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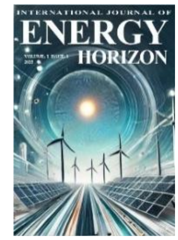


Research Paper

# Electrolyzer Systems as Hydrogen Refueling Stations: A Review of Capex, Opex, and LCOH Calculations

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ABSTRACT

In order to lower transportation-related carbon emissions and promote the use of hydrogen-powered cars, this article offers an economic analysis hydrogen refueling station (HRS) that is connected to photovoltaic (PV) system. In the study, the HRS system with alkaline and PEM electrolyzers with a nominal hydrogen production rate of 30 $Nm^3.h^{-1}$ was compared. While the alkaline HRS system required 192.5 kW PV installed power, the PEM HRS system required 214.5 kW PV installed power. In order to evaluate the HRS system, the levelized cost of hydrogen (LCOH) was calculated by taking into account the initial investment costs, operating expenditures and the amount of hydrogen produced. Economic analysis of a PV integrated system for an inactive HRS in Ankara was conducted. Based on a daily hydrogen production capacity of 65 kg for both electrolyzers with identical nominal outputs, the results of the techno-economic analysis over a 10-year operational period indicate that the levelized cost of hydrogen (LCOH) is calculated as 6.39 $\$.kg^{-1}$ $H_2$ for the alkaline electrolyzer and 7.73 $\$.kg^{-1}$ $H_2$ for the PEM electrolyzer, respectively. This study helps to build sustainable energy infrastructure including PV integrated HRS design, calculation and economic evaluation. The findings give academics, industry stakeholders, and policymakers important information to support energy sustainability and the goal of a carbon-neutral transportation sector.

## 1. INTRODUCTION

In the global effort to mitigate climate change and reduce greenhouse gas emissions, hydrogen has emerged as a promising clean energy carrier. Its high mass-specific energy content (120 $MJ\cdot kg^{-1}$) and low environmental impact make it a suitable alternative to fossil fuel-based energy systems **[1]**. When produced from renewable sources such as solar or wind energy, hydrogen can support a wide range of applications, including energy storage, industrial processes, and zero-emission transportation systems.

Hydrogen has the unique ability to store surplus renewable electricity through water electrolysis, enabling energy balancing across different sectors. The stored hydrogen can later be reconverted into electricity via fuel cells or used directly to fuel buildings or vehicles. Among these applications, fuel cell electric vehicles (FCEVs) have garnered growing attention due to their high efficiency and zero emissions - with water being the only byproduct**[2].** However, the widespread adoption of FCEVs is contingent upon the development of reliable hydrogen infrastructure, particularly hydrogen refueling stations (HRS), which serve as the cornerstone of hydrogen-powered transportation systems **[3]**

HRS are crucial for the commercial viability of FCEVs, as they ensure reliable access to hydrogen fuel. Despite the increasing deployment of FCEVs in recent years, the lack of accessible and economically viable refueling infrastructure remains a significant bottleneck **[4]**. To overcome this challenge, the integration of renewable energy sources, especially solar photovoltaic (PV) systems-with on-site hydrogen production at HRS has been proposed as an environmentally and economically favorable solution. Water electrolysis powered by renewable electricity is considered one of the most sustainable hydrogen production pathways, promoting energy sector decarbonization and cross-sector coupling.

Various electrolyzer technologies can be used in renewable-powered HRS configurations, including alkaline electrolyzers, proton exchange membrane electrolyzers (PEMWEs), anion exchange membrane electrolyzers (AEMWEs), and solid oxide electrolyzer cells (SOECs). Among them, alkaline electrolyzers are considered a mature and cost-effective technology for large-scale hydrogen

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and scalability **[5, 6]**. On the other hand, PEM electrolyzers offer distinct advantages such as high current density operation, compact system design, and rapid dynamic response, making them particularly well-suited for integration with intermittent renewable energy sources **[7]**.

Previous research has explored the techno-economic feasibility of HRS integrated with renewable energy. For instance, Atabay and Devrim analyzed an HRS using AEMWE powered by a 5 MW PV system, reporting a levelized cost of hydrogen (LCOH) of 8.54 €·kg$^{-1}$ for a daily capacity of 170 kg **[3].** Gökçek and Kale compared hybrid wind-PV-battery and wind-battery configurations, yielding hydrogen costs of 8.92 and 11.08 USD·kg$^{-1}$, respectively **[8]**. Similarly, Kayfeci et al. indicated that the LCOH for PV/electrolysis systems could reach up to 23.33 USD·kg$^{-1}$, compared to just 2.08 USD·kg$^{-1}$ for natural gas-based steam methane reforming **[9]**. While Barhoumi et al. reported an LCOH of 3.32 EUR·kg$^{-1}$ using PV-electrolysis (excluding compression and storage costs) **[10]**, Zhao and Brouwer found that solar-powered HRS had an LCOH of 9.14 USD·kg$^{-1}$, reduced to 6.71 USD·kg$^{-1}$ for wind-powered systems **[11]**. Perna et al. reported an LCOH of 7.92 EUR·kg$^{-1}$ for an HRS with a capacity of 450 kg/day using PV-assisted alkaline electrolysis **[12]**.

Despite the growing body of literature, most existing studies tend to focus on a single electrolyzer type or general economic trends without conducting a comparative techno-economic analysis of different electrolyzer technologies under identical renewable energy inputs. Moreover, integrated assessments that consider realistic daily refueling capacities, operational lifetimes, and full system-level costs (including compression, storage, and dispensing units) remain limited. These research gaps hinder the development of robust strategies and investment decisions needed to scale up hydrogen infrastructure.

In this study, we aim to address these limitations by presenting a comparative techno-economic analysis of HRS configurations that utilize two different electrolyzer technologies - alkaline and PEM - integrated with a photovoltaic system. HRS systems with alkaline and PEM electrolyzers with a nominal hydrogen production rate of 30 Nm3.h$^{-1}$ were used for comparison. In the alkaline HRS system, the alkaline electrolyzer required 192.5 kW PV installed power and in the PEM HRS system, the PEM electrolyzer required 214.5 kW PV installed power. The levelized cost of hydrogen (LCOH) was calculated over a 10-year operational period, considering capital and operational expenditures.

The findings provide actionable insights for policymakers, researchers, and industry stakeholders to support the design and deployment of sustainable hydrogen infrastructure in line with decarbonization goals.

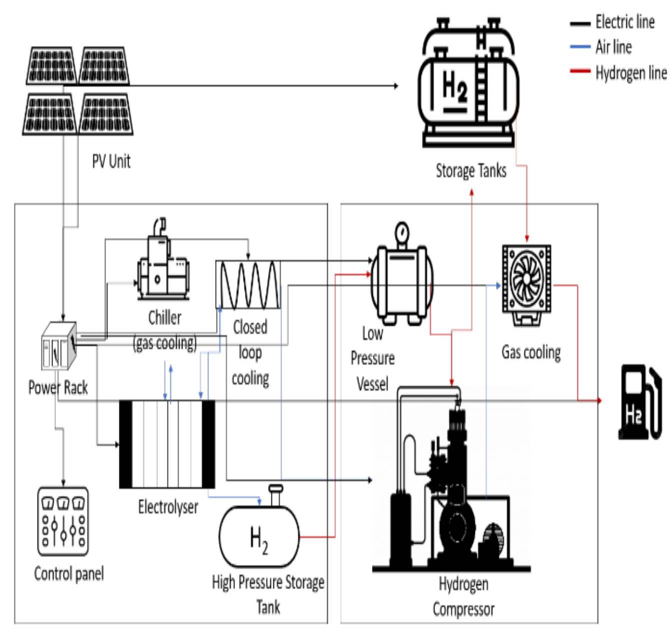
## 2. PROPERTY OF HRS

The planned HRS is designed as an integrated system that encompasses on-site hydrogen production, compression, high-pressure storage, and dual-pressure dispensing units for refueling hydrogen-powered vehicles. The facility is capable of producing up to 65 kg of hydrogen per day, which corresponds to the daily refueling needs of approximately 13 hydrogen fuel cell electric vehicles (FCEVs). Two different system configurations are considered for the hydrogen production unit: one based on a 156 kW alkaline electrolyzer, and the other utilizing a 174 kW PEM electrolyzer, both powered by PV systems with a maximum installed capacity of 192.5 kW and 214.5 kW, respectively. The entire HRS system is modular in design and comprises the following main components:

- A 9 m containerized hydrogen production unit (housing the electrolyzer and associated balance-of-plant),
- A 6 m containerized compression unit,
- High-pressure storage tanks with a total water volume of 4350 liters at 450 bar,
- Dispensers for vehicle and boat refueling at two different pressure levels.

Figure 1 provides a schematic overview of the HRS configuration. Both alkaline and PEM-based system layouts follow a similar structural and operational design, differing primarily in electrolyzer technology and corresponding performance characteristics. This dual-configuration approach enables a comparative techno-economic evaluation of the two electrolyzer technologies under identical operating conditions.

**Figure 1.** Schematic representation of HRS**[13]**




### 2.1. Method of Process

The hydrogen produced by the electrolyzer is first directed to a low-pressure (LP) storage tank operating at approximately 10 bar. This intermediate storage serves as a buffer before compression. The stored hydrogen is then compressed using a multi-stage hydrogen compressor, which incrementally increases the gas pressure from 10 bar up to 450 bar. Following compression, the hydrogen is transferred to a high-pressure storage system, composed of tanks designed to operate at 450 bar. These storage units ensure the availability of pressurized hydrogen for continuous and efficient refueling operations.

The hydrogen is finally delivered to vehicles via a dispenser unit calibrated to supply fuel at 350 bar. The pressure regulation from the high-pressure storage to the dispensing unit ensures safe and controlled refueling. A schematic flow of this system involves:

Electrolyzer → LP Storage (10 bar) → Compressor → HP Storage (450 bar) → Dispenser (350 bar).

The modular configuration of the HRS offers significant advantages in terms of scalability, on-site hydrogen generation, and integration with renewable energy sources, thereby reducing dependency on centralized hydrogen production and distribution networks. The system's compact design allows for flexible deployment in urban and semi-urban environments, while enabling localized, low-emission hydrogen supply. From a safety perspective, the HRS is equipped with advanced monitoring and control systems, including pressure relief valves, gas leak detectors, and automated emergency shutdown mechanisms, which ensure the safe handling of high-pressure hydrogen throughout the compression, storage, and dispensing processes.

**Table 1.** Technical specifications of the main components.

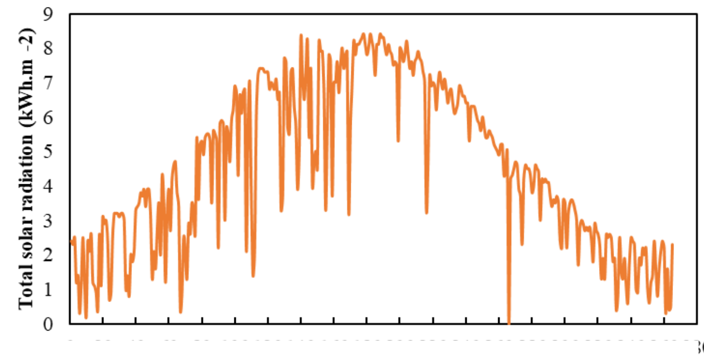
| **PV Panel** | |
|---|---|
| Maximum Power (Pmax) **[14]** | 550 W |
| G1, ref | 1000 W/m |
| Tm, ref | 25°C |
| NOCT | 43°C |
| Temperature Coefficient, $\mu_p$ | 0,00005 |
| Number of PV Panels for Alkaline Electrolyzer | 350 |
| Number of PV Panels for PEM Electrolyzer | 390 |
| **Alkaline Electrolyzer [15]** | |
| Power | 156 kW |
| $H_2$ Nominal Flow | 30 $Nm^3 h^{-1}$ |
| Power Consumption | 5.2 $kWh.Nm^{-3}$ |
| Tap Water Consumption | 1.5 - 2 liters.$Nm^{-3}$ $H_2$ |
| Electrolyte Quantity | 360 L |
| Electrolyte | $H_2O$ + 30% wt. KOH |
| **PEM Electrolyzer [16]** | |
| Power | 174 kW |
| $H_2$ Nominal Flow | 30 $Nm^3 h^{-1}$ |
| Power Consumption | 5.8 $kWh.Nm^{-3}$ |
| Tap Water Consumption | 0.8 – 1.2 liters.$Nm^{-3}$ $H_2$ |
| **Hydrogen Compressor [16]** | |
| Mechanical Efficiency | %88 |
| **Gas Storage System** (NEL, n.d.) | |
| Low-Pressure Buffer Tank | 10 bar |
| Cascade System High-Pressure Tank | 450 bar |
| **Cooling Unit (Chiller and Closed Loop Cooling) [16]** | |
| Car Dispensing Pressure | 350 bar |
| Hydrogen delivery temperature | -40°C |

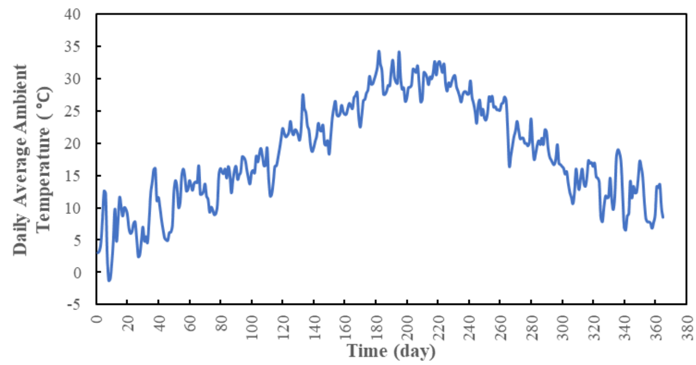
## 2.2. Solar Radiation of Ankara

The quantity of energy generated by solar panels depends on many factors, including panel size, efficiency, amount of sunlight available, and temperature. In addition, it depends on the potential solar radiation and ambient temperature of the region where PV will be installed. The establishment of an HRS using a PV-based renewable energy system was chosen as a possible application area in Çankaya, Ankara, Türkiye. The meterological data's are taken from Turkish State Meteorological Service. Figure 2 shows the total global solar radiation and Figure 3 shows the ambient temperature of Ankara.

**Figure 2.** Total global solar radiation in Ankara

**Figure 3.** Ambient temperature of Ankara




## 2.3. HRS Components

### *2.3.1. PV system*

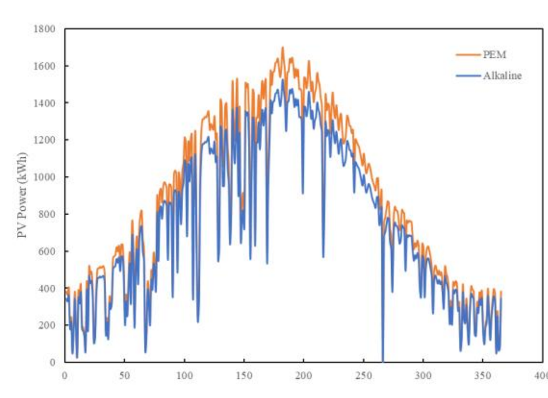
Using data on observed daily global irradiance, sunlight length, and ambient temperature, equations 1 and 2 were used to determine the daily power of the PV **[3]**.

$$T_m = T_a + G_1 \left(\frac{NOCT - 20}{800}\right) \tag{1}$$

$$P_{PV} = N_{PV} \frac{G_1}{G_{1,ref}} \left[P_{PV,max} + \mu_p (T_m - T_{m,ref})\right] \tag{2}$$

$T_m$ is module temperature (°C), $T_a$ is ambient temperature (°C), $G_I$ and $G_{I,ref}$ refer to solar irradiance and reference solar irradiation of PV ($kW/m^2$), $\mu_p$ is module power coefficient, NOCT is the nominal operating cell temperature **[14]**. While $N_{PV}$ is the number of PV panels, $P_{PV,max}$ is the max power of PV panels. In the system design, a panel with a power of 550 W was selected. While 350 panels were used for the Alkali Electrolyzer, 390 panels were used for the PEM Electrolyzer in the system. Figure 4 shows the maximum power that calculated by Equation 2 produced in PV versus the daily radiation in Ankara.

**Figure 4.** Daily produced PV power



### 2.3.2. Electrolyzer

The Alkaline Electrolyzer and PEM Electrolyzer are chosen for hydrogen generation in this research. Alkaline electrolyzer operating at up to 10 bar pressure, this electrolyzer can produce 30 $Nm^3/h$ of hydrogen while consuming 150 kW of electricity and utilizing 1.5-2 liters.$m^{-3}H_2$ of tap water. The PEM Electrolyzer, operating at up to 30 bar pressure, can produce 32 $Nm^3/h$ of hydrogen while consuming 150 kW of electricity and utilizing 0.8–1.2 $L/m^3$ $H_2$ of tap water Equation 3 calculates the daily energy consumption of an alkaline electrolyzer **[3].**

$$E_{Electrolyzer} = P_{Electrolyzer} \times t_{day} \quad (3)$$

where $E_{Electrolyzer}$ is the electrolyzer's daily electricity consumption (kWh), $P_{Electrolyzer}$ is its nominal power (kW), and $t_{day}$ is the alkaline electrolyzer's operational time.

### 2.3.3. Hydrogen Compressor

Outlet pressure for commercial alkaline electrolyzer in the proposed Hydrogen refueling station is approximately 10 bar. In order to use it in hydrogen-powered vehicles, A compressor capable of compressing hydrogen at high pressures (450 bar for this system) must be used. Equation 4 was used to calculate the hydrogen compressor's power **[8].**

$$W_{comp} = C_p \frac{T_1}{\eta_c}\left[\left(\frac{P_2}{P_1}\right)^{\frac{r-1}{r}} - 1\right] m_c \quad (4)$$

where r is the isentropic exponent of hydrogen (r = 1.4), $m_c$ is the gas flow rate through the hydrogen compressor in kilograms per second ($kg.s^{-1}$) , $T_1$ is the inlet gas temperature of the hydrogen compressor (293 K), $\eta_c$ is the compressor efficiency, $P_1$ and $P_2$ are the inlet and output gas pressures of the hydrogen compressor, respectively, and Cp is the specific heat of hydrogen at constant pressure (14.304 $kJkg^{-1}$ $K^{-1}$) **[8].**

$$E_{Compressor} = W_{compressor} \times t_{comressor} \quad (5)$$

$E_{Compressor}$ is the daily energy consumption of the compressor and $t_{comressor}$ represents the compressor's daily operating time.

### 2.3.4. Cooling System

Distribution system is constructed in accordance with the SAE J2601 refueling procedure, which specifies the temperature range for hydrogen precooling (-30/-40°C). Because of its negative Joule-Thompson coefficient, hydrogen expands during refueling, raising the gas's temperature **[8]**. Precooling the hydrogen is necessary to prevent a temperature rise over 85°C, which poses a risk to the hydrogen tank in FCEVs **[4]**. In calculating the required cooling power, it was assumed that hydrogen would fill minutthe vehicle tank at 350 bar and -40 °C for 5 minutes.

Equation 6 was used to calculate HRS's cooling power requirement **[17].**

$$P_{cool} = N_{veh}\dot{m}_{H_2} C_{p_{H_2}}\left(T_{in_{H_2}} - T_{out_{H_2}}\right) \quad (6)$$

where $C_{p_{H_2}}$ is the specific heat for hydrogen at constant pressure ($kJ.kg^{-1}.K^{-1}$), $N_{veh}$ is the number of cars, and $\dot{m}_{H_2}$ is the mass flow rate ($kg.s^{-1}$). The input temperature (K) of hydrogen is $T_{in_{H_2}}$, and the exit temperature (K) of hydrogen is $T_{out_{H_2}}$.

## 2.4. Techno-Economic Analysis

Economic evaluation based on the LCOH study has been conducted to determine cost of the suggested HRSs**[18]**. Based on the HRS's capacity ($kg.day^{-1}$), LCOH is a useful economic measure that enables determining the ultimate cost of producing, compressing, and storing hydrogen. Equation 7 is used for calculation **[4]**:

$$LCOH = \frac{\text{Total Costs(\$)} - \text{Electrical Revenue(\$)}}{H_2\text{Annual Production (kg)}} \quad (7)$$

Total costs shown in equation 8 include annual investment costs ($C_{inv,a}$), annual replacement costs ($C_{rep,a}$), and annual operating costs ($C_{O\&M}$) **[12]**.

$$\text{Total Costs (€)} = C_{inv,a} + C_{rep,a} + C_{O\&M} \quad (8)$$

Equations 10 and 11 are used to annualize investment and replacement expenses while taking equation 9's capital recovery factor (CRF) into account **[3].**

$$CRF = \frac{i\,(1+i)^n}{(1+i)^n - 1} \quad (9)$$

$$C_{inv,a} = C_{inv}.CRF \quad (10)$$

$$C_{rep,a} = \frac{C_{rep}}{(1+i)^t} CRF \quad (11)$$

where the plant lifetime (n), the nominal discount rate (i), and t represent the replacement cost and the related year. Table 2 illustrates the techno-economic specs of the components. This table takes into account the cost per kW of the commercial products selected for high efficiency, the operational costs specified in the literature, and the replacement cost per kW for the products that have completed their lifetime in the process selected for the LCOH calculation. In addition, depending on the hydrogen capacities produced, decisions were made for the cooler, compressor and dispenser.

**Table 2.** Techno-economic specs of the components.

| **Component** | **Parameter** | **Price ($)** |
|---|---|---|
| PV **[19]** | Installation cost [$kW^{-1}$] | 226,24 |
| | Replacement cost [$kW^{-1}$] | 0 |
| | Operation and maintenance [$year^{-1}$ ] | 56,1 |
| | Pv power (kW) | 0,55 |
| | Lifetime [year] | 25 |
| Electrolyzer (PEM) **[8]** | Installation cost [$kW^{-1}$] | 1500 |
| | Replacement cost [$kW^{-1}$] | 0 |
| | Operation and maintenance [$year^{-1}$ ] | 6750 |
| | Max electrolyzer power (kW) | 150 |
| | Lifetime [year] | 10 |
| Electrolyzer (Alkali) **[19]** | Installation cost [$kW^{-1}$] | 1198 |
| | Replacement cost [$kW^{-1}$] | 0 |
| | Operation and maintenance [$year^{-1}$ ] | 3594 |
| | Max electrolyzer power (kW) | 150 |
| | Lifetime [year] | 10 |
| Storage tank (PEM) **[19]** | Installation cost [$kg^{-1}$ ] | 585 |
| | Replacement cost [$kg^{-1}$ ] | 0 |
| | Operation and maintenance [$year^{-1}$ ] | 16380 |
| | Stored $H_2$ [kg] | 140 |
| | Lifetime [year] | 20 |
| Storage tank (Alkali) **[19]** | Installation cost [$kg^{-1}$ ] | 585 |
| | Replacement cost [$kg^{-1}$ ] | 0 |
| | Operation and maintenance [$year^{-1}$ ] | 15210 |
| | Stored $H_2$ [kg] | 130 |
| | Lifetime [year] | 20 |
| Compressor **[20]** | Total Installation cost | 125625 |
| | Replacement cost [$kg^{-1}$] | 0 |
| | Operation and maintenance [$year^{-1}$] | 25125 |

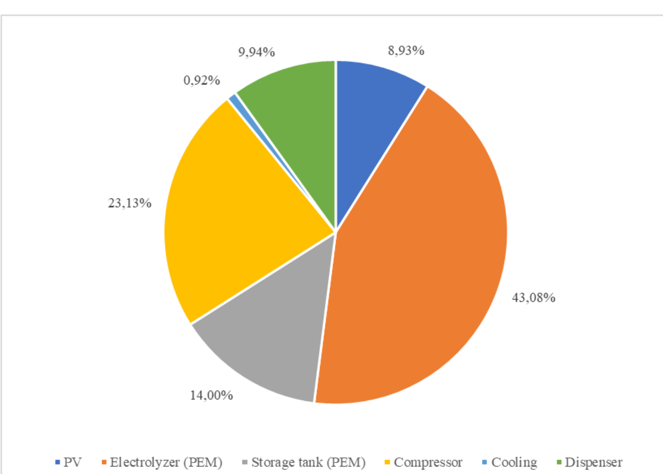
| | | |
|---|---|---|
| | Lifetime [year] | 20 |
| Cooling<br>**[3]** | Installation cost [$.kg$^{-1}$] | 5000 |
| | Replacement cost [$.kg$^{-1}$ ] | 0 |
| | Operation and maintenance [year$^{-1}$] | 0 |
| | Lifetime [year] | 20 |
| Dispenser<br>**[8]** | Total Installation cost [$] | 54000 |
| | Replacement cost [kW$^{-1}$] | 0 |
| | Operation and maintenance [year$^{-1}$] | 16200 |
| | Lifetime [year] | 10 |

## 3. RESULT AND DISCUSSION

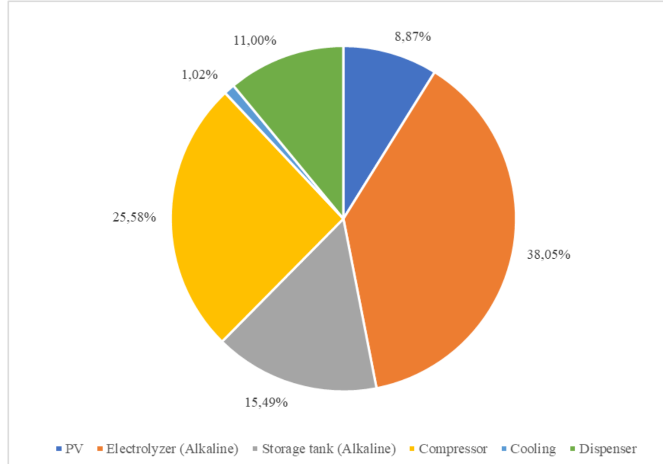
This study evaluated two HRS configurations, each designed to meet a daily hydrogen demand of 65 kg-sufficient to refuel 13 vehicles equipped with 5 kg tanks. In order to enhance energy reliability, a grid-connected photovoltaic (PV) system was employed. While the PV-generated electricity serves as the primary energy source for both systems, the grid is utilized to compensate for any shortfalls, ensuring continuous operation.

The analysis revealed that the capital expenditure (CAPEX) of HRS configurations is strongly influenced by the required PV capacity. The PV-integrated alkaline HRS demonstrated a total CAPEX of approximately $43,500, whereas the PV-integrated PEM HRS exhibited a higher CAPEX of approximately $48,500. This difference arises from the higher specific energy consumption of the PEM electrolyzer, which necessitates a larger PV capacity to produce the same amount of hydrogen. Excluding the PV system, the electrolyzer represented the most substantial component of the total installation cost. Moreover, the electrolyzer's shorter operational lifespan compared to other system components introduces an additional replacement cost during the system's lifetime.

The findings underscore that the high upfront capital investment remains a key barrier to the widespread deployment of green hydrogen infrastructure, particularly in small-scale applications or in regions with limited financial resources. To ensure the long-term economic viability of HRS systems, it is essential to account for not only initial costs but also ongoing maintenance and replacement expenses. Efficient and optimized system operation should be prioritized to minimize lifecycle costs and support the broader adoption of sustainable hydrogen-based transportation. A comparative analysis of the capital cost distribution for two HRS configurations-integrated with either a PEM electrolyzer or an alkaline electrolyzer-is presented in Figure 5 (a and b).




**a)**




**b)**

**Figure 5. a)** Cost ratios of PEM HRS components **b)** Cost ratios of alkaline HRS components

As depicted in Figure 5 (a), the PEM-based system allocates the largest portion of its capital expenditure to the electrolyzer unit (43.08%), followed by the compressor (23.13%) and storage tank (14.00%). In contrast, the alkaline-based system exhibits a slightly more balanced cost structure, with 38.05% allocated to the electrolyzer, 25.58% to the compressor, and 15.49% to the storage tank in Figure 5 (b). The PV subsystem accounts for a similar share in both configurations (approximately 9%), though the absolute PV capacity required in the PEM system is higher due to its greater electricity consumption. Dispenser and cooling systems represent minor but non-negligible shares in both systems. Overall, the PEM-based HRS demonstrates a more capital-intensive profile, largely due to the higher cost and energy demands of PEM technology, whereas the alkaline system distributes costs more evenly across subsystems. These distinctions are particularly relevant for project developers seeking cost-effective solutions for small-scale or budget-constrained hydrogen infrastructure projects.

## 4. CONCLUSIONS

This study presents a comparative techno-economic analysis of HRS configurations integrated with grid-connected PV systems, taking into account the local climatic and geographical conditions of Ankara, Türkiye. The proposed HRS includes four main components: a water electrolyzer, hydrogen storage unit, PV system, and a dispenser. Two types of electrolyzer technologies-alkaline and PEM-each with a nominal hydrogen production capacity of 30 Nm³/h¹ (equivalent to 65 kg/day), were analyzed in terms of their enera gy requirements, capital investments, and long-term economic performance.

The analysis revealed that the alkaline HRS configuration required approximately 192.5 kW of installed PV capacity, whereas the PEM-based system required 214.5 kW due to its higher specific energy consumption. Over a 10-year operational period, the LCOH was calculated to be 6.39 $/kg· $H_2$ for the alkaline system and 7.73 USD/kg $H_2$ for the PEM system. These findings highlight the sensitivity of overall system economics to electrolyzer efficiency and energy input requirements.

In addition to capital expenditures, the study also considers the impact of component reliability and replacement over the system’s lifetime. As hydrogen infrastructure comprises various subsystems-such as compressors, cooling units, and dispensers-with different operational lifespans, stochastic component failure and replacement frequencies must be considered for a more realistic cost assessment. As recommended by Atabay and Devrim, incorporating the average number and timing of component replacements improves the accuracy of long-term economic projections **[3].**

Ultimately, while green hydrogen production systems may not yet be economically superior to conventional methods in all contexts, their environmental advantages and alignment with global decarbonization goals make them essential for future energy systems. The integration of renewable sources like PV with HRS infrastructure represents a critical step toward establishing a sustainable, carbon-neutral hydrogen economy. Continued research and policy support will be necessary to reduce initial capital barriers and to promote widespread adoption of such systems at both regional and global scales.

## 5. RECOMMENDATIONS AND FUTURE WORK

To enhance the economic feasibility and technical reliability of PV-integrated hydrogen refueling stations, several strategies can be recommended. First, further research should focus on the optimization of system components through hybrid configurations, such as the incorporation of battery energy storage systems (BESS) or hybrid renewable sources (e.g., PV-wind combinations) to reduce reliance on grid electricity and to smooth fluctuations in renewable energy supply. Second, future studies should also assess the environmental impacts of such systems through life cycle assessment (LCA), enabling a more holistic evaluation that includes carbon footprint, water use, and resource intensity. Moreover, site-specific analyses using different geographic and climatic conditions would improve generalizability and help identify the most favorable deployment regions.

From a policy perspective, supportive regulatory frameworks and financial incentives-such as feed-in tariffs, carbon credits, or investment subsidies-will be critical to promote early adoption and reduce capital cost burdens. Finally, pilot-scale demonstration projects and real-world data collection are encouraged to validate techno-economic models and guide industry stakeholders and policymakers in making evidence-based decisions regarding green hydrogen infrastructure deployment.

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