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# Techno-economic viability and future price projections of photovoltaic-powered green hydrogen production in strategic regions of Turkey

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ABSTRACT

This study assesses the economic feasibility of utilizing photovoltaic power for producing green hydrogen in Mersin, Çeşme, and Bandırma. We considered the factors for site selection, such as regional hydrogen demand, solar energy potential, water availability, export opportunities, and existing infrastructure. The research focuses on generating electricity, hydrogen, and oxygen using a 5 MW photovoltaic system. The research finds that the capacity factor for Çeşme, Mersin, and Bandırma is 18.9%, 17.7%, and 15.4% respectively, determining the optimal electrolyzer size. A comprehensive cost analysis is conducted. We employed two methodologies to evaluate the levelized cost of hydrogen. The first approach integrates the levelized cost of electricity for the photovoltaic system, while the second approach considers the annualized capital and operational expenditure for all system components. The analysis highlights the impact of electrolyzer efficiency and timeframe on hydrogen production costs. Estimated costs for Bandırma in 2023 are US$6.8 per kilogram at 70% electrolyzer efficiency, projected to decrease by 2050. With 80% electrolyzer efficiency, costs in 2023 would be US$5.87 per kilogram, with further reductions projected for 2050. We have observed similar trends for Çeşme and Mersin. In conclusion, this study provides a comprehensive cost estimation, taking into account varying discount rates, energy purchase agreement prices, CAPEX and OPEX values, revenues, and site selection, while considering electrolyzer efficiency, to enhance the economic feasibility of photovoltaic-electrolyzer systems.

## 1. Introduction

The rapid and extensive implementation of renewable energy systems is vital in achieving global decarbonization goals by 2050, intending to reduce greenhouse gas (GHG) emissions. Photovoltaic (PV) systems and wind turbines (WT) are the key sustainable choices for GHG emission reduction, as extensively studied in the literature. Due to the technological advancements have substantially reduced the costs of PV and WT technologies (Kandilli and Ulgen, 2009). Fig. 1 shows the promising trend in cost reduction and improved cost-effectiveness of PV systems across different scenarios according to American PV market data (NREL, 2022).

The intermittent and fluctuating nature of renewable energy sources (RES) requires having backup power generation or energy storage systems (ESS) to emulate a stable baseload and load-following power supply (McIlwaine et al., 2021). Hydrogen ($H_2$) technologies emerge as an environment-friendly and versatile solution for energy storage, offering adaptability for both large-scale energy quantities and small backup systems. It is a promising option for long-term energy storage due to its potential to enhance system stability and enable the integration of RES (Maestre et al., 2021). The utilization of hydrogen derived from RES holds significant potential as a key element in future global energy systems (Akhtar et al., 2023). Fig. 2 illustrates the concept of generating green hydrogen from PV systems and then utilizing it in various applications. Harnessing the power of PV systems to produce electricity and subsequently converting it into green hydrogen stands at the forefront of sustainable energy innovation, bridging the gap between renewable energy sources and versatile hydrogen applications. It plays a pivotal role in facilitating the transition towards decarbonization objectives, serving as a foundational component in achieving sustainable energy goals. Presently, the utilization of hydrogen at a large scale is primarily confined to oil refineries, as well as in the processes of

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producing methanol and ammonia. The concept of a hydrogen economy extends beyond these conventional applications, positioning hydrogen as an energy carrier with specific goals of catering to industrial heating, power generation and transportation sectors (Gu et al., 2020; Hong et al., 2021; Temiz and Dincer, 2021; Xu et al., 2022). The conversion of electricity into hydrogen presents a viable approach to mitigate the impact of renewable electricity on power grids (Lew et al., 2010). Additionally, hydrogen facilitates the integration of renewable electricity into sectors that are challenging to electrify, such as heat and industry (Undertaking and H, 2019).

Despite its potential benefits, the current cost of green hydrogen production remains relatively high compared to conventional grey hydrogen, with costs reaching up to US$15 per kilogram of $H_2$ (Bauer et al., 2022; Kayfeci et al., 2019). This cost disparity is primarily due to the substantial investment required for electrolysis, especially when comparing hydrogen production methods based on fossil fuels (Schmidt et al., 2017; Shaner et al., 2016). Therefore, there is a crucial need for comprehensive cost assessments. These assessments play a vital role in determining the current production expenses of green hydrogen and exploring when it may achieve cost parity with grey hydrogen, priced at around US$1 to US$2 per kilogram of $H_2$ (Bauer et al., 2022; Hosseini and Wahid, 2016; Parkinson et al., 2019). In a comprehensive cost evaluation by Christensen et al. the price of $H_2$ in the US from 2020 to 2050 is projected to decrease from 10.61 $/kg to 5.97 $/kg, with the minimum price dropping from 4.56 $/kg to 2.44 $/kg. In the EU, during the same period, the median $H_2$ price is expected to decrease from 19.23 $/kg to 10.02 $/kg, while the minimum price is anticipated to decrease from 4.06 $/kg to 2.23 $/kg (Christensen, 2020). In another study, promising hydrogen production hubs located in European coastal areas and islands were examined. The findings indicate that the current cost of electrolytic hydrogen production stands at 3.7 €/kg $H_2$, and a reduction to 2 €/kg $H_2$ by the year 2040 is feasible (Terlouw et al., 2022).

The levelized cost of hydrogen (LCOH) variability is a prevalent phenomenon. This variability can be primarily attributed to site-specific factors, including the dynamic nature of power purchase agreement (PPA) prices, fluctuating discount rates, and diverse capacity factors that are commonly employed in research studies (Bourne, 2012). Christensen et al. conducted a cost evaluation of hydrogen production by examining various configurations. Their approach involved using fixed electricity prices and capacity factors to calculate hydrogen costs, both in Europe and the United States. Electricity prices and electricity generation from renewable sources exhibit significant variability and intermittency, which is highly dependent on specific geographical locations (Christensen, 2020). Discount rates are used as fixed between 5 and 8 % for

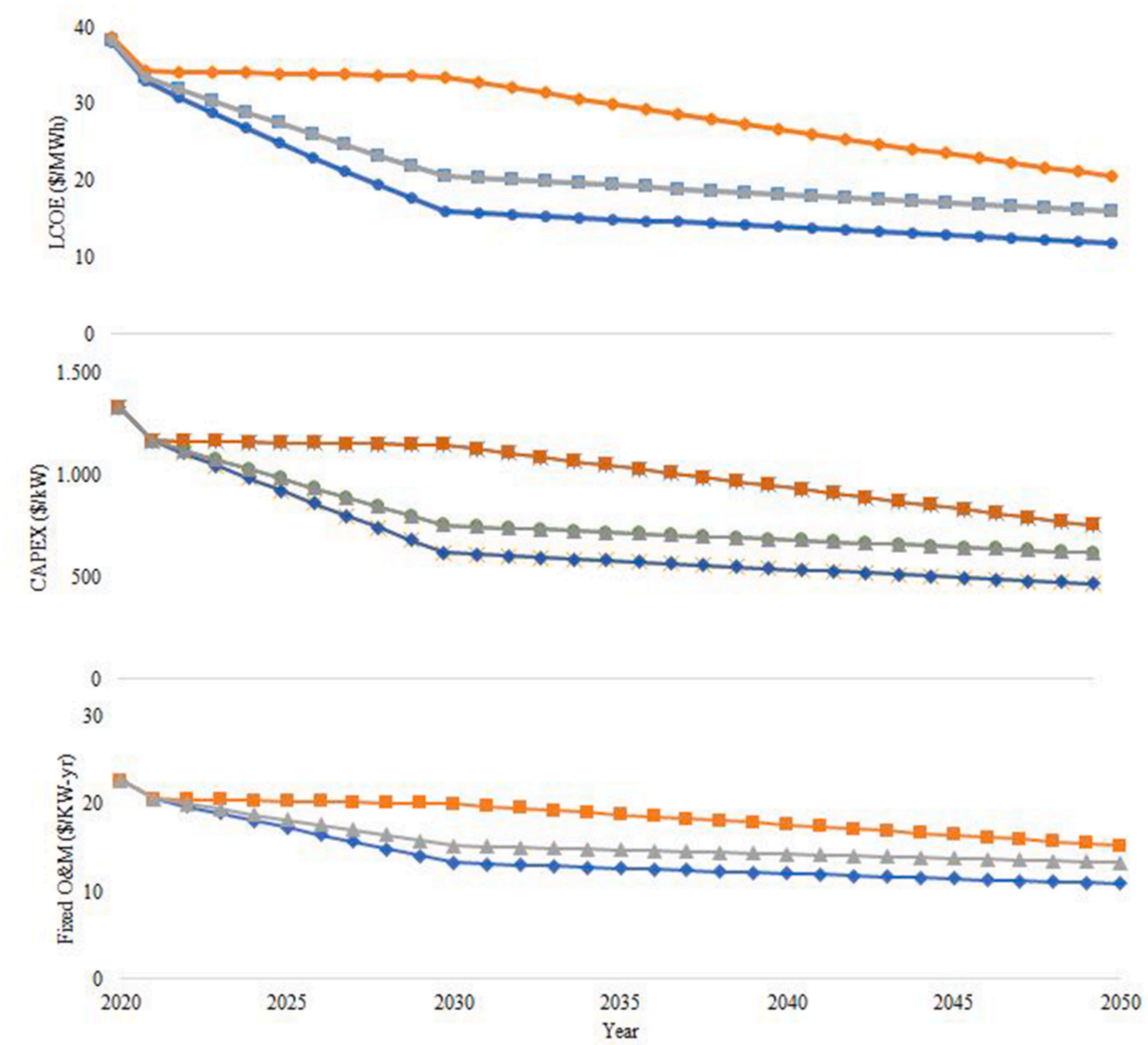


**Fig. 1.** Projections of parameter values by scenario, financial case, cost recovery period, and technological detail by the National Renewable Energy Laboratory (NREL) (NREL, 2022).

calculating LCOH. However, it is important to note that discount rates are subject to a high degree of uncertainty and are influenced by various factors. Therefore, rather than relying on a single fixed value for analysis, conducting sensitivity analyses is recommended to account for this variability (Parra et al., 2019; Yates et al., 2020).

The LCOH is significantly influenced by PPA prices on grid-connected systems and examining an extensive 8760-h dataset can provide valuable insights. Although, PPA prices have an hourly varying structure, a fixed PPA price is often used in many analyses for simplicity. It is essential to consider the changes for comprehensive and accurate assessments (Bhandari and Shah, 2021).

Two fundamental factors play pivotal roles in the site selection for installing renewable energy production plants: exclusion criteria and evaluation criteria. Exclusion criteria are meticulously applied in some studies to precisely identify and eliminate unsuitable locations for renewable energy projects, ensuring a robust selection process. Evaluation criteria are used to assess and rank the suitability of identified sites. It encompasses a range of dimensions, including environmental, economic, social, and technical aspects (Ayough et al., 2022). The literature presents a variety of studies where these criteria are examined for their impact, and various methods are applied (Ahmad and Zeeshan, 2023a,b; Gómez-Gardars et al., 2022; Pradeleix et al., 2015). In this study, the process of selecting the most appropriate regions was conducted using a comprehensive decision-making procedure, guided by the insights derived from the referenced study (Shura, 2021). It considered various factors, such as regional hydrogen consumption, solar energy potential, water availability, export opportunities, port accessibility, industrial activities, proximity to water sources, international pipeline networks, and existing infrastructure. Motivated by the wind-supported hydrogen production facility planned for Bandırma, we selected this location as a reference point for PV-supported cost assessment and cost comparison with other areas. The "Southern Marmara Hydrogen Coast Platform" project, initiated by the Southern Marmara Development Agency in 2023 with support from the European Union's Horizon Europe Framework Program, aims to achieve Turkey's first green hydrogen production for use in the chemical industry. Within the scope of this project, it is planned to produce 500 tons of green hydrogen, supported by wind energy, per year in Bandırma. The objective is to utilize this green hydrogen in chemical industry processes and the production of components like methanol and ammonia (GMKA, 2023).

Examining the literature, numerous studies have addressed the cost of PV-driven hydrogen production, both in current scenarios and future projections. These studies typically focus on locations with optimal meteorological conditions, such as high solar radiation, to demonstrate the feasibility of hydrogen production. In this research, we've taken a comprehensive approach by considering various factors such as the availability of water resources, the required space for storage, and proximity to energy-intensive and chemical industries. Furthermore, we considered the presence of ports and transportation infrastructure to determine suitable locations for hydrogen production. In addition to meteorological and geographical considerations, we have recognized the significance of economic parameters, especially in countries where these parameters are subject to rapid fluctuations. To address this, unlike many previous studies, we have undertaken dynamic analyses, considering varying PPA prices and discount rates on an hourly basis throughout the year (8760 h). Moreover, as technology continually advances, we have also explored the impact of varying electrolyzer efficiencies on the overall process. While several models in the literature provide simplified analyses, our study employs a simulation model that encompasses detailed component-level modelling, ensuring a more comprehensive evaluation of the entire system. By bridging the gap in the existing literature with this study, we aim to offer a valuable resource for policymakers involved in the decision-making processes related to the establishment of green hydrogen production facilities in Turkey. Furthermore, considering the current global emphasis on reducing dependence on hydrocarbons, our research underscores the potential of blending hydrogen into natural gas pipelines as a promising avenue. Turkey's strategic geographical location, serving as a vital link between energy sources and demand regions, positions it as a key prospective energy hub (Harunoğullari, 2020). Leveraging its abundant renewable energy resources, particularly for hydrogen production, and integrating it with natural gas pipelines can yield significant advantages. This potential development holds paramount importance not only for Turkey but also for Europe's transition towards a more sustainable and renewable energy future (Tutar and Eren, 2011).

## 2. Materials and methods

### 2.1. System description and site selection

In this study, we investigate a 5 MW PV array supplied directly to both the grid and a 1 MW Proton exchange membrane (PEM) electrolyzer, utilizing a Maximum power point tracking (MPPT) controller and a DC converter for optimal power delivery. MATLAB Simulink is used to calculate the electricity generated by the PV system, with surplus energy being fed back to the grid through an inverter. Generated hydrogen was compressed into tanks and employed to manage seasonal demand fluctuations and to balance supply fluctuations.

We utilized a 22-year average (1983–2005) with a temporal resolution of 60 min for validated ground data, specifically Global horizontal irradiance (GHI) values and air temperature obtained from the National Aeronautics and Space Administration (NASA) Surface Meteorology and Solar Energy database. These data were employed to compute the

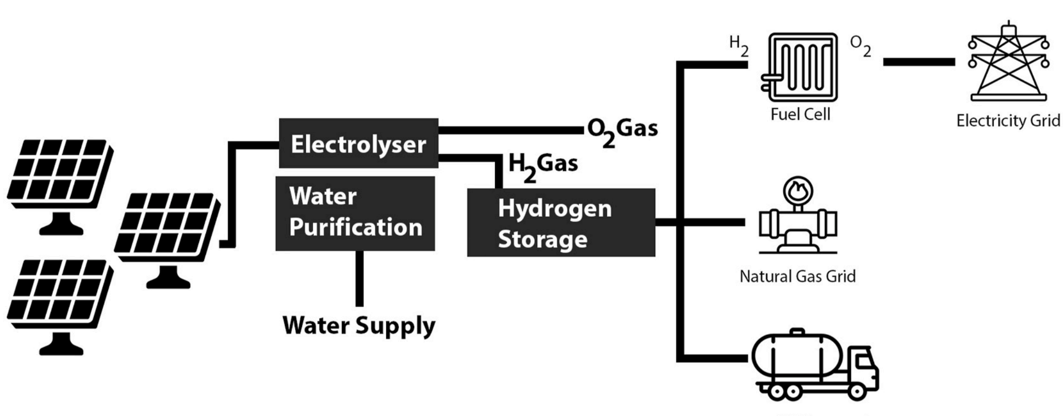


**Fig. 2.** PV-electrolyzer hydrogen production and applications: A concept.

production of electricity, oxygen, or hydrogen by the PV-electrolyzer system.

Mersin, Çeşme, and Bandırma provinces as optimal locations for implementing the PV-PEM electrolyzer system:

- The solar energy potential of Mersin is 1700–1750 kWh/m$^2$/yr (Gepa, 2021). It is located along the Mediterranean coast and has advantageous access to water resources. It occupies a key location for export opportunities, particularly owing to its substantial port facilities. Mersin province has energy-intensive industries and chemistry. It is connected to international pipeline networks and boasts well-developed infrastructure (Shura, 2021).
- Çeşme, is located in the Izmir region which ranks as the third-largest city in Turkey, contributing 6.4% to the gross domestic product. The solar energy potential of 1800 kWh/m$^2$/yr (Gepa, 2021). Access to Izmir Port is easily attainable due to Çeşme's proximity, positioning it favourably for international trade. The coastal location provides an advantage in terms of access to water resources and access to İzmir port (Shura, 2021).
- Bandırma is considered one of Turkey's most important industrial zones, featuring a robust presence in energy-intensive industries and chemical production. The solar energy potential of 1531 kWh/m$^2$/yr and notably high wind energy potential with 2nd installed capacity of Turkey (Gepa, 2021). Bandırma has advantageous access to water resources. The presence of Bandırma Port, a substantial harbour along the Marmara Sea, significantly contributes to export opportunities (Shura, 2021).

The irradiance and temperature data for these three regions; Mersin, characterised by its highest average August temperature of 28.1 °C, exhibits an annual average solar irradiance of 4.77 kWh/m$^2$/day, peaking at 7.55 kWh/m$^2$/day during July. On the other hand, Çeşme displays an average August temperature of 25.3 °C, accompanied by an annual average solar irradiance of 5.08 kWh/m$^2$/day, reaching its peak of 8.34 kWh/m$^2$/day in June. Meanwhile, Bandırma, featuring an August average temperature of 24.4 °C, exhibits an annual average solar irradiance of 4.17 kWh/m$^2$/day, with the highest recorded value of 7.06 kWh/m$^2$/day in July. The average monthly irradiance data, prepared using validated solar data collected over 8760 h on a daily basis with a temporal resolution of 60 min, is depicted in Fig. 3.

The research defines the study boundary based on Fig. 4 which is implemented in MATLAB-Simulink. It encompasses the primary equipment of the hydrogen production plant, including the solar PV system (including MPPT and inverter), electrolyzer, compressor, and storage components. The key specifications of these primary equipment components are detailed in Table 1.

The system structure and assumptions used in the analysis are presented below.

1. The system sells surplus energy to the grid when the electrolyzer capacity is exceeded.
2. The analysis used hourly PPA prices announced by EPIAS for the year 2021 as the grid sale price for calculating electricity revenue (Epiaş, 2021).
3. To account for potential future reductions in PPA prices, the analysis incorporated calculations for revenue and unit energy-hydrogen costs. These calculations were derived by assuming discounted rates of 10% and 20% for the years 2035 and 2050, respectively, about the PPA prices recorded in 2021.
4. The analysis also considered the sale of oxygen produced through the system.
5. The analysis included average 8760-h solar radiation and temperature data from 1983 to 2005 for the Bandırma, Çeşme, and Mersin regions.
6. The analysis was conducted for three different electrolyzer efficiencies: 70%, 75% and 80%.

### 2.2. Energy output model of a photovoltaic plant

The mathematical model was developed in MATLAB Simulink environment and a single-diode model was used to simulate the behaviour of the PV system. Subsequently, the generated hourly energy production data was employed to assess the feasibility of hydrogen production.

### 2.3. Mathematical model of the photovoltaic system

A solar cell can be represented by a simple equivalent circuit, illustrated in Fig. 5, which consists of a diode in parallel with a current source (Castañer and Silvestre, 2002).

The photocurrent generated by the cell is directly proportional to the intensity of the incident radiation and is supplied by the output of the current source. The I–V characteristics of the solar cell are predominantly determined by the diode properties (Castañer and Silvestre, 2002).

$$I = I_L - I_D - I_{SH} \tag{1}$$

The net current output of the solar cell is the result of the difference between the photocurrent ($I_L$) and the sum of the normal diode current ($I_D$) and the current passing through the parallel resistance ($I_{SH}$). These individual currents can be characterized as follows (Castañer and Silvestre, 2002):

$$I_D = I_0 \cdot \left(e^{\frac{q(V+I.R_s)}{AkT_C}} - 1\right) \tag{2}$$

where V is terminal voltage, $R_s$ is series resistance, A is diode ideality factor, K is Boltzmann constant and $T_c$ is variable temperature. The circuit model considers the temperature dependence of the photocurrent (I) as well as the saturation current ($I_0$) of the diode (Castañer and Silvestre, 2002):

$$I_0 = I_{rs} \cdot \left(\frac{T_c}{T_R}\right)^3 .e^{\frac{qE_G}{Ak} \cdot \left(\frac{1}{T_R} - \frac{1}{T_C}\right)} \tag{3}$$

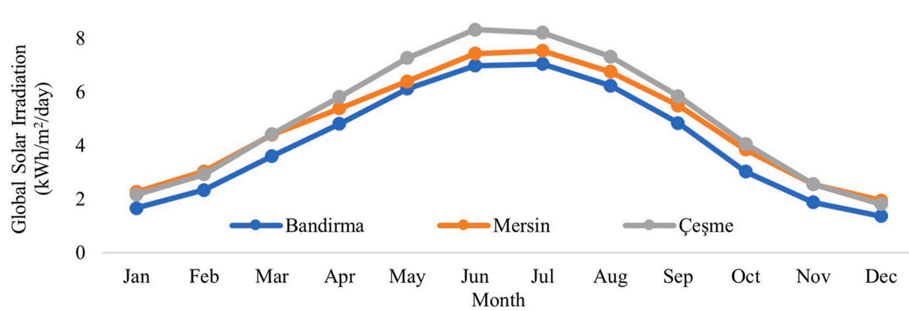


**Fig. 3.** The monthly average global solar irradiation for Mersin, Bandırma, and Çeşme.

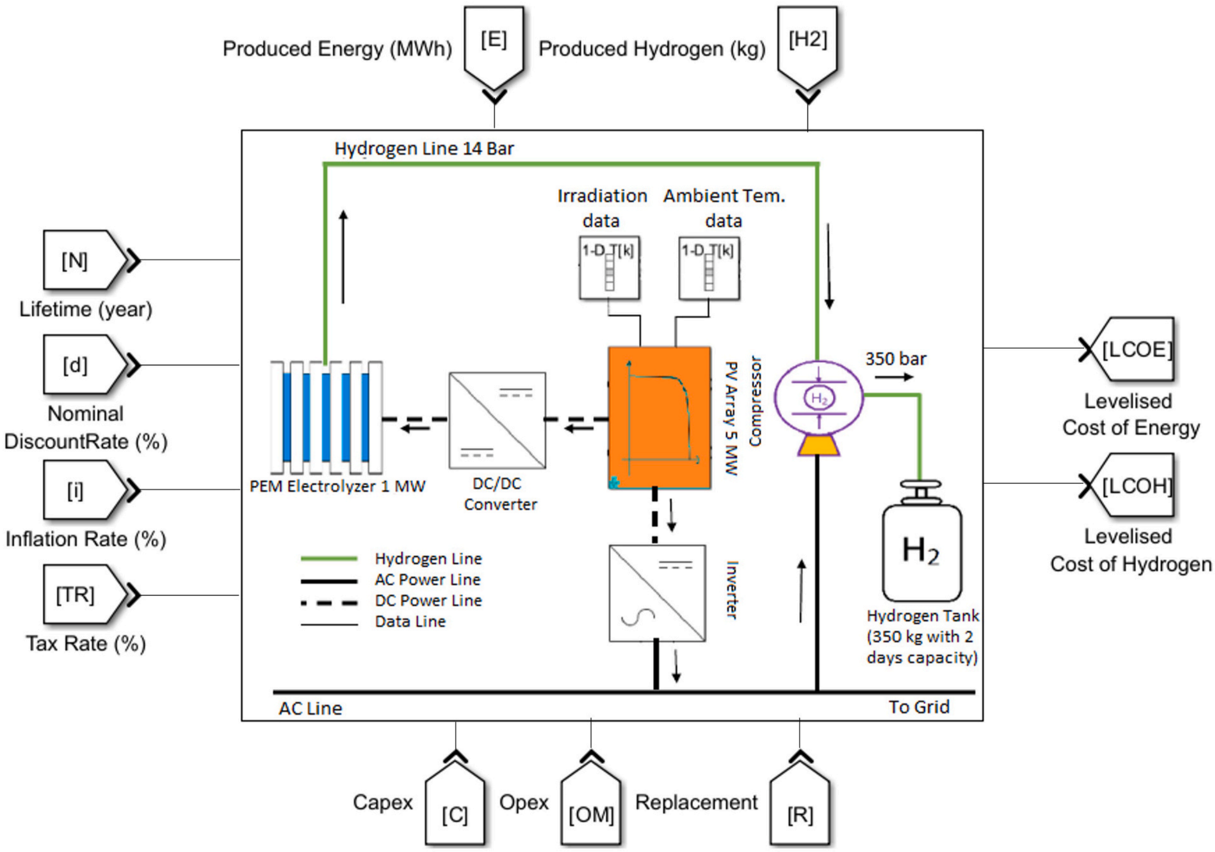


**Fig. 4.** Integrated techno-economic analysis system model for PV-Electrolyzer simulation.

**Table 1**
System components and specifications.

| Component | Specifications |
|---|---|
| PV System | 5 MW |
| PEM Electrolyzer | 1 MW |
| Hydrogen Store Tank | 350 kg |
| Hydrogen Compressor | 41 kW |

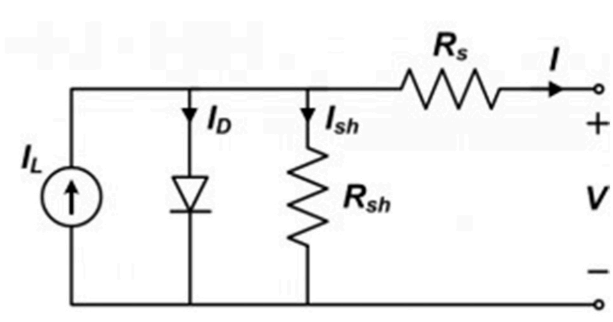


**Fig. 5.** The single-diode model for PV.

$I_{rs}$ is reverse saturation current, q is charge (1,6 × $10^{-19}$ C), $T_R$ is reference temperature (298 K). The expression for the parallel resistance current is provided below. Additionally, total output current of the PV system can be determined by employing the following equation (Castañer and Silvestre, 2002):

$$I_{SH} = \frac{V + IR_S}{R_{SH}} \tag{4}$$

where, $R_{SH}$ is shunt resistance.

$$I = I_S.S_N + I_t.\left(T_c - T_{ref}\right) - I_D - I_{SH} \tag{5}$$

The maximum power point of a PV system was determined using a mathematical model and MPPT algorithm on an hourly basis (Fig. 6).

Maximum power point of the system ($P_m$) is calculated using the below equation:

$$P_m = v_{bus}.i_{boost} \tag{6}$$

where $v_{bus}$ is the maximum voltage point and $i_{boost}$ is the maximum current point of the system.

### 2.4. Electrolyzer

The amount of hydrogen generated by system exhibits a direct correlation with the quantity of electricity produced by the PV facility and can be represented by the following expression (Dicks and Rand, 2018):

$$M_{H_2} = \frac{P_m.\eta_{elc}}{HHV_{H_2}} \tag{7}$$

The amount of hydrogen (kg) generated through the utilization of electricity produced by a PV plant ($P_m$) can be determined via the subsequent expression, in which the electrolyzer efficiency ($\eta_{elc}$) is postulated to be 70%, 75% and 80%, respectively, and the higher heating value of hydrogen ($HHV_{H2}$) is 39.4 kWh/kg (Parkinson et al., 2018).

### 2.5. Hydrogen storage tank and compressor

The hydrogen storage system uses a 350 kg tank to store hydrogen for a two-day period. A compressor is necessary to boost the pressure of the hydrogen generated by the 30-bar PEM electrolyzer to 350 bar.

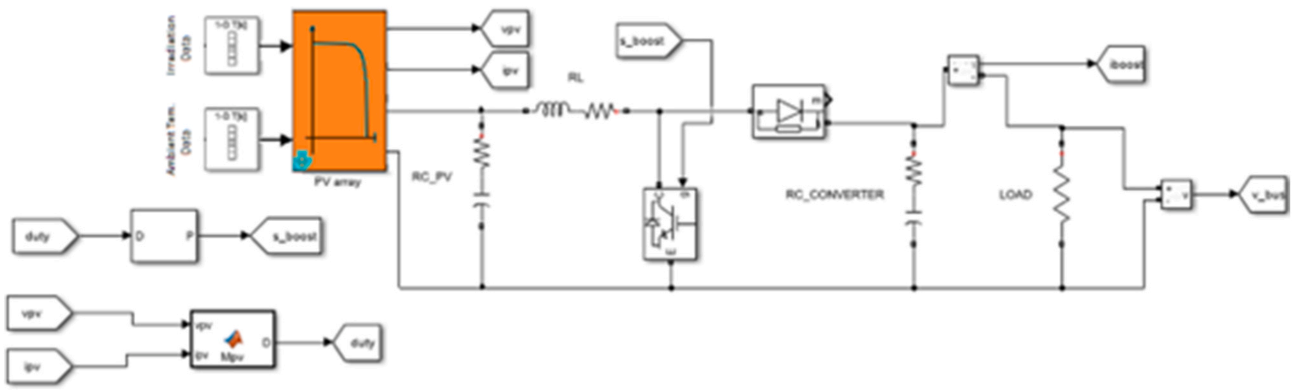


**Fig. 6.** MATLAB-Simulink model of PV and MPPT system.

Energy consumption of the compressor can be calculated using the following equation (Li et al., 2009):

$$W_{Comp} = C_p . \frac{T_1}{\eta_c} . \left[ \left( \frac{P_2}{P_1} \right)^{\frac{r-1}{r}} - 1 \right] . m_c \quad (8)$$

The energy consumption of a hydrogen compressor was evaluated based on the specific heat of hydrogen at constant pressure (Cp), which is 14.304 kJ/kg K, as well as the inlet gas temperature ($T_1$) of 293 K. The compressor's efficiency ($\eta_c$) as well as the inlet and outlet gas pressures ($P_1$ and $P_2$, respectively) were also considered, along with the isentropic exponent of hydrogen (r), which is 1.4. The rate of gas flow through the compressor ($m_c$) was also considered. In particular, the compressor's energy consumption was calculated from 14 to 350 bar pressure, assuming a compressor efficiency of 80% (Bahou, 2023).

### 2.6. Economic evaluation

The LCOH model has been used for economic analysis. Essentially, the LCOH method is built upon the principles of the widely employed LCOE method within the renewable energy sector. This method serves to express the life cycle cost of renewable energy sources in terms of the cost per unit of energy output.

The LCOE approach incorporates various cost factors, such as capital expenditure (CAPEX), operational expenditure (OPEX) and discount rate, to determine the overall energy cost. For a PV plant, LCOE is determined by calculating the ratio of the total annualized cost of the PV plant to the annual energy output of the plant. Mathematically, this can be expressed as follows (Darling et al., 2011):

$$LCOE = \frac{CAPEX_{pvplant} . CRF_{pvplant} + OPEX_{PVplant} - Revenues}{E_{pvplant}} \quad (9)$$

The calculation considers both the total installed cost of the PV plant ($CAPEX_{pvplant}$) and the capital recovery factor ($CRF_{pvplant}$) for the PV plant.

The equations (10) and (11) enables the computation of the cost recovery factor (Chen et al., 2020):

$$CRF = \frac{i.(1+i)^N}{(1+i)^N - 1} \quad (10)$$

$$i = \frac{i' - f}{1 + f} \quad (11)$$

The CRF is used to assess the present value of a series of equivalent annual cash flows, referred to as an annuity. It considers the project's lifespan, the real discount rate (i), the nominal discount rate (i'), and the expected inflation rate (f). The real discount rate for analysis was calculated as 5.88% using Equation (11), with an inflation rate of 2%, and a nominal discount rate of 8% given in Table 2. Sensitivity analysis was then performed, considering nominal discount rates of 4%, 6%, 8%, 10%, and 12%."

**Table 2**
Projected costs of system components and base economic considerations in the model.

| Components or Economic Assumptions | 2023 | 2035 | 2050 | Unit | Reference |
|---|---|---|---|---|---|
| PEM Electrolyzer (1 MW) CAPEX Low | 1.280 | 0.545 | 0.460 | [M US $] | (Bertuccioli et al., 2015; Christensen, 2020) |
| PEM Electrolyzer (1 MW) CAPEX High | | 1.031 | 0.820 | [M US $] | (Bertuccioli et al., 2015; Christensen, 2020) |
| Electrolyzer OPEX | 5 | 5 | 5 | [%] | |
| PV CAPEX Low | 1044 | 579 | 466 | [US $/kW] | NREL (2022) |
| PV CAPEX High | 1161 | 1046 | 751 | [US $/kW] | NREL (2022) |
| PV OPEX Low | 18.888 | 12.63 | 10.86 | [US $/kW-yr] | NREL (2022) |
| PV OPEX High | 20.413 | 18.77 | 15.22 | [US $/kW-yr] | (NREL,2022) |
| Tank (350 kg) CAPEX | 210,000 | 210,000 | 210,000 | [US$] | Bellotti et al. (2022) |
| Tank (350 kg) OPEX | – | – | – | [US$] | |
| Compressor (41 kW) CAPEX | 337,976 | 337,976 | 337,976 | [US$] | Bellotti et al. (2022) |
| Compressor (41 kW) OPEX | 20,278 | 20,278 | 20,278 | [US$] | Bellotti et al. (2022) |
| Oxygen Price | 0.1 | 0.1 | 0.1 | [US $/kg] | Bellotti et al. (2017) |
| Nominal Discount Rate | 4–12 | 4–12 | 4–12 | [%] | |
| Inflation Rate | 2 | 2 | 2 | [%] | Gu et al. (2022) |
| Project Lifetime | 20 | 20 | 20 | [yr] | |
| Tax Rate | 20 | 20 | 20 | [%] | |

Two methodologies were used to calculate LCOH in a solar PV-hydrogen system, The first approach involved calculating LCOE for the PV system, which was then used with the electrolyzer components to determine LCOH. The second approach considered the annualized values of CAPEX and OPEX for both the PV and hydrogen production systems. By employing these methodologies, a comprehensive evaluation of LCOH was achieved, encompassing various costs and factors (Darling et al., 2011).

In the first approach:

$$LCOH = \frac{(CAPEX_{elc,tank,comp.}).CRF_{H2plant} + OPEX_{elc,comp.} + LCOE.System_{consumed_{electrical}} - Revenue}{H_{2_{produced}}} \quad (12)$$

In the second approach:

$$LCOH = \frac{CAPEX_{pvplant,elc,tank,comp.}.CRF_{pvH2plant} + OPEX_{PVplant,elc,comp.} - Revenues}{H_{2_{produced}}} \quad (13)$$

The varied CAPEX and OPEX values used in LCOH calculation, are presented in Table 2. The variations in CAPEX values are related to several factors, including differences in funding assumptions, system limitations, the year of cost estimates, and component sizes. In this study, the low and high limits of CAPEX and OPEX values were determined with data obtained from the literature and used in the LCOH analysis. Table 2 provides a comprehensive overview of the key economic parameters integrated into the model, including projected costs for PEM and PV systems for the years 2023, 2035, and 2050, taking into consideration both upper and lower cost estimates. The CAPEX value of the compressor was calculated with Equation (14), while the OPEX value was assumed to be %6 of CAPEX (Bellotti et al., 2022).

$$CAPEX = 23907.Psize[kW]^{0.71} \quad (14)$$

Table 2 also includes information on the CAPEX and OPEX values for the compressor and tank.

### 2.7. Sensitivity analysis

A sensitivity analysis is carried out to numerically assess the impact of varying selected key parameters on the hydrogen ($H_2$) production scenarios. The LCOH is influenced by various factors, including the amount of hydrogen produced, CAPEX, CRF, OPEX, revenues, and the quantity of generated and consumed electricity. In our economic sensitivity analysis, we have examined the impact of varying discount rates, PPA, and CAPEX on LCOH. Additionally, the electrolyzer efficiency, driven by advancements in electrolysis technology is considered in sensitivity analysis. On the other hand, the influence of meteorological data within a limited range was considered in the sensitivity analysis. The daily average radiation data for the regions under analysis, namely Bandırma, Mersin, and Çeşme, show minor variations at 4.17, 4.77, and 5.08 kWh/m$^2$, respectively. These closely aligned radiation values are integrated into the sensitivity analysis. Conversely, it's important to note that the salvage cost and OPEX values were not regarded as sensitive variables in this research.

## 3. Results and discussion

The research evaluates the hydrogen production potential using PV in three locations in Turkey. This evaluation involves estimating energy generation from PV systems and analysing hydrogen production. Additionally, LCOH is calculated using the levelized cost concept to assess the economic viability of hydrogen production. The study also considers future hydrogen price estimations to provide a comprehensive analysis. Furthermore, cost reduction scenarios and sensitivity analyses are conducted to identify key factors influencing hydrogen production costs. The study concludes by performing cost reduction scenarios to identify critical variables that have a significant impact on the cost of hydrogen production.

The monthly energy production of a 5 MW solar PV plant is presented in Fig. 7, with Çeşme leading at 8305 MWh annually, followed by Mersin at 7740 MWh and Bandırma at 6731 MWh. The capacity factors are calculated for Çeşme, Mersin, and Bandırma 18.9%, 17.7%, and 15.4%, respectively.

In addition, the monthly hydrogen production quantities for the 3 regions are given in Fig. 7. The annual total production for hydrogen and oxygen in Mersin, Çeşme and Bandırma are determined as 61–488 tons, 62–497 tons and 57–458 tons, respectively (Efficiency of 70%). Notably, July has the highest monthly production.

The annual production quantities of hydrogen and oxygen were determined for the respective locations considering electrolyzer efficiencies of 75% and 80%: Mersin (65–523 tons and 69–557 tons), Çeşme (66–532 tons and 71–568 tons) and Bandırma (61–490 tons and 65–523 tons). These findings shed light on the potential implications of future electrolyzer efficiency advancements on the unit energy-based efficiency improvements.

We conducted extensive economic analyses using crucial data on the CAPEX and OPEX of key components, such as the PV system, electrolyzer, hydrogen tank, and compressor. Projections for the years 2023, 2035, and 2050 were utilized based on reliable and well-established sources in the field. This analysis enabled us to determine the potential cost ranges for hydrogen production during these specific time intervals, considering both optimistic and pessimistic estimations.

The individual CAPEX and OPEX costs for each system component are depicted in Fig. 8, and these values are given in a divided-by-1000 format. The data also highlights the relative percentage impact of these costs on the overall budget. Notably, the CAPEX investment for the PV system significantly influences the total system cost. Regarding OPEX, the PV system was observed to have higher associated costs.

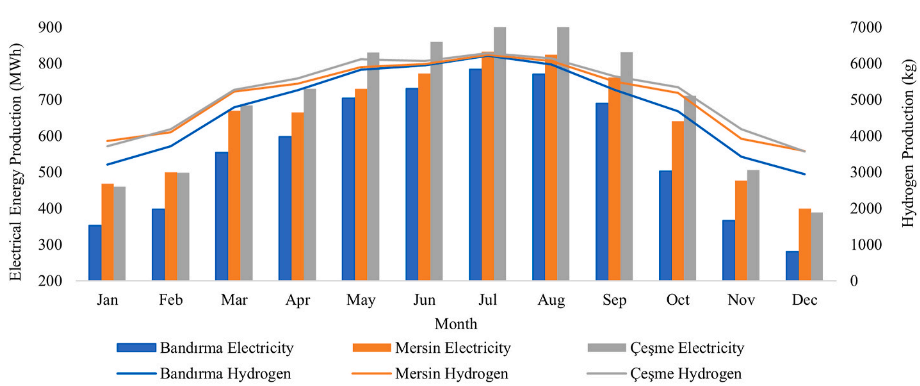


**Fig. 7.** Comparative monthly generation of electricity and hydrogen from the proposed system in Bandırma, Mersin, and Çeşme.

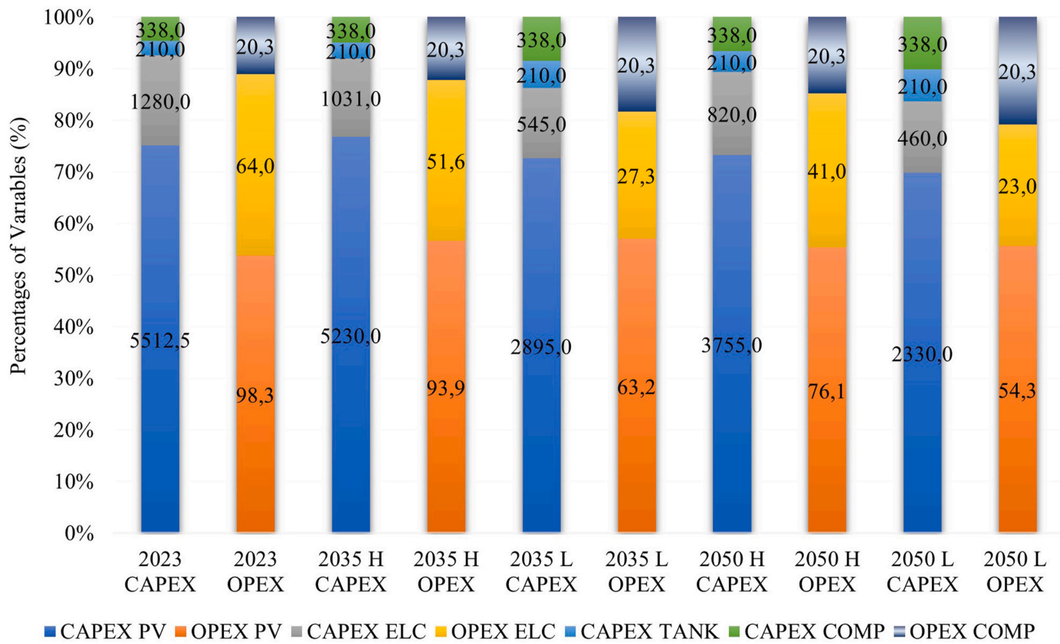


**Fig. 8.** Breakdown of individual CAPEX and OPEX costs for each system component: Graphical overview.

However, it is important to note that the cumulative effect of electrolyzer and compressor costs on OPEX outweighed their respective impacts on CAPEX.

Considering the advancements in the evolving technological landscape and the expected cost reductions, we discovered that the cost of a 5 MW PV system is projected to range from US$5.512M in 2023 to US $2.330M - US$3.755M in 2050. Likewise, the cost of a 1 MW electrolyzer is expected to decline from US$1.280M in 2023 to US$0.460M- US $0.820M in 2050.

In the LCOE analysis, we extensively assessed the revenue from electricity sales and focused on determining the revenue based on the hourly PPA prices provided by EPIAS, which served as the grid sale price for the year 2021. Hourly PPA prices were utilized to estimate the revenue for each hour of the year, resulting in a duration of 8760 h in the Bandırma region (Fig. 9). This enabled us to capture the temporal variation of PPA prices and the corresponding electricity revenue throughout the year.

Two cost scenarios were used to calculate the LCOH for using a 1 MW electrolyzer in three regions. In the first scenario, LCOE was determined by assessing PV system expenses, which were then included in the calculation of LCOH as energy-related costs. Other system components were individually evaluated.

In the second scenario, PV system component costs were combined with hydrogen production components to compute hydrogen costs for 2023, 2035, and 2050. Optimistic and pessimistic scenarios for 2035 and 2050 were examined, establishing cost ranges. Potential reductions in component costs and grid electricity revenue were factored in. Additionally, improved electrolyzer efficiency from technological advancements was considered. Upon reviewing the results of the analyses conducted according to the 1st scenario its outcomes:

The cost of hydrogen production exhibits variability contingent upon electrolyzer efficiency and temporal considerations in Bandırma (Fig. 10a.). The estimated cost of hydrogen is US$6.8 per kilogram in 2023 with an electrolyzer efficiency of 70%. Projections indicate a forthcoming reduction, with anticipated cost ranges spanning from US $2.93 to US$6.09 per kilogram in 2035 and US$2.36 to US$4.46 per kilogram in 2050. Conversely, enhancing the electrolyzer efficiency to 80% decreases the cost to US$5.87 per kilogram in 2023, accompanied by projected ranges of US$2.48 to US$5.25 per kilogram in 2035 and US $1.98 to US$3.82 per kilogram in 2050.

Likewise, in Çeşme (see Fig. 10b), the cost of hydrogen production is contingent upon electrolyzer efficiency and temporal horizons. The projected cost of hydrogen is US$5.43 per kilogram in 2023 at 70% electrolyzer efficiency. Progressing forward, the cost is expected to range from US$2.13 to US$4.82 per kilogram in 2035 and US$1.68 to US $3.49 per kilogram in 2050. By increasing electrolyzer efficiency to 80%, the cost of hydrogen decreases to US$4.67 per kilogram in 2023, with projected ranges of US$1.79 to US$4.14 per kilogram in 2035 and US$1.38 to US$2.97 per kilogram in 2050.

The LCOH is anticipated to exhibit similar patterns in Mersin (Fig. 10c) and is estimated to be US$5.85 per kilogram in 2023 with an electrolyzer efficiency of 70%. Looking ahead, calculated ranges span

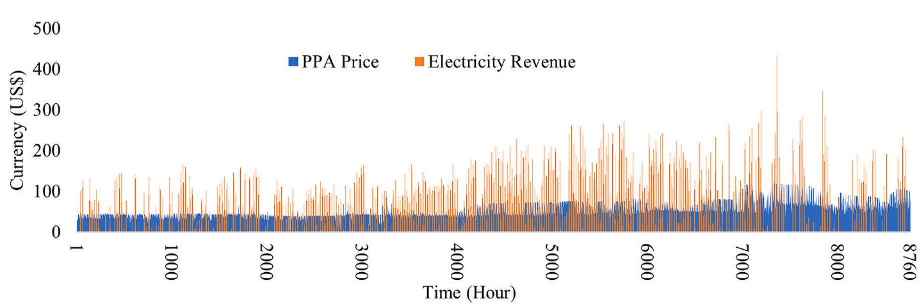


**Fig. 9.** The hourly PPA prices and revenue forecast for Bandırma.

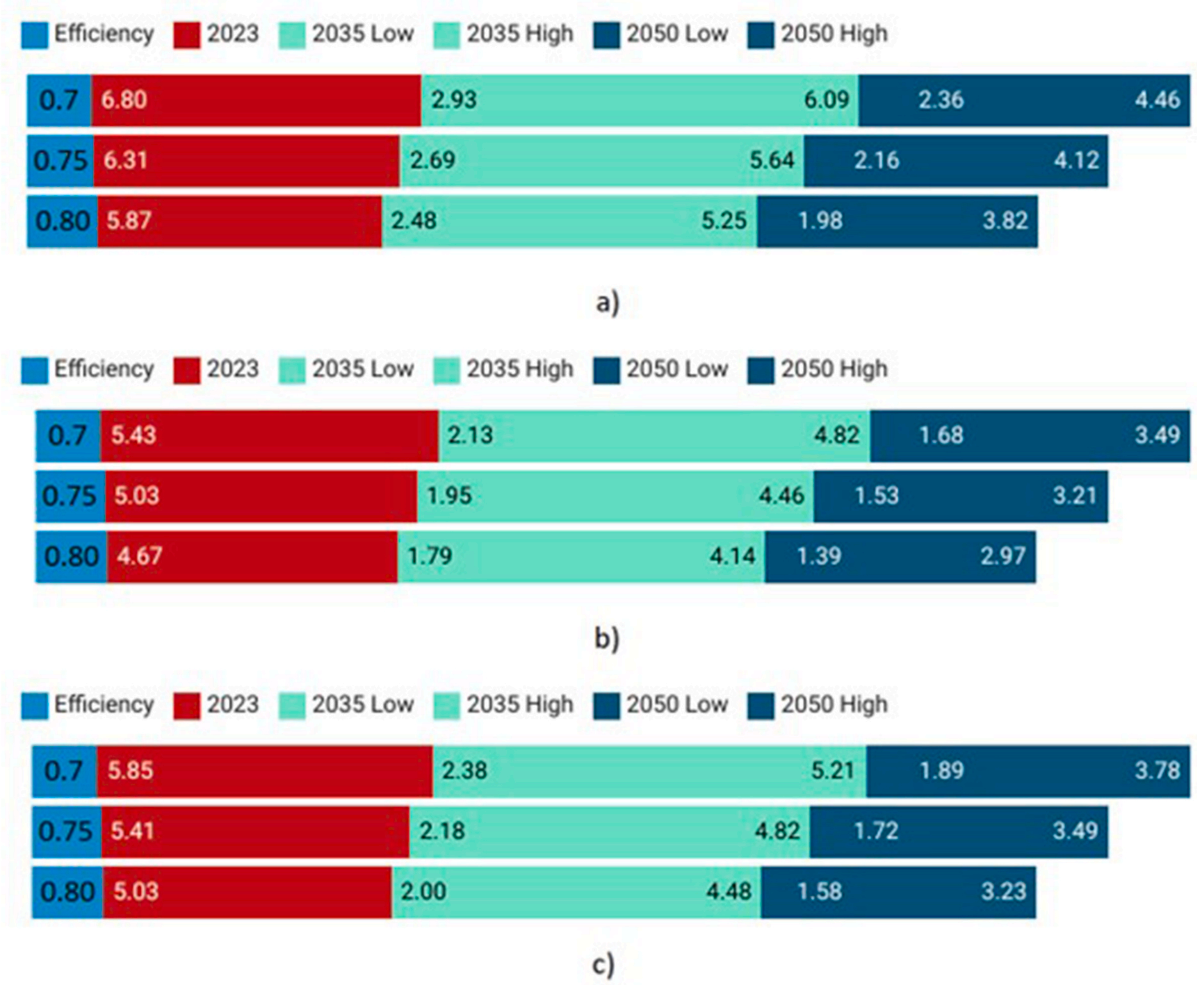


**Fig. 10.** Green hydrogen production cost analysis for a) Bandırma, b) Çeşme, and c) Mersin: 2023, 2035, and 2050 projections (1st scenario).

from US$2.38 to US$5.21 per kilogram in 2035 and US$1.89 to US$3.78 per kilogram in 2050. With an electrolyzer efficiency of 80%, the cost of hydrogen decreases to US$5.03 per kilogram in 2023, accompanied by expected ranges of US$2.00 to US$4.48 per kilogram in 2035 and US $1.58 to US$3.23 per kilogram in 2050.

The above findings indicate that the cost of hydrogen production is influenced by geographical location and electrolyzer efficiency. Notably, elevating electrolyzer efficiency from 70% to 80% results in a significant cost reduction across all three locations. Furthermore, future projections reveal a downward cost trajectory, reflective of technological advancements and economies of scale.

The results from the second scenario, shown in Fig. 11, indicate that the economic analysis considers both PV system components and hydrogen production system components. As a result, the LCOH is found to be higher in this case. The literature review reveals that the calculation of levelized hydrogen cost usually does not include LCOE from sustainable sources, which is essential for producing green hydrogen. (Kalbasi et al., 2021; Nami et al., 2022; Perez et al., 2021).

The real discount rate is a parameter of high uncertainty that exerts a major influence on the LCOH (Rodriguez et al., 2014). Thus, we aim to quantify the impact of discount rate on LCOH and provide an illustration of the potential LCOH reduction through technology de-risking. In Fig. 12, the changes in LCOH values between the years 2023, 2035, and 2050 under varying discount rates in the range of 4%–12% were illustrated for the Bandırma region. The analysis reveals a remarkable decrease in LCOH, achieving a reduction of 43.16% in 2023, ranging between 43.58% and 48.73% in 2035 and between 44.4% and 49.8% in 2050.

Both CAPEX and PPA prices are also significant parameters subject to high uncertainty and they play a crucial role in determining LCOH. In this study, the PPA price is set at a reduction of 10% and 20% assumed for 2035 and 2050, respectively. Furthermore, another parameter that varies over the years is CAPEX, considering the projected future prices of system components included in the analysis. Fig. 13 presents the calculated LCOH values based on varying PPA and CAPEX for the Bandırma region. To estimate the corresponding hydrogen cost associated with these values, a regression model was employed for prediction. Hence, a model was formulated based on an equation obtained with an $R^2$ value of 0.99863, yielding the following expression:

$$\mathrm{LCOH} = [1.700498 + 1.385634 * CAPEX - 56.3829 * PPA].$$

Considering the diverse findings and cost variations in different scenarios, scales, and regions, it's clear that the economics of PV-hydrogen production is complex. This highlights the need for a comprehensive approach when incorporating renewable hydrogen technologies. Our research highlights the utilization of PV with PPA for hydrogen production, with a specific focus on supplying the grid rather than for self-consumption. In 2023, our analysis calculated the LCOH through the PV-PPA-PEM approach at $5.03 per kilogram. In the year 2023, our study calculated the cost of hydrogen production through PV-PPA-PEM to be US$5.03 per kilogram. Looking ahead, cost projections for 2035 ranged from US$1.95 to US$4.46 per kilogram, and for 2050, they ranged from $1.53 to $3.21 per kilogram. In contrast to our study, research conducted in the regions of Morocco, Benguerir, and Spain (Touili et al., 2019) reported higher hydrogen production costs through

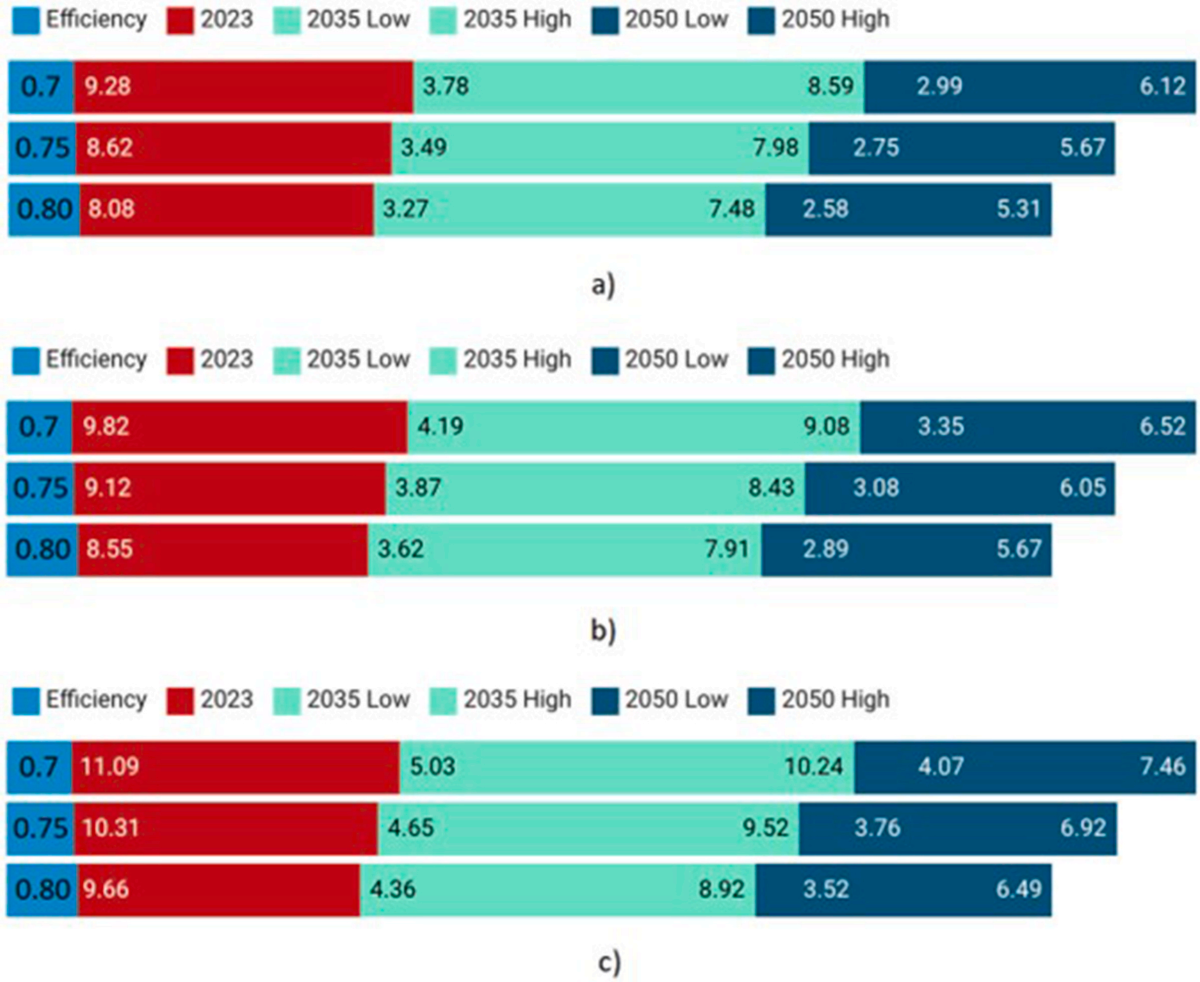


**Fig. 11.** Green hydrogen production cost analysis for a) Çeşme, b) Mersin, and c) Bandırma: 2023, 2035, and 2050 projections (2nd scenario).

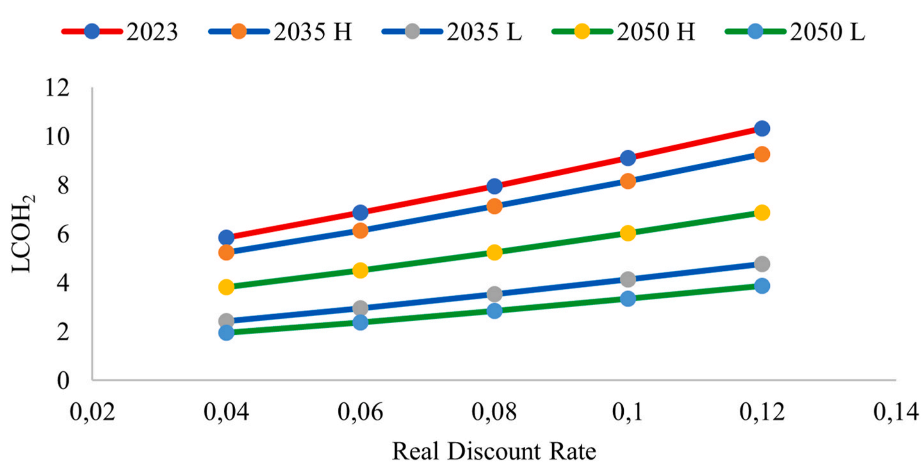


**Fig. 12.** Discount rate impact on LCOH: Bandirma 2023, 2035, and 2050 analysis (4–12%).

the electrolysis process, solely powered by PV systems, at US$5.78/kg and US$5.96/kg, respectively. Notably, these regions possess a higher solar radiation potential compared to our study areas. However, the higher costs observed in this research can be attributed to the exclusion of grid connection sales in their cost calculations.

Highlighting the significance of scale, Huang et al. demonstrated that utilizing a 100 MW PV system for PV-PEM hydrogen production resulted in costs ranging from US$4.2 to US$9.1 per kilogram. Their projections extended to 2030, showing costs varying between $2.24 and $4.48 per kilogram, and further to 2050, with projected costs ranging from US $1.12 to US$2.52 per kilogram. These findings emphasize the cost advantages of larger-scale PV and electrolyzer installations, typically lower than our LCOH values (Huang et al., 2023).

Incorporating capacity factors, a study by Gallardo et al. (2021) in Chile explored hydrogen production through various scenarios, including direct PV to PEM and PPA, resulting in hydrogen costs of US

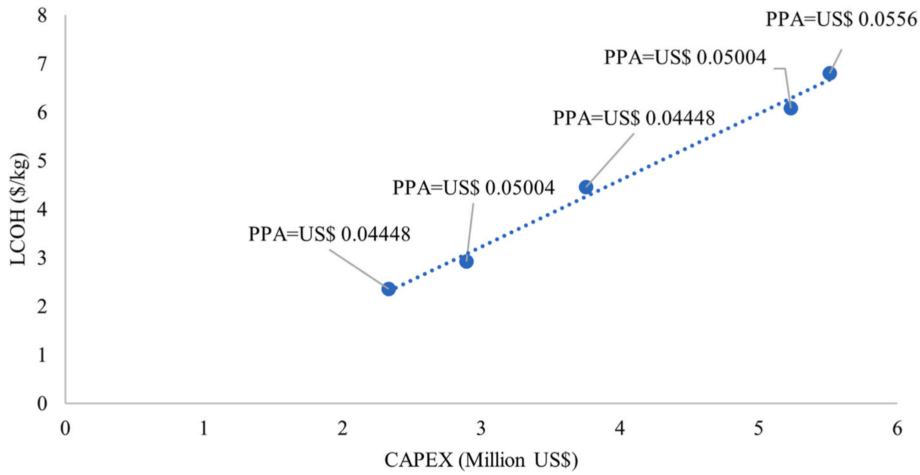


**Fig. 13.** The sensitivity analysis with the varying PPA and CAPEX.

$3.13 and US$3.77 per kilogram, lower than our LCOH values respectively (Gallardo et al., 2021). This underscores the significance of considering capacity factor when assessing the economics of PV-hydrogen production.

## 4. Conclusion

In conclusion, this research represents a pioneering effort in evaluating hydrogen production potential using photovoltaic technology. The primary outcomes of this research comprise:

- The research highlighted substantial disparities in energy production potential among the chosen sites, with Çeşme demonstrating the highest capacity at 8305 MWh/year, followed by Mersin with 7740 MWh/year and Bandırma at 6731 MWh/year.
- The solar capacity factor was found to play a crucial role in determining the appropriate electrolyzer size for each location, with percentages of 18.9% for Çeşme, 17.7% for Mersin, and 15.4% for Bandırma, respectively.
- Elevating electrolyzer efficiency from 70% to 80% led to substantial cost reductions across all locations, highlighting the importance of technological advancements in improving system efficiency.
- The cost of hydrogen production is site-specific and influenced by electrolyzer efficiency and other economic factors. Future projections indicate a downward cost trajectory due to technological advancements and economies of scale. For instance, in Bandırma, the estimated cost of hydrogen in 2023 was US$6.8 per kilogram at 70% electrolyzer efficiency, with projected costs ranging from US$2.36 to US$4.46 per kilogram in 2050. By increasing electrolyzer efficiency to 80%, the cost was reduced to US$5.87 per kilogram in 2023, with anticipated ranges of US$1.98 to US$3.82 per kilogram in 2050. Similar trends were observed for Çeşme and Mersin. Although the costs of green hydrogen may currently seem higher than those of grey hydrogen, with the inclusion of upcoming carbon taxes shortly, the costs of grey hydrogen are expected to become competitive.
- The analysis demonstrated the impact of the real discount rate on the levelized cost of hydrogen, emphasizing the importance of low-interest rates and technology de-risking for the economic viability of photovoltaic-electrolyzer systems.
- The capital expenditure value and power purchase agreement price variations were shown to be significant parameters affecting the levelized cost of hydrogen. Future reductions in component costs and changes in power purchase agreement prices were considered in the analysis.
- The methodology employed in this study can be adapted and applied to other regions, providing a basis for further exploration and optimization of solar-hydrogen systems. Future research should consider emerging technologies to enhance efficiency and cost-effectiveness.
- This research holds particular significance for Europe's hydrogen production and distribution landscape. By examining various cities and regions in Turkey, it contributes to the broader European transition towards a low-carbon economy.

In summary, this research contributes valuable insights into the potential benefits and considerations of solar-driven hydrogen production systems, highlighting their role in advancing sustainable energy solutions. Policymakers, industry professionals, investors, and researchers can use these findings to inform their decisions and actions in the pursuit of a greener and more environmentally friendly future.

## CRediT authorship contribution statement

**M. Gül:** Software, Conceptualization & Methodology, Visualization, Writing. **E. Akyüz:** Conceptualization & Methodology, editing, Writing.

## 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.

## Data availability

Data will be made available on request.

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