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Technical assessment of green hydrogen production in Kuwait

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ABSTRACT

Kuwait has the potential to produce green hydrogen from renewable energy. Hydrogen production is receiving increased attention and has become a core research area. In Kuwait, there are various sites of average daily wind speeds exceeding 4 m/s, so they are promising for green electricity production using wind turbines. The wind power can be used to operate water electrolysers to produce hydrogen. This study is conducted to assess the opportunities and feasibility of green hydrogen production using wind power at three sites in Kuwait. The average daily wind speeds, recorded at height 10 m from the ground, were obtained for each site. A wind turbine of rated power 2.4 MW and an electrolyser of capacity 1.8 MW were used for the modelling. The power curve of the turbine was used to evaluate the wind power and the amount of produced hydrogen. The results show that Kuwait Airport site has an estimated annual production of about 300 metric tonnes. For WAFRA site, the estimated annual production was 172 metric tonnes and for ABDALY site was 145 metric tonnes. The annual average specific hydrogen production was highest for ABDALY site (15.52 kg hydrogen/kW turbine power) followed by WAFRA site (15.31 kg/kW) then Kuwait Airport site (13.24 kg/kW).

Nomenclature

Abbreviations		KOH	Potassium hydroxide
AE	Alkaline electrolyser	n	Exchanged electrons
AEM	Anion exchange membrane	NaOH	Sodium hydroxide
AWE	Alkaline water electrolysis	Ni	Nickel
HER	Hydrogen evolution reaction	O_2	Oxygen
HPR	Hydrogen production rate	O^{2-}	Oxygen ion
OER	Oxygen evolution reaction	OH^-	Hydroxyl ion
PEM	Polymer electrolyte membrane	P	Wind turbine power
PPS	Polyphenylene sulphide	K_2CO_3	Potassium carbonate
PV	Photovoltaic	T	Temperature
SOEC	Solid oxide electrolysis cells	U_{cell}	Cell voltage
Parameters and Variables		U_{rev}	Thermodynamic voltage
CO_2	Carbon dioxide	U_{therm}	Enthalpic voltage
F	Faraday constant	v_g	Wind speed at 10 m
h	Turbine hub height	v_w	Wind speed at height h
H^+	Hydrogen cation	ΔG	Gibbs energy
H_2	Hydrogen	ΔH	Molar enthalpy
K_2CO_3	Potassium carbonate	ΔS	Entropy change
K_2TiO_3	Potassium titanate		

1. Introduction

1.1. Background

Hydrogen is the most plentiful element all over the globe. It is also a promising renewable energy carrier, from the environmental point of view [1]. The hydrogen atom comprises single proton and single electron; so, it is the lightest element of exceptional properties. Hydrogen has superior mass-based energy density of about 120 MJ/kg with remarkable low volume-based energy density of only 8 MJ/L [2]. Nevertheless, hydrogen is not directly available as a gas as it is found combined with other elements forming water, for example. Therefore, the key challenge for obtaining the hydrogen efficiently and economically is to separate it from natural compounds such as water [3,4]. At present, the main hydrogen production methods include methane steam reforming; methane partial oxidation; methane pyrolysis; fermentative hydrogen production; and electrolytic processes [5–7].

According to Milani et al. [8], about 87 million tonnes of hydrogen are produced every year from traditional and renewable sources. In 2023 hydrogen production reached 97 Mt [9]. As of 2020, about 95% of the produced hydrogen was obtained from traditional fossil fuels,

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particularly through steam reforming of methane (natural gas); but, the fossil fuel-based production methods annually generate about 830 million tonnes of carbon dioxide. The remaining 5% of hydrogen production was made from water electrolysis using renewable energy sources [10]. For hydrogen production, various colour shades are used to distinguish the adopted technology and the used energy source, see Table 1. At present, hydrogen is described using colours blue, grey, brown, black, and green [11].

Blue hydrogen is produced from natural gas through steam reforming. In these process, natural gas is divided to produce hydrogen (H_2) and carbon dioxide (CO_2). Most of the generated CO_2 (about 85%–95%) is captured via carbon capture technology; but some of CO_2 is difficult to capture [12].

Grey hydrogen is produced by steam reforming of traditional fossil fuels like natural gas or coal. The production process of this type is similar to that of the blue hydrogen; nevertheless, the generated CO_2 is emitted into the atmosphere and not captured [13].

Brown hydrogen is the most produced at present as it is obtained from the gasification of brown coal or methane as they are rich in hydrocarbons. Accordingly, higher CO_2 emissions are generated with the production of this type at rate of 10–12 tonnes CO_2 per tonne of hydrogen [12].

Black hydrogen is produced by coal gasification. Throughout this process, syngas is generated of which hydrogen gas can be separated using membranes or absorbents. The remaining gases are then emitted to the atmosphere [14].

Green hydrogen is produced from water by electrolysers operated by renewable electricity. During the production process, the water is split into hydrogen (H_2) and oxygen (O_2). The process is termed green because it is conducted with zero carbon emissions. Solar and wind are the most commonly used renewable energies for producing the green hydrogen [14,15].

1.2. Hydrogen production electrolysers

The main reaction used to describe the process of water splitting in electrolysis is [4]:

$$H_2O + \text{Electricity}\left(237.2\frac{kJ}{mol}\right) + \text{Heat}\left(48.6\frac{kJ}{mole}\right) \overset{\text{yields}}{\rightarrow} H_2 + \frac{1}{2}O_2 \quad (1)$$

Depending on the operating conditions such as the electrolyte and their ionic agents (OH^-, H^+, O^{2-}), four types of water electrolysis are found: Alkaline water (AW), Anion Exchange Membrane (AEM), Polymer Electrolyte Membrane (PEM) and Solid Oxide [4,16]. Amongst these types, the most efficient and widely utilised are the Alkaline Water Electrolysers (AWE) and the Polymer Electrolyte Membrane (PEM) type.

The alkaline water electrolysers are used to produce hydrogen on an industrial scale. In 1939, a large-scale (10,000 m^3/h) alkaline water electrolysing system was introduced for the first time [16]. Usually, alkaline water electrolysers operate at low temperatures in the range from 30 to 80 °C using alkaline (KOH/NaOH) solution at high concentration. In these electrolysers, stainless steel electrodes with nickel (Ni) coating layer are used along with separators in the form of diaphragms [4]. The electrochemical reaction takes place when the alkaline solution and water pass the porous diaphragm structure [17,18]. Alkaline water electrolysers are suitable for large-scale hydrogen production duties. However, their main challenge is the limited current density in the range of 0.1–0.5 A/cm^2 caused by the limited mobility of the hydroxyl ion (OH^-), and the increased corrosion rates of the electrolytes [16]. Also, the accumulation of potassium carbonate (K_2CO_3) salt near the anode pores significantly decreases the ion movement through the diaphragm and thereby reduces the hydrogen production rates. Moreover, the hydrogen produced by alkaline electrolysers are of low purity (about 99.9%) because the diaphragm is unable to stop gas crossover from one cell side to the other [19].

For alkaline electrolysers, the commonly used electrolyte is solution of potassium hydroxide (KOH) or sodium hydroxide (NaOH) in water. The concentration of these substances is usually in the range from 25 to 30% to ensure good ion transportation between the electrodes [20]. Alkaline electrolysers operate based on mature technology with industrial versions of high hydrogen hourly yields around 650 m^3. This type has long service life so that they can continually operate for tens of thousands of hours at an efficiency of around 70% [21]. During normal duty, the alkaline electrolyser operates at an atmospheric pressure and a temperature of about 80 °C to produce about 50–485 m^3H_2/h, using KOH electrolyte solution of concentration 25%. During the duty, the energy consumption is ranged from 4.1 to 4.3 kWh/Nm^3 to produce hydrogen of purity about 99.9% [22].

During operation, the alkaline electrolyser efficiency is negatively affected by the increased current density. Therefore, these electrolysers operate at current density of about 0.3 A/cm^2 for highest efficiency. Meanwhile, the industrial alkaline electrolyser may operate at high current density of about 0.4 A/cm^2 [23]. Better operation of alkaline electrolysers may be achieved by increasing the operating temperature, but the service life of the components significantly decreases due to the corrosion of electrodes caused by salt solution. Thus, other materials have been proposed to limit the corrosion and extend the system service life including potassium titanate (K_2TiO_3), polyphenilene sulphide (PPS), etc. [21].

In PEM water electrolysis, polymer membrane is usually utilised as electrolyte. It usually operates at low temperatures range from 30 to 80 °C using high current densities ranged from 1.0 to 2.0 A/cm^2 to produce high purity (99.999%) hydrogen and oxygen gases [4]. Compared with alkaline type, PEM electrolyser has faster hydrogen evolution reaction kinetics due to the increased electrodes active area and less electrolyte pH. Also, PEM electrolysers have fast response so that they are recommended for many industries due to their improved stability. But, they are expensive and require costly components [15]. Comparisons between alkaline and PEM electrolysers are listed in Table 2.

1.3. Electrolysis reaction

During electrolysis process, the hydrogen formation is known as hydrogen evolution reaction (HER) and the oxygen formation is termed as oxygen evolution reaction (OER). To improve the reactions, electro-

Table 1
Shade colours of the produced hydrogen [4].

Colour	Technology	Source	Cost (\$/kg H_2)	CO_2 emissions
Brown	Gasification	Brown coal (Lignite)	1.2 to 2.1	High
Black	Gasification	Black coal (Bituminous)	1.2 to 2.1	High
Grey	Reforming	Natural gas	1.0 to 2.1	Medium
Blue	Reforming and carbon capture	Natural gas	1.5 to 2.9	Low
Green	Electrolysis	Water	3.6 to 5.8	Minimal

Table 2
Comparisons between AE and PEM electrolyser.

	Alkaline electrolysers	PEM electrolysers
Advantages	Advanced technology	Fast and dynamic response
	Low cost	Increased current density
	Long-term stability	Improved hydrogen gas purity
	Available in MW range	Improved voltage efficiency
	Needs non-noble catalysts	Compact design
Disadvantages	Low current density	Expensive components
	Low operating pressures	Acid corrosive environment
	Low purity gases	Possible decreased durability
	Corrosive liquid electrolyte	Available below MW range

catalysts such as platinum are utilised. In addition to platinum, other materials can be utilised including phosphides, nitrides, carbides, etc. to modify the orbital surface for more electron capture and improved reactions [22]. Nevertheless, the reactions vary with the electrolyser type. For instance, the reactions for the alkaline electrolysers are:

$$\text{Cathode reaction (HER)} : 2H_2O(l) + 4e^- \rightarrow 4OH^-(g) + 2H_2(g) \tag{2}$$

$$\text{Anode reaction (OER)} : 4OH^-(g) \rightarrow 2H_2O(l) + 4e^- + O_2(g) \tag{3}$$

Meanwhile, the reactions for the PEM electrolysers are:

$$\text{Cathode reaction (HER)} : 4H^+(aq) + 4e^- \rightarrow 2H_2(g) \tag{4}$$

$$\text{Anode reaction (OER)} : 2H_2O(l) \rightarrow O_2(g) + 4H^+(aq) + 4e^- \tag{5}$$

During operation, it is essential to use a barrier (diaphragm for instance) to ensure separation of the produced gases. Without barrier, the produced hydrogen may migrate away from the cathode and mix with oxygen forming undesired mixture, especially in alkaline electrolysers. Meanwhile, barriers are not needed for the system of solid electrolytes (e.g., membranes) as they act as barrier for the PEM electrolysers during water splitting. During electrolysis process, thermal energy and electricity are needed. Increasing the thermal energy significantly decreases the required electricity; but increases the corrosion rates, especially for the alkaline types [24].

Smolinka and Garche [25] and Cavaliere [26] reported that the voltage to apply between the electrodes should be about 1.23 V for water splitting under atmospheric pressure and temperature 25 °C. For water splitting, the required energy is denoted as standard molar enthalpy (ΔH) which is the energy needed to split 1.0 mol of water into 0.5 mol of oxygen and 1 mol of hydrogen. This energy is expressed as:

$$\Delta H = \Delta G - T\Delta S \tag{6}$$

where ΔG is the Gibbs energy needed for water decomposition and ΔS is the entropy change during water splitting.

In Eq. (6), Gibbs energy represents the minimum electrical energy while entropy change represents the minimum thermal energy required for water molecule splitting. The electrical energy needed for the reaction is supplied by renewable energy source to produce green hydrogen, whereas the thermal energy is ensured by the reaction temperature. The voltages needed for electrolysis can be evaluated from Eq. (6). The lowest needed reaction voltage is termed the thermodynamic value (U_{rev}), whereas the second is the enthalpic voltage (U_{therm}). These voltages are defined by Eq. (7) and Eq. (8) [27]:

$$U_{rev} = \Delta G\, nF \tag{7}$$

$$U_{therm} = \Delta H\, nF \tag{8}$$

where n is the exchanged electrons (usually equals 2), F is the Faraday constant (96,485C/mol).

At standard conditions, the electrolysis reactions of water take place with standard values of Gibbs energy (273.22 kJ/mol) and enthalpy change (285.8 kJ/mol). Accordingly, the voltages expressed by Equations (7) and (8) become $U_{rev} \approx 1.23\ V$ and $U_{therm} \approx 1.48\ V$. Thus, the difference between these voltages is about 0.25 V, but these parameters vary with the temperature [26]. For instance, Smolinka and Garche [25] reported that the required thermal energy (ΔH) and electric energy sharply decrease when the system temperature approaches 100 °C, before they slowly increase with further temperature increase, due to the change of water state at this temperature. Based on these conditions, the splitting reaction varies as follows:

- When $U_{cell} < U_{rev}$, no splitting reaction can happen
- When $U_{rev} < U_{cell} < U_{therm}$, more thermal energy would be needed to initiate the reaction
- When $U_{therm} < U_{cell}$, an exothermic reaction takes place

2. GREEN hydrogen production

There is a growing global interest in producing hydrogen from renewable energy resources and therefore, more efforts are required to assess the feasibility of green hydrogen production. Various research studies have been conducted to investigate the performance and costs of green hydrogen production using solar and wind energy. Green hydrogen is produced through various technologies including Polymer Electrolyte Membrane (PEM) and Solid Oxide Electrolysis Cells (SOEC) systems, with electricity needs projected to drop to 45 kWh/kg and 40 kWh/kg, respectively, in 2050. The electrolyser life for both technologies is about 20 years with operational capacity factors of 97% for PEM and 87.5% for SOEC. The operating hours for PEM are higher than SOEC, and by 2050, the capital cost of PEM will be approximately two thirds that of the SOEC system for equivalent electricity consumption [28–30].

Benghanem et al. [28] utilised green electricity produced by photovoltaic (PV) solar arrays and wind turbines for water electrolysis. Menanteau et al. [31], performed cost analysis research on green hydrogen production using wind power. In this research, the green hydrogen production expenses from the wind sources were mainly reliant on the demand request. Genç et al. [32] conducted a study in which wind-operated electrolyser was studied to assess the changes of hydrogen production costs with the system operating parameters. Various cases have been analysed including changes of the wind turbine hub heights. The rated power of the wind turbines used to operate the electrolyser were 120 kW and 40 kW. The outcomes of this study demonstrated achievement of remarkable reduction of green hydrogen production costs by using wind turbines at higher hub levels [32].

Large scale wind turbines have been selected, as source of green power, for operating electrolysers to produce green hydrogen by Olateju et al. [33]. The authors investigated a wind-operated hydrogen production system of large capacity with wind power of 563 MW. The outcomes of this study enabled further modelling and simulation of the wind-operated system. In their study, Matzen et al. [34] carried out an economic assessment of wind-operated hydrogen production system. The authors also conducted a feasibility study using cost indicators obtained by comparing the hydrogen production using renewable and traditional energy sources. It was found that, at the prevailing methanol prices, the cost of producing hydrogen is between US$0.40 and US $0.70/kg H_2, to give an NPV of zero. Further modelling work has been conducted [35] on a wind-operated hydrogen production system equipped with energy storage for an electrolyser operated with 563 MW wind turbine. To optimise the electrolyser size and energy storage facility, wind speed data were used [36] and the best scenario involved using 81 electrolysis units of total capacity 3495 kW achieving hydrogen production of 760 Nm^3/h. The electrolysers were operated using 60 units of battery storage for green electricity of 360 MWh. The results demonstrated low hydrogen production costs of 9.0 dollars/kg while 63% of the cost was dedicated to the wind turbines.

In their research, Herwartz et al. [37] focused on a system combining wind turbines and fuel cells for green hydrogen production for trains in Germany. In this study, water electrolyser was operated using wind power, which demonstrated improved potential to be adopted by the rail transportation systems. Another investigation into the possibility of using wind power to produce green hydrogen has been conducted by Mostafaeipour et al. [38]. The authors analysed the impact of wind speed variations on hydrogen production in various cities. In another study [39], an assessment of four large-scale wind turbines in Abadeh city was conducted. It was found that hydrogen produced by wind power was sufficient to run 22 cars every week using specific models of wind turbines.

The practical issues while producing hydrogen using wind energy have been predcited by Dutton et al. [40] who pointed out the impact of wind energy fluctuation on the performance and productivity of electrolysers. Morover, the authors proposed methods to improve the generated power of the turbine used for green hydrogen production. In their research, Sherif et al. [41] offer a comprehensive review of the technolgies that can be used for hydrogen production and highlighted the significance of utilising wind energy for hydrogen generation on competitiveness enhancement of wind power production facilities. The outcomes of Sherif et al. [41] were supported by the assessment [42] of the annual production of hydrogen using wind power, which exceeds 116×10^{12} MJ. Thus, a life cycle assessment was conducted [43] and reported the wind operated hydrogen production systems as promising technologies for green hydrogen production.

Recently, interests in green hydrogen production projects have increased among Gulf countries. Olabi and Jouhara [44] focused on an assessment of the current hydrogen supply chains in the Gulf Cooperation Council. Kuwait for instance has adopted green hydrogen production strategies. Several green hydrogen production projects have considered such as the pilot project of installing 50 MW water electrolyser in Al Dibdibah. This project comprises PV solar-operated system requiring about 200 GWh/year of electricity to produce 3000 tonnes of hydrogen. With an electricity price of about $33/MWh, a cost of $3.3/kg hydrogen is anticipated [45,46]. Feasibility of green hydrogen production in Kuwait is studied in this research due to several reasons. First, there is a growing interest in expanding the green hydrogen production projects, which is supported by the 2021 green hydrogen Strategy White Paper [47]. Second, hydrogen production projects represent essential elements of diversification of energy and economic projects in Kuwait [48]. Third, Kuwait has promising renewable energy resources such as high intensity of solar irradiance and high wind speeds at different sites [46,48].

This study is conducted to study the performance of a wind-operated water electrolyser for green hydrogen production in Kuwait, using Microsoft Excel model. The main goal of this research is to predict and compare the electrolyser performance at three sites in Kuwait of promising wind power. Kuwait has different sites of great potential for green hydrogen production. One of the promising locations is the Shagaya Renewable Energy Park as it receives an average daily solar radiation of 5.2 kWh/m^2 and a wind speed of 5 m/s [45,49,50]. In addition to Shagaya site, other sites in Kuwait could be promising for hydrogen production using wind power such as Kuwait Airport site, Wafra site, and Abdaly site. This study is therefore conducted to assess the potential of these three sites in producing hydrogen via water electrolyser operated using wind power.

3. MODEL development

3.1. Equipment specifications and wind speeds

To investigate the possibility of installing wind-operated electrolysers for hydrogen production in Kuwait, three proposed sites were compared to assess the successful installation of the system. These sites are Kuwait Airport site, WAFRA site, and ABDALY site. For each site, wind speed data were obtained and an average daily wind speed for each month was calculated and used for the modelling.

The hydrogen production system modelled in this study comprised an alkaline water electrolyser of capacity 1800 kW, and an onshore wind turbine of rated power 2400 kW. Data on the specifications of the electrolyser were obtained from Wang et al. [29], AlRafea et al. [36], and Hussam et al. [44]. The specifications of the wind turbine and electrolyser are listed in Table 3.

Since the hub height of the selected wind turbine is 120 m, wind speeds at this hub height were evaluated using the power law as follows:

$$v_w = v_g \left(\frac{h}{10}\right)^{0.16} \tag{9}$$

where v_g is the wind speed at each site, recorded at 10 m height from the ground; v_w is the wind speed at the rotor hub height ($h = 120$ m) from the ground.

Table 3
Wind turbine and electrolyser specifications.

Wind turbine: ONSHORE	
Type	Axial flow turbine
Model	Nordex N117 Gamma
Rated power	2400 kW
Number of blades	3
Rotor diameter	116.8 m
Hub height	120 m
Cut-in wind speed	3 m/s
Rated wind speed	11 m/s
Cut-out wind speed	20 m/s
Electrolyser:	
Capacity	1800 kW
Efficiency	95%
Energy to hydrogen conversion rates:	
100% electrolyser load	48.76 kWh/kg
50% electrolyser load	45.16 kWh/kg
25% electrolyser load	43.36 kWh/kg

At each site, the recorded wind speeds at 10 m height and the average daily wind speeds calculated using Equation (9) are listed in Table 4.

3.2. Wind power evaluation

The power curve of the wind turbine was obtained. At each speed, the corresponding power was obtained. The data points were plotted using Microsoft Excel. The plot was used to predict the best fit polynomial relationship between the turbine power (P, kW) and the wind speed at 120 m (v_w, m/s). In developing the relationship between the power and wind speed, the wake effect was ignored and the relationship was:

$$P = -2.1005\, v_w^4 + 48.7\, v_w^3 - 363.49\, v_w^2 + 1270.6\, v_w - 1684.3 \tag{10}$$

For each site, the monthly wind power was evaluated and matched the electrolyser capacity. For wind power higher than the electrolyser capacity of 1800 kW, an electrolyser full load (1800 kW) was used. For wind power less than 1800 kW, the ratio between the turbine power and electrolyser capacity was evaluated because it affects the hydrogen production rate, as previously listed in Table 3. Therefore, the wind power was converted into energy, using electrolyser efficiency of 0.95, as follows:

$$\text{Energy to electrolyser}\left(\frac{kWh}{day}\right) = \text{Power}\,(kW) \times 24\left(\frac{h}{day}\right) \times 0.95 \tag{11}$$

The relationship between the electrolyser percentage of operating load and the hydrogen production rate was obtained as follows:

Table 4
Average daily wind speeds for the modelled sites (m/s).

Month	K_AIR site		WAFRA site		ABDALY site	
	10 m	120 m	10 m	120 m	10 m	120 m
Jan	5.51	8.19	4.40	6.55	3.82	5.68
Feb	5.53	8.23	4.42	6.58	4.05	6.02
Mar	5.57	8.29	4.39	6.53	4.03	5.99
Apr	5.98	8.90	4.48	6.66	4.23	6.29
May	6.50	9.68	4.64	6.90	4.34	6.47
Jun	8.22	12.24	5.57	8.29	5.57	8.29
Jul	6.65	9.90	5.02	7.47	4.76	7.08
Aug	6.05	9.00	4.48	6.66	4.53	6.74
Sep	5.87	8.73	4.39	6.53	4.27	6.35
Oct	5.06	7.53	4.02	5.98	3.81	5.67
Nov	5.22	7.77	4.17	6.21	3.75	5.58
Dec	5.35	7.96	4.06	6.04	3.61	5.37

$$\text{Energy to hydrogen}\left(\frac{kWh}{kg}\right) = 7.1917\left(\frac{\%\,load}{100}\right) + 41.565 \quad (12)$$

Then, the energy to electrolyser (Equation (11)) and the energy to hydrogen conversion rates (Equation (12)) were used to evaluate the average daily hydrogen production rate HPR from the equation:

$$\text{HPR}\left(\frac{\text{kg}}{\text{day}}\right) = \frac{\text{Energy to electrolyser (kWh/day)}}{\text{Energy to hydrogen (kWh/kg)}} \quad (13)$$

The number of days in each month was used to evaluate the monthly hydrogen production in metric tonnes. Then, these values were added to obtain the annual hydrogen production for each site.

4. Results

4.1. Power and energy to electrolyser

For each site, the power produced by the wind turbine and used to operate the electrolyser, along with the energy supplied to the electrolyser, are shown in Table 5.

As shown in Table 5, the wind speeds at Kuwait Airport site were high enough to produce power higher than the electrolyser capacity during the months from April to September (denoted by the bold numbers in Table 5). At the other two sites, the wind power produced by the turbine was always less than the electrolyser capacity. Therefore, at Kuwait Airport site, the power supplied to the electrolyser was set at 1800 kW, which equals the electrolyser capacity. At the airport site, which has high wind speeds, the excess power produced by the turbine was stored. The excess power storage was only possible during the months April to September as shown in Table 6.

At Kuwait Airport site, as shown in Table 6, the power produced by the wind turbine in April was 1984 kW, which is higher than the electrolyser full load of 1800 kW. At this site in June, the highest produced wind power was 2400 kW whereas the next highest produced power was 2345 kW in July. During each month listed in Table 6, only 1800 kW was supplied to the electrolyser and the rest of the power generated by the turbine was stored. At the other two sites, the wind power developed by the turbine at any month was less than the electrolyser full load so that the electrolyser was always operating at part load at WAFRA and ABDALY sites. Thus, the electrolyser only operates at full capacity at Kuwait Airport site during April to September months.

4.2. Daily hydrogen production rates

When the electrolyser operates at its full load of 1800 kW, it will receive highest amount of energy of about 41,040 kWh. Under this condition, the electrolyser is expected to produce a maximum daily amount of hydrogen of 842 kg. The condition of maximum production can only be ensured when the system is installed at Kuwait Airport site during months April to September. But, during months October to March, the daily hydrogen production at Kuwait Airport site is to be less than 842 kg.

Table 5
Power and energy to the electrolyser.

Month	K_AIR site		WAFRA site		ABDALY site	
	Power (kW)	Energy (kWh)	Power (kW)	Energy (kWh)	Power (kW)	Energy (kWh)
Jan	1645	37510	862	19654	545	12426
Feb	1663	37923	874	19921	659	15021
Mar	1691	38552	854	19465	647	14760
Apr	**1800**	**41040**	910	20739	758	17291
May	**1800**	**41040**	1014	23109	828	18875
Jun	**1800**	**41040**	1693	38591	1693	38603
Jul	**1800**	**41040**	1284	29284	1096	24998
Aug	**1800**	**41040**	910	20750	944	21526
Sep	**1800**	**41040**	855	19502	783	17861
Oct	1311	29892	645	14698	540	12323
Nov	1434	32694	727	16573	513	11686
Dec	1529	34856	664	15130	452	10310

Table 6
Produced and stored power at Kuwait Airport site.

Month	Turbine power (kW)	Power to store (kW)	Energy to store (kWh)
Apr	1984	184	4190
May	2285	485	11066
Jun	2400	600	13680
Jul	2345	545	12421
Aug	2028	228	5193
Sep	1907	107	2442

4.2.1. Hydrogen production at Kuwait airport site

The average daily hydrogen production at Kuwait airport site for each month is shown in Fig. 1.

As depicted in Fig. 1, the wind-operated hydrogen production system if installed at Kuwait Airport is expected to operate at maximum daily green hydrogen production of 842 kg during months April to September. The system is expected operate with hydrogen production capacity of about 800 kg per day during months January to March. Meanwhile, the lowest hydrogen production of the system if installed at Kuwait Airport site is expected to be about 639 kg/day in October.

4.2.2. Hydrogen production at WAFRA site

The average daily hydrogen production at WAFRA site is shown in Fig. 2.

As shown in Fig. 2, the electrolyser when installed at WAFRA site will never operate at maximum load and will never give maximum hydrogen production due to the relatively low wind speeds. At this site, the highest daily hydrogen production is expected to be 799 kg in month of June, which presents about 95% of the electrolyser capacity. The next highest hydrogen production is expected to be 627 kg (74.5% of the electrolyser capacity) in July. Meanwhile, the lowest hydrogen production of the electrolyser is to be 333 kg in October, which is about 40% of the electrolyser full capacity.

4.2.3. Hydrogen production at ABDALY site

The average daily hydrogen production at ABDALY site is shown in Fig. 3.

As shown in Fig. 3, the pattern of hydrogen production at ABDALY site was similar to that at WAFRA site. At ABDALY site, the electrolyser is also expected to operate at part load every month due to the relatively low wind speed and accordingly low wind power. Similar to the WAFRA site, the highest system production when installed at ABDALY site is expected to take place in June and then in July. The highest production in June is expected to be 800 kg per day, which is about 95% of the

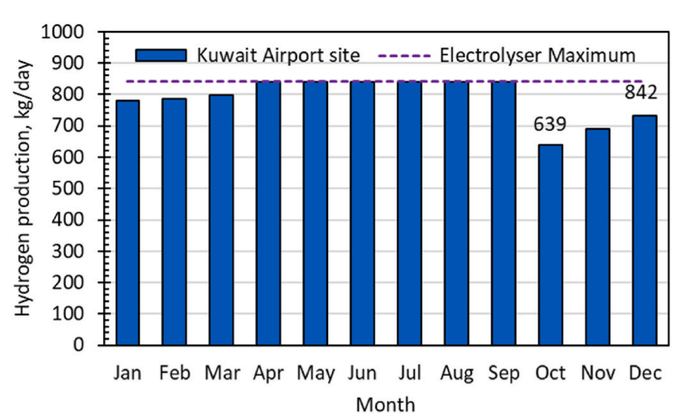

Fig. 1. Average daily hydrogen production at Kuwait Airport site.

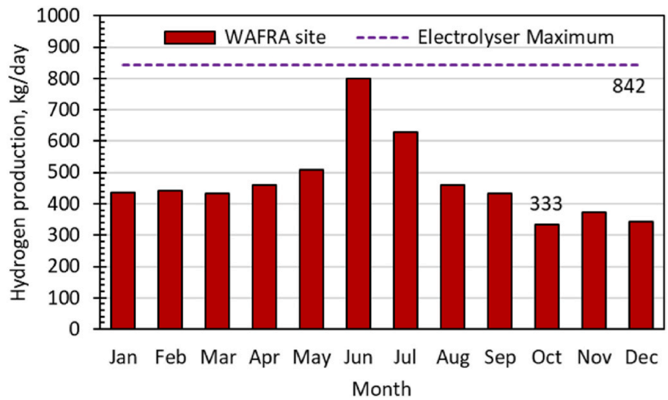

Fig. 2. Average daily hydrogen production at WAFRA site.

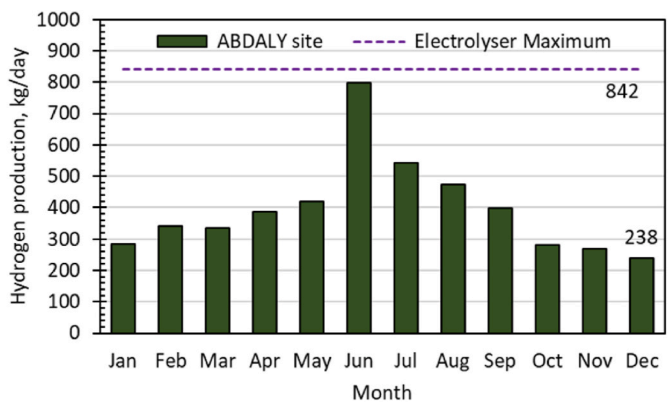

Fig. 3. Average daily hydrogen production at ABDALY site.

electrolyser full capacity. In July, the production rate is expected to be about 544 kg/day, which is about 65% of the maximum daily electrolyser production capacity of 842 kg. The lowest hydrogen production of the system when installed at ABDALY is expected to take place in December with rate of about 238 kg, which is about 28% of the electrolyser full production capacity.

4.3. Monthly and annual hydrogen production

The monthly production of hydrogen at each site was evaluated by multiplying the average daily production times the number of days of each month. For the three sites, the monthly production was evaluated as shown in Table 7 and the annual production is shown in Fig. 4.

As shown in Fig. 4, the annual maximum hydrogen production capacity of the electrolyser was estimated at 307.3 metric tonnes. When

Table 7
Monthly hydrogen production (metric tonnes) for the three sites.

Month	K_AIR site	WAFRA site	ABDALY site
Jan	24.2	13.5	8.8
Feb	22.0	12.4	9.5
Mar	24.7	13.4	10.4
Apr	25.3	13.8	11.6
May	26.1	15.7	13.0
Jun	25.3	24.0	24.0
Jul	26.1	19.4	16.9
Aug	26.1	14.2	14.7
Sep	25.3	13.0	12.0
Oct	19.8	10.3	8.7
Nov	20.7	11.2	8.0
Dec	22.7	10.6	7.4
SUM	**288.1**	**171.5**	**145.0**

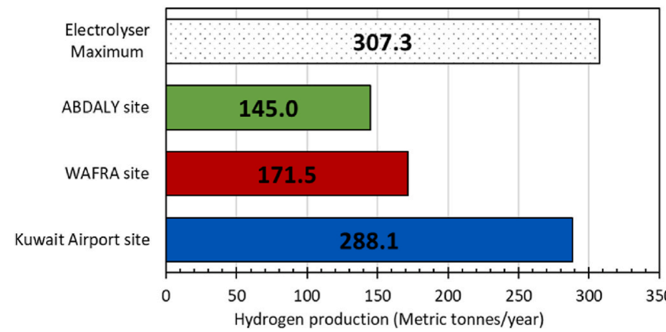

Fig. 4. Annual hydrogen production at the three sites.

the system is installed at Kuwait Airport site, the annual hydrogen production is expected to be about 288 metric tonnes. The second highest annual production will be 172 metric tonnes when the system is installed at WAFRA site. The lowest annual hydrogen production is expected to be 145 metric tonnes when the system is installed at ABDALY site.

4.4. Specific hydrogen production rates

For each site, the specific hydrogen production rate was evaluated as the ratio between the average monthly hydrogen production (expressed in kg) and the power to be produced by the wind turbine (expressed in kW). The results are listed in Table 8.

As shown in Table 8, the lowest specific hydrogen production for all sites is found during June. The highest specific production was in October for Kuwait Airport site (15.1 kg/kW) and WAFRA site (16.01 kg/kW); but the highest specific hydrogen production for ABDALY site was 16.30 kg/kW in December. The results in Table 8 show that the annual average specific hydrogen production was highest for ABDALY site (15.52 kg hydrogen/kW turbine power) followed by WAFRA site (15.31 kg/kW) then Kuwait Airport site (13.24 kg/kW).

5. Conclusions

Energy production from renewable resources have significant role in the industrial development of any country. Therefore, Kuwait is actively enhancing its renewable energy capabilities. For instance, Kuwait Oil Company has launched an ambitious project to generate 25 GW of green hydrogen by 2050 for both domestic use, industrial use and export. In the context of the above, the article examines the opportunities and feasibility of green hydrogen production using wind power at three sites

Table 8
Specific hydrogen production (kg/kW) for the three sites.

Month	Site name		
	Kuwait Airport	WAFRA	ABDALY
January	14.68	15.70	16.16
February	13.24	14.17	14.44
March	14.63	15.72	16.01
April	12.73	15.13	15.34
May	11.42	15.50	15.75
June	10.52	14.15	14.15
July	11.13	15.14	15.38
August	12.87	15.64	15.59
September	13.24	15.21	15.30
October	15.10	16.01	16.16
November	14.46	15.38	15.68
December	14.83	15.99	16.30
Maximum	*15.10*	*16.01*	*16.30*
Minimum	*10.52*	*14.15*	*14.15*
Average	***13.24***	***15.31***	***15.52***

in Kuwait. The hydrogen production system is modelled using Excel Spreadsheets. The model includes onshore wind turbine of rated power 2400 kW to operate water electrolyser of capacity 1800 kW. The study considered installing the system at three different sites in Kuwait. Based on the results of this study, it can be concluded that.

- The highest hydrogen production is 842 kg/day.
- The full load annual hydrogen production of the electrolyser is 307.3 metric tonnes.
- The highest annual hydrogen production is 288 metric tonnes when the system is installed at Kuwait Airport site, which is the best performance site.
- The second-best performance is found at WAFRA site with an annual production of about 171.5 metric tonnes.
- When the system is installed at ABDALY site, the annual hydrogen production is expected to be 145 metric tonnes.
- The annual specific hydrogen production was highest for ABDALY site (15.52 kg//kW) followed by WAFRA site (15.31 kg/kW) then Kuwait Airport site (13.24 kg/kW).

For future work, it is recommended to simulate the performance of wind-operated electrolyser using TRNSYS software. It is also recommended to investigate the change of electrolyser performance if it is solar-powered or powered using wind/solar hybrid system.

CRediT authorship contribution statement

Abdulrahman Alhajeri: Writing – original draft, Formal analysis, Data curation. **Heba Ghazal:** Writing – original draft, Supervision, Investigation, Data curation, Conceptualization. **Valentina Olabi:** Writing – original draft, Formal analysis, Conceptualization. **Hussam Jouhara:** Writing – review & editing, Writing – original draft, Supervision, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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