model does not choose to build an electrolyzer capacity larger than what is already available since the required hydrogen demand is met. Hence, dumping energy is more economical than building storage or increasing the electrolyzer size.

Figure 5. Actual generation versus utilized generation in Saudi Arabia.



Source: Authors.

Figure 6. Actual generation versus utilized generation in Germany.



Source: Authors.

In the case of Saudi Arabia, the model dumps 326.7 GWh of energy, representing 3.8% of the total energy generated (from PVs). However, in Germany, the model dumps 165.9 GWh of energy, representing 1.8% of the total energy generated (from wind). Importantly, these operational details would not have been captured without a detailed model possessing an hourly temporal resolution, such as the model developed in this paper.

5.4. H_2 Shipment Costs Are Likely To Decline in the Future

The IEA (2023b) Energy Technology Perspectives 2023 report estimates the levelized cost of delivering H_2 by shipping liquified H_2 to be approximately $2.50/kg for distances greater than 8,000 km. Although the cost of shipping in the form of ammonia or a liquid organic H_2 carrier is less than that of shipping liquefied H_2, the process of transforming pure hydrogen into a carrier and converting it back to hydrogen is energy intensive.

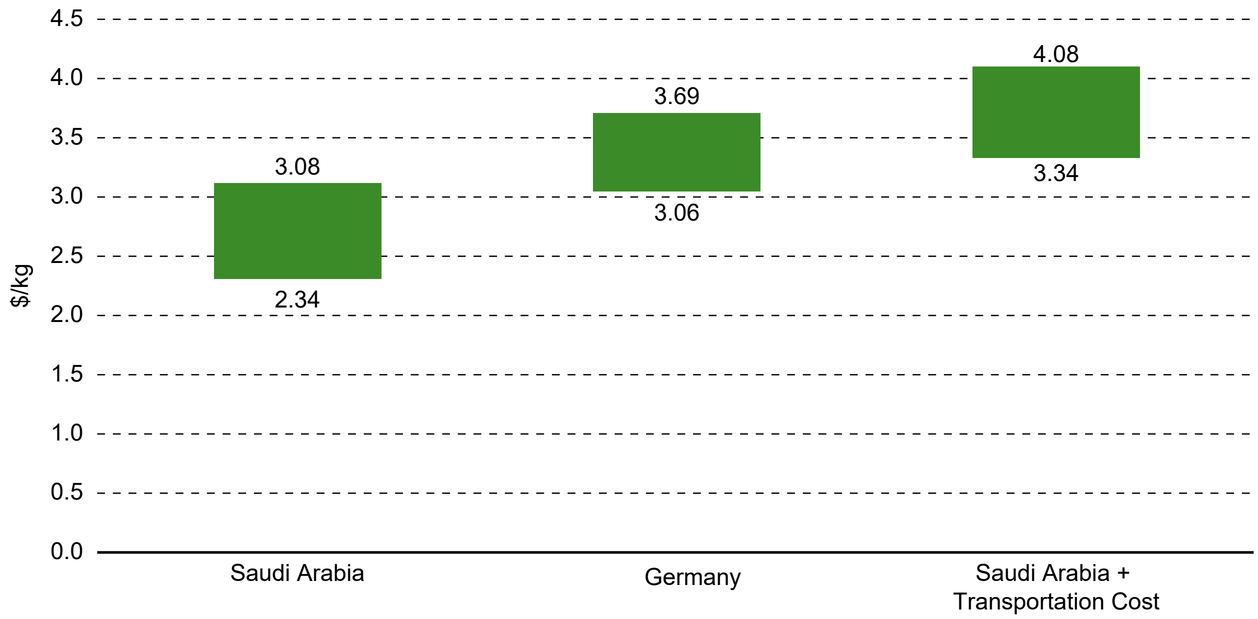
Furthermore, to compare the competitiveness of Saudi-produced green H_2 with that of Germany, the cost of H_2 transport is adapted from the literature based on the estimated cost in $/kg for the shipping option and distance. A joint study by the Saudi-German Energy Dialogue expects the levelized cost of shipping H_2 in the form of ammonia and conversion to H_2 to be approximately $1/kg by 2030 for distances greater than 8,000 km (BMWK and MoE 2022).

Several factors contribute to the high cost of shipping H_2. First, H_2, which is extremely light molecule, requires cooling below -253 degrees Celsius, which is much lower than that of liquefied natural gas. Thus, shipping H_2 requires special equipment and countermeasures for storage and handling. Using today's technology, liquefaction can consume more than 30% of the energy content of H_2, thus making it prohibitively expensive (U.S. DOE 2022). Second, H_2 is highly flammable, requiring special safety precautions when transporting it. Third, the infrastructure for shipping H_2 is currently limited, driving up the cost of transporting H_2.

Through post-processing and a financial model, the LCOH is calculated. The LCOH considers the CAPEX and operational expenditure (OPEX) of both renewable generation and electrolyzers and assumes a WACC for discounting.

Calculated based on the model results, the LCOH production is lower in Saudi Arabia ($2.34 to $3.08/kg$H_2$) than in Germany ($3.06 to $3.69/kg$H_2$). Assuming a shipment cost of $1/kg$H_2$, H_2 could be delivered from Saudi Arabia to Germany as ammonia for $3.34 to $4.08/kg$H_2$, which is relatively competitive with the locally produced green H_2 produced in Germany (Figure 7).

Figure 7. The levelized cost of hydrogen ($/kg) in Saudi Arabia, Germany and with the cost of transportation from Saudi Arabia to Germany.



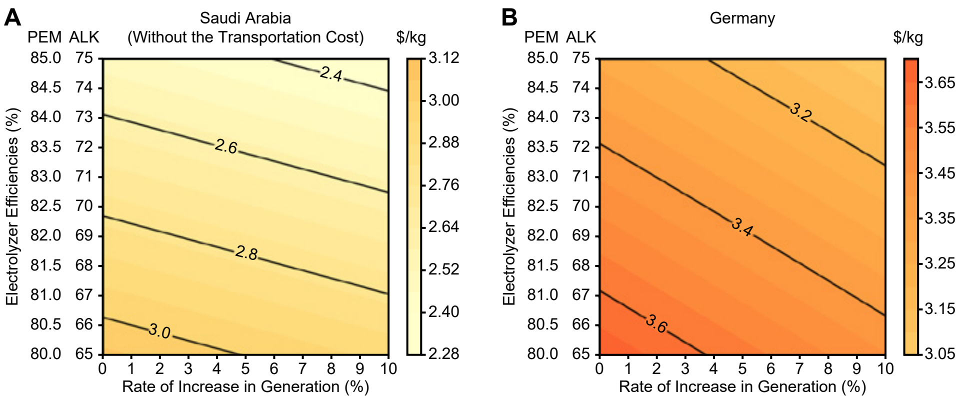
Source: Authors.

5.5. Sensitivity Analysis of Efficiencies and Natural Resources

Upon closer examination of the impact of the variables on the LCOH, it becomes evident that improvements in electrolyzer efficiencies lead to significant cost reductions. In Saudi Arabia, increasing electrolyzer efficiencies results in a cost decrease from \$3.08 to \$2.49/kgH_2, representing a substantial difference of approximately \$0.60/kgH_2, excluding transportation costs. Similarly, in Germany, the cost decreases from \$3.69 to \$3.29/kgH_2, a noteworthy difference of approximately \$0.40/kgH_2. These findings underscore the pivotal role that advancing electrolyzer technologies will play in cost reduction in the years to come.

We also run a sensitivity analysis of natural resources. Assuming that RE resources are 10% better than expected, the price in Saudi Arabia decreases from \$3.08/kgH_2 to \$2.92/kgH_2, translating to a notable difference of approximately \$0.16/kgH_2. In Germany, the reduction is from \$3.69 to \$3.45/kgH_2, reflecting a difference of approximately \$0.24/kgH_2. Figures 8 and 9 show the results without and with transportation costs, respectively.

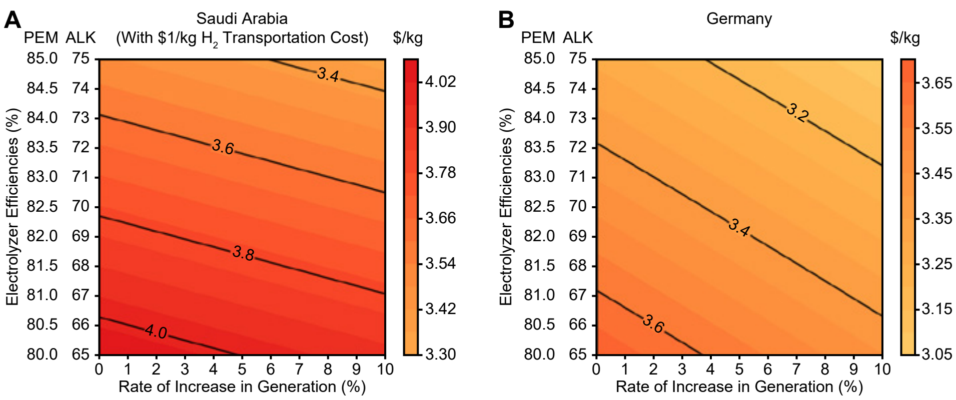
Figure 8. Comparison between the LCOH in Saudi Arabia (without the transportation cost) and that in Germany in terms of the increase in generation from natural resources and electrolyzer efficiencies.



Note: Appendix A shows the numbers in more detail.

Source: Authors.

Figure 9. Comparison between the LCOH in Saudi Arabia (with a cost of transportation to Germany of \$1/kgH_2) and that in Germany in terms of the increase in generation from natural resources and electrolyzer efficiencies.



Note: Appendix A shows the numbers in more detail.

Source: Authors.

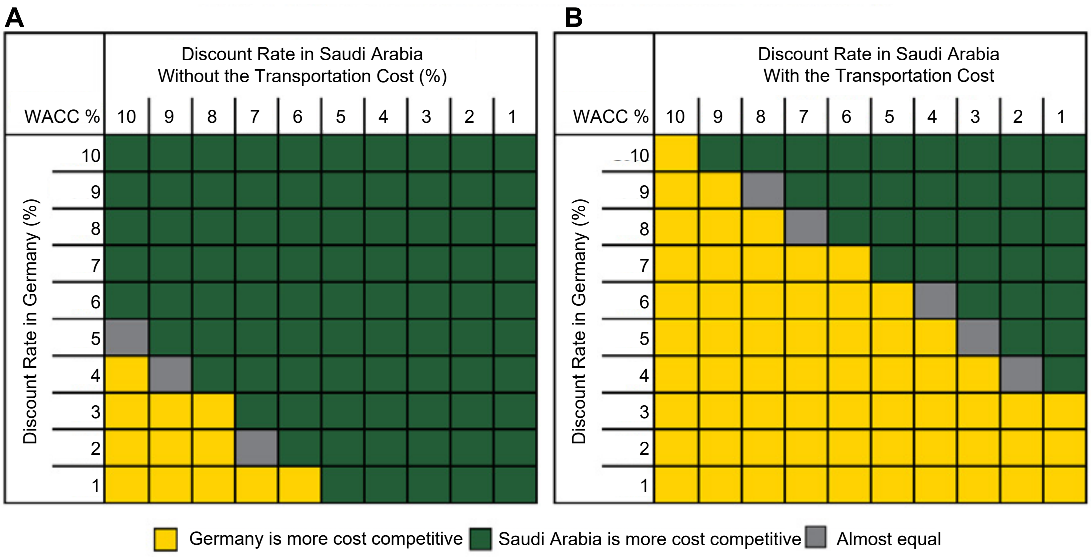
5.6. Sensitivity Analysis of Discount Rates

Thus far, all the variations considered were generally outside the control of any country. Specifically, countries do not have control over their natural resource abundance or how global technology costs evolve. Rather, these parameters are dictated. This situation is not entirely true for the discount rate (i.e., WACC). The discount rate can be impacted by the debt-to-equity ratio, a country's credit rating, the company developing the project, and the guarantees provided, among other factors, as discussed in the literature (Nukala and Rao 2021). In other words, countries can influence the WACC depending on the financial model adopted and the prevailing investment environment.

The WACC for renewable projects in Europe can be as low as 2.6%. However, this rate is achieved when there are revenue support mechanisms in place (e.g., a feed-in tariff). Without such support, the WACC increases significantly and can reach 9.6% (IEA 2022a).

On this basis, we conduct a sensitivity analysis to assess the impact of varying discount rates ranging from 1% to 10%, as shown in Figure 10. The core objective of this analysis is to evaluate the implications of this discount rate adjustment for the LCOH for Germany and Saudi Arabia. Specifically, we assess the circumstances under which importing hydrogen from Saudi Arabia emerges as the more cost-effective option for Germany.

Figure 10. (a) A sensitivity analysis of the discount rates between Saudi Arabia (without the transportation cost) and Germany and **(b)** a sensitivity analysis of the discount rate between Saudi Arabia (with the transportation cost) and Germany.



Source: Authors.

Figure 10(a) shows that, as expected, most of the grid is green, indicating that hydrogen production in Saudi Arabia is more economical than that in Germany when the transportation cost is not included. The only exception appears at the bottom left region of the grid where the difference in that WACC is significant (i.e., a high WACC for Saudi Arabia and a low WACC for Germany).

However, when the cost of transportations from Saudi Arabia to Germany is included, as shown in Figure 10(b), the yellow region is enlarged: Fewer cases result in Saudi Arabia being a lower-cost producer. Nonetheless, there are still many situations in which Saudi Arabia is a lower-cost producer. Carefully inspecting Figure 10(b), we see that these are the situations in which the WACC in Saudi Arabia is lower than that in Germany by at least 2% in absolute terms.

6. Conclusion

This study used a power-to-carrier methodology to assess the competitiveness of producing green H_2 in Saudi Arabia and Germany. Our analysis showed that with an H_2 shipment cost of ~$1/kg (in the form of ammonia), green H_2 produced in Saudi Arabia can be delivered to Germany at a price range of $3.34 to $4.08/kg in 2030. These costs are considered competitive with green H_2 produced in Germany. Overall, Saudi Arabia can be a competitive global player in the hoped-for green H_2 future.

Due to the dominance of natural resources in both geographies, green H_2 production is dominated by PVs in Saudi Arabia, while it is dominated by wind in Germany. Given the technological costs, we find that, on average, the total investment requirements for a renewable-based H_2 production system in Saudi Arabia are ~25% lower than those in Germany. While our model used an exemplary target of 0.213 Mt of H_2 by 2030, the findings in this study can be extended to a larger target without loss of generality.

Furthermore, for electrolyzer technologies, alkaline technology dominates deployment. On the one hand, alkaline electrolyzers are inexpensive but inefficient. On the other hand, PEM and solid oxide electrolyzers possess higher efficiencies but higher costs. In the context of this paper, the lower costs of alkaline electrolyzers outweigh the higher efficiencies of PEM and solid oxide electrolyzers. Additionally, battery storage, even with projected price reductions, is not economical in the context of this paper. The model favors dumping overgeneration over building battery storage that can store overgeneration for later use.

All the factors above are noncontrollable. Regarding the WACC, which can be viewed as a factor that can be controlled within reason, we find that Saudi Arabia can deliver hydrogen to Europe competitively in all scenarios if the discount rate in Saudi Arabia is lower by 200 basis points.

Based on the detailed analysis conducted in this paper, we see that natural solar resources, the low technology costs of solar PVs and the healthy financial and economic status of Saudi Arabia collectively contribute to making Saudi Arabia, without incentives, a cost-competitive producer of hydrogen compared with Europe. The results provided in this paper can help frame the export hydrogen policy in the Arabian Gulf more broadly given the several climate and economic resemblances.

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Appendix

8.1. Appendix A

Table A1. Comparisons between the LCOH in Saudi Arabia and in Germany (with a transportation cost of $0.50/kg, $1.00/kg and $1.50/kg).

Electrolyzer Efficiencies (%)		Saudi Arabia (Without the Transportation Cost) – Rate of Increase in Generation (%)											Germany – Rate of Increase in Generation (%)										
PEM	ALKLINE	0	1	2	3	4	5	6	7	8	9	10	0	1	2	3	4	5	6	7	8	9	10
80.0	65	3.08	3.06	3.04	3.03	3.01	3.00	2.98	2.97	2.95	2.94	2.92	3.69	3.66	3.64	3.62	3.59	3.57	3.55	3.52	3.50	3.48	3.45
80.5	66	3.02	3.00	2.99	2.97	2.96	2.94	2.92	2.91	2.89	2.88	2.86	3.65	3.62	3.60	3.58	3.55	3.53	3.51	3.48	3.46	3.44	3.41
81.0	67	2.96	2.94	2.93	2.91	2.90	2.88	2.87	2.85	2.84	2.82	2.80	3.61	3.58	3.56	3.54	3.51	3.49	3.47	3.44	3.42	3.40	3.37
81.5	68	2.90	2.88	2.87	2.85	2.84	2.82	2.81	2.79	2.78	2.76	2.75	3.57	3.54	3.52	3.50	3.47	3.45	3.43	3.40	3.38	3.36	3.33
82.0	69	2.84	2.83	2.81	2.80	2.78	2.76	2.75	2.73	2.72	2.70	2.69	3.53	3.50	3.48	3.46	3.43	3.41	3.39	3.36	3.34	3.32	3.30
82.5	70	2.78	2.77	2.75	2.74	2.72	2.71	2.69	2.68	2.66	2.64	2.63	3.49	3.46	3.44	3.42	3.39	3.37	3.35	3.33	3.30	3.28	3.26
83.0	71	2.72	2.71	2.69	2.68	2.66	2.65	2.63	2.62	2.60	2.59	2.57	3.45	3.42	3.40	3.38	3.35	3.33	3.31	3.29	3.26	3.24	3.22
83.5	72	2.67	2.65	2.64	2.62	2.60	2.59	2.57	2.56	2.54	2.53	2.51	3.41	3.38	3.36	3.34	3.31	3.29	3.27	3.25	3.22	3.20	3.18
84.0	73	2.61	2.59	2.58	2.56	2.55	2.53	2.52	2.50	2.48	2.47	2.45	3.37	3.34	3.32	3.30	3.28	3.25	3.23	3.21	3.18	3.16	3.14
84.5	74	2.55	2.53	2.52	2.50	2.49	2.47	2.46	2.44	2.43	2.41	2.40	3.33	3.30	3.28	3.26	3.24	3.21	3.19	3.17	3.14	3.12	3.10
85.0	75	2.49	2.48	2.46	2.44	2.43	2.41	2.40	2.38	2.37	2.35	2.34	3.29	3.26	3.24	3.22	3.20	3.17	3.15	3.13	3.10	3.08	3.06

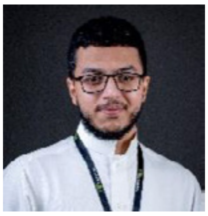
Electrolyzer Efficiencies (%)		Saudi Arabia + 0.5$/kg Transportation Cost – Rate of Increase in Generation (%)											Germany – Rate of Increase in Generation (%)										
PEM	ALKLINE	0	1	2	3	4	5	6	7	8	9	10	0	1	2	3	4	5	6	7	8	9	10
82.0	67	3.58	3.56	3.54	3.53	3.51	3.50	3.48	3.47	3.45	3.44	3.42	3.69	3.66	3.64	3.62	3.59	3.57	3.55	3.52	3.50	3.48	3.45
82.3	68	3.52	3.50	3.49	3.47	3.46	3.44	3.42	3.41	3.39	3.38	3.36	3.65	3.62	3.60	3.58	3.55	3.53	3.51	3.48	3.46	3.44	3.41
82.5	69	3.46	3.44	3.43	3.41	3.40	3.38	3.37	3.35	3.34	3.32	3.30	3.61	3.58	3.56	3.54	3.51	3.49	3.47	3.44	3.42	3.40	3.37
82.8	70	3.40	3.38	3.37	3.35	3.34	3.32	3.31	3.29	3.28	3.26	3.25	3.57	3.54	3.52	3.50	3.47	3.45	3.43	3.40	3.38	3.36	3.33
83.1	71	3.34	3.33	3.31	3.30	3.28	3.26	3.25	3.23	3.22	3.20	3.19	3.53	3.50	3.48	3.46	3.43	3.41	3.39	3.36	3.34	3.32	3.30
83.4	72	3.28	3.27	3.25	3.24	3.22	3.21	3.19	3.18	3.16	3.14	3.13	3.49	3.46	3.44	3.42	3.39	3.37	3.35	3.33	3.30	3.28	3.26
83.6	73	3.22	3.21	3.19	3.18	3.16	3.15	3.13	3.12	3.10	3.09	3.07	3.45	3.42	3.40	3.38	3.35	3.33	3.31	3.29	3.26	3.24	3.22
83.9	74	3.17	3.15	3.14	3.12	3.10	3.09	3.07	3.06	3.04	3.03	3.01	3.41	3.38	3.36	3.34	3.31	3.29	3.27	3.25	3.22	3.20	3.18
84.2	75	3.11	3.09	3.08	3.06	3.05	3.03	3.02	3.00	2.98	2.97	2.95	3.37	3.34	3.32	3.30	3.28	3.25	3.23	3.21	3.18	3.16	3.14
84.5	76	3.05	3.03	3.02	3.00	2.99	2.97	2.96	2.94	2.93	2.91	2.90	3.33	3.30	3.28	3.26	3.24	3.21	3.19	3.17	3.14	3.12	3.10
84.7	77	2.99	2.98	2.96	2.94	2.93	2.91	2.90	2.88	2.87	2.85	2.84	3.29	3.26	3.24	3.22	3.20	3.17	3.15	3.13	3.10	3.08	3.06

Electrolyzer Efficiencies (%)		Saudi Arabia + 1.0$/kg Transportation Cost – Rate of Increase in Generation (%)											Germany – Rate of Increase in Generation (%)										
PEM	ALKLINE	0	1	2	3	4	5	6	7	8	9	10	0	1	2	3	4	5	6	7	8	9	10
82.0	67	4.08	4.06	4.04	4.03	4.01	4.00	3.98	3.97	3.95	3.94	3.92	3.69	3.66	3.64	3.62	3.59	3.57	3.55	3.52	3.50	3.48	3.45
82.3	68	4.02	4.00	3.99	3.97	3.96	3.94	3.92	3.91	3.89	3.88	3.86	3.65	3.62	3.60	3.58	3.55	3.53	3.51	3.48	3.46	3.44	3.41
82.5	69	3.96	3.94	3.93	3.91	3.90	3.88	3.87	3.85	3.84	3.82	3.80	3.61	3.58	3.56	3.54	3.51	3.49	3.47	3.44	3.42	3.40	3.37
82.8	70	3.90	3.88	3.87	3.85	3.84	3.82	3.81	3.79	3.78	3.76	3.75	3.57	3.54	3.52	3.50	3.47	3.45	3.43	3.40	3.38	3.36	3.33
83.1	71	3.84	3.83	3.81	3.80	3.78	3.76	3.75	3.73	3.72	3.70	3.69	3.53	3.50	3.48	3.46	3.43	3.41	3.39	3.36	3.34	3.32	3.30
83.4	72	3.78	3.77	3.75	3.74	3.72	3.71	3.69	3.68	3.66	3.64	3.63	3.49	3.46	3.44	3.42	3.39	3.37	3.35	3.33	3.30	3.28	3.26
83.6	73	3.72	3.71	3.69	3.68	3.66	3.65	3.63	3.62	3.60	3.59	3.57	3.45	3.42	3.40	3.38	3.35	3.33	3.31	3.29	3.26	3.24	3.22
83.9	74	3.67	3.65	3.64	3.62	3.60	3.59	3.57	3.56	3.54	3.53	3.51	3.41	3.38	3.36	3.34	3.31	3.29	3.27	3.25	3.22	3.20	3.18
84.2	75	3.61	3.59	3.58	3.56	3.55	3.53	3.52	3.50	3.48	3.47	3.45	3.37	3.34	3.32	3.30	3.28	3.25	3.23	3.21	3.18	3.16	3.14
84.5	76	3.55	3.53	3.52	3.50	3.49	3.47	3.46	3.44	3.43	3.41	3.40	3.33	3.30	3.28	3.26	3.24	3.21	3.19	3.17	3.14	3.12	3.10
84.7	77	3.49	3.48	3.46	3.44	3.43	3.41	3.40	3.38	3.37	3.35	3.34	3.29	3.26	3.24	3.22	3.20	3.17	3.15	3.13	3.10	3.08	3.06

Electrolyzer Efficiencies (%)		Saudi Arabia + 1.5$/kg Transportation Cost – Rate of Increase in Generation (%)											Germany – Rate of Increase in Generation (%)										
PEM	ALKLINE	0	1	2	3	4	5	6	7	8	9	10	0	1	2	3	4	5	6	7	8	9	10
82.0	67	4.58	4.56	4.54	4.53	4.51	4.50	4.48	4.47	4.45	4.44	4.42	3.69	3.66	3.64	3.62	3.59	3.57	3.55	3.52	3.50	3.48	3.45
82.3	68	4.52	4.50	4.49	4.47	4.46	4.44	4.42	4.41	4.39	4.38	4.36	3.65	3.62	3.60	3.58	3.55	3.53	3.51	3.48	3.46	3.44	3.41
82.5	69	4.46	4.44	4.43	4.41	4.40	4.38	4.37	4.35	4.34	4.32	4.30	3.61	3.58	3.56	3.54	3.51	3.49	3.47	3.44	3.42	3.40	3.37
82.8	70	4.40	4.38	4.37	4.35	4.34	4.32	4.31	4.29	4.28	4.26	4.25	3.57	3.54	3.52	3.50	3.47	3.45	3.43	3.40	3.38	3.36	3.33
83.1	71	4.34	4.33	4.31	4.30	4.28	4.26	4.25	4.23	4.22	4.20	4.19	3.53	3.50	3.48	3.46	3.43	3.41	3.39	3.36	3.34	3.32	3.30
83.4	72	4.28	4.27	4.25	4.24	4.22	4.21	4.19	4.18	4.16	4.14	4.13	3.49	3.46	3.44	3.42	3.39	3.37	3.35	3.33	3.30	3.28	3.26
83.6	73	4.22	4.21	4.19	4.18	4.16	4.15	4.13	4.12	4.10	4.09	4.07	3.45	3.42	3.40	3.38	3.35	3.33	3.31	3.29	3.26	3.24	3.22
83.9	74	4.17	4.15	4.14	4.12	4.10	4.09	4.07	4.06	4.04	4.03	4.01	3.41	3.38	3.36	3.34	3.31	3.29	3.27	3.25	3.22	3.20	3.18
84.2	75	4.11	4.09	4.08	4.06	4.05	4.03	4.02	4.00	3.98	3.97	3.95	3.37	3.34	3.32	3.30	3.28	3.25	3.23	3.21	3.18	3.16	3.14
84.5	76	4.05	4.03	4.02	4.00	3.99	3.97	3.96	3.94	3.93	3.91	3.90	3.33	3.30	3.28	3.26	3.24	3.21	3.19	3.17	3.14	3.12	3.10
84.7	77	3.99	3.98	3.96	3.94	3.93	3.91	3.90	3.88	3.87	3.85	3.84	3.29	3.26	3.24	3.22	3.20	3.17	3.15	3.13	3.10	3.08	3.06

Notes

About the Authors



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Khalid is an analyst in the Utilities and Renewables program at KAPSARC. He is an electrical power and machines engineer with a bachelor's degree from the Department of Electrical Engineering at King Abdulaziz University. His work at KAPSARC has focused on renewables, energy modeling and the electric power systems field.

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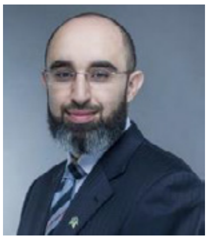
Ahmed is a research lead in the Utilities and Renewables program at KAPSARC. He is an electrical engineer with an M.Sc. in renewable energy systems from Loughborough University. Prior to joining KAPSARC, he worked as an R&D engineer at Saudi Electricity Company for more than five years, heading research on renewables and energy storage.

Ahmed's current research focuses on emerging technologies, critical minerals and power system modeling to help shape the future of the energy mix and the technologies that can contribute to achieving the KSA's green targets.

Shahid Hasan

Shahid is a research fellow at KAPSARC. His current research focuses on electricity sector transitions and hydrogen economics, as well as policy and regulatory issues in the Middle East and globally. He also studies the development of regional electricity markets in the GCC, the Middle East and North Africa. He previously consulted extensively on policy, regulatory and market design for governments, electricity regulators, public utilities and electricity industries in India and Southeast Asia.



Amro M. Elshurafa

Amro is the acting director of the Utilities and Renewables program at KAPSARC, Riyadh, Saudi Arabia, and has more than 20 years of experience in energy and technology accrued on three continents. His expertise includes renewable energy policy, electricity sector regulation, power systems modeling and hybrid microgrid design and optimization. He has led and executed several national modeling initiatives at both the distributed and utility scales and is listed among the top 2% of scientists globally, according to Elsevier. BP has adopted some aspects of his research in creating its seminal annual statistical review. Credited with more than 50 papers and patents, Dr. Elshurafa holds a Ph.D. in electrical engineering, complemented by an MBA in finance.

About the Project

This study falls under the "Assessment of the Changing Economics of the Saudi Electricity Industry" project within KAPSARC's Utilities and Renewables program. The study assesses the competitiveness of green hydrogen production in Saudi Arabia and Germany using a power-to-carrier modeling framework in PLEXOS. The model optimizes electrolyzer technology, electrolyzer capacity and the carbon-free energy mix to achieve a specified annual green hydrogen production target. The study's findings provide insights into the critical factors for establishing Saudi Arabia as a cost-competitive producer and exporter of green hydrogen compared to Europe.

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