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The Feasibility of Implementing Cost Reduction Strategies for Green Hydrogen Production in Oman

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Abstract

Oman is strategically positioned to become a market leader in green hydrogen production in the Middle East, leveraging its abundant solar resources, favorable climate, and strong policy framework under Oman Vision 2040. With a national target of producing 1.38 million tons of green hydrogen by 2030 and allocating 50,000 square kilometers of land for this initiative, Oman aims to diversify its economy and reduce reliance on fossil fuel exports. This study identifies key cost drivers in green hydrogen production-electricity, electrolyzer costs, engineering, and balance of plant-with electricity alone accounting for 75% of operational costs. To address this, the use of solid oxide electrolyzers is proposed, as they can efficiently utilize Oman's high ambient temperatures to enhance electrolyzer performance.

The regions of Thumrait, Marmul, and Duqm emerge as the most suitable locations for green hydrogen plants due to their high solar radiation and moderate ambient temperatures, which contribute to improved photovoltaic (PV) efficiency and higher power output. Based on stakeholder interviews and site assessments, the study recommends the implementation of comprehensive policies by Hydrom, including tax incentives, subsidies, and duty-free imports to stimulate investment. It also advocates for the parallel development of associated renewable sectors such as solar and wind to lower electricity costs and emissions.

Furthermore, the research underscores the importance of building strategic value chains by integrating green hydrogen into local industries like steel, mining, and transport, while also establishing export routes to major markets in Europe and Asia. The diversion of excess electricity from hydrogen production into the national grid is also proposed to support Oman's long-term climate goals. Overall, this study highlights Oman's potential to lead the region in green hydrogen development through strategic planning, technological investment, and policy support.

Keywords
Green hydrogen, Renewable energy, Oman Vision 2040, Solar radiation, Electrolyzer efficiency, Hydeom (Hydrogen Oman).

1. Introduction
Global warming and climatic change have forced most of the world to reconsider their energy sources and adopt more renewable fuels. The Sultanate of Oman has taken a similar approach, hoping to produce 16% of its electricity through green energy sources by 2025 and 30% by 2030 (Green Hydrogen Association, n.d). These goals align with Oman's Vision for 2040 and the National Energy Strategy. Among these efforts is increasing the production of green hydrogen, which has no residue and only emits water vapour, which is harmless to the environment. Oman is building its capacity

to produce 1 million tons of green hydrogen annually in 2030, increasing to 8.5 million tons by 2050.This huge capacity will equal the total hydrogen demand of the European market and present new energy markets for the Sultanate.

Oman's large tracts of land and green energy transition make it suitable to produce large quantities of hydrogen for internal usage and export. However, green hydrogen (GH) production requires high initial investments in plant construction, machinery procurement, labour, and daily operational costs. This paper assesses the current Oman GH industry, identifying cost drivers and strategies for reducing production costs. It also evaluates the growth of the domestic sector and assesses how international collaboration can help to minimize production costs.

1.1 Objectives

The study aims to provide a comprehensive feasibility assessment of implementing cost-reduction strategies for green hydrogen production in Oman by exploring technological, economic, and policy-based interventions with the potential role of international collaborations. The main research questions of this study are:

- What are the primary cost drivers of green hydrogen production in Oman?
- Which challenges affect the growth of green hydrogen production in Oman? How can these challenges be solved?
- Which policies and initiatives will increase investments in Oman's domestic green hydrogen production sector?

The main objective of this study is to explore Oman's economic, political, and technological sectors for suitable cost-reduction strategies that can reduce the production cost of green hydrogen. Other objectives of the study are:

- To identify key cost drivers in the hydrogen production industries and determine potential cost-saving areas
- To identify the economic and technological factors hindering the growth of the green hydrogen production sector.
- To assess the feasibility of cost reduction through economies of scale.
- To determine the impact of government intervention through policies, incentives, or regulation in reducing domestic production costs
- To determine the effect of international collaboration, information, and technology sharing in reducing domestic production costs.

2. Literature Review

Governments worldwide are seeking to reduce their carbon emission significantly by 2050. These governments have turned to hydrogen as a substitute for oil since it's a low to zero-emission fuel naturally abundant in the earth's atmosphere and water. IEA (2023) asserts that hydrogen is present in 0.14% of the planet's crust, 71% in water bodies, and 4% can be found in the atmosphere. Its abundance makes hydrogen a suitable alternative to fossil fuels since it has no residue and only emits water vapour when burned. However, hydrogen is not typically found in its purest form; it can be produced by burning fossil and renewable fuels. The need for additional manufacturing processes to produce green hydrogen has created steep production costs that easily outweigh the cost of mining and refining fossil fuels. The world produces only 75 MtH2/yr of green hydrogen, which amounts to only 3% of the global energy demand. The production was mainly confined to developed states like China, Germany, Japan, and Australia, with fuel-dependent countries like Saudi Arabia, Oman, and Algeria having little to no green hydrogen-producing plants. The current production is too small to transition to a hydrogen-based economy, leading to the IEA states pledging to increase green hydrogen production by 445 megawatts per year through its Announced pledge scenario (IEA, 2023). Oman has pledged to increase its green hydrogen production to 1Mt by 2030, 3.75Mt by 2040, and 8.5Mt by 2050.

2.1 Drivers of green hydrogen production in Oman

The main drivers of green hydrogen production in Oman are Vision 2040, IEA pledges, and expanding its diversification away from fossil fuels. Oman's Vision 2040 aims to become a zero-carbon economy by 2050 as part of its initiative to mitigate climate change and improve its environmental performance. The country established Hydrogen Oman (Hydrom) to develop its domestic hydrogen sector through strategic planning and allocation of government land for renewable hydrogen projects. Further, the Sultanate allocated over 50,000 square kilometres of land for green hydrogen projects under Royal Decree 2023/10. Oman has already implemented wind, solar power, and solar IPP projects to help achieve this goal, and the establishment of green hydrogen plants will further increase its green capacity. ITA (2024, 2) adds that Oman plans to invest $140 billion in the hydrogen production industry. It has established the Oman Sustainability Center under the Ministry of Energy and Minerals to oversee its transition plans.

Currently, Oman is in the land allocation and assessment phase with no existing green hydrogen production plants. It has eight large projects for green hydrogen production, which amount to $49 billion in total investments. These projects are expected to produce 1.38 million tons of green hydrogen annually by 2030. Oman also secured 47-year commercial agreements with developers from numerous countries like the UK, UAE, Kuwait, Germany, India, and Singapore to oversee a 7-year construction phase and 40-year operation period. It also agreed with the Netherlands to develop liquid hydrogen supply chains between the countries.

2.2 Primary cost drivers of green hydrogen production in Oman

One key hindrance is the cost of electrolyzers whose electrodes are made from expensive and rare materials like iridium and platinum. Also, the manufacturing process for electrolyzers requires advanced and precise technology, which tends to increase the cost of the final product. According to Lichner (2024, 2), all electrolyzers have a specific stack that splits water into oxygen and hydrogen. The stack consists of plastic membranes, gas-tight, and welded bipolar plates, which are expensive to acquire, manufacture, and assemble. Another study by Wang (2023, 1) states that this stack makes up 33% of the total cost for electrolyzers. Another 40% comes from additional technical equipment needed to perform the process, such as power electronics, gas purification, and separation. 27% of the total costs come from labor, electrode housing, and equipment installation as shown in Figure 1 below.

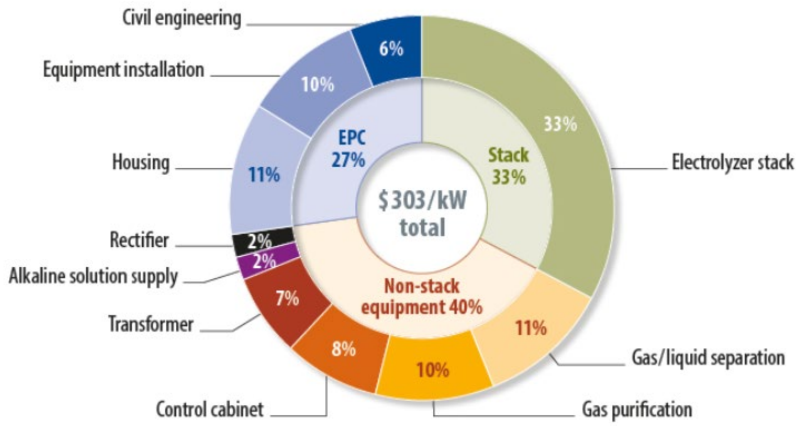

Figure 1. Low-end benchmark capex for alkaline electrolysis system in China (**Source: Wang (2023, 4)**

Another cost driver is the high electricity cost of electrolysis. Water electrolysis is energy-intensive, with 39.7kWh producing 1 kg of hydrogen. Electrolyzers have an energy conversion efficiency of 70%, meaning that 30% of electricity is lost due to heat, further increasing the operating costs of green hydrogen plants. Also, green hydrogen production requires electricity from renewable energy sources like wind and solar power. The cost of such systems is often higher than that of conventional electricity sources. In Oman, solar power costs between $4.6-$6/kWh, meaning that green hydrogen plants must pay $182.62-$238 for every 1 kg of hydrogen produced.

2.3 Policies and initiatives to increase investment in Oman's domestic market

Oman's policies and initiatives should mirror those already set by Morocco. Morocco is the only African country producing green hydrogen due to its comprehensive policies in the sector. The government introduced the Morocco offer, a comprehensive incentive outlining all the guidelines and tax incentives that benefit investors in the green hydrogen sector and other renewable energies. The offer allocates one million hectares for renewable energy projects. It collaborates with government agencies and local and international companies to finance and develop green hydrogen production plants (Lebrouhi et al., 2024, 490). Since water electrolysis also requires renewable energy, the Moroccan government has established solar and wind farms, which provide 858 and 1,788 megawatts, respectively (Touili et al., 2019, 3). These plants can provide the energy requirements needed for green hydrogen production in the country. Oman is following the same trend by establishing similar laws that encourage cooperation between established green hydrogen producing states and new ones.

3. Methods

The study will conduct semi-structured interviews with a mix of open and closed-ended questions to ensure the researcher can perform follow-up on vital topics. The mixed questions also offer more flexibility to the interviewees, allowing them to share their ideas and opinions on Oman's current and future green hydrogen framework (Magaldi & Berler, 2020). The study uses a mixed methods design to answer the research questions. Based on the design, the quantitative data was collected from secondary data sources, while qualitative data was collected from semi-structured interviews. The secondary data was collected from systematic searches on search engines and relevant academic databases like JSTOR, EBSCO, ScienceDirect, and the Directory of Open Access Journals (DOAJ). Additional data was obtained from government documents and websites focusing on green hydrogen production in Oman. The study used specific search terms to filter website and database information, which included "green hydrogen," "Oman," "Cost drivers," and "green hydrogen policies." These search terms were designed to answer the research questions while comprehensively understanding Oman's green hydrogen capabilities, challenges, and opportunities.

4. Results and Discussion

This section explores the key factors shaping the cost and potential of green hydrogen production in Oman. From electricity prices and electrolyzer technology to the benefits of scaling up, it dives into what makes the process expensive—and where savings can be found. It also touches on real challenges, like the current shortage of local expertise and the need for more supportive policies. At the same time, Oman's climate and strategic location open up exciting opportunities to become a regional leader in green hydrogen

4.1Results

According to a report by IRENA, the main cost drivers of green hydrogen production are electricity, electrolyzer costs, engineering, and balance of plant costs. Electricity accounts for nearly 75% of the cost of operating a green hydrogen plant. Electrolyzers have an energy conversion efficiency of 70%, meaning that 30% of electricity is lost due to heat, further increasing the operating costs of green hydrogen plants. Also, green hydrogen production requires electricity from renewable energy sources like wind and solar power. The cost of such systems is often higher than that of conventional electricity sources. In Oman, solar power costs between \$4.6-\$6/kWh, meaning that green hydrogen plants must pay \$182.62-\$238 for every 1 kg of Hydrogen produced. Figure 2 shows the cost breakdown for 1MW PEM electrolyzer.

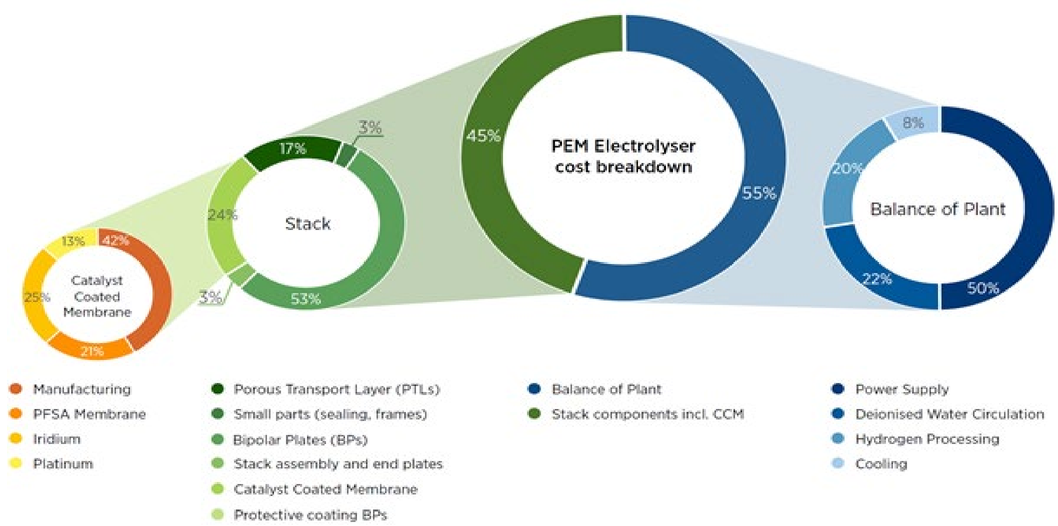

Figure 2. Cost breakdown for 1MW PEM electrolizer

According to Lichner (2024), all electrolyzers have a specific stack that splits water into oxygen and Hydrogen. The stack consists of plastic membranes, gas-tight, and welded bipolar plates, which are expensive to acquire, manufacture, and assemble. Another study by Wang (2023) states that this stack makes up 33% of the total cost for electrolyzers.

Another 40% comes from additional technical equipment needed to perform the process, such as power electronics, gas purification, and separation. 27% of the total costs come from labour, electrode housing, and equipment installation. Despite the high cost of electrode stacks, they are a vital requirement of any green hydrogen plant, and Oman has little power to influence stock prices. However, the Sultanate can minimize the operational costs of these electrolyzers by choosing the right stack. Solid oxide electrolyzers can reduce power loss and increase system efficiency by conducting heat from the surrounding atmosphere. Solid oxide electrolyzers are among the most advanced systems worldwide, and their ability to elevate the operating temperature of their anode and cathode overpotentials makes them the best electrolyzers for reducing electricity costs. In contrast, AEM electrolyzers (57-69 kWh per 1 kg of Hydrogen) and PEM electrolyzers (50-78 kWh per 1 kg of Hydrogen) have a much higher electricity consumption rate. They cannot work under atmospheric conditions, meaning they consume more than solid oxide electrolyzers (Ionomr Innovations, 2020).

Another factor developers officials need to consider is the stack size. One of the interviewees mentions that despite the high cost of green hydrogen production, creating larger green hydrogen plants can reduce the average operational cost through economies of scale. This fact is supported by IRENA, which mentions that scaling a green hydrogen plant from 1-20 MW can reduce a third of its original expenses. Scaling up the plant can also reduce costs related to the balance of plant, gas conditioning, and electricity costs. Morocco benefits from such stack size advantages as shown by their KfW Development Bank's hybrid Solar and wind power plant, which produces 100MW of Hydrogen annually. The country plans to increase its green hydrogen production capacity by constructing the S2H2+Bm's green hydrogen production plant and the HDF Energy and Falcon Capital Dakhla's White Dunes project, which will produce 500,000 and 200,000 tons of Hydrogen annually. The developers will need to consider their stack sizes and the capacity of the electrolyzer when constructing green hydrogen plants to ensure the country can benefit from economies of scale.

The interviews showed a constant theme of the lack of expertise in the area from Oman citizens. According to Hydrom's CEO, less than 0.005% of Oman residents have been trained in green hydrogen production and electrolyzers. This presents a significant challenge to the industry since the technology relies on expertise, and hiring untrained officials will likely increase operational costs. Under Oman Vision 2040, Hydrom will oversee the Sultanate's rise in local capacity by offering scholarships and developing renewable energy courses for its young generation, and that’s also part of the In-Country-Value requirements the developers have to contribute (Hydrom, 2024). However, such a program is expected to increase its local capacity within the next 6-20 years, which could cause the country to fall behind on its renewable energy goals. Ahshan (2021) recommends that the initial stages of Oman's energy transition be done using expatriates who can train other workers on running the intricate machines while keeping up with the Sultanate's goals. Additionally, Oman can mutually agree to develop and operate green hydrogen plants with developed nations like Germany, China, and Japan to meet its goals.

The central opportunity theme from the interviews was the strategic location of Oman. The country is situated on the Arabian Sea with maritime access to major buyers like India and China through the Indian Ocean. The government is also near Europe and can move liquified Hydrogen to the continent via road, rail, and sea. South Asia and Europe consume nearly half of the world's electricity, making them potential buyers of hydrogen gas. Figure 3 below shows EIA’s energy use per region from 1980-2016.

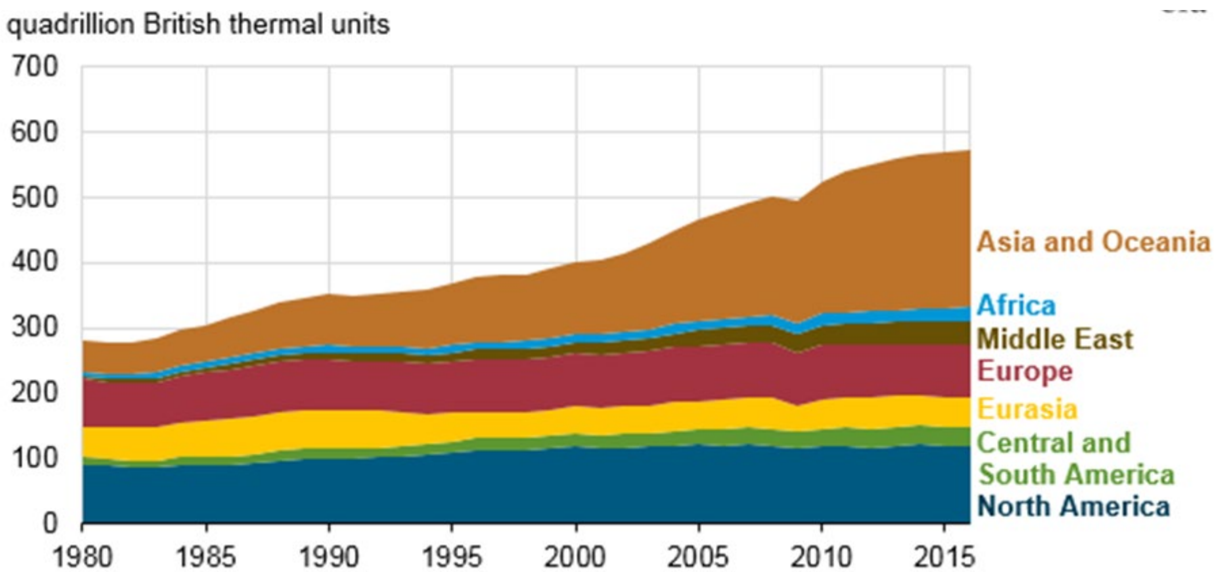

Figure 3. Energy use by world region from 1980 to 2016 (**Source: EIA (2019)**

4.2 Discussion

A key advantage for the Sultanate regarding electricity is its hot and dry desert climate. Electrolyzers convert a considerable amount of energy to create the optimal operating temperature of the solid oxide electrolyzers. The optimal temperature for solid oxide electrolyzers is 500-850 °C, and Oman has an average daily temperature of 25-40 °C (Taibi et al. 2020). These high temperatures, coupled with the conductive nature of metal electrolyzers, mean the anode and cathode overpotentials will be decreased, increasing the electrolyzers' efficiency and ability to split water molecules through thermal energy. Perspectives from the interviewees also align with this assumption. Hydrom CEO Abdulaziz Al Shidhani states, "Our hot climate makes us a suitable green hydrogen-producing country since it reduces the amount of energy lost during the electrolysis process. It also hastens the construction process, leading to lower construction costs. Our unique climate in the Middle East stands to save us billions in building and operating these green hydrogen plants."

These findings coincide with Tian et al. (2024) research, which shows that the highest hydrogen production occurs in summer months with peak sun hours. Conversely, hydrogen production is relatively lower in the winter months. In the case of Oman, where winters are usually between 20-30 C, space cooling is more prevalent than heating. The high solar intensity means that any excess electricity generated during Oman’s summer and winter seasons can be channeled to the power grid to help meet their industrial and residential demands. However, in the current set up for the green hydrogen production plant in Oman, the whole system is a stand-alone system. Where the electricity produced by renewable energy will only feed the electrolyzer along with the facility around it.

Another study by Ahshan (2021) investigates the solar intensity of 15 locations in Oman. These locations were selected based on their potential for green hydrogen production and their inclusion under the national decree. The sites included Ibri, As-Suwayq, Thumrait, Masirah, Nizwa, Salalah, Muscat, Sur, Sohar, Khasab, and Fahud. Among them, Thumrait, Marmul, and Duqm recorded the highest levels of solar radiation, making them more suitable for establishing green hydrogen plants. The high solar radiation in these areas results in lower PV cell operating temperatures, which improves the conversion efficiency of the PV systems. Green hydrogen plants built in such regions are expected to achieve higher maximum power output due to the combination of lower ambient temperatures and improved system efficiency. Below in Figure 4, shows the reduction in maximum power output due to temperature derating effect in those area. Source: Ahshan (2021)

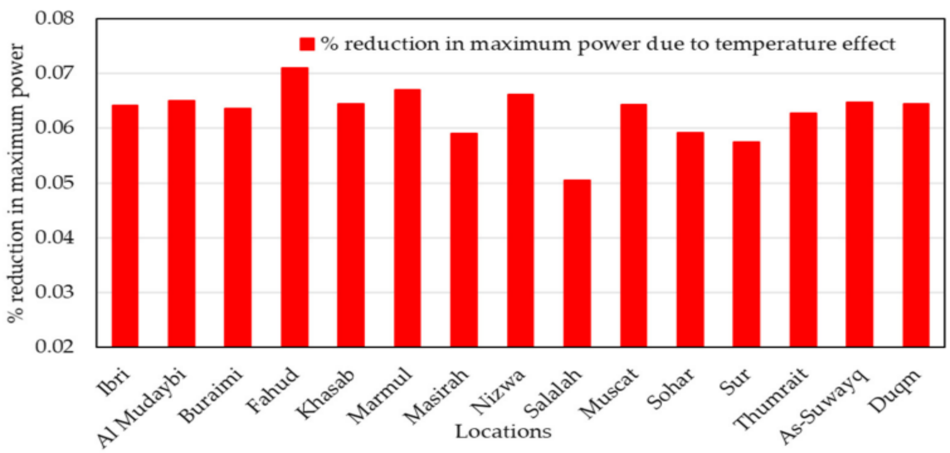

Figure 4. Percentage reduction in maximum power due to temperature derating factor

Oman stands to benefit from cost savings by installing large-scale hydrogen plants. Oman's Vision for 2040 allocates over 50,000 square kilometres of land for building renewable energy projects under Royal Decree 2023/10. Oman plans to build eight green hydrogen plants on the allocated land, which are expected to produce 1.38 million tons of green Hydrogen by 2030. Such an endeavour will require the purchase and operation of large stack sizes, likely reducing operation costs due to economies of scale. The Sultanate also benefits from the numerous commercial agreements with developers and countries with existing green hydrogen plants like the UAE, Germany, India, and Singapore. These agreements will oversee the construction and operational phase of each green hydrogen gas plant, allowing the country to save on labour costs and benefit from the expertise of these developers while building on its local capacity. Other agreements with countries like the Netherlands will oversee research and development of customized storage and transportation mediums for liquified Hydrogen. This agreement will establish pipeline and sea supply routes into Europe and America. Oman also has a commercial agreement with GasLog to develop the port of Amsterdam for the liquefaction, storage, and export of Hydrogen. The agreement will also research and develop specialized vehicles to export liquefied Hydrogen to Asia and Europe. Such strategic agreements will reduce Oman's research and development costs by leveraging the skills and expertise of partner countries. It will also allow Hydrom officials to obtain the expertise needed to build and operate large-scale hydrogen plants.

Another key opportunity for the renewable energy transition is to increase the country's economic diversification. According to Barghash et al. (2022), Oman largely depends on oil exports for a significant portion of its GDP. Recent government initiatives seek to reduce this dependency by diversifying the country's economy to agriculture and renewable energy production. Oman's green hydrogen framework aligns with its economic diversification goals. It will introduce new industries, such as chemical production and hydrogen-based manufacturing, that diversify its exports, offer new job opportunities for its citizens, and increase the scale of the green hydrogen domestic market.
One unique challenge of the green hydrogen venture is Oman's rigid government policies. These policies offer little to no incentives for investors in the green hydrogen sector and will likely minimize investments. The country's policies must be changed to encourage the sector's growth and promote the domestic market of green hydrogen. Ideally, these policies should mirror those of new green Hydrogen-producing countries like Morocco. Morocco has a comprehensive offer for investors in the industry, including tax incentives and allocating land for building new infrastructure. The

Moroccan government has allocated one million hectares to establish renewable energy industries. It offers collaboration with local and international companies and government agencies to finance and develop renewable infrastructure, allowing investors to benefit from the expertise of developed countries like Germany and China, which have commercial agreements with Morocco (Lebrouhi et al., 2024). Morocco also offers tax incentives for associated industries like solar and wind farms. According to Touili et al. (2019), the Moroccan offer has seen associated renewable energy industries grow by 28% in the last 10 years to produce 7,000 gigawatt hours of electricity. These associated industries' growth has reduced the operational cost of Morocco's green hydrogen production, increasing efficiency and boosting their capacity.

Oman must implement comprehensive incentives to increase investments in its green hydrogen sector. The government must implement tax incentives to encourage investors, such as import duty and VAT exemptions for green hydrogen machinery and components. The government should also increase its value chains by linking some local industries, such as transportation and mineral production, to the renewable energy sector. Creating such value chains will ensure sufficient demand for the green Hydrogen produced. Lastly, the Omani government should establish several partnerships to supply the green Hydrogen produced in Asia, Europe, and America. Oman has a geographical advantage because it is close to Europe and Asia's primary green hydrogen consumers. The country should establish consumer partnerships to ensure a stable supply chain for green Hydrogen.

4.3 Proposed Improvements

This study recommends the following for the development of Oman's green hydrogen sector:

- Implementation of comprehensive policies: Hydrom should implement comprehensive policies like duty-free imports, tax incentives, subsidies, and collaboration to encourage investments in its renewable energy sector
- Development of associated industries: Water electrolysis relies on renewable energy sources like water and wind farms. Hydrom should encourage growth in these sectors to reduce electricity costs and carbon emissions.
- Strategic location: green hydrogen plants should be built in places with low ambient temperatures, like Duqm and Thumrait. These lower temperatures increase the PV cells' conversion efficiency, leading to maximum power output.
- Excess electricity: production from these regions can be diverted back to the power grid to offset the GHG emissions in line with the 2050 vision.
- Creation of value chains: Oman must establish a local hydrogen market in its different industries, like steel manufacturing, transport, and mining, to create a local market. It should also develop supply routes to major buyers in Europe and Asia.

5. Conclusion

Oman can become a market leader in green hydrogen production in the Middle East. The country is already transitioning to renewable energy and seeks to diversify its economy and remove its dependency on the export of fossil fuels. Oman's Vision 2040 outlines its goals to produce 1.38 million tons of green Hydrogen by 2030 and allocates 50,000 square kilometres of land to achieve this goal. Based on the interviews, the primary cost drivers of green hydrogen production are electricity, electrolyzer costs, engineering, and balance of plant costs. Electricity accounts for 75% of the operational cost of green hydrogen plants. Oman can minimize this cost by purchasing solid oxide electrolyzers, which can increase electrolyzer heat in atmospheric conditions. Oman experiences a hot and humid climate, reaching nearly 40 °C. The most suitable areas to build green hydrogen plants in Oman are Thumrait, Marmul, and Duqm. These areas have the highest solar radiation, making them more suitable for solar and hydrogen generation. The high solar radiation in these areas leads to lower PV cell operating temperatures that improve the conversion efficiency of the PV systems. Increased conversion efficiency leads to higher maximum power, making plants more profitable.

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Biographies

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Dr. Mira Chitt is an Associate Professor in Mechanical Engineering. She is the Head of Mechanical Engineering Department at Global College of Engineering and Technology (GCET), Muscat, Sultanate of Oman. She received her M.Sc. in Fluid Mechanics from Grenoble Alpes University, France and her Ph.D. in Mechanical Engineering from Paris-Saclay University, France in 2019. She joined GCET in 2021.Her research interests are in the area of Fluid mechanics, Heat Transfer, Management and Logistics. Dr Mira has published several research papers in peer-reviewed international journals and conference proceedings.