Research Article

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Large-scale green hydrogen production using alkaline water electrolysis based on seasonal solar radiation

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Abstract: The research study provides a techno-economic analysis for the green hydrogen generation based solar radiation data for both the single and hybrid alkaline water electrolyzer and energy storage system systems. In addition, a carbon footprint study is conducted to estimate the developed system carbon dioxide emissions. The optimal size of the alkaline water electrolyzer and energy storage system is determined by a genetic algorithm that takes into account a carbon tax on carbon emissions. Based on itemized cost estimating findings, unit hydrogen production costs for a single system and a hybrid system were $6.88/kg and $8.32/kg respectively. Furthermore, capital cost it has been found as a key element in determining the optimal scale of the alkaline water electrolyzer and energy storage system, which are essential for minimizing the unit hydrogen production cost. Lastly, an effort to minimize the capital cost of producing green hydrogen is required when the rising trend of the carbon dioxide tax is taken into account.

Keywords: alkaline water electrolysis; hydrogen energy; photovoltaic energy; renewable hydrogen.

1 Introduction

The use of renewable energy can overcome the difficulties of burning fossil fuels, since during operation it does not produce any harmful gases that contribute to global warming or greenhouse gases. However, the cost of generating power is the largest obstacle. There has been a recent resurgence of interest in clean energy technology to manufacture green hydrogen using solar and wind energy. This technology has reached recently a major milestone. Is due to the global trend and the movement towards future net-zero emissions (Krishnan et al. 2022). Global hydrogen consumption is expected to increase to 130 million metric tonnes by 2024 from 80 million metric tonnes in 2020 (Council 2021).

Despite having a few disadvantages, such as being flammable, hydrogen has a higher power density of around 125–145 MJ/kg (Helferty 2022), which is approximately three times higher than crude oil. It can also be manufactured anywhere by using electricity generated from renewable energy sources such as the wind and sun energy, which can supply the electrolysis of water in hydrogen and oxygen in the electrolyzer (Rasul et al. 2022). Then, without endangering the environment, a stand-alone hydrogen manufacturing system might be developed (Yu et al. 2020).

Large number of research studies has been conducted to assess the overall effectiveness of producing hydrogen using available locally renewable sources of energy. Several recently published articles have examined the industrial production of hydrogen using renewable sources due to its potential involvement in the emission reductions of the energy industries.

Hoisang and Sakaushi (2022), review of the need for a large-scale and cost-effective production of green hydrogen by combining electrolysis of water and renewable energy sources. The need for dimensionally robust electrodes of the next production has arisen as a result of the need to reduce emissions while providing energy independence in the twenty-first century. Numerous aspects of dimensionally stable electrocatalysts are discussed in the paper. Despite the fact that dimensionally stabilized electrodes are an established technology from the perspective of the current industry, fresh scientific advancements are still required to match the vast array of contemporary technical requirements required to reach a net-zero society. Ajanovic

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and Haas (2021) examine the primary obstacles to the expanding use of hydrogen and fuel cell in vehicles. Due to the importance of their economic success for their future deployment, considerable emphasis is placed on it. The cost of mobility is determined by the total cost of ownership, and future improvements are assessed based on technical advances. To realize the full advantages of hydrogen and fuel cell technology in the transportation sector, it is vital to establish stable, long-term regulatory frameworks and to synchronize regional efforts in order to take advantage of scale economies.

Mazzeo et al. (2022) examine solar and wind systems, and hybrid systems, for the production of green hydrogen globally. A comprehensive data set representing the combination of wind turbine (WT) and photovoltaic (PV) system for hydrogen production at various sites was created using interactive design. Several non-dimensional variables were applied and evaluated for the purpose of standardizing the quality assessment technique for renewable-based hydrogen production systems. Authors analyzed systems for 28 geographical sites, the yearly and monthly values of these variables, as well as the calculate overall quantity of green hydrogen production. It has been shown, that small-scale applications, such as those for home users, or large-scale applications, such as those for industrial users, in addition to any hydrogen requirement and climatic circumstances, may be readily tested using the method described. Guerra et al. (2020) conducted a comprehensive techno-economic study to determine the economic viability of producing green ammonia in Chile using green hydrogen. Additionally, they met the electrical needs of nitrogen fabrication using renewable energy. In their economic part the authors analyzed the transit of nitrogen between Chile and Japan. In addition, a complete sensitivity analysis was conducted to identify the influence of the most significant factors on the economic indicators of the green nitrogen factory.

Weidner et al. (2022) evaluated the production of hydrogen on a large scale using projected life-cycle modeling. The findings show that the effects of expected levels of production on climate change are 3.0–5.5 times higher than the allotted global limit, with green hydrogen from wind energy remaining below the limit. Compared to other studies, the implications for both the environment and human health are much less severe; however, the metal deficiency and ecotoxicity consequences of green hydrogen need further consideration. When conducting a projected life cycle analysis, environmental destruction costs grow the most for blue hydrogen, but it decreases most significant for green hydrogen generation using solar photovoltaic systems. This approach helps in the evaluation of probable unexpected outcomes and adds to the discussion of both blue and green hydrogen. The paper by Bhattacharyya et al. (2017) discusses the design of a photovoltaic energy system that satisfies the energy needs of the electrochemical reaction, accompanied by an examination of the system performance under various environmental circumstances. The energy required for electrolysis depends on the intended hydrogen rate of production and the electrolytic cell working parameters, and it has been estimated based on a thermodynamic study. The mean solar irradiation data are determined using area-specific weather information. Is have been presented that current solar module production characteristics can be estimated using a five-parameter single component of a solar panel as a result of solar irradiance and have been linked to hydrogen production rates. For real operating circumstances, the module thermodynamics and conversion performances have also been anticipated.

The potential of Algeria to produce hydrogen using renewable energy resources was evaluated by Rahmouni et al. (2017). Wind, and solar power are examples of renewable energy. Authors evaluated renewable resource information from both economically and graphically point of view using the Geographical Information System. It analysis a computer information system was used to construct and illustrate the geographic range of geographic data. The research studies analyze the potential for the production of renewable energy from these essential renewable resources. The possibility for the hydrogen generation through an electrochemical reaction using solar and wind photovoltaic power is shown on the maps for each location. Finally, substantial conclusions are reached from the comparison of the predicted hydrogen capability of the two factors at each location. Touili et al. (2018) modelled the photovoltaic-electrolyze combination, while electrical power and hydrogen generation for 76 locations scattered across Morocco were chosen. The solar irradiation statistics were taken from weather stations. Presented results indicate that Morocco has a considerable hydrogen production capacity, with daily, and yearly production ranging between 6500 and 9000 tonnes/ km^2. The outcomes of this study are extremely important because they provide regulators and investors with a comprehensive view of the country's hydrogen capacity, allowing them to evaluate hydrogen production throughout the entire country.

Gouareh et al. (2015) examined the most favorable areas for hydrogen production in Algeria by means of geothermal energy and carbon dioxide as a hybrid nanofluid. The scientists initially selected places with substantial carbon dioxide emissions to be collected and stored, and then analysed the potential for power and hydrogen production. Due to the significant industrial concentrations in the northeast and southwestern U.S., it has been determined that the best locations are in the northeastern and southeastern U.S. Gondal, Masood, and Khan (2018) assess the potential of Pakistan diverse renewable energy sources. The possibility of hydrogen by existing methods using each of these renewable energy resources is then estimated. Numerous evaluations have been made on the accessibility and use of sustainable energy in Pakistan; however, no particular studies have been conducted on the use of renewable resources in the development of hydrogen production or an electricity infrastructure. Presented analysis shows that solar energy is the most viable feedstock for building a hydrogen supply chain, with the ability to produce seven million tonnes of hydrogen per year. Ayodele and Munda (2019) studied the feasibility and economic viability of sustainable hydrogen production using renewable energy resources at 15 locations in 5 South African provinces. The potential influence of changes in wind turbine operational parameters, the effect of exponential shear properties, and the economic benefits and burdens of renewable hydrogen production have also been investigated. According to the findings, South Africa has a high potential for green hydrogen production, and the technological, economic, and ecological consequences of using the generated hydrogen to satisfy the energy demands of rural populations in South Africa using a fuel cell are favorable.

Marino et al. (2019) present a stand-alone photovoltaic system that uses storage accomplished using electrolytic hydrogen, which would be transformed into electricity in fuel cell technology. Presented study focus on size optimization of the system component chain in relation to the required electric load. A positive yearly balance was maintained among hydrogen production and consumption, and excess energy output was not allowed to be retained or transformed into hydrogen owing to battery or tank capacity limitations. Analysis demonstrates that in order to prevent excessive gas pressures, extra energy cannot be employed if the nighttime load is active and the system is isolated from the grid unless huge storage tanks are used. Therefore, only grid-connected systems are recommended for use in public or residential areas, where the visual effect of tanks is scarcely desirable and safety regulations prohibit excessive gas pressure. Arsalis et al. (2018) designed a PV based system for hydrogen production with zero emissions and total autonomy. The research provides a comprehensive mathematical model of each system component. According to the presented analysis the suggested system performs better in the using of single component scenario. Carroquino et al. (2018) have established the technical and economic viability of a standalone solar-powered electricity with hydrogen production facility. The results indicate annual production of electricity approx. 75 MWh and 1220 Nm^3 of hydrogen, preventing the release of more than 5 tonnes of carbon dioxide into environment.

Valente et al. (2021) compared various performance indicators of sustainable energy hydrogen derived from wind-powered electrolysers and biomass combustion with those of standard hydrogen production from catalytic steam reforming using five different indicators: climate change, acid rain, levelized cost, forced labour, and health expenditure. The outcomes led to the identification of the "operating a vehicle production stage" as the primary impact source. The hydrogen generated using renewable sources has been shown to have lower economic life-cycle environmental performance than conventional hydrogen generation. However, the anticipated increase in the process efficiency would substantially improve the future performance of sustainable hydrogen in all most important sustainability criteria. Yates et al. (2020) investigate a wide range of input assumptions in order to determine the primary cost drivers, objectives and localized conditions required for affordable standalone photovoltaic system with hydrogen hydrolysis. To maximise the size of photovoltaic system relative to the electrolyzer size, Authors evaluated the levelized cost of hydrogen production based on historical meteorological data for particular areas and model system accordingly. Presented research study and methodology demonstrate the possibilities for green hydrogen production through off-grid photovoltaic as well as the advantages of remote systems in regions with abundant solar resources. The performance and cost benchmarks for electrolyzer technology were also evaluated. Hassan (2020) developed a procedure for optimizing solar-hydrogen energy systems to provide renewable energy to typical grid-connected households. Using optimal fuel cell capacity, the solar-hydrogen energy system was developed to meet the electrical load and increase the renewable energy self-consumption. The results indicated that proposed method reduced the cost of power by roughly $0.21/kWh. The acquired study revealed that the suggested numerical analysis approach has a unique quality that can be used to optimize hybrid renewable energy systems.

Koleva et al. (2021) assess solar-electrolysis system combinations using a computational programming model developed in order to optimize the net present value of the system. The system was evaluated in California using unique meteorological circumstances and financial incentives. The results indicate that a range of potentially cost-competitive options are possible for hybrid consumer markets, with factors determining a hydrogen production cost of around $6.5/kg. Schulthoff et al. (2021) examined the importance of hydrogen in future electric power systems based on projected costs. The generating mix includes intermittent renewable energy sources such as solar and wind energy, as well as gas turbines powered by natural gas using carbon capture storage and hydrogen tank. The research indicates that under specified circumstances, pumped storage retention completely substitutes rechargeable batteries. In addition to solar photovoltaics and pumped storage retention, the combination of hydroelectric energy storage response reduced overall costs.

The carbon constraint determines the generating mix and initiates hydrogen incorporation. Guo et al. (2019) characterized the flow of energy and flow rate in the photocatalytic separation of water from numerous spatial and temporal scales, highlighting that the reduced efficiencies of the photocatalytic splitting of water are due to obstructions in the transfer of energy and flow rate, as well as non-coupling and non-matching of the transfer of energy and mass flow. The fundamental insights gained from this approach suggest that, in addition to material optimization, the engineering and scientific design of sunlight collection, interfacial response, and mass transfer are of major importance. Based on various economic variables, including the unit price of electricity, the real challenge, and the mechanization scale, Lee et al. (2019) analyzed sought to identify a suitable and plausible scenario in which alkaline hydrogen production is expensed in the definitions of the levelized cost of hydrogen. The results of the set of circumstances analysis show that the unit cost of electricity, accompanied by the educational curve and loading stage, is the most efficient economic factor in determining the cost of hydrogen, demonstrating that the beginning of huge excess power production, inevitably produced from renewable sources, can be extremely important for the production of hydrogen from alkaline hydrogen production to be economically feasible compared to the predicted cost of hydrogen of $1.25/kg.

For three distinct sites in Europe, Kuckshinrichs and Koj (2018) report the levelized cost of hydrogen for enhanced alkaline water electrolysis in: Austria, Germany, and Spain. The study demonstrates the significant differences between individual and societal hydrogen costs. The highest cost of hydrogen is produced from such a societal viewpoint by including all cost factors and relatively low discount rates. The significant distinctions in the case study discussed here are brought about by the complete treatment of environmental consequences, with the potential for global warming caused by power production serving as the primary environmental cost source. The research also addresses the vulnerability of hydrogen costs with regard to factors like plant lifespan, carbon dioxide prices, and tax levels. Shaner et al. (2016) conducted a study for photo-electrochemical and solar-hydrogen production in order to evaluate the profitability of each technique and provide a foundation for comparability between any of these techniques. The result indicated that the cost of the hydrogen product was $11.2/kg. Attempts to directly reduce carbon dioxide from the atmosphere through chemical modification may yield products with values higher than hydrogen, but there are numerous obstacles to overcome, including electrocatalytic activity and selectivity, carbon dioxide mass transit rates, and material expense. As solar hydrogen production is cost-competitive with current large-scale thermochemical methods for carbon dioxide reduction, significant advances are necessary, but the obstacles to enhancing economic viability are even larger. Using a cost-of-energy method, Darling et al. (2011) evaluated the cost of solar power compared to electricity and cost of hydrogen production obtained from conventional sources. In general, the cost of hydrogen is viewed as a fixed amount, and the theoretical underpinnings are rarely disclosed or even understood. On the basis of input parameter distributions, Authors show a novel method for determining the cost of hydrogen for photovoltaic system and shed light on some of essential assumptions. This paradigm makes evident the impact of preconceptions and margins of error. In another research study, Ceran et al. (2021) investigated the effects of ageing on the modelling and operation of a solar system with hydrogen storage over a 10-year period, focusing on the decline in energy output and the need for supplementary hydrogen. After ten years of system operation, the results demonstrate approx. 30–37 % increase in the fuel requirements from an external source relative to the baseline state. The degradation of the components was represented using the unit hydrogen.

Despite the fact that the production of hydrogen from renewable sources of energy has zero-carbon capabilities, the substantial infrastructure needed has non-negligible consequences throughout the life span (Abdulateef et al. 2021; Jaszczur et al. 2020) or end-of-life management of hazardous waste (Hassan et al. 2022a, 2022b). Table 1 provides a summary of pertinent prior research.

To the best of our knowledge, there are not many articles in the literature that deal with the problem of producing green hydrogen on an industrial scale to be ready for the new green hydrogen manufacturing systems using alkaline water electrolysis system with energy storage. This paper targeted to integrated into the solar power plant for the highest hydrogen production at the lowest cost thorough examination of green hydrogen production using (2.5 MWp) solar farm. The consideration was for two scenarios for energy supplied that feed the alkaline water electrolyzer (AWE): (i) using only solar energy and (ii) using only solar energy and an energy storage system (ESS) to provide an economical understanding via a quantitative study that includes an economic study, carbon emissions analysis, and optimization for the suggested systems.

Table 1: Summary of the green hydrogen production projects.

Country	Production	Relevant details	Reference
US	Blue and green hydrogen	Various production methods, including the potential cost of carbon	Borole and Greig (2019)
Germany	Green hydrogen	Renewable energy for 2017 and projected to 2050	Bareiß et al. (2019)
Saudi Arabia	Green hydrogen	Renewable energy for green hydrogen projected to 2050	Al-Sharafi et al. (2017)
UK	Blue and green hydrogen	Cost assessment of multiple technologies with climate change mitigation	Parkinson et al. (2019)
China	Green hydrogen	Cost evaluation of alternative climate change mitigation technologies	Ren et al. (2015)
Spain	Green hydrogen	Changes in sustainable energy efficiency and lifetime between 2030 and 2050	Valente et al. (2020)
Canada	Grey and green hydrogen	Cost-benefit analysis of solar and fossil solutions for climate mitigation	Sadeghi et al. (2020)
Switzerland	Blue and green hydrogen	Multiple hydrogen production methods with consequences commercialization	Al-Qahtani et al. (2021)
Netherlands	Green hydrogen	Prediction of future parameters for the production of green hydrogen	Delpierre et al. (2021)
India	Green hydrogen	Solar radiation photocatalyst recovery of clean energy hydrogen	Preethi (2022)
Iran	Green hydrogen	Determine the amount of available solar energy for green hydrogen production.	Rezaei et al. (2020)
Turkey	Green hydrogen	Prepare a hydrogen production roadmap foreach city in Turkey	Karayel et al. (2022)
Egypt	Green hydrogen	Model for green hydrogen energy and roadmaps for 2030	Abdallah, Asfour, and Veziroglu (1999)
Germany	Green hydrogen	Using sustainable energy projection 2030 and 2050	Schropp et al. (2022)

2 Experimental measurement

Diyala city has attempted to implement a low-carbon transition in the energy industry by passing regulations pertaining to renewable energy, carbon dioxide, and clean fuel consumption, and was selected as a destination for green hydrogen production plant. Taking into account 6000 m^2/kW of required land area for photovoltaics and the photovoltaic system performance equal to 19 % of, a land area of 5000 m^2 was taken into consideration for the photovoltaic system. Data on solar irradiance was acquired using the FT0300 weather station.

Solar radiation and ambient temperature were collected for the year of 2022 with 1 min resolution. In Figure 1 solar irradiance and ambient temperature for each quarter of the year are presented.

3 Proposed system model

Figure 2 illustrates the system under consideration with two scenarios: with and without energy storage (ESS). It can be seen that the system consists of four basic components: the first component is a photovoltaic array (Hassan et al. 2021), followed by an electrolyzer (EL) and energy storage system, and a hydrogen storage tank (HT). The alkaline water electrolyzer unit extracted hydrogen and oxygen from water. The hydrogen storage tank completes the developed system.

The photovoltaic panels are positioned with the optimal yearly adjustment, for presented location tilt angle (β) = 31° and azimuth angle (γ) = 0 south facing. The numerical simulation was executed with a one-minute time step resolution (Abbas et al. 2022a; Hassan et al. 2022d) and the aim is to determine the capacity of an alkaline water electrolyzer that can have optimum match capacity solar energy station.

4 Technical and economic model

4.1 Power generation and hydrogen production model

The intensity of incident direct solar radiation and other weather factors, such as the surrounding humidity and temperature, etc., are used to estimate the photovoltaic power production. The calculation for PV output powers as (Jaszczur et al. 2018, October; Jendar et al. 2022).

$$P_{PV} = f_{PV} Y_{PV} \left[1 + \alpha_P \left(T_C - T_{C,\mathrm{STC}}\right)\right]\left(\frac{S_T}{S_{T,\mathrm{STC}}}\right) \tag{1}$$

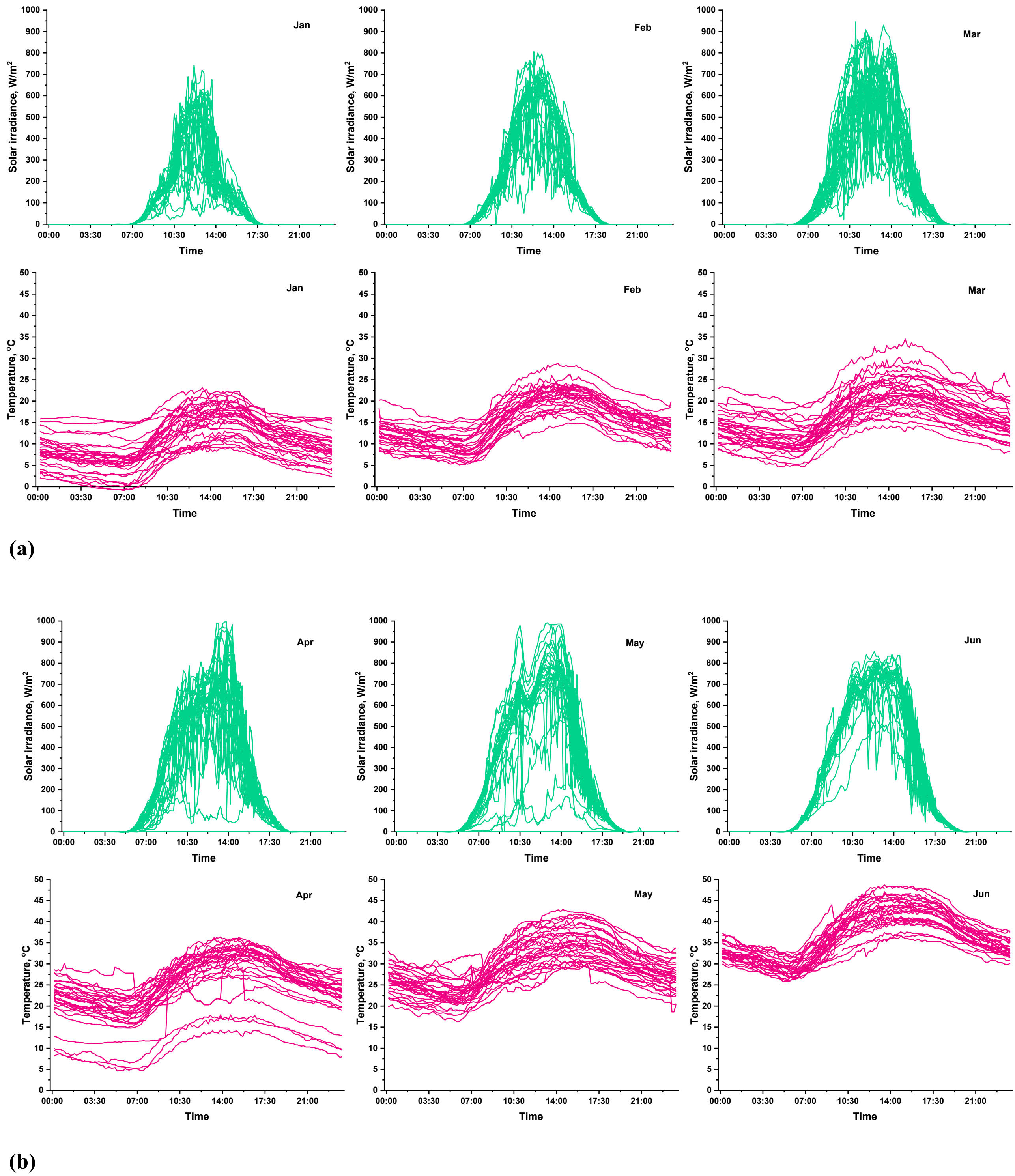
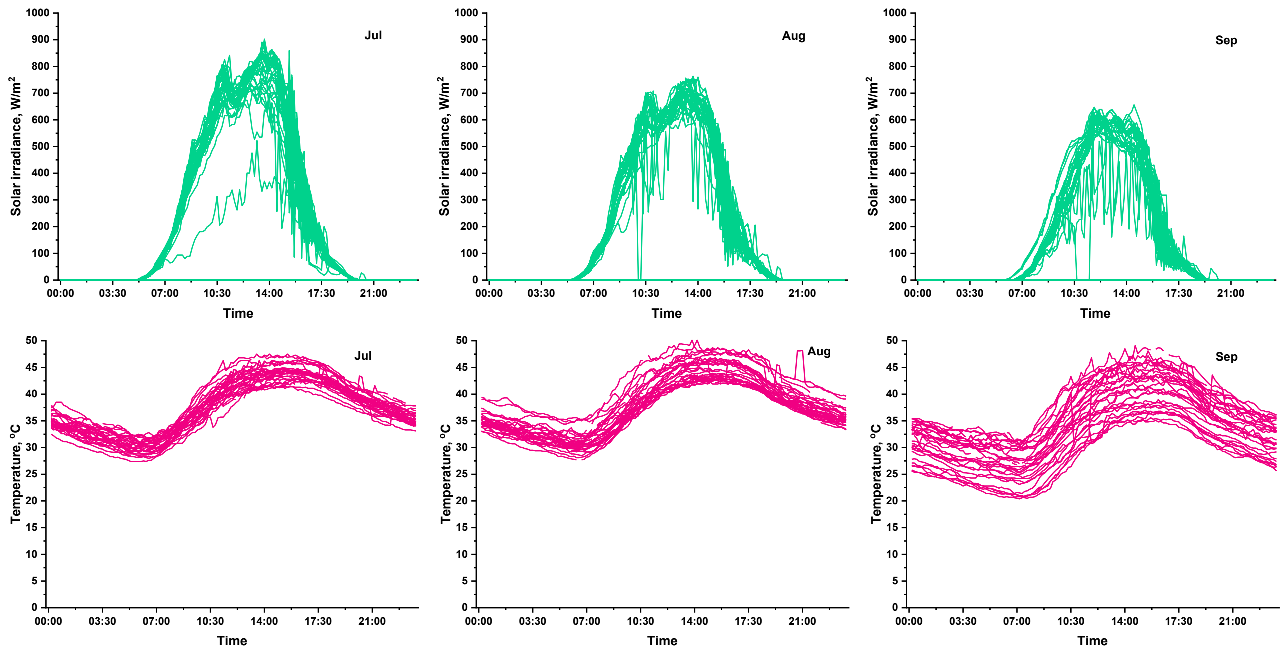


Figure 1: Solar irradiance (green) and ambient temperature (red) data of Diyala city based on the year quarter: (a) 1st quarter (January, February, March), (b) 2nd quarter (April, May, Jun), (c) 3rd quarter (July, August, September), and (d) 4th quarter (October, November, December) of the year 2022.

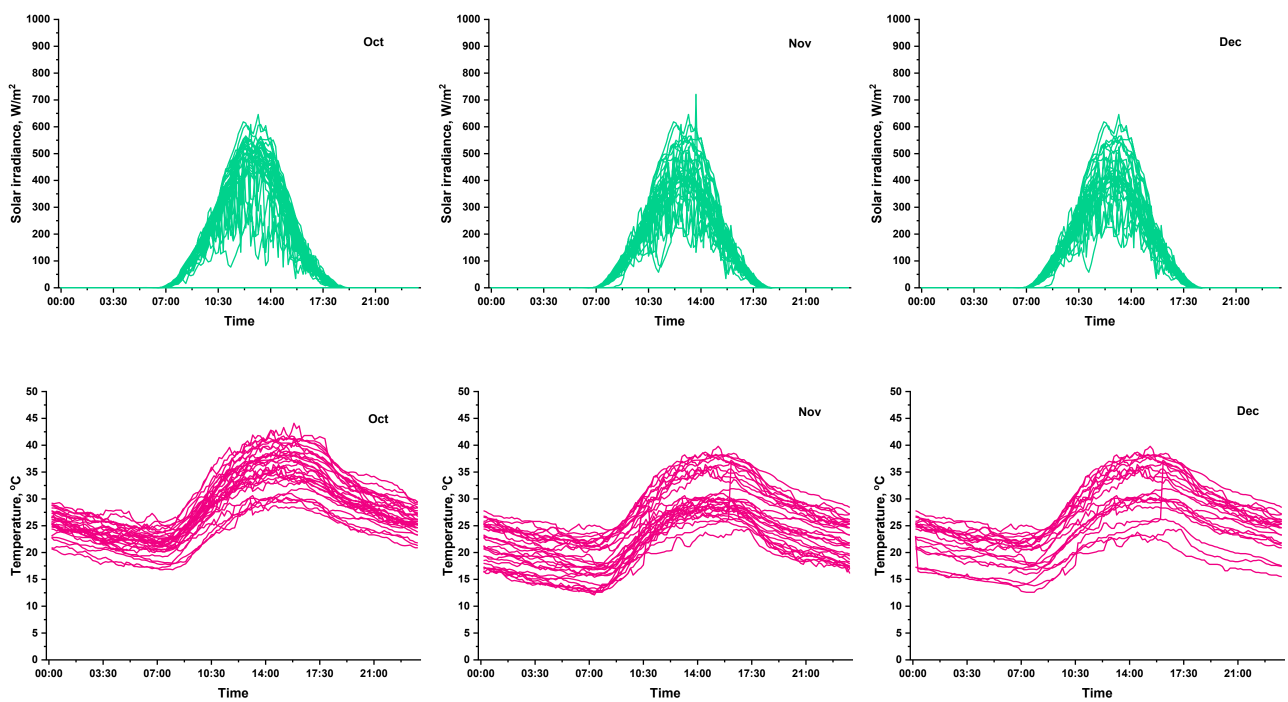
The main effect on battery power is the ESS of charge state and could be estimated using the following formulas (Abbas et al. 2022b; Hassan 2021):

ESS charging,

$$P_{\mathrm{ESS},t} = P_b(t-1)\cdot(1-s_d) + (P_n(t) - P_k(t)/(\eta_N))\cdot\eta_b \quad (2)$$



(c)



(d)

Figure 1: Continued.

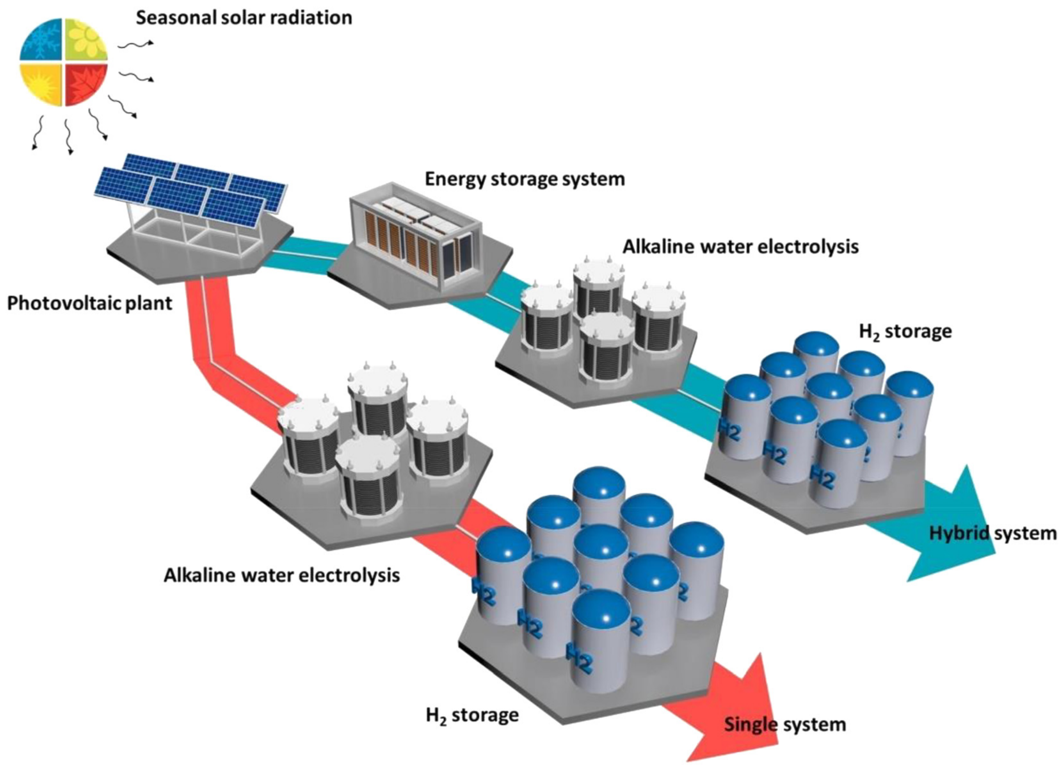


Figure 2: Scenarios of AWE based on PV and PV + ESS.

ESS discharging,

$$P_{\mathrm{ESS},t} = P_b(t-1)\cdot(1-s_d) - (P_n(t)/(\eta_b)\cdot P_k(t)) \tag{3}$$

The quantity of electrical energy input required by the electrolyzer can be calculated as (Abdulateef et al. 2021; Palej et al. 2019).

$$I_E = A_E.\, m_{H_2} + B_E.\ m'_{H_2} \tag{4}$$

The power required to compress the hydrogen contained in the hydrogen tank can be calculated as (Hassan et al. 2022e; Hussain et al. 2021):

$$P_{\mathrm{com}} = \left[\left(\frac{P_{hto}}{P_{hti}}\right)^{\frac{\gamma-1}{\gamma}}\right]\left(\frac{g}{g-1}\right)R\left(\frac{T_{htci}}{\eta_{htc}}\right)Q_{H_2} \tag{5}$$

The predicted pressure within the hydrogen tank can be calculated as follows:

$$P_{\tan K} = \left(\frac{R\,T_{htci}}{V_{h\tan K}}\right)\eta_{h\tan K} \tag{6}$$

The PV panel provides DC electricity, but the demand is typically AC, therefore, the converter is required to convert DC power to AC power, in addition, applied in the power system to regulate the energy flow. The efficiency of the converter can be calculated as (Alhurayyis, Elkhateb, and Morrow 2020; Rajesh et al. 2022):

$$\eta_{con} = \frac{P_{ocon}}{P_{icon}} \tag{7}$$

As seen in Figure 2, and this characteristic made it challenging to determine the size and capacity of AWE and ESS, respectively. The following equations were used to calculate the power that was used to feed AWE and delivered from photovoltaic power plant:

(i) by using only solar energy:

$$P_{\mathrm{AWE},t} = P_{PV,t} \quad \text{for} \quad P_{PV,t} \geq P_{\mathrm{AWE},t} \tag{8}$$

(ii) by using solar energy and an ESS:

$$P_{\mathrm{AWE},t} = \begin{cases} P_{PV,t} & \text{for } P_{PV,t} \geq P_{\mathrm{AWE},t} \\ P_{\mathrm{ESS},t} & \text{for } P_{\mathrm{ESS},t} \geq P_{\mathrm{AWE},t}\,;\, P_{PV,t} = 0 \\ P_{PV,t} + P_{\mathrm{ESS},t} & \text{for } P_{PV,t} + P_{\mathrm{ESS},t} \geq P_{\mathrm{AWE},t} \end{cases} \tag{9}$$

4.2 Economic model

In this study, a detailed cost of green hydrogen production was evaluated in order to determine the optimal AWE and ESS capacities for 2.5 MWp of solar PV power plant. Therefore, the supplementary costs constituted capital expenditure, while labour, water, land, maintenance, and other costs represented operational expenditure.

Table 2 provides details on all technical and economic criteria (Lee et al. 2021). On the contrary, the ESS cost was included in the investment cost category for the hybrid system, which was presumed to be composed of a lithium-ion battery.

The construction, hydrogen plant balance (HPB), maintenance, water, and other costs taken: 0.3 % of total capital costs, 45 % of AWE capital 2 % of total capital costs. The power plant has been designed for 10-year life span.

More specifically, the initial capital cost must be converted to a yearly capital cost by using a discount factor known as the capital recovery factor (CRF) as illustrated in (Razmjoo and Davarpanah 2019; Turton et al. 2008).

$$\mathrm{CRF} = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{10}$$

where i is the discount rate 4 % and n is the 10-year life span.

The AWE for the hydrogen production rate is calculated as (Jang et al. 2022; Yang et al. 2022)

$$Q_{H_2} = \eta_f\left(\frac{N_C I_e}{2F}\right) \tag{11}$$

The cost of producing one kg of hydrogen can be computed using the following expression (Hassan and Jaszczur 2021; Hassan et al. 2022c):

$$COH = \frac{I + \sum_{t=1}^{n}\frac{M_C}{(I+i)^t}}{\sum_{t=1}^{n} H_t} \tag{12}$$

4.3 Carbon emissions assessment

Carbon emissions analysis is a technique to quantify the total carbon dioxide emission from the production of green hydrogen using renewable power (von der Assen et al. 2014; Müller et al. 2020). In this study, the system was used with a scope that includes renewable energy generated using photovoltaic energy with ESS support. The carbon dioxide emissions from the production of green hydrogen by the proposed system based on the specified component: PV plant is 0.06 $kgCO_2$/kW; AWE unit is 3.23 $kgCO_2$/kg; ESS unit is 7.89 $kgCO_2$/kW (Kätelhön et al. 2019).

5 Optimisation process

Using a genetic algorithm, the optimal sizes and capacities of AWE and ESS are determined. A genetic algorithm is a technique for determining the optimal solution whenever a system is difficult to represent in terms of its performance (Xue et al. 2021).

With the initial step of the optimization method, several variables were produced for the AWE scale and the ESS capacity, ranging from 0.5 to 5 MW and 0.5 MWh to 5 MWh, respectively. Using the economic modelling process, unit hydrogen production costs were estimated for each completely random number and sorted in increasing order to determine the unit hydrogen production cost with the lowest possible cost. The optimum solution was selected if the minimum unit hydrogen production cost differential between the current trial and the prior trial was less than the tolerance threshold. Iteratively, this procedure was repeated until the ideal solution was reached. In addition, the ideal approach was determined by implementing a carbon dioxide emission. In this instance, the carbon dioxide tax for each nation was used and added to the unit cost of hydrogen production to evaluate the environmental effect based on the results of a carbon emissions study (Hassan 2020; Hassan and Jaszczur 2021). Figure 3 shows the flow diagram of a simulation of an energy system.

6 Results and discussion

Based on real environmental data and the system shown in Figure 2, a set of parametric simulation was executed with a one-minute time step resolution. The solar power plant has a capacity of 3 MWp, and the modules are positioned at the optimal annual angle for the specified site (south-facing tilt angle = 30° and azimuth angle = 0°). The impact of ambient temperature on the PV energy production was accounted and a power coefficient equal to −0.26 %/°C (Monocrystalline Luminous PV module and converter). It was established that the derating factor was 95 %, with the remaining 5 % comprising energy losses in the wiring, dust, etc. The

Table 2: The technical and economic specifications.

Component	Model	Efficiency (%)	Cost	Life span (year)	Ref.
PV module	Luminous	18.7	$780/kW	15	Monocrystalline Luminous PV module and converter
ESS	Vision	92	$250/kW	4	Vision batteries
Converter	Luminous	>95	$450/kW	10	Monocrystalline Luminous PV module and converter
AWE	Geemblue	>95	$601.2/kW	10	Electrolyser Geemblue

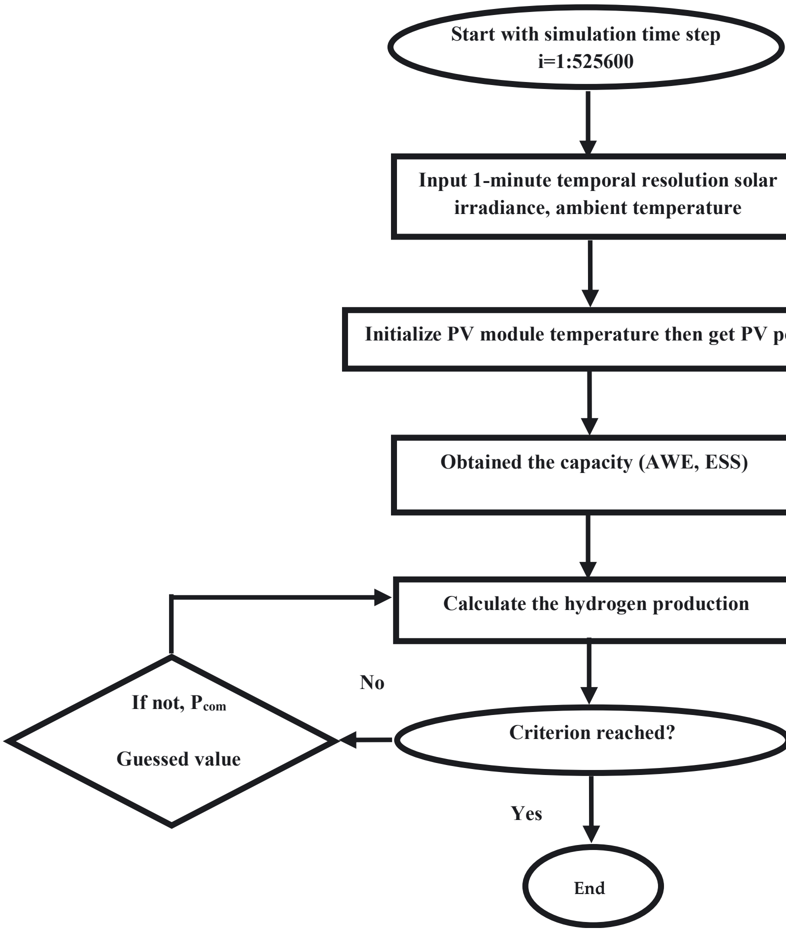


Figure 3: Algorithm of the proposed system with simulation steps.

electrolyzer is available in a range of capacities (0.5 MW, 1 MW, 1.5 MW, 2 MW, 2.5 MW, and 3 MW) in order to determine the optimal capacity that can be integrated into the solar power plant for the highest hydrogen production at the lowest cost. The recommended price for parts of the system is based on the economic realities in Iraq and a rate of inflation of 0.6 %.

The annual energy generated by the solar power plant is 4722.760 MWh, with a daily mean output of 12.939 MWh at 4334 operation hours per year. Figure 4a shows the year-quarterly energy production (three months per quarter). The highest energy produced during the second quarter of the year was recorded at 1533 MWh due to the highest solar irradaince and longest day hours, while the fourth quarter recorded the lowest value at about 697.63 MWh. Figure 4b shows the annual production of hydrogen for several AWE capacities; The highest production was 113,331 kg at 2.5 MW AWE capacity, with the lowest hydrogen cost of $6.86/kg as presented in Figure 4c. Figure 4d shows the hydrogen production capacity factor for various AWE capacities. It can be inferred for figure that hydrogen production capacity factor decreases with increasing AWE capacity.

Figure 5 shows the graph for the hydrogen production sensitivity analysis result, which demonstrated that the most relevant parameter was a reduction in PV and AWE efficiency. Change in those parameters results significant in an increase in unit hydrogen production with obtained price to $8.6/kg. In other words, the drop in yearly hydrogen production has approx. 25 % impact on the unit price of hydrogen production.

Increasing AWE size increase energy requirement; annual energy consumption at 2.5 MW AWE was 4706 MWh, as shown in Figure 6a; at the same time, increased AWE capacity reduced the; The lowest excess energy from PV equal to 17.202 MWh was observed at the 2.5 AWE capacity, as shown in Figure 6b.

The daily power excess that is not consumed by the electrolyzer is presented in Figure 7 for the selected day (10th for each month). The second and third quarters of the year had the highest excess energy, while the first and fourth quarters lowest one. The energy generated by the solar panels at sunrise was insufficient to run the electrolyzer (as shown in the red circle), and at the end of the day, before the sunset, the power generated was insufficient to run the

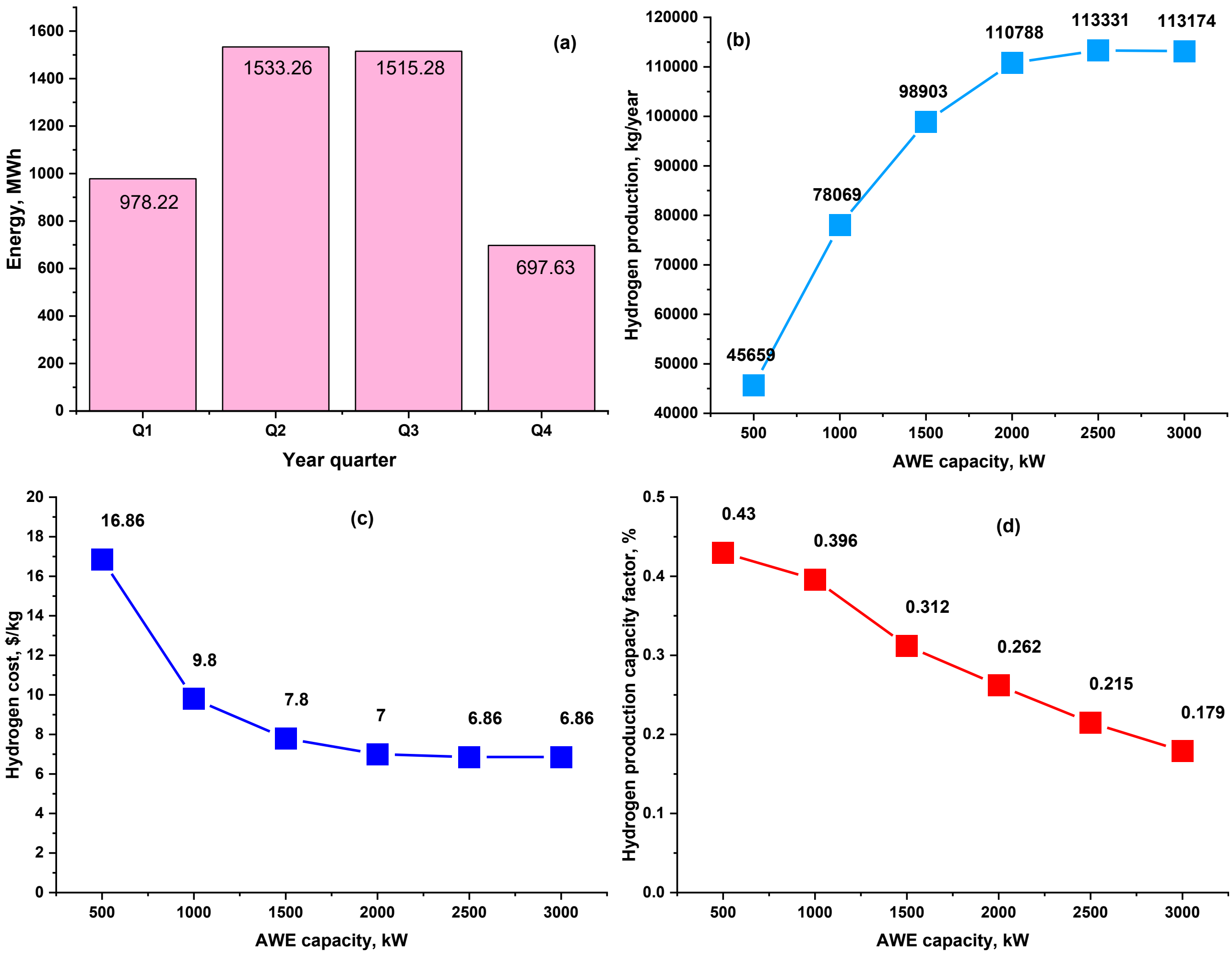


Figure 4: Quarterly energy production by solar power plant throughout the year (a); annual hydrogen production at several AWE capacities (b); hydrogen cost at several AWE capacities (c); hydrogen production capacity factor at several AWE capacities (d).

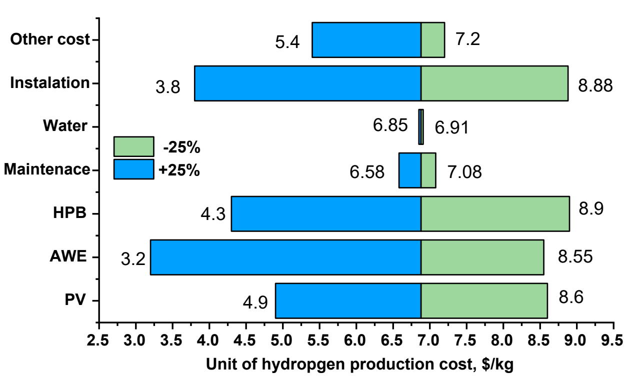


Figure 5: Sensitivity analysis of the cost of hydrogen production.

electrolysis as well; this power was then used to finance an investment in the ESS, which was used to generate hydrogen in the following section.

Figure 8a and b show the quarterly hydrogen production and the excess energy generated by the PV power plant, respectively.

The excess energy presented in Figures 6, 7, and 8 that is produced by the PV power plant and is not used in the AWE capacity, designed to charge the BSS. There are several capacities that have been designed in order to obtain the best capacity for storing excess energy and using it for hydrogen production during periods of no photovoltaic system production (cloudy days and nights). Figure 9 shows the annual simulation results for determining the optimal energy storage system capacity to match the extra energy produced by about 240,000 Ah of battery storage. The vast majority of the stored energy was used to make hydrogen. Due to the fact that 2.5 MW AWE capacity is regarded as the maximum scale for using the stored energy in a 0.51 MWh energy storage system, the energy storage

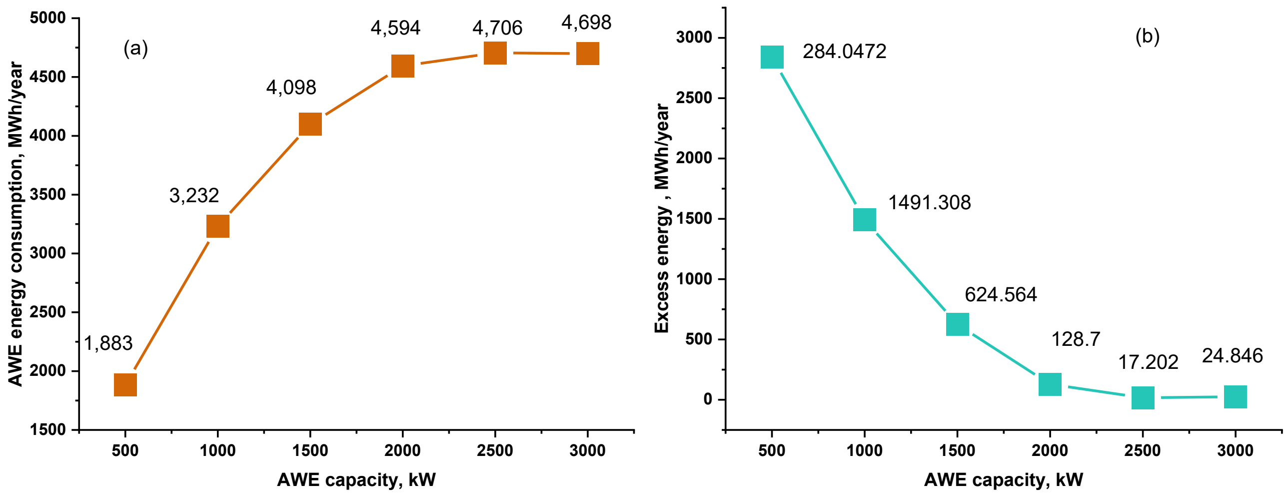


Figure 6: Annual energy consumption by AWE at several capacities (a); excess energy generated by solar power plant at several AWE capacities (b).

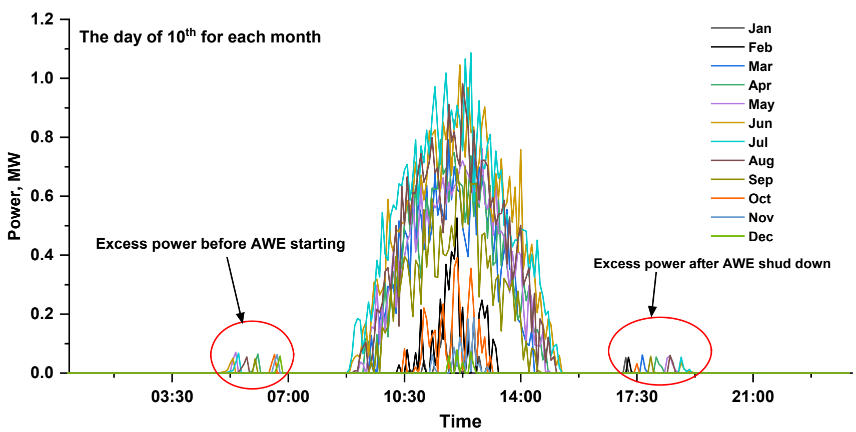


Figure 7: Daily excess power of the selected day (10th) for all months.

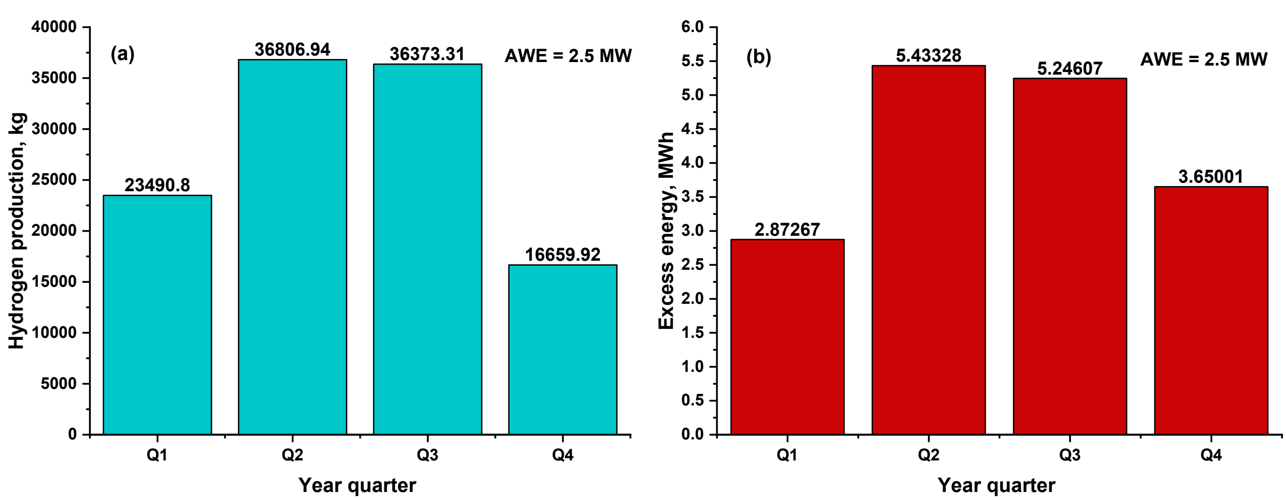


Figure 8: Annual quarterly of 2.5 MW AWE (a) hydrogen production; (b) excess energy generated solar power plant.

system has a capacity of 0.51 MWh. As demonstrated in Figure 9 shows how the optimal AWE scale changes depending on the installed energy storage system capacity. The battery capacity needed for energy storage depends on several factors, including the amount of energy required, the desired discharge time, and the efficiency of the energy conversion and storage system. The capacity of the AWE also plays a role, as it determines the rate at which hydrogen gas can be produced, which in turn affects the rate at which battery energy can be stored for the high production of hydrogen. In order to determine the optimal battery capacity for a given application, it is necessary to conduct a detailed analysis of the energy requirements and usage patterns, taking into account factors such as peak demand, daily cycles, and seasonal variations. This analysis can then be used to estimate the required battery capacity and choose an appropriate battery capacity from the options given (216,000 Ah, 240,000 Ah, 255,000 Ah, and 270,000 Ah). Which is the best estimate of energy storage with battery capacity for optimum AWE capacity was 240,000 Ah for the best fit at the best estimated relative value (1).

These results demonstrate that the optimum storage system capacity and AWE capacity should be identified to increase the energy savings of the hybrid system producing green hydrogen.

Figure 10 illustrates the techno-economic analysis of the results of the hybrid system, including the unit hydrogen production cost, the annual quantity of hydrogen produced, and a comparison of the unit hydrogen production cost for a single and hybrid system. As shown in Figure 10, as the energy storage cost drops, the minimal hydrogen production cost region shifts in the direction of a decrease in the AWE scale and an increase in the acquired energy storage capacity. These results show that the use of

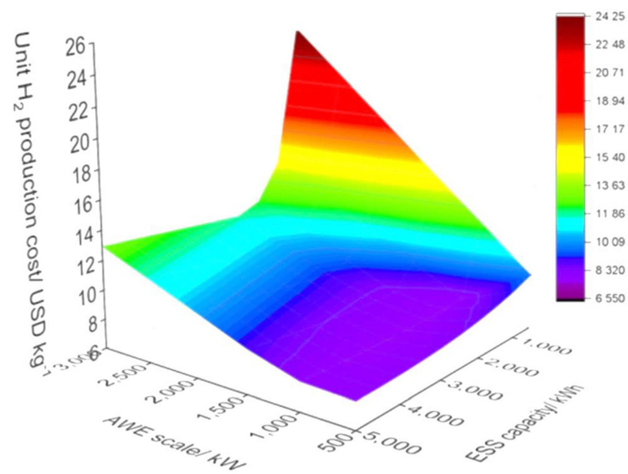


Figure 10: The techno-economic analysis for green hydrogen production cost.

energy storage as a bridge between a solar power plant and an AWE is an effective strategy to reduce the unit cost of hydrogen production by decreasing the AWE capacity.

As shown in Figure 10a and b, the highest possible quantity of annual hydrogen production can be achieved with 0.5–3 MW of installed AWE scale and 0.5–5 MWh of energy storage capacity at two energy storage prices, but a single system requires 2.5 MW of AWE scale and 0.5 storage system to achieve the maximum amount of annual hydrogen production.

Figure 11a and b, show the carbon emissions in terms of carbon dioxide emissions for 0.5 MWh of ESS capacity based on the 2.5 MW AWE. The results indicate that normalization provided a proportional contribution of each component to overall carbon dioxide emissions, and total carbon dioxide emissions (see Figure 11b). It is clear that carbon emissions, shown by the red line marking in each instance of the AWE

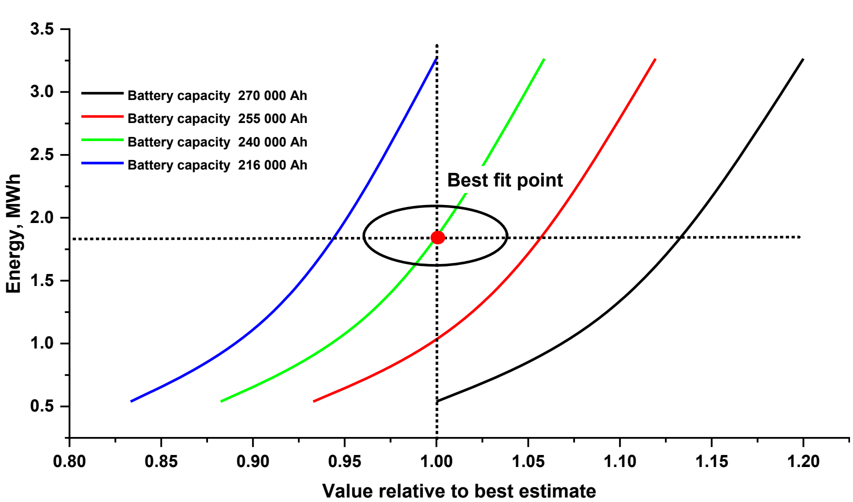


Figure 9: The best estimate of energy storage capacity.

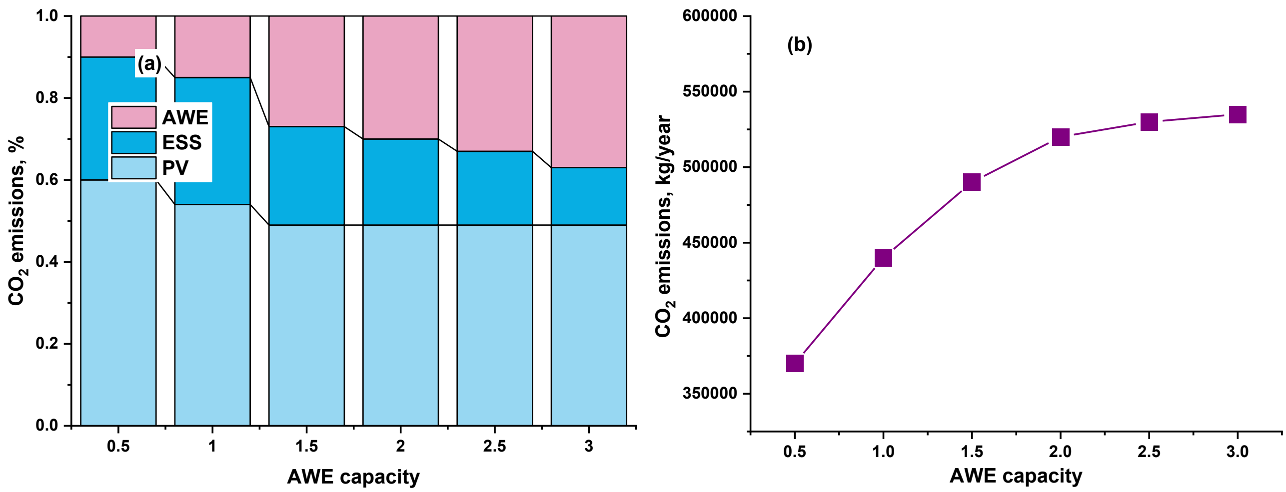


Figure 11: Carbon dioxide emissions analysis results at several AWE capacities.

capacity, grows as the ESS and AWE capacities increase, reaching 531,000 kg/year in the case of 2.5 MW AWE and 0.5 MW ESS capacities.

The cost per unit of hydrogen generation increases when the carbon dioxide emissions tax increases, as seen in Figure 12. Furthermore, the unit cost of hydrogen generation, changes by about \$1.3/kg depending on whether the carbon dioxide emissions tax is \$50/t, or \$150/t. This is true for conservative, intermediate, and optimistic scenarios (Hassan et al. 2021, 2022b, 2022c, 2022d, 2022e, 2023b, 2023c). By comparing conservative and optimistic production scenarios, it may be possible to cut capital costs by about \$6/kg, and for the most optimistic scenario the unit hydrogen production cost of blue hydrogen, which is made by steam methane reforming, and carbon sequestration when the carbon dioxide emissions tax is less than \$35/t (Country C. D. W. 2019; Parkinson et al. 2019). Presented study indicate that the Department of Energy, unit hydrogen production cost goal must be met by lowering the cost of green hydrogen production system components through technological innovation (Hassan et al. 2023a, 2023b, 2023c; Lee et al. 2022).

7 Conclusions

Reckless use of coal-based energy not only reduces the resources of this valuable resource but also environmental problems such as climate change. Nations all over the world have attempted a paradigmatic transition from carbon-based technologies to sustainable energy gathering. Since electricity can be generated by combining hydrogen and oxygen in a fuel cell, hydrogen is seen in this sense as the next-generation energy resource for renewable energy. In such system hydrogen can be produced via water

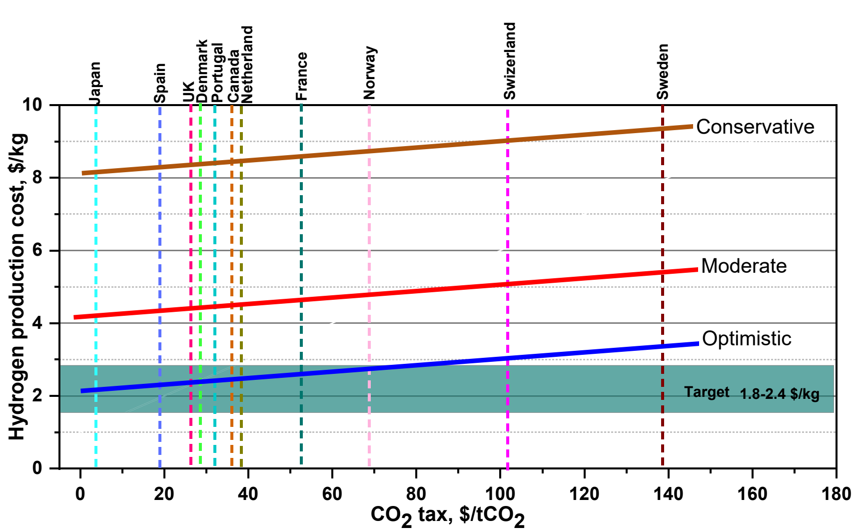


Figure 12: Carbon dioxide emissions tax ranging based on hydrogen production cost.

electrolysis technology. Although the majority of hydrogen is now created by steam methane reforming, modern techniques are widely developed and green hydrogen should indeed be produced by water electrolysis using renewable energy. Additionally, since water electrolysis in classical electrolyzer is an outdated technology, the green hydrogen production system is impractical in terms of the unit hydrogen cost of production. Our research presents financial recommendations for the installation of an industrial-scale green hydrogen production system based on techno-economic analysis, a carbon footprint, and genetic algorithms, in terms of AWE scale and energy storage capacity. To produce green hydrogen in current research study, single and hybrid systems are proposed. As a practical example the techno-economic evaluation was carried out for 2.5 MWp PV system, using Diyala's seasonal solar radiation data.

According to our findings, installing 2.5 MW of AWE coupled with 2.5 MWp of photovoltaic power is advised for the single system with the lowest unit cost of hydrogen production. For a green hydrogen production system with energy storage, the optimum AWE size is strongly dependent on cost, of the energy storage. For presented case reaching 0.5 MWh when the storage cost is low and at the same time the AWE cost is high. Therefore, it is advised to set the AWE and energy storage at their optimal sizes in order to reduce the cost of hydrogen production and to increase the supply of green hydrogen, which will accelerate the entry of the hydrogen society. A carbon dioxide tax is also a major impediment to lowering the cost per unit of hydrogen generation, demonstrating the importance of technological advancement for capital cost reduction.

8 Future perspectives

As a future prospect, this study may be expanded to derive or quantify efficient system layout and scale approaches. By optimizing the system, the energy needs of the electrolyzer unit may be met by many renewable energy sources rather than by taken electricity from the grid.

One further study should be conducted to show that by applying an appropriate energy storage technology to the hybrid renewable energy system in selected regions, the performance of the system could well be improved, with greater satisfying load percentages and utilization factors and a lower grid energy interaction aspect. Whenever the grid is unable to absorb any excess energy generated by the PV or WT system and the excess energy must be dispersed. On the contrary, if the grid is incapable of delivering required power, the electrolyzer will only be able to absorb smaller amounts of electricity and will not be able to create all of the required hydrogen. The incorporation of a system to store batteries or hydrogen in storage containers is a viable solution to this problem.

In future research, there should also be a second scenario and a full techno-economic study to figure out the optimal solution and location for the system. The site use of solar and wind power systems and the economics of producing hydrogen are not included in this study. It is possible to compare the economic improvements of hydrogen system production in various locations. All of these optimizations would have the same hydrogen output as a primary limitation. The end result would be a socioeconomic classification of hydrogen generation sites based on their concrete capacity and full load durations.

Abbreviations

AWE	Alkaline Water Electrolyzer
AC	Alternative Current
ESS	Energy Storage System
DC	Direct Current
NOCT	Nominal Operation Cell Temperature
PV	Photovoltaic
STC	Standard Test Conditions
WT	Wind Turbines
CRF	Capital recovery factor

List of Symbols

A_E, B_E	Coefficient of the consumption curve (kW/kg/h)
F	Faraday constant
f_{PV}	PV reduction factor (%)
g	Polytrophic coefficient
h_f	Faraday efficiency (%)
H_t	Amount of hydrogen produced per year in kilograms.
i	Discount rate (%)
I	Initial investment cost ($)
I_e	Electrolyser current (A)
I_E	Electrolyser input power (kW)
M_C	Maintenance cost in ($)
m_{H2}	Nominal hydrogen mass flow (kg/h)
n	Project lifetime
η_b, η_N	Battery charger and inverter efficiency, respectively (%)
N_C	Number of cells in series
P_{hti}	Hydrogen tank inlet pressure (kW)
P_{hto}	Hydrogen tank outlet pressure (kW)
P_{com}	Hydrogen compressor input power (kW)
P_{tank}	k Predicted pressure within the hydrogen tank (kW)
P_{icon}	Converter input power (kW)
P_{ocon}	Converter output power (kW)
$P_b(t-1)$	Power at the beginning of interval t (kW)
$P_n(t)$	Energy generated by PV array at the time t (kW)
$P_k(t-1)$	Power at the end of interval t (kW)
$P_{\mathrm{AWE},\ t}$	Power of AWE (kW)

$P_{ESS,\ t}$	Power of ESS (kW)
Q_{H2}	Rate of hydrogen generated by the electrolyser (kg/h)
R	Gas constant (Nm/kg)
S_{STC}	Incident solar radiation at standard test conditions (kW/m^2)
S_T	Incident solar radiation (kW/m^2)
SD	Self-discharge factor
T_C	Temperature of the PV (°C)
$T_{C,NOCT}$	Cell temperature at which NOCT (°C)
T_{htci}	Hydrogen tank compressor inlet temperature (°C)
$V_{h\ tan\ K}$	Volume of hydrogen tank (m^3)
Y_{PV}	Nominal capacity of PV (kW)
α_P	Temperature coefficient of power (%/^{o}C)
η_C	Efficiency of PV (%)
$\eta_{h\ tan\ K}$	Efficiency of hydrogen tank (%)
η_{con}	Efficiency of converter (%)
η_b	Efficiency of ESS (%)
η_f	Efficiency of AWE (%)
γ	PV module azimuth angle (degree)
β	PV module tilt angle (degree)

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