Systems & Control Transactions

Research Article - Peer Reviewed Conference Proceeding
ESCAPE 35 - European Symposium on Computer Aided Process Engineering
Ghent, Belgium. 6-9 July 2025
Jan F.M. Van Impe, Grégoire Léonard, Satyajeet S. Bhonsale, Monika E. Polańska, Filip Logist (Eds.)

PSE PRESS

Solar-Driven Hydrogen Economy Potential in the Greater Middle East: Geographic, Economic, and Environmental Perspectives

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ABSTRACT

The production of hydrogen from solar energy has surged in popularity in recent years, driven by global initiatives to combat climate change. The Greater Middle East (GME) region, with its favorable geographical position, offers considerable potential for solar-based hydrogen generation. This study combines Geographic Information System (GIS) spatial analysis and the Analytical Hierarchy Process (AHP) with data-driven optimization models to assess land suitability and hydrogen production potential within the region under various scenarios. Findings highlight that water availability is the primary limiting factor, followed closely by road accessibility in determining land suitability for hydrogen production. According to the AHP analysis, only 3.8% of the GME region is highly suitable for such initiatives. Projections suggest that by 2050, the region could achieve a total hydrogen production capacity of up to 1590 Mt/y, potentially avoiding around 4586 Mt of CO_2 emissions if all highly suitable land is utilized effectively. Furthermore, the levelized cost of hydrogen (LCOH) is expected to decrease to a range of $2.56-4.17/kg, while green ammonia and methanol costs are anticipated to fall between $0.56-0.79/kg and $0.67-0.93/kg, respectively. This study offers valuable insights that contribute significantly to the global hydrogen discourse and provides essential guidance for policymakers aiming to develop comprehensive strategies for advancing the hydrogen economy in the GME region.

Keywords: Optimization, GAMS, Modelling and Simulation, Energy Management, Hydrogen, GIS-MCDM

INTRODUCTION

The Greater Middle East (GME) region, encompassing the Middle East, Türkiye, Iran, Iraq, North Africa, Central Asia, and the Caucasus, is strategically located within the global sunbelt and possesses significant potential for solar-driven hydrogen production. For these nations, hydrogen presents an opportunity to decrease dependence on fossil fuels while positioning themselves as major exporters to burgeoning hydrogen markets in the EU, Japan, and South Korea, all of which are actively investing in this sector. Saudi Arabia aims to capture 10% of the global hydrogen market by 2030 [1], while Egypt targets a market share of 4-8%. Additionally, various countries in the region have set ambitious hydrogen production goals and initiated several large-scale projects [2]. Despite these advancements, the green hydrogen industry in the GME remains nascent, with uncertainties surrounding the future dynamics of energy trade in this evolving economy. This raises critical questions about which countries will emerge as dominant players and their capacity to meet both local and global hydrogen demands. To address this, it is essential to first estimate the hydrogen production potential of the region by evaluating the suitable land area, accompanied by a technical, economic, and environmental evaluation for a broader perspective.

Several studies have examined the hydrogen potential of countries in this region, most of which utilize GIS analysis to identify suitable land areas [3,4]. However, accurately estimating hydrogen production potential requires precise data acquisition, such as hourly solar profiles, which are crucial for making informed decisions regarding solar and electrolyzer operations. The complexity of handling such extensive data often limits these analyses to single locations or a few major cities within a country. Furthermore, only a handful of studies address economic factors, and even fewer incorporate an environmental perspective. In this study, GIS-AHP analysis is employed to estimate the amount of suitable land available for hydrogen production. Additionally, data-driven optimization models are utilized to facilitate hydrogen production estimates on a larger scale. This research considers thirty countries in the GME region, evaluating their hydrogen potential alongside key metrics such as the levelized cost of hydrogen (LCOH), levelized cost of ammonia (LCOA), and levelized cost of methanol (LCOM). The potential for CO_2 emissions reduction is also assessed through Life Cycle Assessment (LCA) analysis.

METHODOLOGY

The study area comprises thirty countries with a total area of 29,544,619 km^2. A spatial resolution of 1km x 1km was selected, yielding 29.5 million alternatives (locations) as candidates for suitable sites in the GME region. To determine the most appropriate sites, six key criteria were examined: solar resource availability, proximity to water bodies and waterways, topographical slope, land use, and land cover, accessibility to roads, and proximity to protected or restricted areas. An AHP analysis was then performed which compares all these factors pairwise and assigns weights to them based on their relative importance. The AHP extension tool within ArcMap software was employed to guarantee the accuracy of calculations. The consistency matrix and the scores assigned to each criterion are detailed in the supplementary material.

A data-driven optimization model was employed to estimate the annual hydrogen production potential (AHPP) and the LCOH using a two-stage approach. In the initial stage, 100 locations within the GME region were randomly selected, and their hourly solar profiles were sourced from the Global Solar Atlas. The optimization model was then executed for these locations, yielding optimized data such as electrolyzer operating hours, solar-to-electrolyzer ratios, and power loss. Based on the specific power output of these locations, they were categorized into ten distinct intervals. Average feature values for each interval were calculated, leading to the development of a predictive model. In this model, each location is first assigned to an interval based on its PVOUT and subsequently assigned the average feature values corresponding to that interval. All analyses were conducted for the years 2024 and 2050 under two distinct scenarios. In Case 1 (conservative scenario), it was assumed that each location would be utilized only partially, at a rate of 5% for hydrogen projects. This scenario considered a 2 MW solar plant paired with a 1 MW electrolyzer. In Case 2, an optimistic scenario was evaluated, assuming full utilization of the available area (100% coverage). For this scenario, a 38 MW solar plant with a 19 MW electrolyzer was proposed.

The power ($P_{t,m}$) produced by the solar plant at time *t* in month *m* is estimated as follows:

$$P_{t,m} = \emptyset_{t,m} \times C, \;\; \forall\, t \in T, \forall\, m \in M, \tag{1}$$

where $\emptyset_{t,m}$ is temporal photovoltaic power output (kWh/kWp) data for the time *t* in the month *m*. C is the capacity of the solar plant and the primary decision variable in the model.

The power supplied to the electrolyzer can neither exceed its capacity (δ) nor fall below its minimum threshold power (α). This is modeled as:

$$P_{t,m} \le \delta, \;\; \forall\, t \in T, \forall\, m \in M, \tag{2}$$

$$P_{t,m} \le B_{t,m}, \;\; \forall\, t \in T, \forall\, m \in M, \tag{3}$$

$$P_{t,m} \ge \alpha \times \delta - \varepsilon \times (1 - B_{t,m}), \forall\, t \in T, \forall\, m \in M, \tag{4}$$

where $B_{t,m}$ represent binary variables to allow power to the electrolyzer and ε represents the upper bound for power to the electrolyzer according to the Big-M formulation method.

The amount of hydrogen ($H_{t,m}$) produced by the electrolyzer at time *t* in month *m* is estimated as:

$$H_{t,m} = \eta \times P_{t,m}, \;\; \forall\, t \in T, \forall\, m \in M, \tag{5}$$

where η is the electrolyzer efficiency. The total annual hydrogen (*TH*) produced is calculated as follows:

$$TH = \sum_{t,m} H_{t,m} \times d_m, \tag{6}$$

where dm is days in month *m*.

A discounted cash flow model is formulated for the economic analysis. The LCOH in $/kg is defined as:

$$LCOH = \frac{NPV\ of\ total\ costs}{NPV\ of\ hydrogen\ production}, \tag{7}$$

where *NPV* is the net present value. The *NPV* of total costs and hydrogen production is estimated as follows:

$$NPV\ of\ total\ costs = \sum_{n=0}^{20} \frac{CAPEX + OPEX}{(1+r)^n}, \tag{8}$$

where CAPEX and OPEX are the capital and operating expenditure, respectively.

$$NPV\ of\ hydrogen\ production = \sum_{n=1}^{20} \frac{TH}{(1+r)^n}, \tag{9}$$

where r is the internal rate of return and n is the project life. Notably, *CAPEX* incurs at $n = 0$ (construction period) and *OPEX* and hydrogen production occur at $1 \leq n \leq 20$.

An estimation of the levelized cost of energy (LCOE) was used to estimate the LCOA and LCOM. The total lifecycle costs (TLCC) and annual power (AP) output are estimated using:

$$TLCC = \sum_{n=0}^{20} \frac{CAPEX + OPEX}{(1+r)^n}, \tag{10}$$

$$AP = \sum_{n=0}^{20} \frac{PVOut \times C \times 365}{(1+r)^n}. \tag{11}$$

The LCOE is then calculated using (10) and (11) as:

$$LCOE = \frac{TLCC}{AP}. \tag{12}$$

The raw material and utility demand for each derivative is estimated using process simulations as described in our previous studies [5]. The final cost of the derivatives was estimated using equations (7-9).

All assumed parameters are given in the supplementary material.

To evaluate the environmental impact of hydrogen in comparison to gasoline, a cradle-to-grave life cycle assessment (LCA) was conducted. This study quantified the potential reduction in carbon emissions achievable by transitioning to solar-driven hydrogen as an alternative to gasoline, referring to this reduction as "avoided CO_2 potential" for both conservative and optimistic scenarios. For inventory scaling, 1 kg of hydrogen was utilized as the functional unit. The energy produced from hydrogen, estimated at approximately 120–142 MJ/kg, was converted into its gasoline equivalent of 44–46 MJ/kg, based on usage in a typical fuel-efficient vehicle that consumes 70 grams of fuel per kilometer. The LCA was carried out using SimaPro V8.2.3, employing the CML-IA baseline V3.03 characterization method.

RESULTS & DISCUSSION

GIS analysis indicates that water availability is the primary factor influencing land suitability for hydrogen production in the GME region, particularly in the Middle Eastern and North African countries. Overall, about 57% of land is considered unsuitable for the deployment of solar-driven hydrogen production facilities. Locations within a 10 km radius of water bodies are deemed suitable, while those further away are not. Among the thirty countries studied, fourteen have less than 50% of their land with accessible water resources. Another constraint is the land slope which should be below 5° to facilitate the large-scale deployment of solar panels. Among the thirty countries analyzed, five—Tajikistan, Kyrgyzstan, Lebanon, Armenia, and Türkiye—have less than 50% of their land suitable due to slope constraints. Approximately 86% of the total land in these regions is suitable for solar panel installation.

When selecting optimal sites, the proximity to roads is a crucial constraint to consider since hydrogen needs to be transported to the end user. Any location that is within 500m of roads or more than 10 km away from them was considered unsuitable for this analysis. Overall, approximately 40% of the total land in the GME region is considered unsuitable for hydrogen production when factoring in proximity to roads. Analysis of the land cover and land use data revealed that approximately 88% of the GME region consists of barren or open land, characterized by minimal man-made infrastructure or restricted/protected areas. This type of land is particularly well-suited for hydrogen facilities. As a result, this constraint has not significantly affected the overall suitability of the land for such projects.

The AHP analysis results, illustrated in **Figure 1**, categorized the GME region into four suitability levels" highly suitable, moderately suitable, low suitable, and not suitable. The results revealed that only 3.8% (about 1.2 million km^2) of the land is highly suitable, satisfying all the constraints. It is important to highlight that Saudi Arabia distinguishes itself in the region by having the highest number of optimal sites for hydrogen production. In contrast, the Central Asian states face challenges due to their rugged terrain and slope, resulting in a lower availability of suitable land. North African countries, on the other hand, encounter limitations related to water availability, which restricts their land suitability for solar-driven hydrogen production. An exception is Morocco with a high proportion of suitable land.

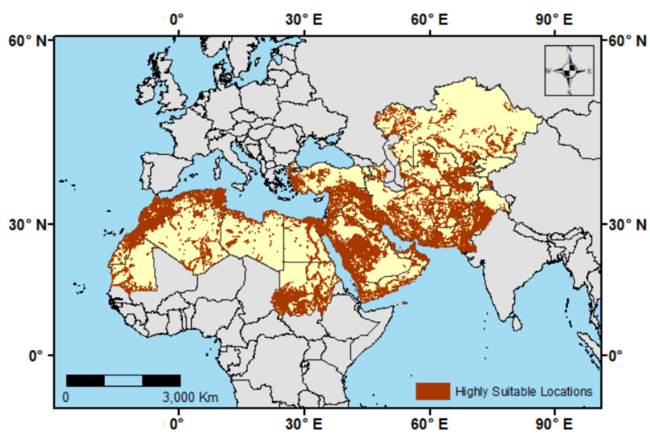

Figure 1 Highly suitable locations identified through the AHP analysis.

Hydrogen Production Potential

To estimate the hydrogen production potential of the GME region, the land area identified as highly suitable through the AHP analysis is utilized. Figure 2 illustrates the annual hydrogen production potential for each country in 2024, along with projections for 2025. For smaller nations such as Armenia, Bahrain, Lebanon, and Qatar, the potential remains below 1 Mt/y even under the 100% coverage scenario. In scenario one, all countries

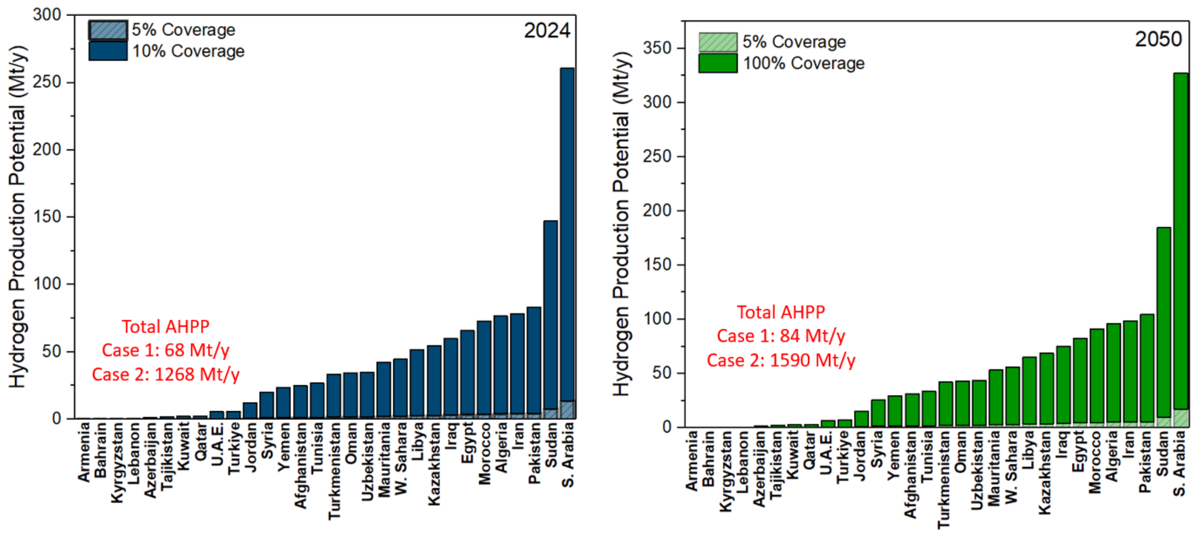

Figure 2: Annual Hydrogen Production Potential (AHPP) of thirty countries in the GME region for Case 1 (5% Coverage) and Case 2 (100% Coverage) for 2024 and 2050.

remain below 15-17 Mt/y, indicating that even with minimal land use, these nations can be self-sufficient in meeting their hydrogen needs. The cumulative potential for this scenario totals 68 Mt/y in 2024 and increases to 84 Mt/y by 2050. In a more optimistic scenario (case 2), the region's hydrogen production potential rises significantly to 1268 Mt/y in 2024 and reaches 1590 Mt/y by 2050. Among the countries analyzed, Saudi Arabia stands out with the highest production potential, projected to reach approximately 327 Mt/y by 2050. Meanwhile, Pakistan, Morocco, and Egypt are expected to achieve production potentials of 104 Mt/y, 91 Mt/y, and 82 Mt/y respectively in this optimistic scenario. According to IRENA, global hydrogen demand is projected to reach 450 Mt/y by 2050 [6], with about one-third of this demand expected to be met through international trade. Given these figures, it is evident that the GME region is poised to play a crucial role in capturing a significant share of the global hydrogen market.

Levelized Cost of Products

A location that is deemed highly suitable based on the aforementioned constraints does not necessarily imply that it is also economically viable. The LCOH serves as the economic indicator for assessing the feasibility of a location by examining the total expenses in the production of hydrogen. Figure 3 illustrates the current and projected ranges of LCOH in the GME region.

The LCOH in the region ranges from 4.6 $/kg to 16.4 $/kg. However, if we consider only the highly suitable locations in the region, Egypt, Saudi Arabia, and Libya have the lowest LCOH of about 4.70, 4.73, and 4.75 $/kg, respectively. On the other hand, Kazakhstan shows the highest LCOH of 7.84 $/kg in 2024. Projections for 2050 indicate that the LCOH range will decrease to 2.5 to 9.1 $/kg with Egypt showing the lowest LCOH while Kazakhstan has one of the highest. Despite the potential for hydrogen production in the region, the LCOH remains higher than that of grey hydrogen produced from fossil fuels, which are still more readily available and affordable in this region. The extent to which a country can lower the CAPEX for solar panels and electrolyzers—through measures such as reducing import taxes—will play a crucial role in facilitating the region's transition to a green hydrogen economy. North African and Middle Eastern countries benefit from abundant solar resources, resulting in relatively lower LCOH in these areas. However, water scarcity may hinder them from fully utilizing this potential. In contrast, Central Asian states have access to good water supplies but face significant challenges due to limited solar resources and challenging topography, which could restrict development. Countries situated between these two extremes—such as Iran, Iraq, Pakistan, Afghanistan, and Turkey—enjoy a favorable balance of both solar and water resources, positioning them well for potential growth in green hydrogen production.

Hydrogen derivatives like Ammonia and Methanol have a significant global market and utilizing green hydrogen to produce these can save up a lot of CO_2 emissions. In addition to being valuable products themselves, these chemicals can easily be transported internationally and can serve as cost-effective hydrogen carriers. Figure 3 illustrates the LCOA and LCOM for 2024 and 2050. For highly suitable locations, green ammonia is expected to cost between 0.96-1.38$/kg in 2024 and 0.56-0.79$/kg by 2050 while green LCOM ranges from 1.12-1.59 $/kg in

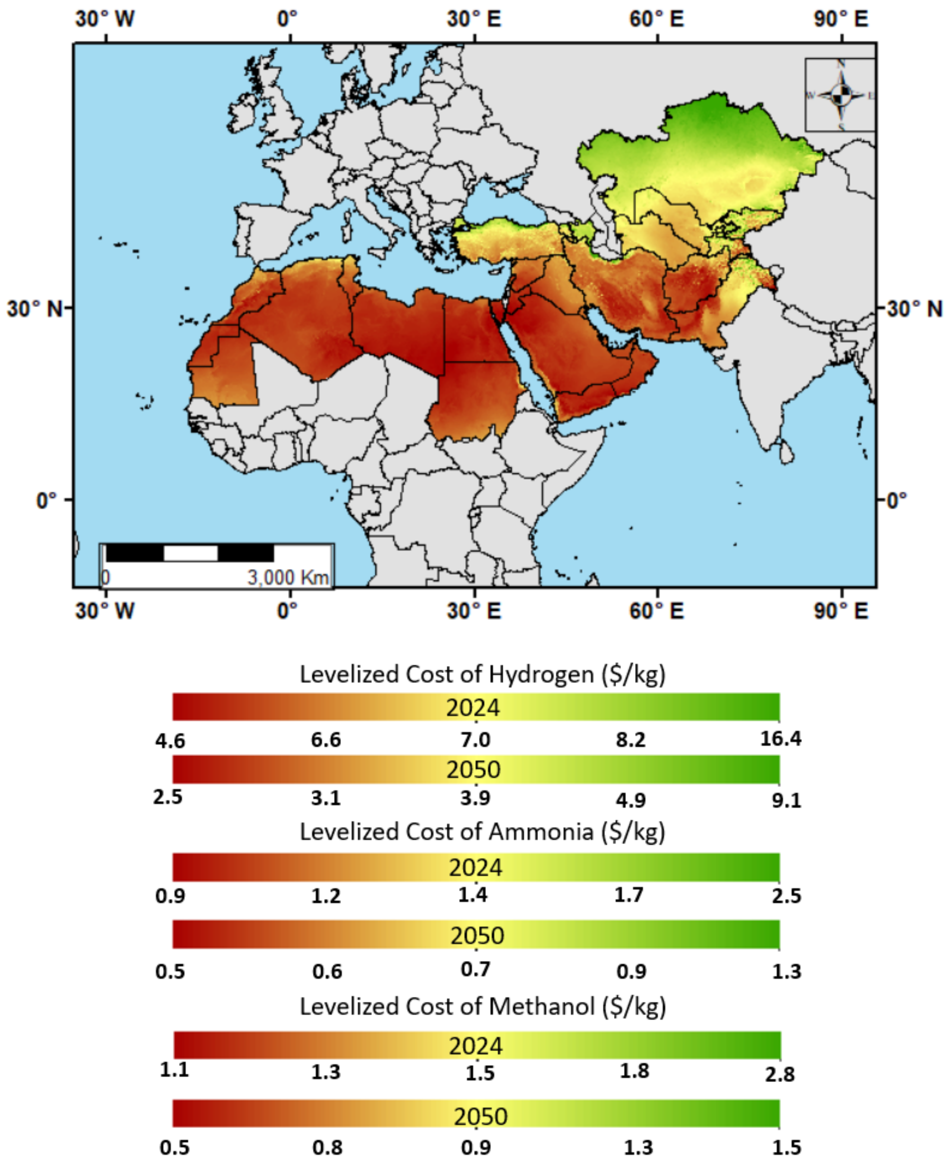

Figure 3: Levelized cost of hydrogen, ammonia, and methanol in the GME region for 2024 and 2050.

2024 and is expected to decrease to 0.67-0.93 $/kg by 2050.

Table 1 CO_2 avoided potential for Case 1: 5% coverage and Case 2: 100% coverage for 2024 and 2050.

Year	Case	CO_2 avoided potential (Mt/y)
2024	1	481
	2	3655
2050	1	603
	2	4586

CO_2 Avoided Potential

The LCA analysis was conducted to quantify the CO_2 emissions that could be avoided by substituting gasoline with green hydrogen. The total potential for CO_2 emissions reduction in the two scenarios is presented in **Table 1**. For the year 2024, the region has the potential to avoid between 481 and 3655 Mt/y of CO_2, depending on whether highly suitable locations are utilized partially (5%) or fully (100%) for hydrogen projects, respectively. By 2050, these values could increase to between 603 and 4586 Mt/y, assuming improved production efficiency of electrolyzers and solar panels. These findings highlight the significant opportunity for the region to achieve its net-zero targets through the adoption of green hydrogen across various sectors. Notably, most countries in the region are self-sufficient and will not need to rely on imported hydrogen to realize this potential.

CONCLUSION

An integrated approach combining GIS-MCDM analysis, along with data-driven optimization models, was employed to assess the hydrogen potential of the GME region through technical, economic, and environmental evaluations. The GIS analysis identified proximity to water resources as the primary constraint affecting land suitability, particularly in North African and Middle Eastern countries. In contrast, Central Asian states face challenges due to rugged topography that renders much of their land unsuitable. Additionally, proximity to roads emerged as another significant factor impacting land suitability. After conducting the AHP analysis, it was determined that only 3.8% of the GME region is classified as highly suitable for solar-driven hydrogen projects, with Saudi Arabia, Sudan, and Pakistan identified as the top three countries with the most favorable land conditions. However, not all suitable locations are economically viable. The LCOH results indicate that Egypt and Libya have very low LCOH due to their excellent solar resources. The region also possesses the potential to produce green ammonia and methanol, which are valuable chemicals with a strong global market demand. Overall, the hydrogen potential suggests that the GME region could capture a significant share of the global hydrogen market, particularly serving European Union countries and Asia-Pacific nations like Japan and Korea that are actively investing in hydrogen economies. Furthermore, it can meet its net-zero targets by integrating green hydrogen across various sectors. However, establishing a robust hydrogen economy will require significant government efforts and investments. This transition may only be feasible if green hydrogen projects become profitable, which hinges on achieving economies of scale in electrolyzer production and reducing costs in the coming years.

DIGITAL SUPPLEMENTARY MATERIAL

Details of the AHP analysis as well as all the assumed parameter values in the optimization code are given in the digital supplementary material.

ACKNOWLEDGEMENTS

This work was supported by the National Research Program for Universities (NRPU), Research and Development Division, Higher Education Commission of Pakistan (20-14827/NRPU/R&D/HEC/2021). This research was also supported by Aalto University through project number 96310047.

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