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Charting Oman's Path to Green Hydrogen: Embracing Opportunities and Overcoming Challenges

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Abstract

Achieving net-zero emissions is a global obligation that requires everyone's participation. In its unwavering commitment to this cause, the Sultanate of Oman (Oman) considers green hydrogen to be a crucial element in its decarbonisation plan, in which green hydrogen is expected to reduce the total carbon emissions in 2050 by 8% (8.5 Mt). Furthermore, Oman intends to position itself as a global hub for the production and export of green hydrogen by 2030, a testament to its dedication to environmental sustainability.

The objective of this study is to explore how Oman's abundant natural resources can be harnessed to address the challenges posed by current technologies used for green-hydrogen production and promote the adoption of renewable energy sources in the country. The paper presents an analysis of the unique opportunities available in Oman: first, in green-hydrogen production by using natural minerals and critical elements extracted from the country's land for the manufacturing of electrolysis systems; and second, in renewable energy sources to power hydrogen plants with clean electrical power, including electrolysis systems. The discussion covers different types of electrolysis, including alkaline water electrolysis (AWE), proton-exchange membrane (PEM) electrolysis, solid oxide electrolysis (SOE), and anion-exchange membrane (AEM) electrolysis. Additionally, it delves into various renewable energy sources, such as onshore wind, solar photovoltaics (PV), concentrated solar power (CSP), among others, all of which are abundant in Oman.

The paper compares the different types of electrolysis and different renewable energy sources in terms of the costs of installation, operation and maintenance, produced electricity, and system lifetime. Additionally, the study examines the challenges associated with electrolysis, such as the limitation of pure water resources required for water-splitting operations in Oman's environment. Moreover, the study discusses challenges associated with renewable energy sources, such as their impact on flora and fauna, the effects of high temperatures and dusty climates on solar systems, and the challenge of cost-effectiveness, providing a comprehensive understanding of the issues at hand.

The most significant findings can be summarised as follows. First, using platinum, which accounts for more than 50% of the total stack costs, makes PEM electrolysers expensive. Oman produces and exports platinum, which could be an opportunity. Second, the installation cost of the CSP system is higher than that of other renewable energy sources. This discourages most investors. It has the advantage, however, of being capable of energy storage. Third, the mountain ranges in Oman provide lower temperatures and dust levels, which minimise the negative impact of high temperatures and dust accumulation on PV cells.

The findings will help future researchers in identifying opportunities for Oman to produce green hydrogen and overcome the current challenges.

Keywords: net-zero, CO_2 emission, green hydrogen, onshore wind, solar photovoltaics (PV), concentrated solar power (CSP)

1. Introduction

Achieving net-zero emissions is a global obligation. Thus, Oman has committed to the Paris Agreement's goal of achieving net-zero emissions by 2050. To contribute to this global effort, Oman aims to become the world's sixth-largest hydrogen exporter by 2030. The hydrogen sector is expected to contribute 8% to Oman's overall emission-reduction plan by 2050. To this end, a study is essential to leverage Oman's natural resources to overcome the challenges posed by the technologies currently used for green hydrogen production and promote the use of renewable energy sources in the country. This paper begins by providing an overview of Oman's current energy consumption, carbon emissions, and the forecast for 2050. It then discusses different methods of hydrogen production, with a focus on electrolysis as a green approach. The associated challenges, including cost-effectiveness, are explored, along with ways to overcome them. The role of renewable energy in producing green hydrogen is highlighted, as renewable energy is necessary to power electrolysis. The paper analyses various renewable energy sources that are applicable to Oman and compares their associated challenges. Finally, the paper provides strategic recommendations to tackle the challenges in green hydrogen production.

1.1. Energy Consumption Today and the Forecast for 2050.

Currently, energy dynamics in Oman are influenced by factors such as population growth, industrial expansion, and urban development. Over the past decade, oil consumption has doubled, and natural gas consumption has tripled. Additionally, the power sector has experienced consistent growth parallel to the gross domestic product (GDP) (Charabi, Al-Awadhi and Choudri, 2018). According to the annual report from the Ministry of Energy and Minerals in Oman, the total electrical energy production in 2022 reached 4.18 terawatt-hours (TWh), a 2% increase compared to 2021. Fossil fuels accounted for more than 94% of the total electrical energy, while only 2% was generated from renewable sources. Fig. 1 provides a breakdown of electrical power production in megawatt-hours (MWh), illustrating the proportion of each source relative to the overall amount (Ministry of Energy and Minerals, 2022).

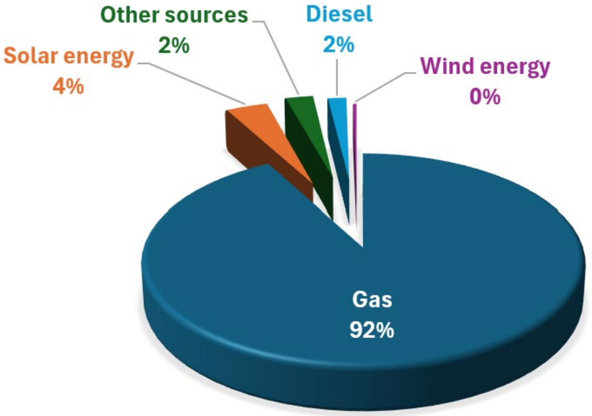

Fig. 1—Production of electricity in Oman by source.

1.2. Carbon Emissions Today and the Forecast for 2050.

Oman conducted a carbon emissions assessment in 2021, revealing that the total carbon emissions amounted to 90 million metric tons (Mt) of carbon dioxide equivalent (CO2e) (Environment Authority, 2022). Unless immediate action is taken, the carbon emissions in Oman are expected to increase by 16% to 104 Mt CO2e by 2050 (Ministry of Energy and Minerals, 2022). Notably, five sectors were responsible for 95% of the Sultanate's total emissions: the industrial sector accounted for 32%, oil and gas sector 26%, electrical power sector 19%, and transportation and buildings sectors 18% collectively. Fig. 2 shows today's carbon emissions by sector (Environment Authority, 2022).

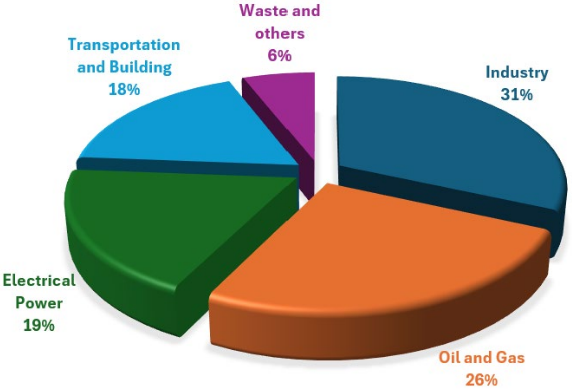

Fig. 2—Today's carbon emissions in Oman by sector.

2. Green Hydrogen-Production Methods

Oman has set a goal to become the world's sixth-largest hydrogen exporter by 2030. The country plans to produce 1.25 million tonnes of hydrogen by 2030 and then increase production to 3.5 million tonnes by 2040 and 8 million tonnes by 2050 (Renewable Hydrogen from Oman, 2023). Some of this hydrogen will be used in Oman to reduce emissions from transportation and industry. It is expected that up to 5% of the total emission reduction in the transportation sector and 5–15% of the total reduction in the industrial sector will be achieved through the use of green hydrogen. Through these two sectors alone, hydrogen is expected to contribute 8% to the overall emission reduction plan by 2050 (Ministry of Energy and Minerals, 2022; Environment Authority, 2022). The remaining emission of the emission reduction plan will be converted into ammonia for export. To ensure that the hydrogen produced contributes to emission reduction, it must be produced from sustainable resources (green hydrogen) (Ministry of Energy and Minerals, 2022; Environment Authority, 2022; Hydrom_om, 2023a; Hydrom_om, 2023b; Ministry of Energy and Minerals, 2023).

2.1. Hydrogen Classification.

Although hydrogen is a colourless gas, colour classification is used to differentiate between the hydrogen-producing methods and their associated greenhouse gas (GHG) emissions (Ramli, 2023). For example, grey hydrogen refers to the hydrogen generated from fossil fuels that result in the release of carbon dioxide (CO2) gases or any GHGs (Dash, Chakraborty and Elangovan, 2023). The cost of producing grey hydrogen is low compared to other hydrogen-producing methods. However, its CO2 emissions are considered medium to high depending upon the technology used. Normally, gasification technologies produce more CO2 than reforming technologies that use natural gas as a source of energy (Shiva Kumar and Lim, 2022; Hydrom_om, 2023b). Blue hydrogen is produced in the same way as grey hydrogen except that a carbon-capture system is used (CCSs) (Dash, Chakraborty and Elangovan, 2023). This method is used to reduce GHG. Producing blue hydrogen is around 40–50% more expensive than producing grey hydrogen. The total CO2 emissions are considered low, however, because of the CCS (Shiva Kumar and Lim, 2022). The third type is green hydrogen. This is considered the cleanest way to produce hydrogen, as it uses renewable energy (Dash, Chakraborty and Elangovan, 2023; Hydrom_om, 2023b). The CO2 emissions are almost nonexistent, especially if electrolysis technology is used. Producing this kind of hydrogen is much more expensive than producing grey or blue hydrogen, an increase of around 400% (Shiva Kumar and Lim, 2022). It is the only type of hydrogen produced naturally, and it is expected to play a vital role in achieving the net-zero emission target globally (Marchant, 2023). While the demand for hydrogen is increasing, the current demand remains concentrated on grey hydrogen. Global production of grey hydrogen grew 3% in 2022. In contrast, blue and green hydrogen grew by less than 1% (IEA, 2023). However, Patrick Gorr, the global hydrogen lead, declared that Japan will become one of the largest consumers of green hydrogen to achieve net-zero emissions by 2050 (Akimoto, 2023). Moreover, Oman is going to great lengths to become one of the largest producers of green hydrogen by 2050 (Renewable Hydrogen from Oman, 2023). Table 1 presents the technology, source of energy, the CO2 emission level, and the estimated cost of production for each type of hydrogen production.

Table 1—Hydrogen colour classification and CO2 emission level (Shiva Kumar and Lim, 2022).

Hydrogen classification	Technology	Source of energy	CO2 emission	Estimated cost USD/kg of H2
Black hydrogen	Gasification	Bituminous	High	1.2–2.1
Grey hydrogen	Reforming	Natural gas	Medium	1–2.1
Blue hydrogen	Reforming + CCS	Natural gas	Low	1.5–2.9
Green hydrogen	Electrolysis	Water	Minimal	3.6–5.8

2.2. Electrolysis.

Oman is moving towards using electrolysis technologies to produce green hydrogen. It is planning to manufacture electrolysers domestically (Hydrom_om, 2023a; Hydrom_om, 2023b; Ministry of Energy and Minerals, 2023) by using natural minerals and critical elements, such as chromite and carbonatite, extracted from its lands (Ministry of Energy and Minerals, 2023). To feed these electrolysers and shift from grey hydrogen to green hydrogen, however, renewable electricity generation must increase significantly. Electrolysis is a method for obtaining pure and clean hydrogen (Huang and Peng, 2006). It was invented in 1800 by William Nicholson and Sir Anthony Carlisle (Aragón-González *et al.,* 2015). This technique splits water molecules into hydrogen and oxygen through electrochemical means, using an electrical power supply (Shiva Kumar and Lim, 2022; David, Ocampo-Martínez and Sánchez-Peña, 2019). It is the most effective way to produce high-purity hydrogen (Cavaliere, 2023). Equation (1) represents the basic reaction of the water electrolysis. This reaction (experimentally and at room temperature) requires a 1.48 V direct current (DC) supply to split the water into hydrogen and oxygen (Shiva Kumar and Lim, 2022). The electrolyser is clean, as it uses water and only emits pure oxygen. The required power can be supplied by renewable energy sources (Shiva Kumar and Himabindu, 2019) to ensure the hydrogen is completely green. According to the Global Hydrogen Review 2023 (IEA, 2023), the global capacity for water electrolysis is rising. By the end of 2022, capacity had increased 20% compared to 2021, reaching around 700 MW. Since the technology was introduced in the 18th century, four types of water electrolysis have been developed based on their operating condition, electrolyte type, and ionic agents: alkaline water electrolysis (AWE), proton-exchange membrane (PEM) electrolysis, solid oxide electrolysis (SOE), and anion-exchange membrane (AEM) electrolysis (Shiva Kumar and Lim, 2022).

$$1H_2O + Electricity\ (237.2\ kJ\ mol^{-1}) + Heat\ (48.6\ kJ\ mol^{-1})\ \rightarrow\ H_2 + \frac{1}{2}O_2 \qquad (1)$$

2.2.1. *Alkaline Water Electrolysis.*

Alkaline water electrolysis is a method of hydrogen production first introduced in 1789 by the scientists Troostwijk and Diemann (Shiva Kumar and Himabindu, 2019; Arabkoohsar, 2023). The technology is highly advanced and has been developed to the point where it can be used commercially to generate a level of megawatts (MW) of power (Bianco, Hawila and Blanco, 2021; Shiva Kumar and Himabindu, 2019). The system operates using a concentrated alkaline solution such as KOH/NaOH at low temperatures (30–80 °C). It is considered preferable to PEM for large-scale applications due to its lower capital cost of approximately 270 USD/kW. However, its lifetime is considered low, with a lifespan of up to 60,000 hours. Additionally, it produces gases of a low purity due to the diaphragm material, which does not prevent gas crossover between the two parts, namely the hydrogen evolution reaction (HER) and the oxygen evolution reaction (OER) (Shiva Kumar and Lim, 2022). Fig. 3 depicts the main components of AWE:

1. Diaphragm: This component prevents gas mixing and enables gas collection. It is usually made of asbestos, Zirfon, or nickel and coated with porous stainless steel.
2. Current collectors: These are gas diffusion layers (GDLs) made of nickel mesh or foam.
3. Separator plates: Also known as bipolar plates (BPs), these are made of stainless steel or nickel-coated stainless steel.
4. End plates: These are plates located at the ends of the cell stack, made of stainless steel or nickel-coated stainless steel.

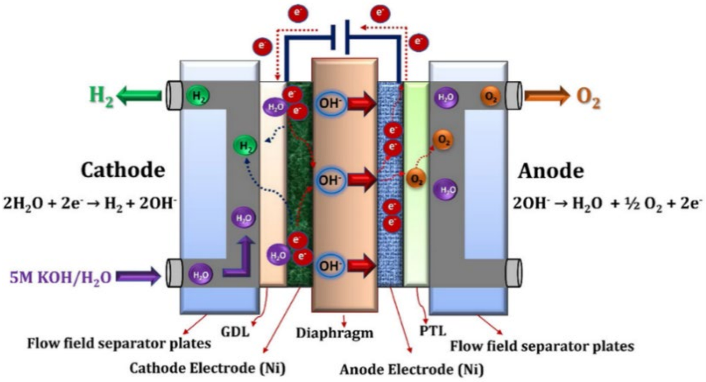

Fig. 3—Main components of AWE (Chaudhary, Bhardvaj and Chaudhary, 2024).

AWE is an electrochemical method that uses a DC electric supply to divide the water molecule (H2O) into hydrogen (H2) and oxygen (O2). The AWE cell comprises two parts, each with its own set of electrodes, namely the cathode and the anode. The cathode electrode produces a HER, which reduces two H2O molecules to create one H2 molecule and two hydroxide OH^- molecules. The H2 molecule is then removed as a product. Both HO^- molecules transfer to the anode side via a porous separator under the influence of the DC supply. The anode side experiences an oxidation of OH^-, resulting in half a molecule of O2 and one molecule of H2O. Equations (2) and (3) and Fig. 9 illustrate both HERs and OERs:

$$2OH^- \rightarrow H_2O + \frac{1}{2}O_2 + 2e^- \qquad (2)$$

$$2H_2O + 2e^- \rightarrow H_2 + 2OH^- \qquad (3)$$

The main challenge of AWE lies in the current density, which is limited to 0.5 A/cm^2 (Shiva Kumar and Lim, 2022). Technically, the current density can be increased up to 2–3 A/cm^2, but it is not commercially viable due to lower efficiency (Taibi *et al.,* 2020). Increasing the current density in the electrolysis process results in a higher rate of hydrogen production, according to Faraday's law (Siracusano *et al.,* 2023).

Sandeep (Sandeep *et al.,* 2017) examined the correlation between hydrogen production and current density. The author notes that the primary challenge in producing hydrogen through water electrolysis is the high operation cost due to electricity expenses. The question therefore arises of how the voltage can be minimised while maintaining a high current density in the cell module. Typically, when we operate at high current density, hydrogen production increases, but so does the cell voltage. This results in lower cell efficiency and increased hydrogen-production costs. Fig. 4 shows the relation between current density and cell voltage.

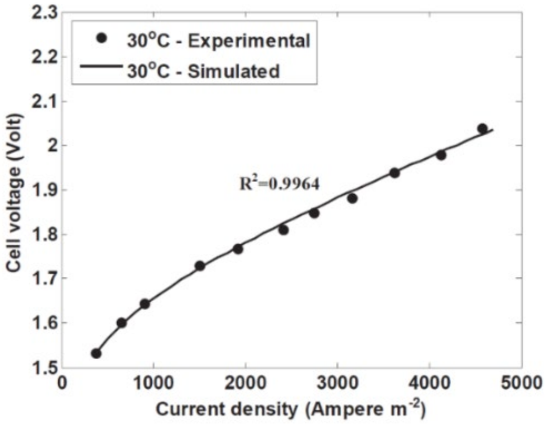

Fig. 4—Correlation between the current density and cell voltage in AWE (Sandeep *et al.*, 2017).

The crossing of gas through the porous diaphragm poses a significant challenge (Shiva Kumar and Lim, 2022). This crossing can adversely affect both the efficiency and safety of the cell, especially when the electrolyser operates at high pressure (Taibi *et al.*, 2020). It is therefore imperative to develop a separator that exhibits low hydrogen permeability, low area resistance, high bubble point pressure, and high OH^- conductivity (Lee *et al.*, 2020).

Degradation of catalyst layers is a significant challenge for electrolysers (Taibi *et al.*, 2020) and has a direct impact on the cell's performance and stability, as shown in Fig. 5. Developing a stable design and high-performance catalyst is essential to ensuring the electrolyser's long-term viability (Xie *et al.*, 2022).

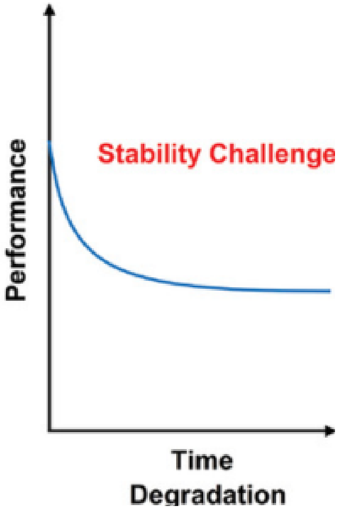

Fig. 5—Relationship between catalyst degradation and electrolyser performance (Xie *et al.*, 2022).

AWE poses several challenges. These include increasing the cell pressure to over 70 bar, lowering electricity consumption to less than 45 units/kg of hydrogen produced, increasing the cell lifetime to 100,000 hours, and reducing the capital cost of stacks smaller than 1 MW to less than 100 USD/kW. Additionally, reducing the capital cost of systems larger than 10 MW to less than 200 USD/kW is an important goal (Taibi *et al.*, 2020).

The estimated cost of an entire hydrogen plant that produces more than 10 MW and uses an AWE is between 500 and 1,000 USD/kW. The electrolyser itself accounts for around 45% of the total plant cost, while 57% of this cost is attributed to the stack assembly and end plates, including the diaphragm. The remaining 28% of the plant's total cost is for the electrical power supply (Taibi *et al.*, 2020). The most significant opportunities for cost reduction in the AWE system are therefore the power supply, followed by the diaphragm, including the electrode costs. Fig. 6 shows the cost breakdown in detail.

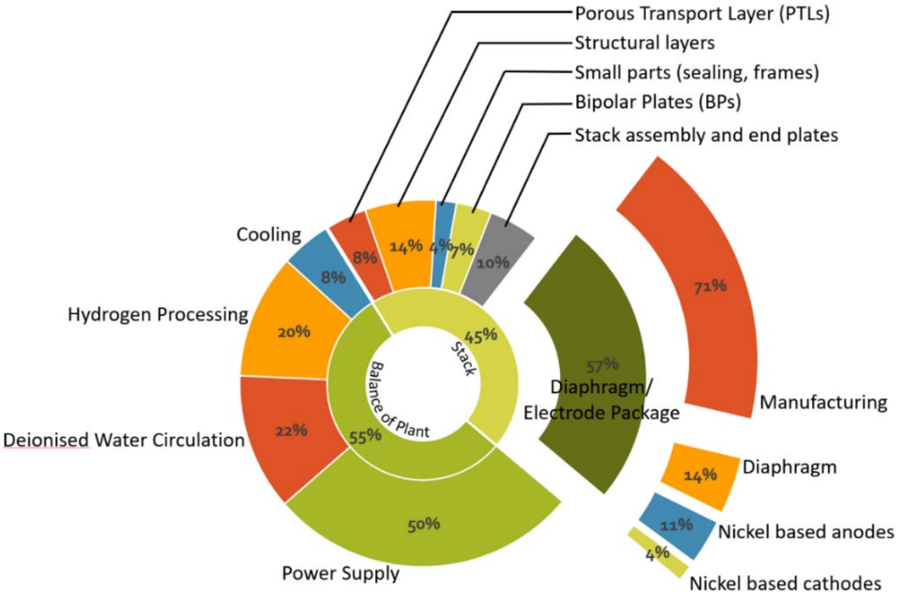

Fig. 6—Cost breakdown of AWE electrolyser.

2.2.2. ***Proton-Exchange Membrane Electrolysis.***

The first PEM water electrolysis was conceptualised by Grubb in the early 1950s, and General Electric developed PEM in 1966 to overcome the limitations of AWE (Shiva Kumar and Lim, 2022; Shiva Kumar and Himabindu, 2019; Aragón-González *et al.,* 2015). A comparison between AWE and PEM has shown that PEM offers an improved current density range and operates at lower voltages and temperatures; it also produces higher purity gases of both H2 and O2, and the stacks in PEM have a longer lifetime than those in AWE (Taibi *et al.,* 2020; Bianco, Hawila and Blanco, 2021; Shiva Kumar and Himabindu, 2019; Shiva Kumar and Lim, 2022; Siracusano *et al.,* 2023). Additionally, the PEM membrane has several advantages, including lower gas crossover, less thickness, higher proton conductivity, and higher operating pressure (Shiva Kumar and Himabindu, 2019). Although PEM currently lags behind AWE in terms of efficiency and cost, this drawback is being addressed through ongoing research and development (Bianco, Hawila and Blanco, 2021). This section discusses various components of a PEM water electrolysis cell, including the membrane electrode assembly (MEA), GDL, and current collectors, and their roles in the overall function of the PEM cell. Fig. 7 depicts the components of the PEM water electrolysis cell.

The MEA, which includes the materials of the membrane, anode, and cathode electrodes, is the heart of the PEM and plays a crucial role in its overall function. Typically, perfluorinated sulfonic acid (PFSA) membranes like Aciplex, Flemion, Fumapem, and Nafion are used. Among these, Nafion is the most commonly used due to properties such as high durability, mechanical stability, high proton conductivity, and the ability to operate at higher current densities (Shiva Kumar and Lim, 2022; Shiva Kumar and Himabindu, 2019).

The GDL is an essential component of the PEM (Cruz *et al.,* 2020; Akay and Yurtcan, 2020) It is responsible for transporting gas and water in the cells (Cruz *et al.,* 2020). Its structure includes two layers: the microporous layer, located close to the electrode, and the macroporous layer, which is closer to the bipolar plate (Akay and Yurtcan, 2020). It is worth noting, however, that it can decrease the reliability and performance of the catalytic layer on the O2 electrode (Cruz *et al.,* 2020).

Current collectors are also known as porous transport layers (Grigoriev *et al.,* 2009; Cavaliere, 2023) and are positioned in both the anode and cathode sides between the MEA and the bipolar plate (end plate) (Cavaliere, 2023). The current collectors allow the electrical current to flow (Shiva Kumar and Himabindu, 2019) from the bipolar plate and distribute itself on the electrode surface where the chemical reaction of water splitting occurs (Cavaliere, 2023; Shiva Kumar and Himabindu, 2019). It is necessary to transport the hydrogen gases produced by the electrodes to the production manifolds using the BPs (Cavaliere, 2023). Furthermore, current collectors provide the membrane with mechanical strength. The materials used for current collectors must have high conductivity and corrosion resistance (Shiva Kumar and Himabindu, 2019).

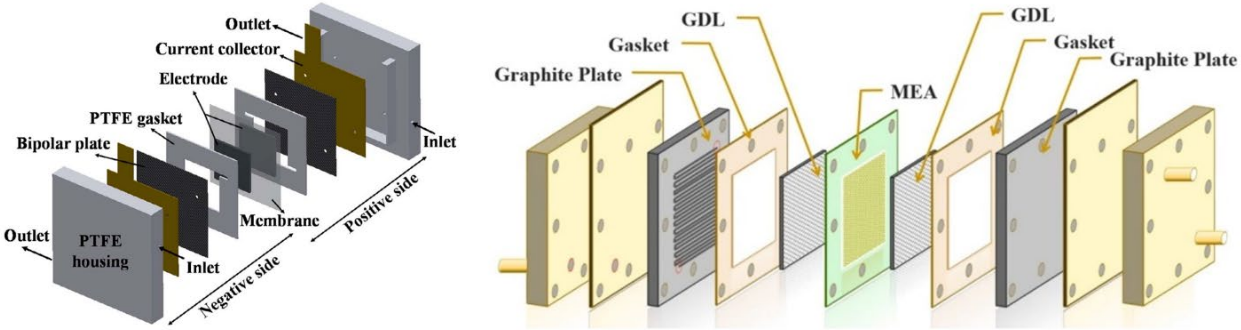

Fig. 7—Parts of a PEM water electrolysis cell (Kim and Park, 2017; Kan-Lin, 2018).

In PEM water electrolysis, water is pumped to the anode side. A potential difference between the electrodes causes an oxidation reaction that splits the water molecules electrochemically into O2 atoms, protons (H^+), and electrons (e^-). The O2 atoms are released from the electrolyser for further processing. The proton (H^+) travels through the conducted membrane to the cathode side, while the electrons (e^-) move from the anode electrode to the cathode side through an external electrical circuit. The reaction is illustrated in Equation (4). On the cathode side, the protons of hydrogen and the electrons recombine to produce high-purity hydrogen (H2). The reaction is shown in Equation (5) and Fig. 9 (Shiva Kumar and Lim, 2022; Shiva Kumar and Himabindu, 2019; Aragón-González *et al.,* 2015).

$$H_2O \rightarrow \frac{1}{2}O_2 + 2H^+ + 2e^- \tag{4}$$

$$2H^+ + 2e^- \rightarrow H_2 \tag{5}$$

The PEM electrolyser has several key advantages. First, it has a fast response time and can quickly and effectively adapt to the unpredictable nature of renewable energy. Second, it produces high-purity hydrogen with high pressure, making it good for storage and transportation. Additionally, the PEM's compact design, along with its high efficiency, high current density, and ability to operate under lower temperatures, has made it an acceptable choice worldwide (Wang *et al.,* 2023; Shiva Kumar and Himabindu, 2019; Shiva Kumar and Lim, 2022).

Researchers often encounter two major challenges when working with PEM technology. The first is the issue of hydrogen gas permeation, which can compromise the safety and efficiency of the PEM operation (Wang *et al.,* 2023). According to the International Renewable Energy Agency (IRENA) (Taibi *et al.,* 2020), however, this challenge is easy to overcome. The second challenge is the high cost associated with PEM technology. Compared to AWE, PEM technology is four times more expensive (Wang *et al.,* 2023; Shiva Kumar and Himabindu, 2019; Taibi *et al.,* 2020).

The estimated capital cost of a PEM system larger than 10 MW is approximately between 700 and 1,400 USD/kW. The stack alone, size greater than 1 MW, has an estimated cost of 400 USD/kW (Shiva Kumar and Himabindu, 2019; Taibi *et al.,* 2020). The biggest opportunities for cost reduction are in BPs (Belali-Owsia *et al.,* 2015; Chanda *et al.,* 2018; Shiva Kumar and Himabindu, 2019; Taibi *et al.,* 2020), which account for around 24% of the entire system cost. BPs are currently in the research and development stage (Shiva Kumar and Himabindu, 2019; Taibi *et al.,* 2020). The reason behind the high cost of BPs is the use of gold or platinum as a material (Karimi *et al.,* 2012; Taibi *et al.,* 2020; Shiva Kumar and Himabindu, 2019). These materials were developed to tackle the challenge of BP's susceptibility to corrosion by creating a corrosion-resistant coating. This coating helps to make the BPs more robust against corrosion, ultimately leading to their characterisation by corrosion resistance (Karimi *et al.,* 2012; Weng, Dlamini and Chen, 2022). It is important to note that 13% of the total cost of the catalyst-coated membrane is due to the use of platinum. Additionally, the production process of platinum requires a large amount of energy, approximately 243 GJ/kg (Taibi *et al.,* 2020). Moreover, the power supply is a significant factor, as it consumes around 28% of the total system amount. According to the analysis conducted by IRENA (Taibi *et al.,* 2020), the key performance indicators suggest that the cost of the PEM electrolysis system will drop to less than 200 USD/kW by 2050. Additionally, the stack itself is expected to cost less than 100 USD/kW. The catalyst-coated membrane accounts for about 11% of the entire system cost and 24% of the total stack costs (Taibi *et al.,* 2020). It is expected to be achieved significantly (Wang *et al.,* 2023).

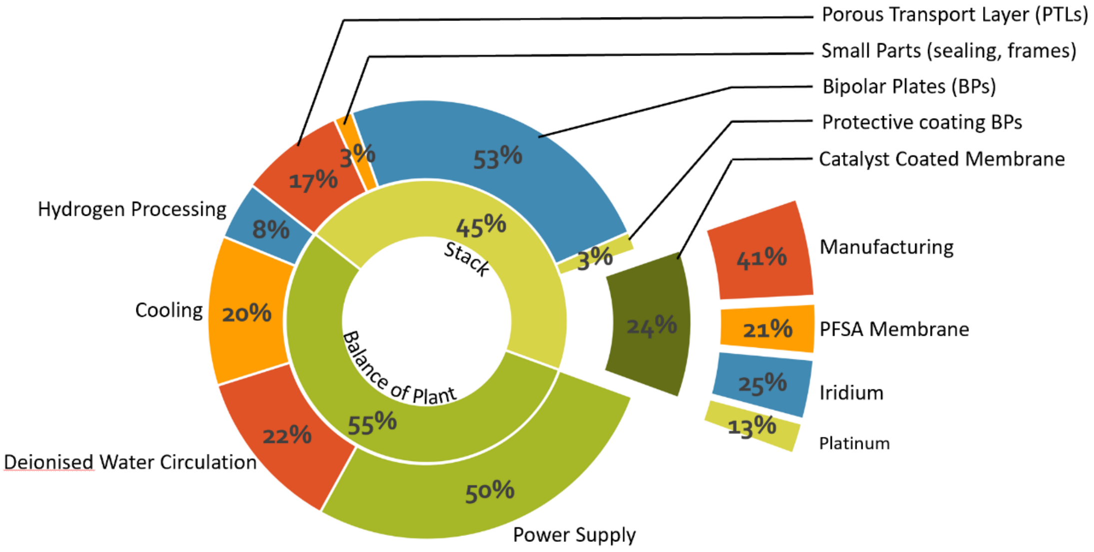

Fig. 8—Cost breakdown of the PEM electrolyser.

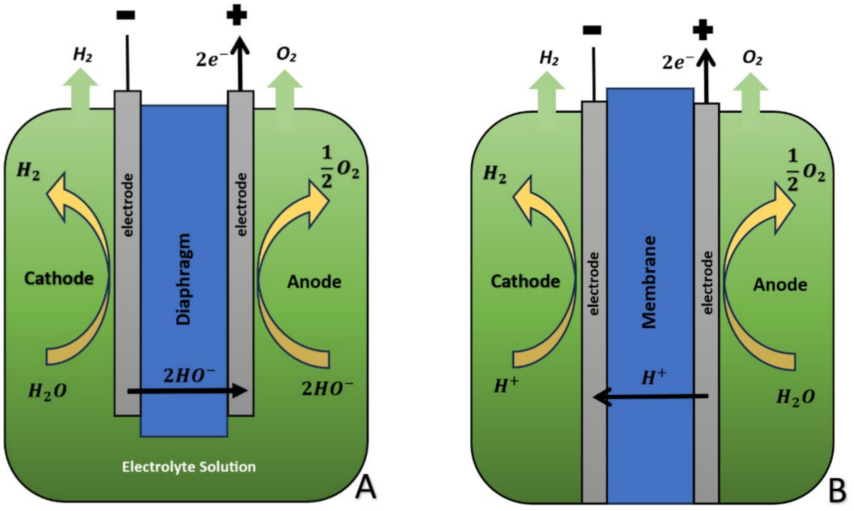

Fig. 9—Water splitting process: (a) AWE; (b) PEM.

2.2.3. Other Water Electrolysis Systems.

There are other electrochemical water-splitting techniques, such as solid oxide electrolysis (SOE). This technique was introduced in the 1980s by Donitz and Erdle and is currently still in the demonstration stage (Shiva Kumar and Himabindu, 2019). A few companies worldwide have begun to offer SOE commercially (Taibi *et al.,* 2020). SOE produces ultra-pure hydrogen and has a higher efficiency. Before being commercialised on a large scale, however, degradation and lack of stability need to be resolved (Shiva Kumar and Himabindu, 2019; Shiva Kumar and Lim, 2022; Taibi *et al.,* 2020).

The anion-exchange membrane (AEM) is a technique for electrochemical water splitting. Davey and Scott published the first paper on this technology in 1957 (Davey and Scott, 1957). An Italian company has developed this technology for commercial use. It is similar to AWE, but the asbestos diaphragm has been replaced by an AEM. Before this technique can be commercialised, however, more work is needed to improve the cell efficiency and stability (Shiva Kumar and Himabindu, 2019).

Table 2 provides a technical comparison of various water electrolysis technologies.

Table 2—Technical comparison of water electrolysis technologies (Taibi *et al.*, 2020; Shiva Kumar and Himabindu, 2019; Bianco, Hawila and Blanco, 2021; Shiva Kumar and Lim, 2022).

	Alkaline	**PEM**	**AEM**	**SOE**
Development status	Commercial	Commercial	Under research & development	Demonstration
Electrolyte	KOH, NaOH	PFSA membranes	DVB polymer	Yttria-stabilised zirconia (YSZ)
Separator	Asbestos, Zirfon or Ni	Nafion	Fumatech	Solid electrolyte YSZ
Porous transport layer anode	Nickel mesh (not always present)	Platinum-coated sintered porous titanium	Nickel foam	Coarse nickel mesh or foam
Porous transport layer cathode	Nickel mesh	Sintered porous titanium or carbon cloth	Nickel foam or carbon cloth	None
Electrode/catalyst (O2 side)	Nickel-coated perforated stainless steel	Iridium oxide	High-surface-area nickel or NiFeCo alloys	Perovskites (e.g. LSCF, LSM)
Electrode/catalyst (H2 side)	Nickel-coated perforated stainless steel	Platinum nanoparticles on carbon black	High-surface-area nickel	Ni/YSZ
Bipolar plate anode	Nickel-coated stainless steel	Platinum-coated titanium	Nickel-coated stainless steel	None
Bipolar plate cathode	Nickel-coated stainless steel	Gold-coated titanium	Nickel-coated stainless steel	Cobalt-coated stainless steel
Frames and sealing	PSU, PTFE, EPDM	PTFE, PSU, ETFE	PTFE, silicon	Ceramic glass
Operating temperature	70–90 °C	50–80 °C	40–60 °C	700–850 °C
Operating pressure (cell)	1–30 bar	<70 bar	<35 bar	1 bar
Nominal current density	0.2–0.8 A/cm^2	1–2 A/cm^2	0.2–2 A/cm^2	0.3–1 A/cm^2
Voltage range	1.4–3 V	1.4–2.5 V	1.4–2.0 V	1.0–1.5 V
Produced H2 purity	99.5–99.998%	99.9–99.9999%	99.9–99.999%	0.999
Voltage efficiency at LHV	50–68%	50–68%	52–67%	75–85 %
Stack unit size	1 MW	1 MW	2.5 kW	5 kW
Electrode area	10,000–30,000 cm^2	1,500 cm^2	<300 cm^2	200 cm^2
Cold start	<50 minutes	<20 minutes	<20 minutes	>600 minutes
Electrical efficiency of stack	47–66 kWh/kg H2	47–66 kWh/kg H2	51.5–66 kWh/kg H2	35–50 kWh/kg H2
Electrical efficiency of system	50–78 kWh/kg H2	50–83 kWh/kg H2	57–69 kWh/kg H2	40–50 kWh/kg H2
Capital costs estimate for >1 MW stacks	270 USD/kW	400 USD/kW	-	>2,000 USD/kW
Capital cost estimate for >10 MW entire system	500–1,000 USD/kW	700–1,400 USD/kW	-	-
Lifetime of stack	60,000 hours	50,000–80,000 hours	>30,000 hours	<20,000 hours
Load range	15–100%	5–120%	5–100%	30–125%

All four types of water electrolysis use water for the splitting process, and so the purity of the water is a consideration, especially in an arid country like Oman. All water electrolysis currently requires high-purity freshwater (Gao, Yu and Gao, 2022; Hu *et al.*, 2023). It takes 9 kg of ultra-pure fresh water to produce 1 kg of green hydrogen (Simoes *et al.*, 2021; Shi, Liao and Li, 2020; Madsen, 2022). There are different sources of ultra-pure freshwater, including groundwater, treated water, and seawater. Table 3 indicates that using groundwater or treated water requires the least amount of raw water, leading to lower power consumption in kilowatt-hours for purification. In contrast, using seawater demands a significant volume of raw water, resulting in higher power consumption for purification.

Table 3—Sources and amount of water required to produce 1 kg of green hydrogen (Madsen, 2022; Kurrer, 2020; Shi, Liao and Li, 2020; Simoes *et al.,* 2021; Bianco, Luo and Nagpal, 2023).

Water source	Ultra-pure water required to produce 1 kg of green hydrogen (litre)	Raw water required to produce ultra-pure water (litre)	Percentage of ultra-pure in raw water	Electrical consumption of electrolysis to produce 1 kg of green hydrogen (kWh)	Electrical consumption of raw water purifying to produce 1 kg of green hydrogen (kWh)
Groundwater or river	11.11	15.56	71.43	50	0.03
Treated water	11.11	16.67	66.67	50	0.03
Seawater	11.11	36.67	30.30	50	0.07

To produce green hydrogen, various water resources must be evaluated in terms of water availability, cost-effectiveness in water transportation, and efficiency in water purification. This is particularly important, as freshwater is a scarce and limited source of water (Simoes *et al.,* 2021).

Fig. 10 illustrates the process required to produce 1 kg of H2. Approximately 35 L of water are necessary to produce 1 kg of green hydrogen using seawater. Of this water, 44% is deionised and used directly for the electrolysis, while the remaining 54% is used for cooling (Bianco, Luo and Nagpal, 2023).

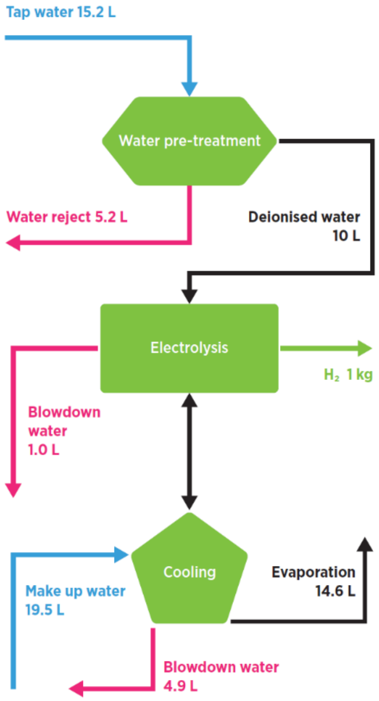

Fig. 10—Water use in green hydrogen production (Bianco, Luo and Nagpal, 2023).

2.3. Renewable Power Supply.

Electrolysis requires an electrical power supply to drive the chemical reaction. To fulfil Oman's 2040 Vision and the target of achieving net-zero emissions by 2050, the hydrogen-production process should be completely decarbonised, and the hydrogen produced should be entirely green. As the electrical power supply is a crucial part of the hydrogen-production process, it must be provided from renewable energy sources. Fig. 11 shows the general arrangement for feeding the electrolyser using renewable energy. Oman has abundant renewable energy resources. Located in the northern hemisphere, precisely at the Tropic of Cancer, Oman experiences some of the highest solar irradiance levels in the world. Additionally, Oman's coastal areas, stretching for 3,165 km, and elevated terrains and mountain ranges exceeding 3,000 m above sea level have significant wind energy potential, making wind power a viable and attractive option for electricity generation. This section outlines the opportunities for renewable energy implementation and the associated challenges.

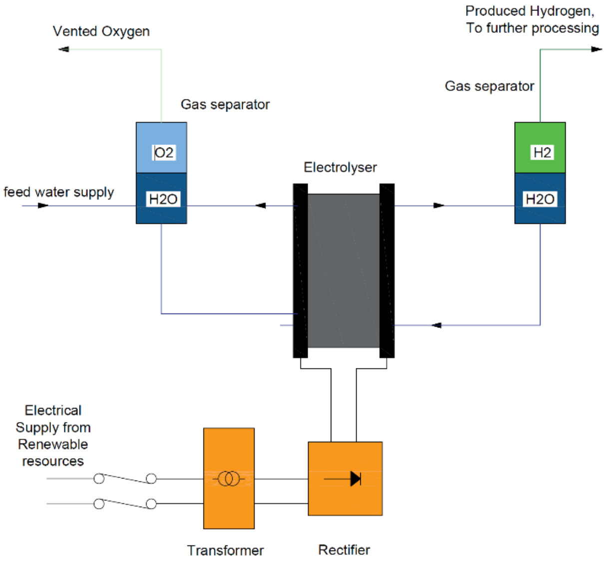

Fig. 11—General arrangement for feeding the electrolyser using renewable energy (Taibi *et al.*, 2020).

2.3.1. *Onshore Wind.*

Oman has a small wind farm called Harweel I, consisting of 13 turbines with a total capacity of 50 MW. The country is planning to build three new wind farms in different locations. These include the Duqm wind independent power project (IPP), Jalan-Bani-Bu-Ali IPP, and Harweel II IPP, with capacities of 200 MW, 100 MW, and 100 MW, respectively. The first two projects are expected to be completed in April 2026, the third in July 2026. The project is currently in the commercial and legal bidding phase (Prabhu, 2023b).

According to the analysis conducted by IRENA (Taylor, Al-Zoghoul and Ralon, 2023), the installation cost of wind farms is 1,274 USD/kW. The cost of electricity is 0.033 USD/kWh. Operation and maintenance costs vary from country to country, but on average a full-service renewal contract costs around 30 USD/kW per year. The expected economic lifetime of a wind farm is 25 years.

The challenges associated with wind turbines can be categorised into three groups: limitations in wind predictability technology, environmental impacts, and climate-related impacts.

Constraints in wind predictability technology: Wind energy is a variable source of energy (Nazir *et al.,* 2019). The speed of the wind is random and varies throughout the year, with fluctuations "seasonally, monthly, weekly, daily, hourly, and sub-hourly", such as gusts and turbulent fluctuations. This variability can cause a loss (cut-off) in the output generated by the turbines when the rotating speed falls below the minimum limit. This, in turn, affects the system's voltage and frequency, leading to disturbances that can affect the system's overall performance (Sharma *et al.,* 2000; Nazir *et al.,* 2019).

Environmental impacts: Wind turbines are often considered a source of noise pollution, causing harm to the environment, animals, and neighbouring residences. The people who live in areas (Nazir *et al.,* 2019) that are crowded by wind turbines suffer from sleep disruption, stress, and hearing issues (Clark and Bohne, 1999; Nazir *et al.,* 2019; van den Berg, 2008). Moreover, wind turbines pose a threat to the environment, including flora and fauna, by killing birds and causing difficulties for other native fauna. This can result in extinction and migration (Nazir *et al.,* 2019).

Climate-related impacts: There are some concerns that increasing the number of wind farms may have a permanent impact on the climate, causing changes in temperature levels. It is believed that wind turbines may reduce daytime temperatures and increase nighttime temperatures, raising environmental concerns. However, the severity of these impacts is still unclear and requires further observation (Nazir *et al.,* 2019).

2.3.2. *Solar Photovoltaics.*

Oman is making serious efforts towards achieving its decarbonisation target and has begun constructing solar PV systems. It has completed three PV projects that are currently in operation. First, the Amin Solar Energy Project, with a production capacity of 100 MW, became operational in 2020. The project is located in Nemr in the southeast of Oman and has been built on a land area of 4 km^2 at a cost of 94 million USD. The second project is the Qabas solar plant, which was established in 2021 with a production capacity of 25 MW. It is located in Sohar in the north coastal area of Oman and has been built on a land area of 0.5 km^2 (Ministry of Energy and Minerals, 2022). The third project is Ibri I & II, which was established in 2022 with a production capacity of 500 MW and is located in Ibri in northwest Oman (Albadi *et al.,* 2019). It has been built on a land area of 13.3 km^2 at a cost of 417 million USD (Ministry of Energy and Minerals, 2022).

Oman has announced a plan to construct two new IPPs, each with a capacity of 500 MW, based on solar PV technology. The two projects, named Manah I and Manah II, will be located next to each other in the Middle North region of Oman (Prabhu, 2023a; Ministry of Energy and Minerals, 2022). The project agreements and tenders were awarded in early 2022, with a projected cost of 460 million USD for the Manah I project (Prabhu, 2023a).

According to IRENA records, the cost of installing a PV system is 876 USD/kW, and the annual operation and maintenance costs are 7.7 USD/kW. These costs are lower than those of a wind farm. However, the cost of electricity generated by the PV system is higher, at 0.049 USD/kWh. The expected lifetime of the system is 25 years (Ministry of Energy and Minerals, 2022).

The hot, arid climate in Oman can have a negative impact on the performance of solar panels. When temperatures rise, the surface of the solar panel heats up, causing a reduction in the operating voltage of the cell, which in turn results in a decrease in the overall output power of the system (Aslam *et al.,* 2022; Dubey, Sarvaiya and Seshadri, 2013; Yuan *et al.,* 2018). This is due to the nature of the PV technology used in the solar panels (Dubey, Sarvaiya and Seshadri, 2013). However, increasing solar irradiance can linearly increase the generated power output (Aslam *et al.,* 2022).

In addition, Oman's arid, dusty desert climate negatively affects the efficiency of PV systems. The accumulation of dust creates a thin layer that partially or fully obstructs the sun's rays from reaching the surface of the PV cells, resulting in a decrease in their performance. Theoretically, the reduction factor of the annual accumulation of dust is 93% (Aslam *et al.,* 2022). However, experiments have shown that a dust layer with a density of 10 g/m^2 is enough to reduce the maximum output power of PV systems by 34% (Chen *et al.,* 2019).

Oman's mountain ranges exceed 3,000 m above sea level. These areas are known to be significantly cooler than other regions in the country. Installing solar PV panels on the top of these mountains could be a way to overcome the challenge of hot weather and benefit from lower amounts of dust compared to other areas of the country. China has already demonstrated how vast mountainous areas can be used to establish large-scale solar power plants (Ying *et al.,* 2023; Yu, 2018), as seen in the Taihang Mountains PV solar farm in Shexian county, Hebei province, in North China (New China TV, 2021; New China, ; Yu, 2018).

2.3.3. Concentrated Solar Power.

In addition to Oman's upcoming wind energy and solar PV projects, plans are underway to build the first concentrated solar power (CSP) project with integrated thermal energy storage and a production capacity of 600 MW in an area near Duqm (Prabhu, 2023c). CSP is a method of generating electricity that uses direct solar irradiation to produce thermal energy. The thermal energy is then converted into mechanical energy, which in turn drives turbines to generate electricity (Aurousseau, Vuillerme and Bezian, 2016). CSP is known for its high capacity, high efficiency, and ability to store energy (Hayat *et al.,* 2019) for more than 8 hours (Pascual, Lisbona and Romeo, 2022; Carro *et al.,* 2023). Four technologies are currently used for CSP: parabolic troughs, power towers, dish engines, and linear Fresnel reflectors (Hayat *et al.,* 2019). According to reports from IRENA, the total cost of installing a CSP system is 4,274 USD/kW. The cost of electricity generated by the CSP is 0.118 USD/kW. The operation and maintenance costs per kWh of the CSP are considerably higher than those of onshore wind farms and solar PV, at 0.022 USD/kWh (Taylor, Al-Zoghoul and Ralon, 2023).

One of the biggest challenges facing the solar energy sector is the unavailability of sunlight for the entire day and year. Additionally, the high cost and the security of the availability of the related materials, especially the cells, pose significant challenges. However, to achieve this, efficient energy storage, cost-effective cells, and an increase in suppliers are needed. Although CSP has advantages such as energy storage and being less affected by rising temperatures, the high cost of CSP has led most investors to prefer using solar PVs (Gamil *et al.,* 2022).

CSP technology is considered to have an eco-friendly environmental impact. Its construction, however, involves numerous hazardous materials that are detrimental to health and easily flammable. In addition, CSP technology requires a vast area of land, which could negatively affect the surrounding flora and fauna, particularly birds, leading to extinction and migration (Hayat *et al.,* 2019).

Like the PV system, dust is a significant challenge for CSP in the countries of the Gulf Cooperation Council, reducing its performance. A study by Hachicha (Hachicha, Al-Sawafta and Hamadou, 2019) in the United Arab Emirates concluded that the accumulation of dust in the CSP's solar collectors caused a 36% reduction in the CSP's thermal efficiency.

2.3.4. Other Sources of Power.

Oman is studying the viability of establishing a waste-to-energy plant in Barka. The idea for this project was introduced in 2016, and the technical and economic feasibility study has been completed. The government is currently evaluating the project from a financial standpoint (Ministry of Energy and Minerals, 2022).

The CEO of Oman Environmental Services Holding Company (Be'ah) announced that the waste-to-energy plant will generate 130–150 MW of renewable energy and process 4,500 tons of municipal waste per day (Be'ah, 2022).

Table 4—Costs associated with renewable energy systems.

	Installation cost	Cost of electricity	Cost of O&M	Lifetime
	USD/kW	USD/kWh	-	Years
Onshore wind	1,274	0.033	30 USD/kW (full-service contract)	25
Solar photovoltaics	876	0.049	7.7 USD/kW	25
Concentrated solar power	4,274	0.118	0.022 USD/kWh	20

3. Findings and Recommendations

This technical paper examines Oman's renewable energy landscape and offers strategic recommendations to address pivotal challenges in green hydrogen production. The following points highlight these challenges and opportunities in Oman's renewable energy strategy:

1. Oman faces a major challenge of water shortage, which makes natural water sources such as groundwater and oases unsuitable for producing green hydrogen. Although Oman is a coastal country, using seawater would require a massive amount of water compared to using groundwater. Additionally, the costs of desalination, capital expenditures (CAPEX), and operational expenditures (OPEX) are too high, which adds to the expenses of electrolysis and renewable energy.

2. The high cost of the entire PEM system, specifically the BPs, which constitute about 24% of the system cost, is a significant challenge. One of the primary reasons for the high cost of BPs is the use of gold or platinum as a material. This presents an opportunity for Oman to leverage its abundant natural resource of platinum in the northern region and use it in the manufacturing of electrolysis, particularly in the production of BPs. This would help reduce the overall cost of electrolysis manufacturing.

3. Oman's hot and arid climate negatively affects the efficiency of PV systems, especially in summer. Dust accumulation also reduces efficiency. The mountainous regions of Oman, which are cooler and have less dust, could provide an opportunity to increase the efficiency of solar PVs. Oman could learn from China's experience in the Taihang Mountains PV solar farm project in the province of Hebei, North China.

4. The installation cost of 4,274 USD/kW and the electricity cost of 0.118 USD/kWh for the CSP system are high compared to those of other renewable energy sources. As a result, many investors find this option economically unfeasible. It has the significant advantage, however, of being capable of storing energy for more than 8 hours.

4. Conclusion

Oman is transforming its energy infrastructure to achieve a sustainable and decarbonised future. Green hydrogen is set to play a pivotal role in this transformation. As demonstrated in this technical paper, Oman's unique geographical and natural resources position it as a promising leader in the green hydrogen sector. This study compares electrolysis technologies and analyses renewable energy integration, addressing cost and environmental concerns to guide future strategies. By using PV, onshore wind, and potentially CSP, Oman has the potential to exceed its hydrogen-production goals.

The findings show that PV energy is the most promising renewable source for producing green hydrogen in Oman due to the country's high levels of solar irradiance. By increasing solar PV capacity, possibly exceeding 1 GW by 2030, Oman can significantly contribute to the decarbonisation of its national grid. Additionally, onshore wind energy is also a viable option, with planned projects expected to add around 400 MW by 2026.

Challenges such as the cost and efficiency of electrolysis technologies, particularly PEM, which is hindered by high capital costs, could be mitigated through strategic investments in local manufacturing leveraging Oman's natural resource of platinum. Furthermore, by integrating renewable energy sources with advanced electrolysis technologies such as AWE and PEM, Oman can potentially reduce its CO2 emissions by over 8% by 2050, aligning with its commitments under the Paris Agreement.

By 2050, Oman could potentially increase its renewable energy capacity by several gigawatts, thus advancing its vision of becoming a global centre for producing green hydrogen. This move would support global sustainability objectives and put Oman in a favourable position to benefit economically by exporting green hydrogen to high-demand markets worldwide. The path towards achieving net-zero emissions is complex and challenging. With consistent research, development, and global cooperation, however, Oman is well equipped to realise its green aspirations and contribute to a sustainable future.

Ultimately, Oman aims to take a leading position in the production of green hydrogen by 2030, leveraging abundant natural resources and renewable energy to overcome production challenges.

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