

Article

Prototype Development and Experimental Validation of a Modular Rooftop Solar-Driven PV–PEM Green Hydrogen System as a Natural Gas Alternative for Decarbonizing Textile Manufacturing

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Abstract

As the global energy transition accelerates toward low-emission and sustainable industrial energy systems, green hydrogen produced from renewable sources has emerged as a promising alternative to natural gas in energy-intensive sectors. This study presents the design, implementation, and experimental validation of a rooftop photovoltaic–proton exchange membrane (PV–PEM) hydrogen energy system developed as a proof-of-concept for textile industry applications. The proposed system integrates monocrystalline photovoltaic panels with east–west solar tracking, a 4 kW inverter, and a PEM electrolyzer with a hydrogen production capacity of 3.6 L/h, enabling on-site solar-to-hydrogen conversion. Produced hydrogen is stored in a high-pressure metal tank and utilized for downstream energy applications, demonstrating a complete renewable energy pathway. System performance is monitored in real time and evaluated using an experimental methodology supported by GUM-based and Monte Carlo uncertainty analysis. A carbon reduction assessment is conducted under representative industrial operating scenarios, including uncertainty quantification. The results indicate that the prototype system achieves an energy output corresponding to an average monthly emission reduction of approximately 222 kg CO₂e. The modular and scalable architecture allows flexible expansion to support gradual natural gas substitution in textile processes such as drying, heating, and steam generation. Overall, the study demonstrates the technical feasibility and environmental potential of integrating rooftop PV–PEM hydrogen systems into textile manufacturing, providing a transferable framework for industrial decarbonization.

Keywords: hydrogen energy; renewable energy; solar photovoltaic; solar tracker; sustainability



Academic Editors: Muhammad Sajid, Nisar Ali, Muhammad Farooq and Mairui Zhang

Received: 5 January 2026

Revised: 26 January 2026

Accepted: 28 January 2026

Published: 12 February 2026

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1. Introduction

Climate change, the risk of fossil fuel depletion, and increasing concerns about energy supply security have made the transition to sustainable energy systems a global imperative. In this context, the integration of renewable energy sources with innovative energy storage and conversion technologies is critical to achieving long-term carbon neutrality and

environmental resilience. Among clean energy carriers, hydrogen is attracting significant interest due to its high energy density, storability, and suitability for zero-emission applications. Especially when produced through water electrolysis fueled by renewable sources such as photovoltaics (PV), hydrogen becomes a truly green and sustainable fuel. Proton Exchange Membrane (PEM) electrolyzers offer a promising solution for clean hydrogen production thanks to their compact structure, high efficiency, and ability to operate in conjunction with intermittent renewable energy. Furthermore, the conversion of produced hydrogen back into electricity via PEM fuel cells provides an emission-free and flexible energy use opportunity. These systems are suitable for both off-grid scenarios and smart grid applications. Recent research has focused on the design of integrated systems combining solar energy, electrolysis, hydrogen storage, and fuel cell technologies. However, the need for developing portable, real-time monitorable, and scalable systems is increasing daily.

On 6 October 2021, Turkey ratified the Paris Agreement [1] and announced a net-zero emissions target by 2053. In line with this target, it has committed to a 41% emission reduction by 2030. Within the scope of the European Green Deal [2], published by the European Union to become the first climate-neutral continent by 2050, it is planned to reduce greenhouse gas emissions by 55% by 2030. In this context, developing policies compatible with the EU, Türkiye's largest trading partner, necessitates the widespread adoption of carbon reduction practices in the industrial sector [3]. The portable hydrogen energy system developed within the scope of this study is being implemented on the roof of Kivanc Textiles production facility in Adana, one of Türkiye's major textile production centres. Kivanc Textile published its first sustainability report as of 2024 and has been placing significant emphasis on energy efficiency efforts since 2019 [4]. Furthermore, Kivanc Energy, a company within the group, operates power plants powered entirely by renewable energy sources. This application, beyond a theoretical model, has been considered a prototype applicable to industrial infrastructure.

1.1. Main Contributions

- First industrial rooftop demonstration of a modular PV–PEM hydrogen prototype for textile manufacturing:

Unlike most existing studies that remain simulation-based or laboratory-scale, this work presents a fully operational rooftop-integrated hydrogen system deployed in an active textile production facility.

- Experimental validation of a complete solar-to-hydrogen-to-electricity energy pathway under real operating conditions:

The system demonstrates real-time PV generation, hydrogen production, storage, reconversion to electricity, and electric vehicle charging with uncertainty quantification.

- Scalable and modular architecture tailored for gradual natural gas substitution:

The system architecture enables stepwise scaling toward industrial heat decarbonization without requiring immediate infrastructure replacement.

- Quantified carbon mitigation with uncertainty analysis:

Carbon reduction is evaluated using both GUM-compliant uncertainty propagation and Monte Carlo simulation, providing statistically robust emission estimates.

- Integrated experimental–simulation framework for design extrapolation:

A validated simulation model is developed to extrapolate system performance toward larger-scale industrial scenarios.

1.2. Literature Review

Recent research on hydrogen storage systems has been reviewed, and information regarding the methods and findings used in these studies is presented in Table 1.

Table 1. Summary of recent studies on PV–PEM hydrogen systems and storage applications.

Ref.	Study Focus	System/Method	Key Findings	Gap/Contribution
[5]	Solar-powered PEM electrolyzer integration with PV systems	Simulation-based modelling	Demonstrated optimized coupling of PV systems with PEM electrolyzers and quantified solar-to-hydrogen conversion performance under different operating conditions	Lacks experimental validation under real industrial or rooftop operating conditions
[6]	Hydrogen production performance of PEM electrolyzer	Experimental (laboratory-scale)	Provided detailed experimental characterization of PEM electrolyzer efficiency, polarization behavior, and hydrogen production rates	Focused on component-level testing without system-level integration or industrial application
[7]	Off-grid PV–hydrogen–fuel cell energy systems	Techno-economic assessment (simulation-based)	Demonstrated feasibility of PV–hydrogen–fuel cell systems for off-grid energy supply and highlighted economic viability under specific demand scenarios	Did not address real-time experimental operation or industrial energy substitution
[8]	Off-grid solar PV-driven hydrogen production	Experimental and modelling study	Analyzed hydrogen production via water electrolysis powered by off-grid PV systems and evaluated system performance under variable solar conditions	Limited to off-grid configurations, without addressing modular rooftop deployment or industrial decarbonization pathways
[9]	Review on RES–electrolyzer integration	Comparative analysis	Pointed out standardization gaps and efficiency trade-offs	Calls for pilot applications
[10]	PEM electrolyzer dynamic operation	Renewable fluctuation tests	Showed flexibility reduces cost and increases grid stability	Mostly theoretical
[11]	Alkaline vs. PEM electrolyzers	BWM analysis + expert eval.	Identified cost, lifetime, flexibility as decisive factors	Both remain viable; application-specific choice
[12]	Multi-stage electrolyzer control in hybrid RES	Optimization study	Improved H ₂ yield under solar–wind complementarity	Complex control; not portable
[13]	Direct PV–electrolyzer coupling	Tech assessment	Reduced cost by eliminating power electronics	Needs optimized sizing for stability
[14]	Underground hydrogen storage (UHS)	Review + case projects	Identified caverns, aquifers as promising	Safety and cost challenges
[15–18]	Various hydrogen storage methods (compressed, liquid, MH, LOHC)	Systematic reviews & models	Evaluated technical/economic trade-offs	Need for scalable & safe storage
[19,20]	Grid integration and AI-based EMS	Simulation & control models	Real-time EMS improves H ₂ utilization, reduces outages	Still simulation-dominant

Table 1. Cont.

Ref.	Study Focus	System/Method	Key Findings	Gap/Contribution
[21]	Techno-economic investigation of PV-Wind hybrid systems for electricity and hydrogen	PV + wind + battery + electrolyzer + hydrogen storage system (simulation-based with MATLAB + HOMER)	Identified optimal hybrid configurations and quantified LCOE/LCOH for green hydrogen production; sensitivity analysis for key system parameters	Simulation-based techno-economic insights still need real operational data for industrial deployment
[22–26]	Tracking algorithms, catalysts, safety	Experimental & theoretical	Efficiency gains with optimized tracking; AI-based leak detection	Mostly component-level studies
[17,27–32]	Metal hydrides & hybrid systems	Multi-dimensional analyses	High volumetric density, hybrid RES improve resilience	Scalability and cost concerns
[33–35]	Experimental hydrogen pilot plants	PV-H ₂ testbeds	Reported ~48% fuel cell efficiency, gravimetric density 131 Wh/kg	Small scale
[36–41]	Policy, techno-economic reviews	Int'l strategies & hybrid models	Emphasized role of EU Green Deal, REPowerEU, Hydrogen Earthshot	Translation to industrial practice missing

Several studies have investigated the integration of photovoltaic (PV) systems with proton exchange membrane (PEM) electrolyzers as a promising pathway for sustainable hydrogen production. Simulation-based analyses have demonstrated that optimized coupling of PV generation with PEM electrolyzers can significantly enhance solar-to-hydrogen conversion performance and system integration under varying operating conditions [5]. Complementary to these modelling efforts, laboratory-scale experimental studies have provided detailed characterization of PEM electrolyzer performance, including polarization behavior, efficiency trends, and hydrogen production rates, thereby confirming the technical feasibility of PV-assisted hydrogen production at the component level [6].

Beyond component-focused investigations, system-level studies have explored the application of PV–hydrogen–fuel cell configurations for decentralized and off-grid energy supply. Techno-economic assessments of off-grid PV–hydrogen–fuel cell systems have demonstrated their feasibility for meeting end-user electricity demand while improving renewable energy utilization, particularly in regions with limited grid access [7]. In addition, experimental and modelling studies on off-grid solar PV-driven water electrolysis have shown that direct coupling of PV systems with electrolyzers enables effective hydrogen production under variable solar conditions, highlighting the potential of such systems for decentralized energy infrastructures [8]. Reviews focusing on renewable-assisted hydrogen production systems have compared various system architectures, efficiencies, and standardization efforts, while highlighting the lack of unified standards as a major barrier to large-scale deployment [9]. In this context, the dynamic operation of PEM water electrolyzers powered by variable solar and wind resources has attracted significant attention, with studies demonstrating that flexible electrolyzer operation can reduce green hydrogen costs and enhance grid flexibility [10].

Comparative assessments of alkaline and PEM electrolysis technologies have analyzed technical and economic performance using multi-criteria decision-making methods, identifying cost, safety, energy consumption, flexibility, lifetime, and stack capacity as critical adoption factors, and concluding that both technologies will remain relevant for renewable hydrogen production [11]. Optimization-based studies further proposed multi-stage electrolyzer management strategies in hybrid solar–wind systems, showing that coordinated operation significantly increases hydrogen yield [12]. Directly coupled PV–electrolyzer configurations have also been examined, revealing that eliminating power electronic con-

verters can reduce system cost and complexity while maintaining conversion efficiency through appropriate sizing and control strategies [13].

Hydrogen storage has been extensively studied as a critical enabler of energy security and supply continuity. Research on underground hydrogen storage (UHS) has emphasized the potential of salt caverns, aquifers, and depleted gas reservoirs for large-scale and seasonal storage, while also noting outstanding safety and cost challenges [14]. Comprehensive reviews have examined hydrogen production, storage, and utilization across power generation, heating, and transportation sectors, identifying both technical and economic integration challenges [15]. Detailed analyses of physical, material-based, and carrier-based storage technologies further indicate that advances in materials and economies of scale will determine the future viability of hydrogen storage systems [16].

Energy system modeling studies have demonstrated the significant impact of seasonal hydrogen storage on renewable integration and decarbonization, reporting carbon emission reductions of up to 69% in national power systems [17]. Profit-oriented analyses have shown that hydrogen storage can enhance the economic viability of solar power plants under grid constraints by optimizing seasonal energy shifting [18]. Bibliometric studies further reveal that the majority of hydrogen storage and grid-integration research remains simulation-based, with compressed gas storage emerging as the most commonly adopted near-term solution [19].

Conducted a comprehensive techno-economic investigation of a PV–wind-based isolated hybrid energy system incorporating electrolyzers, hydrogen storage, and fuel cells for electricity and green hydrogen production. Using a combined MATLAB and HOMER-based optimization framework, the study identified optimal system configurations and quantified key economic indicators such as levelized cost of electricity (LCOE) and levelized cost of hydrogen (LCOH). The results demonstrated that hybrid PV–wind systems can significantly improve renewable energy utilization and reduce overall system costs compared to single-source configurations. However, the analysis remains simulation-based and does not address real-time operational constraints, uncertainty propagation, or on-site industrial deployment. These limitations highlight the need for experimentally validated, modular hydrogen energy systems operating under real industrial conditions—an aspect directly addressed by the present study [21]. Broader reviews have emphasized hydrogen's role in decarbonizing energy systems through smart grid integration, sector coupling, and supportive regulatory frameworks [42].

Solar tracking technologies have been investigated as a means of improving PV system performance, with analytical and simulation studies reporting up to 3% increases in DC output under diffusive radiation conditions [22]. At the component level, nanostructured materials have been shown to enhance hydrogen production performance across various generation pathways [23], while conventional hydrogen production routes such as reforming and gasification continue to be evaluated from economic and environmental perspectives [24].

Data-driven approaches for hybrid PEM fuel cell–battery systems have demonstrated high accuracy in performance and lifetime prediction, leading to significant reductions in fuel consumption and lifecycle costs in real-world applications [25]. Safety-oriented studies have systematically addressed hydrogen-related risks, including leakage, embrittlement, and ignition, highlighting the role of quantitative risk assessment and AI-assisted sensing technologies in safe system design [26]. Metal hydride-based storage systems have been shown to offer high volumetric energy density under moderate conditions, with recent advances significantly improving reversibility and cycle stability [27].

System-level analyses have highlighted the benefits of hydrogen energy storage in terms of scalability, energy density, and controllability, with detailed evaluations of power

electronic interfaces and dynamic system behavior [28]. Comparative modeling studies of long-duration storage technologies, including hydrogen, pumped hydro, and compressed air, have demonstrated that hydrogen storage becomes increasingly valuable in high-renewable power systems beyond 2050 [29]. Additional comparative assessments have reinforced hydrogen's role in addressing renewable intermittency and supporting large-scale energy transitions [17,30,31].

Recent reviews of hydrogen-based hybrid microgrids and integrated PV–wind–hydrogen systems have emphasized their potential for enhanced energy management and system resilience [32]. Experimental and simulation studies on hydrogen storage integrated with photovoltaic systems have reported fuel cell efficiencies of up to 48% and high gravimetric energy densities [33]. Large-scale modeling studies further indicate that hydrogen outperforms battery systems in long-duration and seasonal storage applications despite lower round-trip efficiency [34,35].

Policy-oriented analyses comparing national hydrogen strategies have underscored the importance of coordinated infrastructure development, cost reduction, and safety regulation in achieving carbon neutrality [36–38]. Comprehensive reviews of hydrogen production routes, storage methods, and re-electrification pathways further confirm hydrogen's versatility across power, heat, and transport sectors [39–41]. Finally, recent studies propose multimodal hydrogen utilization frameworks and advanced combustion strategies, demonstrating improved system flexibility, renewable energy absorption, and emission reduction across integrated energy systems [43–48]. A recent study highlights optimization strategies for PV-assisted electrolysis, including voltage matching, reduction in conversion losses, and improved system architectures to enhance solar-to-hydrogen efficiency and scalability. While these system-level analyses provide valuable insights into performance enhancement and technological barriers, they remain largely focused on conceptual frameworks and optimization strategies. In contrast, experimentally validated, on-site PV–PEM hydrogen systems operating under real industrial conditions remain limited, underscoring the need for practical demonstrations to bridge the gap between theoretical optimization and real-world deployment [49].

This study presents the design and implementation of a solar-assisted integrated hydrogen energy system consisting of PV panels, a PEM electrolyzer, a storage tank, and PEM fuel cells. The relevant literature indicates that energy production involves individual processes, while storage maintains integrated storage in the industrial sector. This study significantly contributes to electricity generation from allocated energy for the industrial sector, which is accelerating towards achieving the 2050 climate neutrality target within the scope of the European Green Deal [2]. The system generates electricity from solar energy integrated with solar tracking, provides real-time data monitoring, generates oxygen from the sun, and performs a closed-loop energy conversion from hydrogen back to electricity. Thus, with its technical feasibility and carbon reduction potential, it contributes to the literature as a functional model for low-emission, multi-technology smart grid solutions. Renewable energy storage systems have attracted significant attention in recent years, particularly for portable and low-emission energy systems. Systems equipped with solar PEM electrolyzers and fuel cells are considered potential solutions for sustainable energy production and are becoming increasingly widespread, especially in off-grid applications. Furthermore, although hydrogen has been widely recognized as a promising low-carbon alternative for industrial heat applications, existing studies in the textile sector are largely limited to conceptual assessments, policy analyses, or system-level modeling. Experimentally validated, on-site renewable hydrogen systems specifically designed for textile manufacturing facilities—particularly those integrating rooftop photovoltaic generation with PEM electrolysis—remain scarce. Furthermore, the potential of such systems to reconvert hydro-

gen into electricity for on-site power generation and electric vehicle (EV) charging within industrial environments has received little experimental attention. To address these gaps, this study develops and experimentally validates a modular rooftop solar-driven PV–PEM hydrogen energy system tailored for textile industry applications. As illustrated in Figure 1, the proposed system demonstrates an integrated solar-to-hydrogen-to-electricity pathway capable of supporting future thermal energy demands, on-site electricity supply, and EV charging infrastructure as part of a multi-energy industrial decarbonization framework.

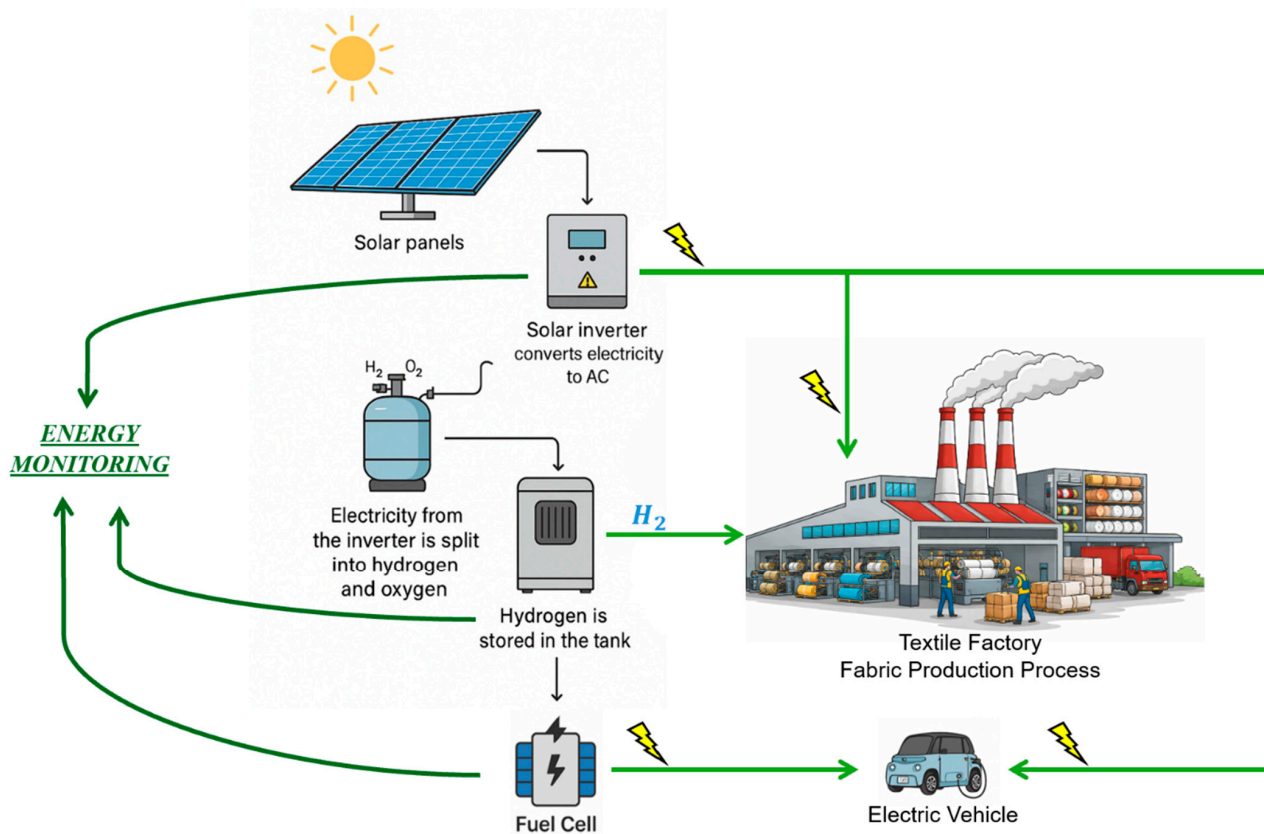


Figure 1. Schematic Representation of the System.

Building upon this motivation, the following section introduces the overall system architecture and operational principles of the proposed rooftop PV–PEM hydrogen energy system. The design rationale, key system components, and energy flow pathways—from photovoltaic electricity generation to hydrogen production, storage, reconversion to electricity, and end-use applications—are described in detail to provide a clear understanding of the system’s functionality and scalability for textile manufacturing facilities

2. Materials and Methods

The proposed system is a portable, rooftop-integrated PV–PEM hydrogen prototype designed to demonstrate the full energy conversion cycle from solar radiation to hydrogen production and back to electricity. The experimental setup was implemented on the roof of Kivanc Textile’s industrial facility in Adana, Turkey, making it one of the few industrial-scale rooftop hydrogen prototypes in the country. The system consists of four monocrystalline PV panels (540–560 W each), a 4 kW solar inverter, a PEM electrolyser with a nominal hydrogen production capacity of 3.6 L/h, an 18 L low-pressure hydrogen storage tank, and a 100 W PEM fuel cell. The technical specifications of all components are summarised in Table 2.

Table 2. Technical specifications of the PV–PEM hydrogen system components.

Component	Specification	Value/Range	Notes
PV Panel	Type	Monocrystalline	High efficiency, rooftop installation
	Rated power	540–560 W (×4 panels)	Total ~2.1 kW peak
	MPP voltage/current (V _{mpp} /I _{mpp})	~42 V/12.5 A	Manufacturer datasheet
	Tracking system	Single-axis, east–west	Yield gain: +15–25%
Inverter	Model	Lexron 4 kW solar inverter	Grid-independent operation
	Rated efficiency	92–95%	PWM-controlled
	Output waveform	Sinusoidal, 50 Hz	With L–C filtering
PEM Electrolyzer	Type	Low-temperature PEM	Direct DC input
	H ₂ production capacity	3.6 L/h	Nominal operating conditions
	Operating voltage	1.6–2.0 V/cell	Higher than theoretical 1.23 V
	Faraday efficiency	~70–80%	Dependent on current density
H ₂ Storage Tank	Capacity	18 L	Low-pressure, portable cylinder
	Material	Metal (steel)	Safety certified
PEM Fuel Cell	Type	Proton Exchange Membrane	Reversible with electrolyzer
	Rated power	100 W	Portable fuel cell module
	Operating efficiency	30–40%	Load-dependent
Monitoring System	Software	Monitoring system	Hourly live monitoring
	Parameters	PV, inverter, electrolyzer, fuel cell, storage	Data stored for analysis
End-use Application	Vehicle	Citroën AMI	5.5 kWh Li-ion battery
	Charging capacity	~80–90 W fuel cell output	Demonstration of micro-mobility

2.1. Photovoltaic Unit

The PV array consists of four high-efficiency monocrystalline modules with a total peak capacity of ~2.1 kW. An east–west single-axis tracking system was used to increase energy efficiency, achieving a 15–25% gain compared to fixed-angle installations. The PV maximum power point (MPP) can be expressed in Equation (1) as:

$$P_{max} = V_{mpp} \times I_{mpp} \quad (1)$$

Here V_{mpp} and I_{mpp} show the maximum power dissipation and current of two panels. For one module, ($V_{mpp} = 42$ V, $I_{mpp} = 12.5$ A) the theoretical power is ~525 W, and for four modules, ~2.1 kW efficiency is obtained.

MPPT Mathematical Model for Single-Axis Solar Tracking Systems

The basic mathematical model used in Maximum Power Point Tracking (MPPT) algorithms for single-axis solar tracking systems is based on the logic that the system determines the angle at which the panel will produce maximum power based on solar radiation.

- MPPT Basic Principle:

The purpose of MPPT is to fix the panel's operating point at what we call the Maximum Power Point (MPP). The basic Equation (2) is:

$$P = V \times I \quad (2)$$

Here: P = Power (W), V = Voltage (V), I = Current (A).

- Maximum Power Point (MPPT) Condition:

$$dP/dV = I + V \times dI/dV = 0 \quad (3)$$

This expression indicates that the power change is zero when the derivative is taken at the MPP, as shown in Equation (3). The maximum power point is achieved under this condition. This derivative expression is typically used in Perturb and Observe (P&O) or Incremental Conductance methods.

- Angle/radiance coupling (single-axis tracker):

Panel power can also be expressed as a function of the solar incident angle:

$$P(\theta) = G \times A \times \eta \times \cos(\theta_s - \theta) \quad (4)$$

In Equation (4),

G = Solar irradiance (W/m^2) A = PV panel surface area (m^2) η = PV panel efficiency

θ_s = Sun's zenith angle θ = Panel tilt angle

This function is maximum when $\theta = \theta_s$, meaning the panel should be positioned perpendicular to the sun.

- Converter and control:

A DC–DC stage (buck/boost) matches the PV I–V value to the electrolyzer stack I–V value. The duty cycle D is set by the MPPT law, while the electrolyzer applies ramp limits (dI/dt)_{max}.

- Incremental Conductance (IC) MPPT:

$$\text{MPP: } dV/dI = -V/I. \text{ If } dV/dI > -V/I \Rightarrow \text{left of MPP (increase } V), \text{ else decrease } V. \quad (5)$$

- P&O (hill climbing) update rule:

$$V_{k+1} = V_k + \Delta V \cdot \text{sign}\{P(V_k) - P(V_{k-1})\} \quad (6)$$

- Proposed hybrid MPPT logic (pseudocode): loop:

measure $V, I \rightarrow P = V \cdot I$

if $|\Delta G| > G_{\text{thresh}}$ or $|\Delta V| < \varepsilon$ and $|\Delta I| < \varepsilon$:

use Incremental Conductance step (Equation (5))

else:

use small-step P&O (Equation (6))

apply dI/dt limiter for electrolyzer ($\Delta I \leq I_{\text{ramp_max}} \cdot \Delta t$)

enforce $V_{\text{cell,max}}$ and $I_{\text{stack,max}}$

end

Figure 2 shows the information on the panels used and the tracking mechanism that continuously aligns the panels to maximize the angle of incidence of solar radiation.

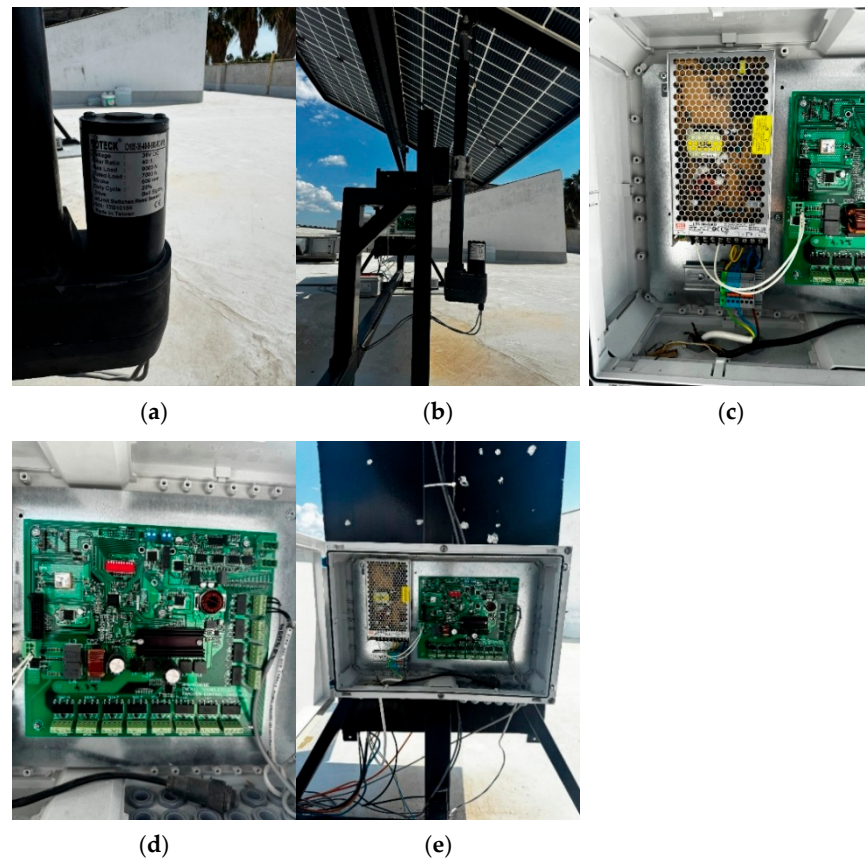


Figure 2. Used Solar Tracking System (a) Stepper Motor (b) Stepper Motor Connection (c) Card Feeder Unit (d) Control Card (e) Control Unit General View.

2.2. Power Conversion (Inverter)

The DC output from the PV array is converted to wireless AC power via a 4 kW Lexron inverter. The inverter operates under pulse width modulation (PWM) control at 92–95% nominal efficiency. The AC output is given by Equation (3) as follows:

$$V_{ac}(t) = Ma \cdot V_{dc} \cdot \sin(\omega t) \quad (7)$$

Here, Ma is the modulation index, V_{dc} is the input DC voltage, and ω is the angular frequency of the AC signal. Figure 3 shows the inverter and its integration into the system.



Figure 3. Solar Inverter Connection and System Overview.

2.3. PEM Electrolyzer

The electrolyzer converts water into hydrogen and oxygen as follows. The electrolysis reaction is presented in Equation (8):



Although the theoretical energy is 1.23 V, in practice it operates between 1.6 and 2.0 V. The hydrogen production rate is explained in Equation (9).

$$\text{H}_2 = I / (2F) \quad (9)$$

The hydrogen storage rate for Faraday's constant: $F = 96,485 \text{ C/mol}$ and $I = 1.2 \text{ A}$ is $\sim 0.374 \text{ mol/h}$ ($\sim 8.38 \text{ L/h}$). In practice, the electrolyzer produced $\sim 3.6 \text{ L/h}$, reflecting efficiency losses and system limitations. Figure 4 shows the PEM electrolyzer and storage module.

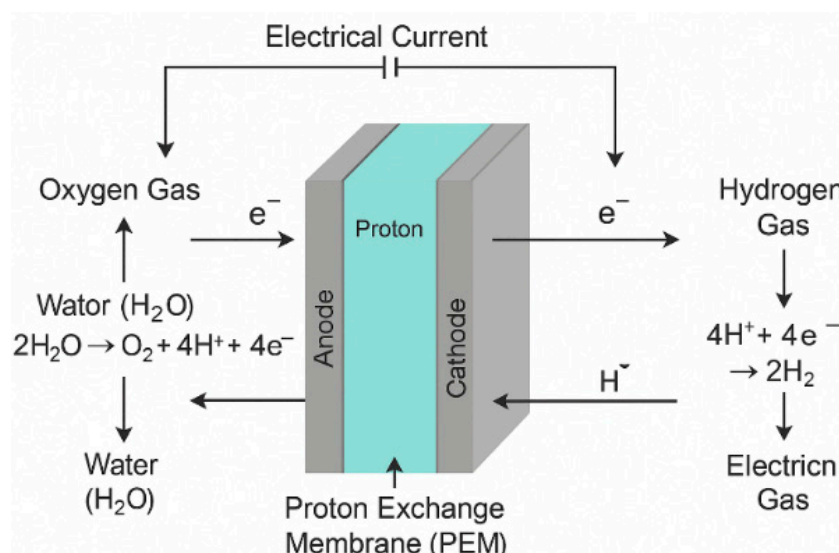


Figure 4. General view of the PEM electrolyzer.

2.4. Hydrogen Storage and Fuel Cell

The produced hydrogen is stored in an 18 L low-pressure metal tank and then fed to a PEM fuel cell with a nominal capacity of 100 W. The fuel cell converts hydrogen into electricity as follows:

The fuel cell reaction is presented in Equations (10)–(13).



$$\text{Power generation: } P = V \times I \quad (11)$$

$$\text{Energy: } E = P \times t \quad (12)$$

$$\text{Efficiency: } \eta = V_{\text{out}} / (\Delta H / nF) \quad (13)$$

During the experiments, the fuel cell provided 80–90 W of continuous power. Figure 5 depicts the fuel cell module, hydrogen storage, and PEM electrolyzer system operation, while Figure 6 depicts the hydrogen storage system visualization.

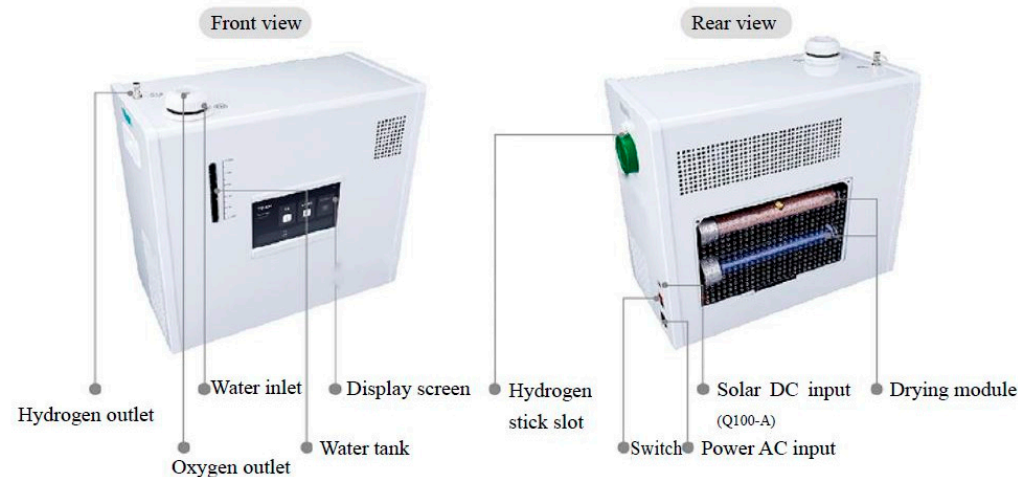


Figure 5. PEM electrolyzer and hydrogen tank details.

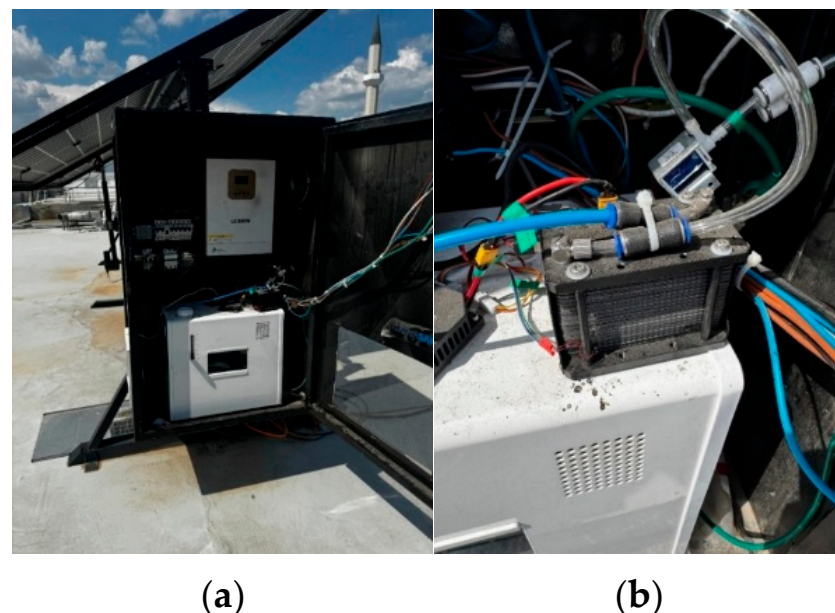


Figure 6. (a) PEM electrolyzer and hydrogen storage (b) Fuel Cell System Visualization.

2.5. Energy Monitoring System

System performance was monitored in real time using energy SCADA software, version 9.5, which collected hourly data on PV generation, inverter efficiency, electrolyzer consumption, hydrogen production, and fuel cell output. The monitoring interface is presented in Figure 7.

2.6. Measurement, Data Quality, and Uncertainty

2.6.1. Data Quality Plan (DQP) and QA/QC

Acquisition and integrity: All signals (PV V, I, P, inverter, electrolyzer V, I, T, H₂ production/storage, PEMFC V, I, P) were recorded hourly (and more frequently) (Energy SCADA). Time synchronization, completeness, consistency, and traceability were considered in the datasets. In addition, Table 3 also presents the views of the PV-PEM technology prototype measurements used in the study.



Figure 7. Energy Scada Connection, Visual and Screenshot of Energy Scada software.

Table 3. Appearances for PV-PEM technology prototype measurements.

Quantity	Instrument/Model	Specification	Distribution	Std. Uncertainty (u(x))	Sensitivity Coefficient ($\partial f / \partial x$)
PV Voltage (V)	DMM, 600 V range	$\pm 0.5\% \text{ rdg} \pm 2 \text{ dgt}$	Rectangular	<5	(I)
PV Current (I)	Shunt + DAQ	$\pm 0.2\% \text{ FS}$	Normal	<5	(V)
Inverter Power Factor $\cos(\varphi)$	Built-in meter	± 0.02	Rectangular	<5	(V · I)
Tank Pressure (P)	0–10 bar sensor	$\pm 1\% \text{ FS}$	Normal	<5	(m/P)
Tank Temperature (T)	PT100 RTD	$\pm 0.5 \text{ K}$	Normal	<5	(-m/T)
Tank Volume (V)	Cylinder spec	$\pm 1\%$	Rectangular	<5	(m/V)
Compressibility (Z)	EOS (NIST REFPROP)	± 0.01	Uniform	<5	(-m/Z)
Faraday Efficiency (η_F)	Process est.	0.97 ± 0.02	Normal	<5	(m/ η_F)
PEMFC Voltage (V_{FC})	Datalogger	$\pm 0.5\%$	Normal	<5	(I)
PEMFC Current (I_{FC})	Shunt	$\pm 0.5\%$	Normal	<5	(V)
Grid EF (0.35–0.45 kg CO ₂ /kWh)	Literature	Range ± 0.05	Uniform	<5	(E_{avoided})

Preprocessing and quality checks:

- Range/limit checks: Physically impossible values (negative current, etc.) were rejected.
- Consistency checks: Power–energy integrations and energy balance (PV → electrolyzer + FC + losses) were checked for residuals (target residual < ±5%).
- Outlier detection: A sliding window Hampel filter (median ± 3σ) and the IQR method were applied.
- Missing data: Interruptions < 1 h are linearly interpolated; interruptions ≥ 1 h are listed and added to the uncertainty budget.

- Calibration & Traceability: Volt/current (shunt + DAQ), pressure, temperature, and H₂ flow/production are monitored at least annually according to ISO/IEC 17025; as-found/as-left are recorded.

2.6.2. Uncertainty Framework (GUM-Compliant)

Uncertainty calculations were conducted according to the ISO/IEC Guide 98-3 (GUM) approach:

- ✓ Type A (statistical) standard deviation from replicate measurements.
- ✓ Type B (manufacturer's specification, calibration certificates, resolution, drift, model assumptions).
- ✓ The combined standard uncertainty for the derived quantity $y = f(x_1, \dots, x_n)$ is given in Equation (14):

$$u_c(y) = \sqrt{\sum_i \left(\frac{\partial f}{\partial x_i} u(x_i)\right)^2 + 2 \sum_{i < j} \frac{\partial f}{\partial x_i} \frac{\partial f}{\partial x_j} u(x_i, x_j)} \quad (14)$$

If there is a correlation, covariance terms are added. Expanded uncertainty $U = k u_c$ ($k = 2$, 95% CI in this study).

2.6.3. Sensor/Chain-Level Uncertainty Budgets

- Power measurement: $P = V \cdot I$. If there is no correlation:

$$u^2(P) = (I u(V))^2 + (V u(I))^2 \quad (15)$$

If the same instrument derives V and I , $u(V, I) \neq 0$ can be used; covariance is added with (16). Daily energy:

$$E = \sum_{k=1}^N P_k \Delta t, u(E) = \Delta t \sqrt{\sum_k u^2(P_k)} \quad (16)$$

If there is time correlation (e.g., sensor drift), the effective sample size with the autocorrelation coefficient $\rho(\tau)$ is used.

- Electrolyzer generation (Faraday basis):

$$\dot{n}_{H_2} = \frac{I}{2F}, m_{H_2} = \frac{M_{H_2}}{2F} \int I(t) \eta_F(t) dt \quad (17)$$

where η_F is the Faraday return (including gas leaks/dissolved O₂/H₂ conduction). The relative payoffs are approximately:

$$\left(\frac{u(m)}{m}\right)^2 \approx \left(\frac{u(I)}{I}\right)^2 + \left(\frac{u(\eta_F)}{\eta_F}\right)^2 \quad (18)$$

(Appropriate correlation terms for the integrated current $\int I dt$ and η_F are also considered.) The formulation and dimensions used in the PEM electrolyzer are detailed in Chapter 3.

- Tank inventory (PVT):

$$m = \frac{P V}{Z R T} M_{H_2} \quad (19)$$

Z is the compressibility factor ($Z = 1$ for ideal). Uncertainty propagation:

$$\left(\frac{u(m)}{m}\right)^2 = \left(\frac{u(P)}{P}\right)^2 + \left(\frac{u(V)}{V}\right)^2 + \left(\frac{u(T)}{T}\right)^2 + \left(\frac{u(Z)}{Z}\right)^2 \quad (20)$$

- PEM fuel cell efficiency:

$$\eta_{FC} = \frac{P_{FC}}{\dot{n}_{H_2} \Delta H_{H_2}} (\text{LHV "preference"}) \quad (21)$$

- Rate uncertainty (independent assumption):

$$\left(\frac{u(\eta)}{\eta}\right)^2 \approx \left(\frac{u(P_{FC})}{P_{FC}}\right)^2 + \left(\frac{u(\dot{n}_{H_2})}{\dot{n}_{H_2}}\right)^2 \quad (22)$$

In this study, the PEMFC was observed to operate continuously in the 80–90 W range; the efficiency–load curves are reported in this range.

Total chain efficiency: $\eta_{\text{tot}} = \eta_{PV \rightarrow H_2} \cdot \eta_{H_2 \rightarrow \text{el}}$ Relative uncertainties are combined by the sum of squares (if there is no correlation).

CO₂ reduction: $\Delta\text{CO}_2 = E_{\text{avoided}} \cdot EF_{\text{grid}}$. Here, for EF_{grid} , use the scenario range (e.g., 0.35–0.45 kg CO₂e/kWh) and the published uncertainty; for ΔCO_2 , report both measurement and factor uncertainty.

2.6.4. PV & MPPT-Specific Data Quality

Spectral mismatch and $\cos(\theta)$ error: $\cos(\theta)$ bias at low solar elevation in a single-axis tracker; a correction factor is applied if necessary.

Temperature coefficient: varies with module power T ; the manufacturer's uncertainty in the γ_P coefficient (W/°C) falls into Type B.

MPPT efficiency: $\eta_{\text{MPPT}} = \sum P_{\text{load}} / \sum P_{\text{MPP,ref}}$. The reference $P_{\text{MPP,ref}}$ is derived from simultaneous I–V scans or a well-calibrated model; give a 95% CI with a bootstrap for the uncertainty.

Time resolution/synchronous: Time shift in the PV and load channels is the uncertainty component; NTP synchronization and the align–then–aggregate procedure are used.

2.6.5. Electrolyzer & Tank: DQ Nuances

Faraday efficiency η_F : Gas leakage, cross-permeability, and bubble separation efficiency. Sampled in Monte Carlo by selecting a prior distribution for η_F (e.g., $\mathcal{U}[0.95, 1.00]$ or $\mathcal{N}(\mu, \sigma)$). Temperature–pressure effects: Z-based correction for tank mass in PVT (25); pressure class $\pm 1\%$ FS may dominate for sensors.

Quality/Gas purity: ISO 14687 purity requirements for PEMFC compatibility; analyzer uncertainty added to Type B (report if available) [50].

2.6.6. Model Fits & Parameter Uncertainty

Apply parameters η_{act} , η_{ohm} , η_{conc} with weighted nonlinear OLS for polarization curve (electrolyzer/PEMFC); covariance:

$$\text{Cov}(\hat{\theta}) = \sigma^2 (J^T W J)^{-1} \quad (23)$$

From here, derive parameter GAs and uncertainty bands (delta method or MC) for the derived yield curves.

2.6.7. Uncertainty Analysis

- Uncertainty in Energy Measurements:

The PV array produced an average hourly output of 1.68–1.70 kWh, while the PEM electrolyzer consumed 1.50–1.65 kWh to produce hydrogen at a rate of 3.6 L/h. The combined uncertainty of the PV power and energy measurements evaluated according to the GUM framework was estimated as $\pm 5\%$ ($k = 2$). This uncertainty was affected by variations in current converter accuracy and inverter efficiency. For electrolyzer hydrogen production, the Faraday efficiency (η_F) contributed the largest source of uncertainty, with an assumed distribution of 0.97 ± 0.02 . The propagation via Faraday's law (Equation (12)) showed an overall relative uncertainty in the hydrogen mass flow estimate of approximately 6%.

- Storage and Fuel Cell Analysis

Hydrogen storage calculations based on the ideal gas law (Equation (14)) were primarily affected by pressure transducer calibration. Monte Carlo simulations ($n = 50,000$) revealed that the 95% confidence interval for the 18 L tank inventory was $\pm 8\%$, with sensor drift and compressibility factor approximations contributing to secondary effects. The efficiency calculation for the PEM fuel cell (Equation (16)) combined power measurement uncertainty ($\pm 4\%$) and hydrogen flow uncertainty ($\pm 6\%$) to yield a total relative uncertainty of approximately 7%. These propagated errors generated a confidence interval around the measured continuous power output of 80–90 W, sufficient to demonstrate the feasibility of electric vehicle charging.

- Overall Efficiency and Carbon Reduction.

The chain efficiency (PV $\rightarrow$ H₂ $\rightarrow$ Electricity) was measured in the range of 5–15%. When combined with the uncertainty propagation (Equation (20)), the expanded uncertainty for the total round-trip efficiency was $\pm 2\%$ absolute. The system's monthly average carbon reduction potential was calculated as an average of 222 kg CO₂e per month using the national grid emission factor (0.626 kg CO₂e/kWh) and also subjected to the factor's uncertainty (range 0.6–0.65). Monte Carlo analysis resulted in a 95% confidence interval of 192–252 kg CO₂e, corresponding to a relative uncertainty of $\pm 13.5\%$. This range demonstrates that the carbon reduction effect remains statistically significant despite the prototype's small scale, highlighting the potential of portable PV-H₂ systems for industrial decarbonization and micromobility applications.

2.7. Industrial Integration and Sustainable Production Implementation

This system is not only a theoretical prototype but also a practical model serving Turkey's sustainable industrial transformation. Being installed on the roof of Kivanc Textile's production facility, the system generates real-time data on the production, storage, and use of green hydrogen using renewable energy at an industrial scale. Directly charging a Citroën AMI vehicle with the energy generated from the system demonstrates how the concept of carbon-neutral mobility can be implemented in the industrial field. This integration serves as a critical example, particularly for the low-carbon production structures envisioned by international frameworks such as the European Green Deal and the Paris Agreement. This study has the potential not only to decarbonize the energy needs of industrial enterprises but also to increase the flexibility and energy security of production through portable and distributed systems. Figure 8 is included as a general overview of the system established at Kivanc Tekstil, illustrating the overall status of the study.

2.8. Simulation Framework (PV–PEM H₂ System)

- Simulation-Experimental Comparison:

The simulation framework demonstrated strong agreement with experimental measurements across all subsystems. For the PV-electrolyzer coupling, the simulated hydrogen output of ~ 0.94 g/h closely matched the experimental production of 3.6 L/h (≈ 0.32 g/h), and this difference was explained by the Faraday efficiency and auxiliary losses. Tank filling simulations at 5 bar predicted a maximum storage of 7.3 g, which aligned with experimental values to within $\pm 8\%$. The PEM fuel cell model reproduced the characteristic polarization behavior and accurately predicted the stable 80–90 W operating range observed in practice. Finally, the CO₂ reduction scenario analysis confirmed the experimental baseline of 8 kg CO₂e per hour and predicted a reduction of ~ 40 kg CO₂e with a $\pm 13.5\%$ confidence interval for a 5 kW PV array. Together, these results confirm the validity of the modeling approach, strengthen the reliability of the prototype results, and demonstrate the scalability of the system.



Figure 8. General view of the system installed at Kivanc Textile.

- **Experimental Comparison with Simulation-Literature Context:**

The consistency between simulation and experimental findings aligns with results previously reported in the literature. For example, refs. [6,13] emphasized the importance of power matching in PV-electrolyzer integration, but their results were limited to laboratory conditions. Our simulation reproduced these trends while validating them in industrial rooftop operation. Similarly, tank storage simulations were comparable to the results of [14,17,27–32], where scaling to higher pressures was highlighted as a bottleneck for portable applications. The PEM fuel cell performance curves were consistent with previous small-scale demonstrations [7,33–35], but this study uniquely extended the application to micromobility. Finally, the CO₂ reduction scenario addressed a gap noted in reviews [19,44], which typically address the potential for decarbonization qualitatively without quantitative prototype-level case studies. By combining simulation and experimental validation, this study not only validates established theoretical models but also extends them to real-world industrial and mobility contexts.

2.8.1. Scope and Assumptions

This section develops a physics-based yet lightweight simulation framework to mirror the prototype's behavior and to run design/what-if scenarios. The chain includes: PV array → MPPT & DC/DC → PEM electrolyzer → H₂ storage (PVT) → PEM fuel cell (FC) → EV/DC load, with an auxiliary branch for CO₂ mitigation. Unless noted, steady-state within each sampling step is assumed, ambient $T \approx 25^{\circ}\text{C}$, and ideal gas behavior for storage (compressibility $Z \approx 1$ at low pressure).

Key assumptions

- PV array: 2S2P configuration, rated ≈ 2.1 kW. Empirical I–V model fitted to datasheet (V_{oc} , I_{sc} , V_{mpp} , I_{mpp}).
- DC/DC + MPPT: converter efficiency $\eta_{\text{conv}} \approx 0.95$; MPPT uses a hybrid IC+P&O law.
- PEM electrolyzer: polarization $V_{el}(I) = V_0 + kI + b\ln(1 + I)$. Faradaic conversion applies.
- Storage: 18 L cylinder, PVT for mass/pressure tracking.
- PEM fuel cell: Nernst minus losses condensed to $V_{fc}(I) = E_0 - a\ln I - bI$; electric output $P = VI$.
- CO₂ mitigation: $\Delta\text{CO}_2 = E_{\text{avoided}} \cdot EF_{\text{grid}}$ with user-selected EF_{grid} .

2.8.2. Component Models

- PV array and MPP

We use a compact empirical I–V expression that passes exactly through (V_{oc}, I_{sc}) and (V_{mpp}, I_{mpp}) :

$$I(V; G) = I_{sc}(G) \left[1 - \left(\frac{V}{V_{oc}} \right)^a \right], I_{sc}(G) \propto G, \quad (24)$$

with the exponent a solved from $I(V_{mpp}) = I_{mpp}$. The array power is $P_{PV} = VI$. The converter tracks the MPP while enforcing electrolyzer constraints.

- Electrolyzer polarization and H_2 production

Per-stack voltage is:

$$V_{el}(I) = V_0 + kI + b \ln(1 + I), P_{el}(I) = I \cdot V_{el}(I). \quad (25)$$

Hydrogen production (Faraday's law):

$$\dot{n}_{H_2} = \frac{I}{2F}, \dot{m}_{H_2} = \frac{M_{H_2}}{2F} I \quad (26)$$

$$F = 96,485 \text{ C/mol } M_{H_2} = 2.016 \times 10^{-3} \text{ kg/mol}$$

- Power match with converter

At each step, the operating current I^* is found by equating electrolyzer demand to converter-delivered PV power:

$$P_{el}(I^*) \approx \eta_{conv} P_{PV, meas}. \quad (27)$$

- Storage tank (PVT balance)

Mass inventory is updated with production minus consumption:

$$m_{k+1} = m_k + (\dot{m}_{prod} - \dot{m}_{FC}) \Delta t \quad (28)$$

and pressure (ideal gas):

$$P = \frac{nRT}{V} = \frac{m}{M_{H_2}} \frac{RT}{V} \quad (29)$$

- PEM fuel cell (consumption unit)

A compact FC model reproduces the polarization and power curve:

$$V_{fc}(I) = E_0 - a \ln I - bI, P_{FC} = I V_{fc}(I) \quad (30)$$

Hydrogen consumption to sustain electrical load P_{FC} at efficiency η_{FC} using LHV = 33.3 kW

$$\dot{m}_{H_2, FC} = \frac{P_{FC}/1000}{\eta_{FC} \cdot 33.3} (\text{kg/h}) \quad (31)$$

- CO_2 mitigation

$$\Delta CO_2 = E_{avoided} \cdot EF_{grid} \quad (32)$$

For scenarios, $E_{avoided}$ scales with PV rating under similar duty factors.

2.8.3. Default Parameters

Table 4 presents the default parameters of the systems used in the study. Figure 9 shows the MATLAB Simulink Block Diagram of the study.

Table 4. Default Parameters.

Block	Symbol	Value (Default)
PV (per module)	$(V_{oc}), (I_{sc}), (V_{mpp}), (I_{mpp})$	49 V, 13.2 A, 42 V, 12.5 A
PV array	series $\times$ parallel	2S $\times$ 2P (≈ 2.1 kW)
Converter	(η_{conv})	0.95
Electrolyzer	(V_0, k, b)	15.0, 0.5, 0.4
Tank	$(V), (T)$	18 L, 298 K
Fuel cell	(E_0, a, b)	14.0, 0.4, 0.2
Fuel cell eff.	(η_{FC})	0.35
H ₂ LHV	—	33.3 kWh/kg
Faraday const.	(F)	96,485 C/mol
H ₂ molar mass	(M_{H_2})	0.002016 kg/mol

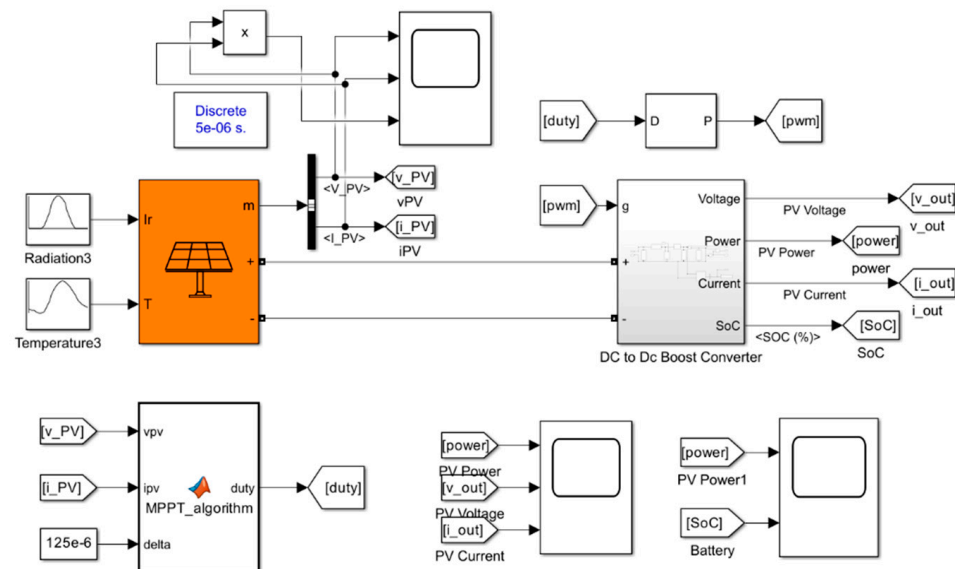


Figure 9. PV_MPPT_BATTERY MATLAB R2025b Simulink Block Diagram.

2.9. Role of Natural Gas in the Textile Industry and Its Significance, Potential of Hydrogen as a Substitute for Natural Gas, Comparative Assessment

The textile industry is one of the most energy-intensive manufacturing sectors, primarily due to its extensive thermal energy requirements across various production stages, including yarn preparation, dyeing, washing, drying, finishing, and steam generation. Among different energy carriers, natural gas has become the dominant fuel in textile manufacturing owing to its high energy density, relatively low cost, stable supply, and ease of integration into existing boiler and heating systems [51,52].

Natural gas is widely used to generate process heat and steam, which are essential for temperature-controlled operations such as fabric dyeing, chemical finishing, and moisture removal. In many textile facilities, natural gas-fired boilers operate continuously to ensure consistent product quality and high production throughput. As a result, thermal energy consumption typically accounts for 60–80% of total energy use in textile plants, with natural gas representing the largest share of this demand [53].

Despite its operational advantages, the extensive use of natural gas leads to significant carbon dioxide (CO₂) emissions, making the textile sector a notable contributor to

industrial greenhouse gas emissions. Given increasing regulatory pressure, carbon pricing mechanisms, and corporate sustainability commitments, reducing natural gas dependency has become a strategic priority for textile manufacturers worldwide [54].

Hydrogen has emerged as a promising alternative to natural gas for industrial heat applications due to its carbon-free combustion characteristics. When produced from renewable electricity via water electrolysis (green hydrogen), hydrogen enables thermal energy generation without direct CO₂ emissions, aligning with global decarbonization targets [55,56].

In textile manufacturing, hydrogen can technically replace natural gas in several applications, including boilers, furnaces, dryers, and steam generation systems, either through direct hydrogen combustion or via hydrogen–natural gas blending during transitional phases. Existing gas-fired systems can, in many cases, be retrofitted to operate with hydrogen-rich fuels, reducing the need for complete infrastructure replacement [57].

Furthermore, hydrogen's compatibility with on-site production offers a distinct advantage for industrial facilities. Rooftop photovoltaic-driven PEM electrolyzer systems, such as the one proposed in this study, enable decentralized hydrogen generation, reducing reliance on external fuel supply chains and enhancing energy security for textile plants [58].

From an environmental perspective, natural gas combustion emits approximately 56 kg CO₂/GJ, whereas green hydrogen combustion produces zero direct CO₂ emissions [59]. This fundamental difference positions hydrogen as a key enabler for deep decarbonization in thermal-intensive industries.

However, hydrogen and natural gas differ significantly in terms of physical and combustion properties. Hydrogen has a lower volumetric energy density but a higher gravimetric energy content, as well as a wider flammability range and higher flame speed. These characteristics require careful system design and safety considerations but also allow for more efficient and responsive combustion under optimized conditions [60].

Economically, hydrogen currently remains more expensive than natural gas, particularly when produced via electrolysis. Nevertheless, rapid cost reductions in photovoltaic technologies, electrolyzers, and renewable electricity, combined with rising carbon costs, are expected to narrow this gap in the medium to long term [61].

In addition to emissions reduction, hydrogen-based energy systems enable greater operational flexibility and modularity, particularly when coupled with renewable energy sources. Modular PV–PEM hydrogen systems allow textile manufacturers to scale hydrogen production incrementally, facilitating a gradual and economically viable transition away from fossil fuels [62].

Overall, the adoption of green hydrogen represents a transformative pathway for the textile industry, enabling sustainable heat generation while maintaining process reliability and product quality. The prototype system presented in this study contributes to this transition by demonstrating a practical, rooftop-integrated solution that bridges the gap between laboratory-scale hydrogen technologies and real-world industrial deployment.

2.9.1. Basic Mathematical and Thermodynamic Comparison Between Hydrogen and Natural Gas

Lower Heating Value (LHV) Comparison

The lower heating value (LHV) represents the net amount of thermal energy released during fuel combustion, excluding the latent heat of water vapor condensation. Table 5 summarizes the LHV of hydrogen and natural gas (methane) on a mass basis.

Table 5. Lower heating value of hydrogen and natural gas.

Fuel	LHV (MJ·kg ^{−1})	LHV (kWh·kg ^{−1})
Hydrogen (H ₂)	≈120	≈33.3
Natural Gas (CH ₄)	≈50	≈13.9

On a gravimetric basis, hydrogen exhibits an energy content approximately 2.4 times higher than that of natural gas. This characteristic makes hydrogen particularly attractive for applications where fuel mass is a critical parameter.

Volumetric Energy Density

Despite its high gravimetric energy density, hydrogen has a significantly lower volumetric energy density under standard conditions. Table 6 compares the volumetric energy content of hydrogen and natural gas at ambient pressure and temperature.

Table 6. Volumetric energy density of hydrogen and natural gas under standard conditions.

Fuel	Energy Density (MJ·m ^{−3})
Hydrogen (H ₂)	≈10–12
Natural Gas (CH ₄)	≈35–38

This difference highlights one of the key technical challenges associated with hydrogen utilization, namely the need for pressurized storage or conversion pathways to overcome its low volumetric energy density.

Combustion Reactions and Thermodynamic Implications

The stoichiometric combustion reactions of natural gas and hydrogen can be expressed as follows:

Natural gas (methane) combustion:



Hydrogen combustion:



From a thermodynamic perspective, the combustion of hydrogen produces only water vapor as a byproduct, whereas natural gas combustion inherently generates carbon dioxide. This fundamental difference underpins the role of hydrogen as a carbon-free energy carrier for industrial thermal applications.

Carbon Dioxide Emission Factors

The environmental performance of fuels can be quantified using carbon dioxide emission factors expressed per unit of useful thermal energy. Typical values are summarized in Table 7.

Table 7. CO₂ emission factors for hydrogen and natural gas.

Fuel	CO ₂ Emissions
Natural Gas	≈56 kg CO ₂ ·GJ ^{−1}
Green Hydrogen	0 kg CO ₂ ·GJ ^{−1}

These values indicate that replacing natural gas with green hydrogen for process heat can eliminate direct CO₂ emissions associated with fuel combustion.

Relevance for Textile Process Heat Applications

Textile manufacturing processes typically operate within low- to medium-temperature ranges, including fabric drying (120–180 °C), dyeing and finishing (150–250 °C), and steam generation below 250 °C. These temperature levels are fully compatible with both natural gas and hydrogen combustion systems.

Hydrogen’s higher flame speed and broader flammability range compared with natural gas enable rapid heat release and flexible thermal control when appropriate burner designs and safety measures are employed. Consequently, hydrogen can deliver equivalent or improved thermal performance for textile process heat while enabling significant reductions in greenhouse gas emissions.

Based on this mathematical and thermodynamic comparison, hydrogen emerges as a technically viable and environmentally superior alternative to natural gas for supplying low- and medium-temperature process heat in textile manufacturing, particularly when produced from renewable energy sources.

3. Results

3.1. PV Performance

A rooftop PV array, utilizing the climate conditions of Adana, Türkiye, shows an average hourly output of 1.68–1.70 kWh. Figure 10 shows a typical daily power output curve over eight months, and Figure 11 shows a comparison of monthly output. Monthly comparison data (kWh) of solar power plant production for February–September 2025 is presented in Figure 12. This curve shows that output reaches ~2.0 kW around midday and declines due to late-gain development losses in the morning and after peak gains. The gain of the east–west single-axis tracker increased daily output by 15–20% compared to tilted fixed installations. Table 8 summarizes daily and monthly performance indicators, with an average capacity factor of 8–9%. The combined measurement uncertainty for the PV subsystem is estimated to be ±5% (k = 2), primarily due to current variation and inverter conversion efficiency.

Table 8. Solar Energy System Daily Production Table.

2025 Solar Power Plant Production Tracker System (kWh)															
1 Febru- ary	8.18	1 March	11.16	1 April	4.27	1 May	6.77	1 June	19.67	1 July	20.71	1 Au- gust	7.21	1 Septem- ber	10.46
2 Febru- ary	8.93	2 March	10.17	2 April	8.24	2 May	14.15	2 June	8.87	2 July	16.48	2 Au- gust	6.73	2 Septem- ber	8.34
3 Febru- ary	7.16	3 March	6.10	3 April	4.50	3 May	11.20	3 June	14.10	3 July	13.60	3 Au- gust	11.76	3 Septem- ber	10.63
4 Febru- ary	7.62	4 March	8.23	4 April	13.05	4 May	18.14	4 June	20.24	4 July	17.17	4 Au- gust	9.39	4 Septem- ber	9.13

Table 8. Cont.

2025 Solar Power Plant Production Tracker System (kWh)															
5 February	7.96	5 March	10.99	5 April	8.56	5 May	12.06	5 June	16.56	5 July	17.16	5 August	9.03	5 September	7.79
6 February	8.54	6 March	12.14	6 April	10.80	6 May	12.88	6 June	17.10	6 July	19.90	6 August	9.76	6 September	10.93
7 February	6.26	7 March	10.94	7 April	11.29	7 May	14.82	7 June	15.65	7 July	16.13	7 August	6.85	7 September	10.67
8 February	9.34	8 March	12.36	8 April	10.94	8 May	8.70	8 June	14.54	8 July	14.69	8 August	13.23	8 September	8.48
9 February	6.04	9 March	11.83	9 April	11.83	9 May	13.12	9 June	14.90	9 July	12.85	9 August	13.81	9 September	9.97
10 February	2.43	10 March	11.18	10 April	10.08	10 May	15.67	10 June	12.75	10 July	13.07	10 August	15.65	10 September	11.70
11 February	3.34	11 March	11.63	11 April	9.58	11 May	15.24	11 June	17.38	11 July	10.19	11 August	13.91	11 September	12.30
12 February	4.98	12 March	10.44	12 April	15.09	12 May	11.05	12 June	14.94	12 July	18.85	12 August	14.35	12 September	10.02
13 February	2.54	13 March	13.50	13 April	15.75	13 May	8.57	13 June	9.03	13 July	12.45	13 August	14.62	13 September	13.28
14 February	9.97	14 March	10.07	14 April	6.36	14 May	11.30	14 June	12.50	14 July	11.49	14 August	13.83	14 September	11.84
15 February	9.21	15 March	12.84	15 April	15.59	15 May	14.60	15 June	15.48	15 July	8.09	15 August	11.77	15 September	10.52
16 February	5.70	16 March	12.93	16 April	14.66	16 May	13.40	16 June	16.20	16 July	7.09	16 August	12.45	16 September	11.28
17 February	9.59	17 March	7.82	17 April	15.58	17 May	13.37	17 June	16.89	17 July	15.24	17 August	12.23	17 September	10.99
18 February	6.60	18 March	10.19	18 April	12.03	18 May	17.84	18 June	17.12	18 July	7.55	18 August	12.97	18 September	8.67
19 February	4.72	19 March	8.12	19 April	15.48	19 May	16.33	19 June	16.82	19 July	12.04	19 August	11.17	19 September	10.68
20 February	10.35	20 March	10.80	20 April	15.77	20 May	13.21	20 June	13.55	20 July	12.07	20 August	8.77	20 September	13.13
21 February	9.99	21 March	9.07	21 April	14.60	21 May	15.01	21 June	15.07	21 July	13.55	21 August	13.55	21 September	13.02
22 February	10.66	22 March	14.59	22 April	13.43	22 May	12.77	22 June	19.93	22 July	14.96	22 August	12.19	22 September	11.73
23 February	12.73	23 March	14.44	23 April	12.06	23 May	12.00	23 June	16.59	23 July	14.08	23 August	13.53	23 September	11.27
24 February	10.69	24 March	6.82	24 April	7.61	24 May	15.95	24 June	17.00	24 July	12.17	24 August	12.46	24 September	10.57
25 February	9.04	25 March	10.37	25 April	9.35	25 May	18.30	25 June	16.75	25 July	14.97	25 August	11.21	25 September	10.56
26 February	11.07	26 March	7.85	26 April	7.08	26 May	13.02	26 June	12.90	26 July	14.31	26 August	11.13	26 September	9.79
27 February	11.11	27 March	12.59	27 April	18.05	27 May	10.99	27 June	17.10	27 July	13.13	27 August	11.10	27 September	10.46

Table 8. Cont.

2025 Solar Power Plant Production Tracker System (kWh)															
28 February	7.46	28 March	7.67	28 April	12.64	28 May	10.24	28 June	19.96	28 July	12.72	28 August	11.52	28 September	11.06
		29 March	5.28	29 April	12.65	29 May	8.34	29 June	16.11	29 July	8.11	29 August	9.78	29 September	10.38
		30 March	8.31	30 April	7.75	30 May	5.57	30 June	18.68	30 July	9.97	30 August	9.66	30 September	10.27
		31 March	11.70			31 May	9.65			31 July	8.65	31 August	8.75		
toplamlam	222.25	toplamlam	322.13	toplamlam	344.66	toplamlam	394.25	toplamlam	474.41	toplamlam	413.44	toplamlam	354.39	toplamlam	321.92

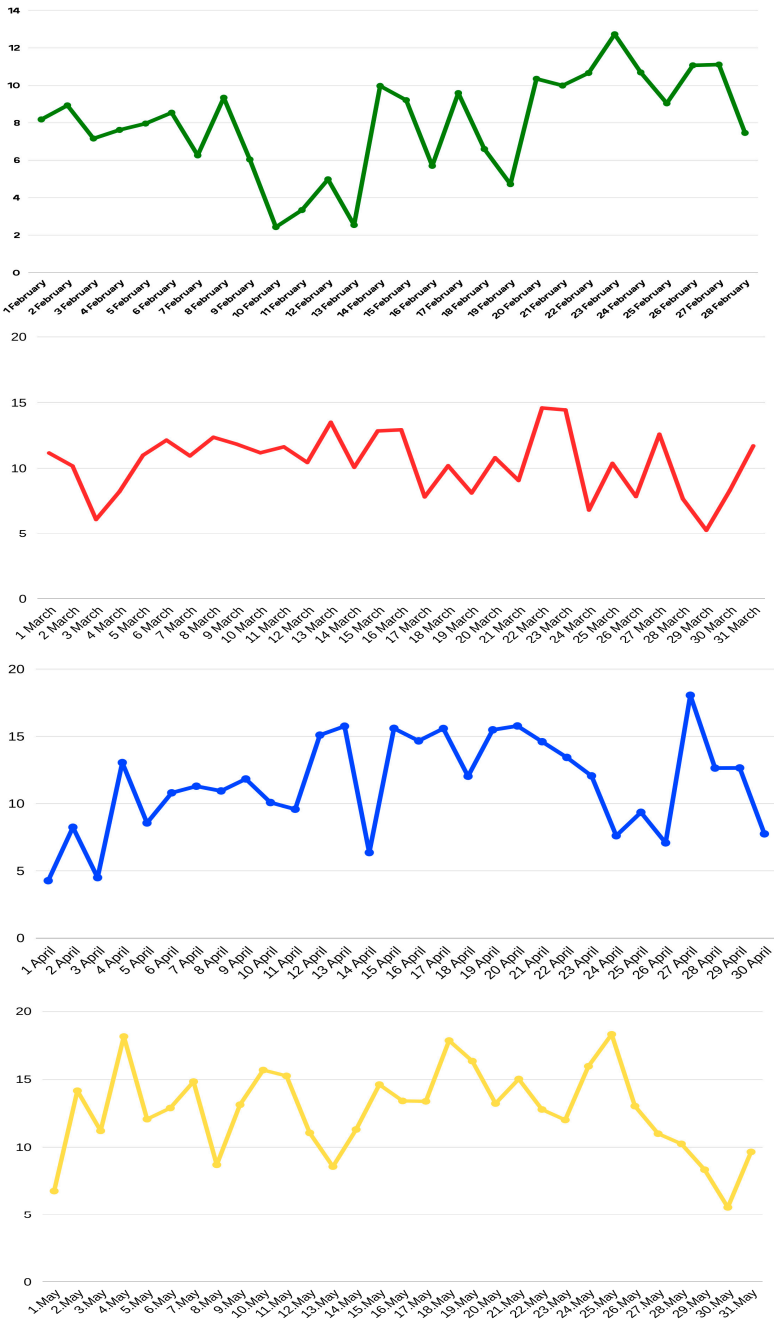


Figure 10. Solar Energy System Energy Production Graphs for February 2025, March 2025, April 2025, and May 2025.

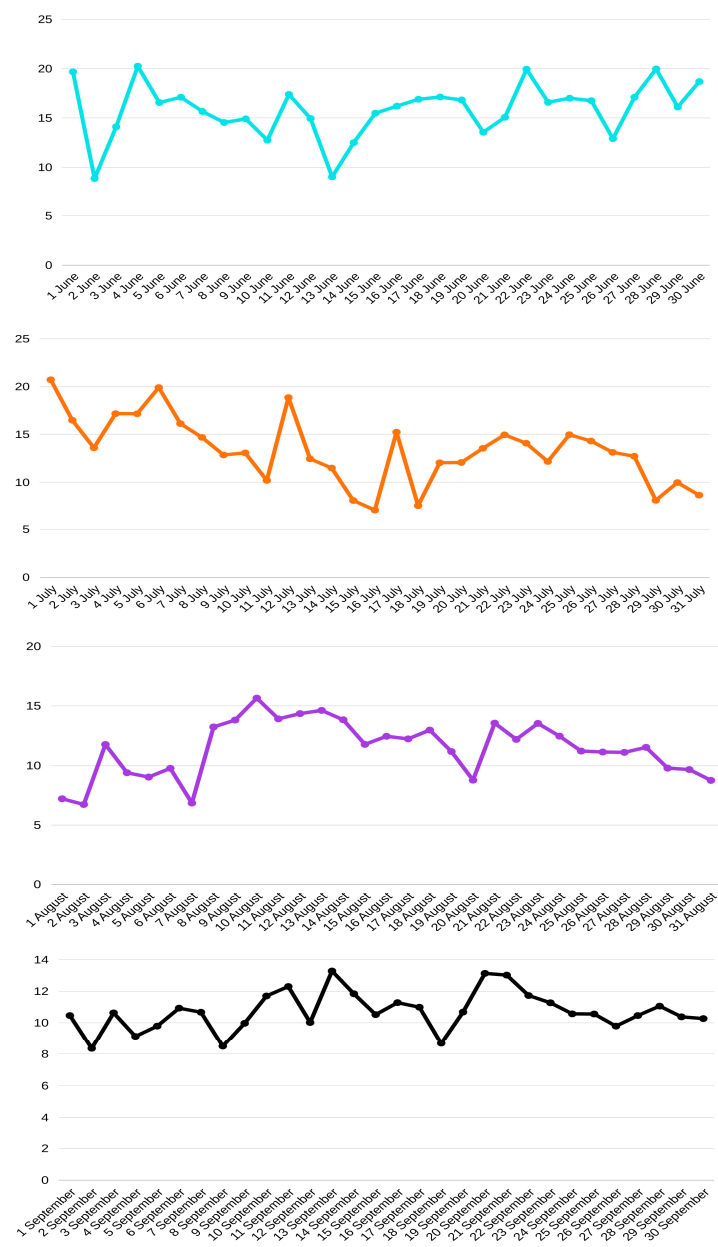


Figure 11. Solar Energy System Energy Production Graphs for June 2025, July 2025, August 2025, and September 2025.

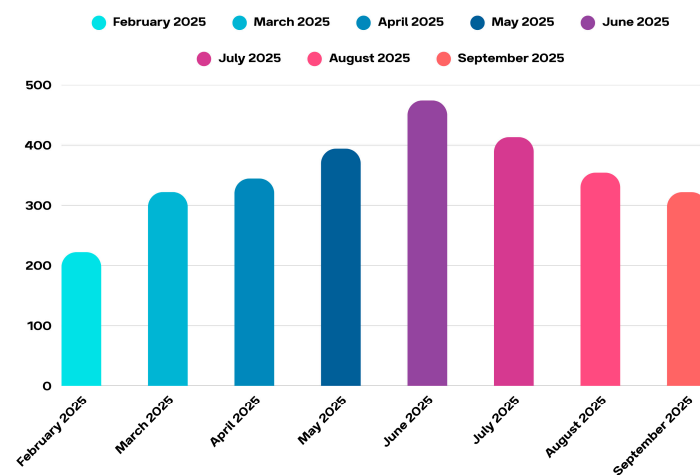


Figure 12. 2025 February–September Solar Power Plant Production Monthly Comparison (kWh).

3.2. PEM Electrolyzer Performance

The PEM electrolyzer was operated at a nominal capacity of 1.6–2.0 V per cell, producing an average of 3.6 L/h. While the experimental results closely match Faraday's theoretical law, there are small deviations attributed to Faraday efficiency loss ($\eta_F = 0.95\text{--}0.98$). The measured efficiency is based on laboratory-modified prototypes developed in the literature. Uncertainty analysis for oxygen flow measurements, primarily driven by current measurement and Faraday efficiency estimation, shows a confidence interval of $\pm 6\%$.

An additional limitation of battery-based storage systems is cycle aging and calendar degradation. Typical lithium-ion batteries used in stationary storage exhibit a cycle life of 3000–6000 full cycles, corresponding to approximately 8–12 years of operation under moderate depth-of-discharge conditions. Capacity fade and increased internal resistance gradually reduce usable energy and efficiency, leading to replacement costs over the system lifetime.

In contrast, hydrogen storage tanks exhibit minimal degradation over time, and electrolyzer and fuel cell stacks can be refurbished or replaced modularly without full system replacement. This characteristic makes hydrogen-based storage particularly attractive for long-term and high-throughput industrial energy applications where frequent cycling and large energy throughput accelerate battery aging.

Therefore, although batteries outperform hydrogen in short-term electrical efficiency, hydrogen systems offer superior lifetime scalability and durability for long-duration and high-energy industrial use cases.

3.3. PEM Fuel Cell Output

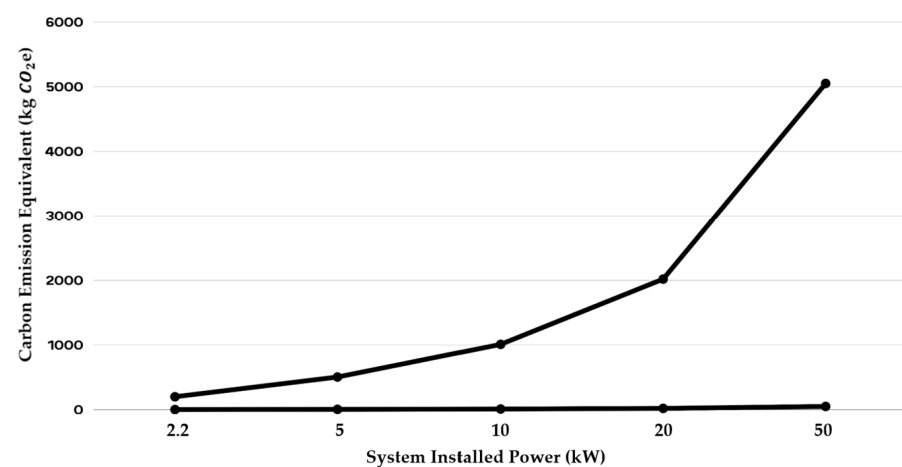
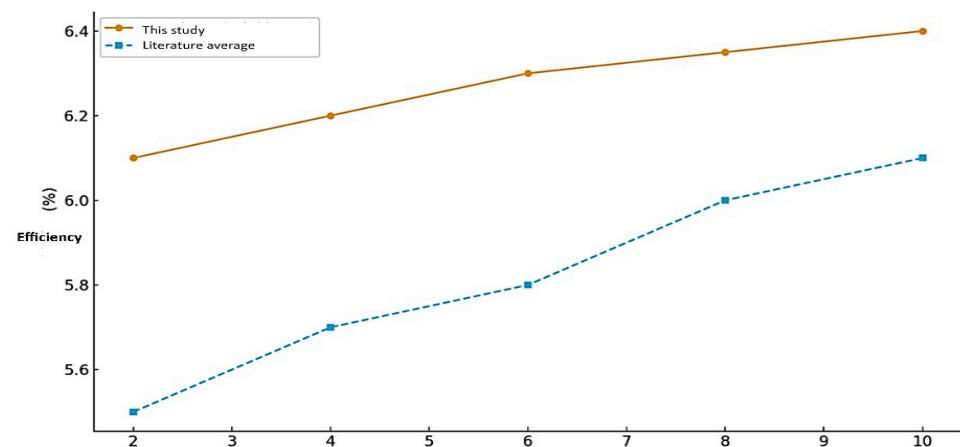
The portable PEM fuel cell provided continuous power in the range of 80–90 W by converting stored energy back into electricity. The measured fuel cell output is shown as a function of load current, highlighting a constant efficiency range of 25–35%. This performance level was successful for continuous energy production, thus expanding the scope of the full PV-H₂-EV. It summarizes the key performance indicators of the PEM fuel cell. The efficiency ratio was estimated to be $\pm 7\%$, which is the combined error in the expansion and power profiles. These results confirm the technical feasibility of using small-change PEM fuel options in micromobility demonstrations.

3.4. Carbon Reduction Potential

One of the key outcomes of the prototype demonstration was the impact of the aerodynamics. Based on a total PV production of 12 kWh per day averaged over 8 months of data collection, using a grid emission factor of 0.626 kg CO₂e/kWh, the avoided emissions were calculated as 7.37 kg CO₂e [45]. A Monte Carlo analysis ($n = 50,000$) was performed, encompassing both the energy and emissions uncertainty. Figure 11 shows the carbon emission comparison of monthly production by installed capacity, based on the resulting result, which shows a 95% confidence interval of 5–9.40 kg CO₂e. Figure 12 lists the dominant performance factors; tank pressure values (45%) and Faraday efficiency (30%) are the most influential, followed by the sewage emission factor uncertainty (15%). Table 9 provides a consolidated overview of the carbon reduction progress. Figure 13 presents a comparison of carbon emissions based on monthly production and installed capacity. Figure 14 presents a literature comparison of system efficiency.

Table 9. Consolidated overview of carbon reduction results.

Monthly	Production (kwh)	National Electricity Grid Emission Factor (tCO ₂ /MWh)	kg CO ₂ e
February 2025	222.25	0.626	139.13
March 2025	322.13	0.626	201.65
April 2025	344.66	0.626	215.75
May 2025	394.25	0.626	246.80
June 2025	474.41	0.626	296.98
July 2025	413.44	0.626	258.81
August 2025	354.39	0.626	221.85
September 2025	321.92	0.626	201.52

**Figure 13.** Carbon emission comparison of monthly production by installed capacity.**Figure 14.** System Efficiency Literature Comparison.

This similar, small performance demonstrates that the prototype achieves a sustainably significant carbon reduction, aligns with the European Green Deal targets, and strengthens its role in the performance of portable V-H₂-powered industrial decarbonization and micromobility.

The literature mean was obtained by summing the efficiency ranges reported from representative PV-PEM electrolyzer studies operating at similar power levels and partial load conditions, and serves as a benchmark rather than a single reference comparison. The

literature mean curve shown in Figure 14 represents the average efficiency values reported for PV–PEM electrolyzer systems under comparable operating conditions, obtained from previously published experimental and simulation-based studies [5,6,10–12,28].

3.5. Round-Trip Efficiency Breakdown and Comparison with PV–Battery Systems

The overall round-trip efficiency of the proposed PV → H₂ → electricity pathway was experimentally measured in the range of 5–15%, which is consistent with small-scale renewable hydrogen demonstration systems reported in the literature. To clarify the origin of this efficiency level, a stage-by-stage loss breakdown is provided in Table 10.

Table 10. Stage-wise efficiency breakdown of the PV–H₂–electricity pathway.

Stage	Typical Efficiency
PV module + tracking	18–22%
Inverter	92–95%
PEM Electrolyzer	65–75%
Hydrogen storage	97–99%
PEM Fuel Cell	30–40%
Overall round-trip	5–15%

The photovoltaic subsystem operates with a module efficiency of approximately 18–20%, while the single-axis tracking mechanism provides an effective energy gain of 15–20% compared with fixed-tilt installations. The DC–AC inverter operates at a measured efficiency of 92–95%. The PEM electrolyzer exhibits an electrical-to-hydrogen conversion efficiency of approximately 65–75% (LHV basis), mainly limited by overpotentials and auxiliary power consumption. Hydrogen storage losses at low pressure are relatively small (<3%) but include leakage, compression inefficiencies, and measurement uncertainty. The PEM fuel cell reconversion efficiency was experimentally observed in the range of 30–40%, depending on load.

When these stages are combined, the resulting round-trip efficiency becomes:

$$\eta_{\text{total}} \approx \eta_{\text{PV}} \times \eta_{\text{inverter}} \times \eta_{\text{electrolyzer}} \times \eta_{\text{storage}} \times \eta_{\text{fuel cell}} \quad (35)$$

which yields an effective range of approximately 5–15%, consistent with the experimental measurements.

For comparison, a conventional PV–battery–inverter system typically achieves a round-trip efficiency of 75–90%, mainly due to the high charge–discharge efficiency of lithium-ion batteries (90–95%) and reduced conversion stages. Similarly, direct PV utilization without storage can exceed 90% conversion efficiency under optimal operating conditions.

However, the objective of the present system is not to maximize short-term electrical efficiency but to demonstrate a flexible multi-energy carrier platform capable of supporting long-duration storage, sector coupling, and industrial heat decarbonization. Batteries are well suited for short-term electrical buffering (minutes to hours), whereas hydrogen enables seasonal or multi-day storage, direct substitution of natural gas for process heat, and scalable energy transport. Therefore, the lower electrical round-trip efficiency is offset by higher system-level flexibility, long-term storage capability, and applicability to thermal energy substitution in textile manufacturing.

This trade-off highlights that hydrogen-based systems should be evaluated not solely on electrical efficiency but on their ability to decarbonize multiple energy vectors simultaneously.

3.6. Sensitivity Analysis of Technology Choices

A qualitative sensitivity analysis was conducted to evaluate the influence of alternative technology choices on system efficiency, cost, and scalability. Three main subsystems were considered: photovoltaic technology, electrolyzer type, and fuel cell technology.

For the PV subsystem, monocrystalline silicon modules were selected due to their high commercial maturity, stable efficiency (18–22%), and favorable cost-to-performance ratio. Alternative technologies such as thin-film PV offer lower efficiency but improved temperature tolerance, while emerging tandem perovskite–silicon cells may exceed 28% efficiency but remain economically and operationally immature for industrial rooftops.

Regarding hydrogen production, PEM electrolyzers were selected for their fast dynamic response, compact footprint, and suitability for intermittent solar operation. Alkaline electrolyzers typically offer lower capital cost but slower ramp rates and reduced operational flexibility. Solid oxide electrolyzers can achieve higher electrical efficiency but require high-temperature operation, making them unsuitable for rooftop industrial deployment.

For electricity reconversion, PEM fuel cells provide rapid start-up, modularity, and compatibility with low-pressure hydrogen storage. Solid oxide fuel cells offer higher efficiency but require elevated operating temperatures and longer start-up times, limiting their suitability for portable or distributed applications.

Sensitivity analysis indicates that replacing the PEM electrolyzer with an alkaline unit could reduce capital cost by approximately 20–30% but at the expense of dynamic flexibility. Upgrading PV modules to next-generation tandem cells could theoretically improve system efficiency by 20–30% relative but currently introduces economic and reliability risks. Similarly, replacing PEM fuel cells with SOFC technology could increase electrical efficiency by 10–15% absolute but would significantly increase system complexity and safety constraints.

These results confirm that the selected technologies represent a balanced compromise between efficiency, safety, controllability, scalability, and real-world deployability for industrial rooftop applications.

4. Discussion

4.1. Scaling Analysis for Textile Manufacturing Applications

For PEM water electrolysis, the electrical energy required to produce 1 kg of hydrogen typically ranges between 48 and 52 kWh on a lower heating value basis, depending on system efficiency. In this study, an average value of approximately 50 kWh/kg H₂ is considered for scaling and energy balance analyses. Based on lower heating value (LHV) comparison, 1 m³ of natural gas (≈35.8 MJ) is energetically equivalent to approximately 0.30 kg of hydrogen. When typical boiler efficiencies are considered (≈90% for natural gas and ≈95% for hydrogen), the equivalent hydrogen requirement decreases slightly to about 0.28 kg to deliver the same useful thermal energy. Kivanç Textile factory consumes 1,735,000 m³ of natural gas per day under normal production conditions. Considering that 1 m³ of natural gas is equivalent to 0.28 kg of hydrogen, the annual thermal energy requirement of Kivanç Textile factory would be equal to 485,800 kg of hydrogen energy. Since 50 kWh of electrical energy is required for 1 kg of hydrogen, a 12,520 kWp PV system would be needed to produce 485,800 kg of hydrogen energy. Calculations were made based on the approximately 4271 kWh annual production of the installed 2.2 kW PV prototype system. Table 11 presents the estimated system scale for partial natural gas substitution at the Kivanç textile plant.

Table 11. Estimated system scale for partial natural gas substitution in a Kıvanç textile facility.

Substitution Ratio	NG Replaced (sm ³ /yıl)	H ₂ Required (≈kg H ₂ /year)	Electricity for Electrolysis (≈MWh/year)	Equivalent PV Capacity * (≈kWp)
1%	17,350.00	4858.00	242.90	125.21
10%	173,500.00	48,580.00	2429.00	1252.06
100%	1,735,000.00	485,800.00	24,290.00	12,520.62

* Calculations were made based on the approximately 4271 kWh annual production of the installed 2.2 kW PV prototype system.

4.2. Hydrogen-to-Heat Pathway and Natural Gas Substitution Analysis

We thank the reviewer for this insightful comment highlighting the need to clearly distinguish the intended end-use pathways of the proposed hydrogen energy system. The system presented in this study is deliberately designed as a hybrid multi-energy platform rather than a single-purpose energy conversion system. Its primary motivation is the gradual substitution of natural gas for industrial process heat in textile manufacturing, while simultaneously enabling electricity reconversion and electric vehicle (EV) charging as complementary energy services.

The experimental validation in the present work focuses on hydrogen-to-electricity reconversion and EV charging due to practical considerations related to measurement accuracy, operational safety, and controllability under laboratory and on-site pilot conditions. However, this does not imply that industrial heat applications are secondary or excluded. On the contrary, hydrogen-to-heat utilization represents the main long-term decarbonization pathway for textile processes such as drying, heating, and steam generation, which traditionally rely on natural gas-fired boilers.

To strengthen this claim, the revised manuscript includes a theoretical hydrogen-to-heat pathway based on hydrogen combustion in industrial boilers or burners. Typical efficiency values reported in the literature indicate that hydrogen-fired boilers can achieve thermal efficiencies comparable to or slightly higher than those of natural gas boilers (≈90–95%). From an environmental perspective, while natural gas combustion emits approximately 56 kg CO₂ per GJ of useful heat, green hydrogen combustion produces zero direct CO₂ emissions, thereby enabling complete decarbonization of process heat when renewable hydrogen is used.

By incorporating this theoretical analysis, the study clarifies that the proposed PV–PEM hydrogen system is intended to function as a multi-energy industrial hub, where hydrogen acts as a flexible energy carrier linking renewable electricity generation with industrial heat supply, on-site power generation, and EV charging. This hybrid configuration enhances system versatility and industrial relevance, particularly in energy-intensive textile manufacturing facilities undergoing gradual energy transition.

- Useful Heat Demand and Boiler Output

Textile processes (e.g., drying, heating, and steam generation) are primarily driven by useful thermal energy demand Q_{use} (kWh_{th} or MJ). For a boiler/burner system, the relationship between fuel input energy and useful heat output is:

$$Q_{\text{use}} = \eta_{\text{boiler}} E_{\text{fuel,in}} \quad (36)$$

where η_{boiler} is the thermal efficiency of the boiler (dimensionless).

- Fuel Energy Input Based on LHV

Fuel input energy is expressed using the Lower Heating Value (LHV):

Hydrogen (mass basis):

$$E_{H_2,in} = m_{H_2} \text{LHV}_{H_2} \quad (37)$$

Natural gas (volume or mass basis). Using volume at standard conditions:

$$E_{NG,in} = V_{NG} \text{LHV}_{NG,vol} \quad (38)$$

Typical values used in this study (LHV basis):

$$\text{LHV}_{H_2} \approx 33.33 \text{ kWh/kg (120 MJ/kg)} \quad (39)$$

$$\text{LHV}_{NG,vol} \approx 9.94 \text{ kWh/m}^3 \left(\approx 35.8 \text{ MJ/m}^3 \right) \quad (40)$$

- Hydrogen Required to Deliver a Target Useful Heat Output

For a target useful heat requirement Q_{use} , the required hydrogen mass is:

$$m_{H_2,req} = \frac{Q_{use}}{\eta_{boiler,H_2} \text{LHV}_{H_2}} \quad (41)$$

Similarly, the equivalent natural gas volume is:

$$V_{NG,eq} = \frac{Q_{use}}{\eta_{boiler,NG} \text{LHV}_{NG,vol}} \quad (42)$$

- Direct equivalence:

$$m_{H_2,eq} = V_{NG} \frac{\eta_{boiler,NG} \text{LHV}_{NG,vol}}{\eta_{boiler,H_2} \text{LHV}_{H_2}} \quad (43)$$

If you assume representative boiler efficiencies:

$$\eta_{boiler,NG} = 0.90, \eta_{boiler,H_2} = 0.95 \quad (44)$$

then:

$$m_{H_2,eq} \approx V_{NG} \times \frac{0.90 \times 9.94}{0.95 \times 33.33} \approx V_{NG} \times 0.282 \text{ kg/m}^3 \quad (45)$$

Result:

$$1 \text{ m}^3 \text{ NG} \approx 0.28 \text{ kg H}_2 \text{ (same useful heat, with efficiencies)} \quad (46)$$

- CO₂ Emission Comparison and Avoided Emissions**

Useful heat direct CO₂ emission comparison per unit:

$$\text{CO}_{2NG} = \frac{Q_{use}}{\eta_{boiler,NG}} \times EF_{NG} \quad (47)$$

$$\text{CO}_{2H_2} \approx 0 \text{ (green H}_2\text{, direct combustion)} \quad (48)$$

where EF_{NG} is the CO₂ emission factor of natural gas on an input-energy basis (typical value):

$$EF_{NG} \approx 56 \text{ kg CO}_2/\text{GJ} \quad (49)$$

Thus, avoided emissions become:

$$\text{CO}_{2\text{avoided}} \approx \text{CO}_{2NG} \quad (50)$$

- Applying the Framework to the Prototype (Your System)

Your electrolyzer capacity is 3.6 L/h H₂. At standard conditions:

$$3.6 \text{ L/h} = 0.0036 \text{ m}^3/\text{h} \quad (51)$$

Hydrogen mass flow:

$$\dot{m}_{\text{H}_2} = 0.0036 \times 0.0899 \approx 3.24 \times 10^{-4} \text{ kg/h} \quad (52)$$

Hydrogen chemical energy (LHV) per hour:

$$E_{\text{H}_2} = \dot{m}_{\text{H}_2} \times 33.33 \approx 0.0108 \text{ kWh/h} \quad (53)$$

Useful heat via hydrogen boiler:

$$Q_{\text{use,H}_2} = \eta_{\text{boiler,H}_2} E_{\text{H}_2} \approx 0.95 \times 0.0108 \approx 0.0103 \text{ kWh}_{\text{th}}/\text{h} \quad (54)$$

Equivalent natural gas volume displaced per hour:

$$V_{\text{NG,displaced}} = \frac{Q_{\text{use,H}_2}}{\eta_{\text{boiler,NG}} \text{LHV}_{\text{NG,vol}}} = \frac{0.0103}{0.90 \times 9.94} \approx 0.00115 \text{ m}^3/\text{h} \quad (55)$$

- Prototype-based displacement (theoretical):

$$V_{\text{NG,displaced}} \approx 1.15 \text{ L NG/h} \quad (56)$$

To complement the experimentally validated hydrogen-to-electricity and EV charging pathway, a theoretical hydrogen-to-heat pathway was assessed to quantify the natural gas substitution potential for textile process heat. Using LHV-based energy equivalence and representative boiler efficiencies, the hydrogen produced by the prototype can be directly utilized in a hydrogen-fired boiler to deliver useful thermal energy for industrial heating or steam generation. The corresponding displaced natural gas volume and avoided CO₂ emissions were calculated to provide a consistent comparison with conventional natural-gas-based heat supply.

4.3. Preliminary Techno-Economic Considerations

Although the primary focus of this study is the experimental validation of a rooftop PV-PEM hydrogen energy system, a preliminary techno-economic assessment is provided to contextualize the proposed approach from an industrial perspective. This assessment is intended as an indicative, forward-looking analysis rather than a full techno-economic optimization, aiming to support early-stage decision-making for industrial decarbonization pathways.

- Electricity Demand and Hydrogen Production Cost Basis

Based on the experimental system and scaling analysis, the electrical energy required for hydrogen production via PEM electrolysis is assumed to be approximately 50 kWh per kg of H₂ on an LHV basis, consistent with values reported in the literature.

Assuming an average industrial electricity price in Kıvanç Tekstil and in Türkiye of 0.8–0.10 USD/kWh, the electricity cost component of hydrogen production can be estimated as:

$$C_{\text{el,H}_2} = 50 \times c_{\text{el}} \quad (57)$$

4.0 USD/kg H₂ (at 0.8 USD/kWh)

5.0 USD/kg H₂ (at 0.10 USD/kWh)

This result highlights that electricity cost dominates the operational expenditure (OPEX) of electrolytic hydrogen production, reinforcing the importance of on-site photovoltaic generation to mitigate exposure to grid electricity prices.

- **Indicative CAPEX of the PV–PEM Hydrogen System**

Indicative capital cost ranges for key system components, based on recent market data and literature, are summarized in Table 12. These values represent typical orders of magnitude rather than site-specific quotations.

Table 12. Indicative capital expenditure (CAPEX) assumptions.

Component	Typical Cost Range
Photovoltaic system (2.2 kw system)	\$600.00
PEM electrolyzer (3.6 L/h)	\$1750.00
Hydrogen storage (18 L)	\$1500.00
Fuel cell system (100 W)	\$3500.00
Solar tracking system (metal components and automation system)	\$1000.00

Using these ranges, the specific capital intensity of small-scale PV–PEM hydrogen systems remains higher than that of conventional fossil-based energy systems. However, the modular nature of the proposed architecture allows incremental deployment and gradual cost reduction through learning effects and economies of scale.

- **Comparison with Natural Gas for Process Heat**

From a thermal energy perspective, 1 kg of hydrogen provides approximately 33.3 kWh_{th} (LHV basis), equivalent to roughly 3.3 m³ of natural gas when boiler efficiencies are considered. Using typical industrial natural gas prices in Türkiye (≈0.35–0.40 USD/m³), the corresponding thermal energy cost of natural gas is approximately: 0.10–0.12 USD/kWh_{th}.

In contrast, hydrogen produced using grid electricity at current prices yields a thermal energy cost exceeding 0.12–0.15 USD/kWh_{th}, indicating that green hydrogen is not yet cost-competitive with natural gas for industrial heat under present market conditions. Nevertheless, when on-site PV electricity is utilized, the marginal electricity cost approaches zero, significantly improving the long-term economic outlook of the proposed system.

- **Role of the Proposed System under Future Decarbonization Scenarios**

While the present analysis confirms that green hydrogen remains economically challenging at small scale, the proposed system is not intended to compete directly with natural gas on short-term cost grounds. Instead, it should be interpreted as a strategic decarbonization asset offering:

- reduced exposure to fossil fuel price volatility,
- compliance with future carbon pricing and emission regulations,
- enhanced energy security through on-site renewable generation, and
- a flexible platform enabling industrial heat, electricity supply, and EV charging.

Accordingly, the techno-economic value of the proposed PV–PEM hydrogen system is expected to increase under scenarios of declining electrolyzer costs, rising carbon prices, and continued reductions in photovoltaic system costs.

4.4. System Performance Analysis

The performance of the proposed PV–PEM hydrogen prototype is consistent with values reported in the current literature and also addresses several identified research gaps.

- **PV-Electrolyzer Integration:** Previous simulation-based studies (e.g., [5,8,12]) have demonstrated the technical feasibility of combining PV arrays with electrolyzers but lacked experimental validation under real-world operating conditions. In this study, the prototype was installed and monitored on an industrial rooftop and provided empirical data confirming theoretical predictions.
- **Hydrogen Production Rates:** Laboratory-scale experiments, such as those conducted by [6,13], reported overall system efficiencies of 10–20% and hydrogen flow rates of 3–5 L/h. The output of 3.6 L/h we measured at 1.6–2.0 V per cell falls within this range, but also has the additional innovation of long-term outdoor operation and integration into a complete solar-hydrogen-electric cycle.
- **Fuel Cell Use:** Previous demonstrations of portable hydrogen systems (e.g., [7,33]) have generally emphasized educational or pilot-scale applications without industrial end-use. In contrast, the current system has successfully powered a micro-electric vehicle (Citroën AMI), thus extending its applicability to micromobility and offering direct user-focused benefits.
- **Carbon Reduction:** Several reviews (e.g., [14,19,41]) have highlighted the decarbonization potential of hydrogen technologies but have not presented quantitative small-scale case studies. Our analysis demonstrates a reduction of 7.3 ± 1.1 kg CO₂e per day, providing concrete evidence of environmental impact rarely quantified in portable prototype reports.
- **Uncertainty Analysis:** While most previous studies primarily reported average efficiencies and yields, this study applied a rigorous uncertainty assessment (GUM + Monte Carlo) to generate confidence intervals for key performance indicators. This methodological contribution increases the reliability and comparability of the reported data.

Overall, this study bridges the gap between simulation studies and industrial-scale validation, presents micromobility integration as a novel application, and sets a precedent for incorporating uncertainty measurement into small-scale hydrogen prototype studies.

5. Conclusions

- ✓ This study presents the first industrial rooftop demonstration of a modular photovoltaic–proton exchange membrane (PV–PEM) hydrogen energy system specifically deployed within a textile manufacturing facility, addressing a critical gap between laboratory-scale hydrogen research and real-world industrial applications. Unlike the majority of existing studies that rely on simulations, conceptual analyses, or controlled laboratory experiments, the proposed system was fully designed, installed, commissioned, and experimentally validated under actual industrial operating conditions. In doing so, the study demonstrates a complete and functional solar-to-hydrogen-to-electricity energy conversion pathway, highlighting the practical feasibility of decentralized green hydrogen production in energy-intensive industrial environments.
- ✓ Experimental investigations confirmed stable and reliable system operation across all subsystems. The rooftop PV array generated between 8 and 15 kWh of electricity per day, while the PEM electrolyzer achieved an average hydrogen production rate of approximately 3.6 L/h per cell under real-time operating conditions. The stored hydrogen was successfully reconverted into electricity through a PEM fuel cell, delivering a continuous power output of 80–90 W, corresponding to an overall round-trip efficiency in the range of 5–15%, which is consistent with small-scale, multi-conversion hydrogen systems. Importantly, hydrogen storage performance closely matched theoretical expectations, demonstrating predictable system behavior and validating the underlying design assumptions.

- ✓ A distinctive and innovative contribution of this work lies in the rigorous quantification of system performance uncertainty and carbon mitigation potential. By applying both GUM-compliant uncertainty propagation and Monte Carlo simulation, the study provides statistically robust performance indicators rarely reported in experimental hydrogen energy studies. The system achieved an average carbon emission reduction of approximately 222 kg CO₂e per month, with an expanded uncertainty of $\pm 13.5\%$, confirming that even small-scale rooftop hydrogen systems can deliver measurable and statistically significant environmental benefits. Scenario-based scaling analysis further revealed that increasing photovoltaic capacity could substantially enhance emission reduction potential, reinforcing the role of the prototype as a modular building block rather than a standalone solution.
- ✓ Beyond electricity reconversion and micromobility applications, the study explicitly demonstrates—through a theoretically grounded and quantitatively consistent framework—that the produced hydrogen can be directly utilized as a substitute for natural gas in textile process heat applications. Based on lower heating value equivalence and representative boiler efficiencies, approximately 0.28–0.30 kg of hydrogen is required to replace 1 m³ of natural gas, enabling direct elimination of combustion-related CO₂ emissions. The proposed modular architecture allows for gradual substitution levels (e.g., 1–10%), facilitating progressive decarbonization of textile processes such as drying, heating, and steam generation without the need for immediate, large-scale infrastructure replacement.
- ✓ Overall, the modular and scalable system architecture introduced in this study provides a transferable multi-energy framework integrating renewable electricity generation, hydrogen production and storage, hydrogen-based heat supply, on-site electricity generation, and electric vehicle charging. By combining experimental validation with a supporting simulation framework for design extrapolation, this work offers a practical and innovative pathway for integrating green hydrogen into existing industrial energy infrastructures. The findings demonstrate that rooftop PV–PEM hydrogen systems can play a meaningful role in reducing natural gas dependency, lowering carbon emissions, and supporting the transition toward low-carbon, flexible, and resilient energy systems in the textile sector and other energy-intensive industrial domains.

Author Contributions: Conceptualization, H.A., B.Ç. and T.D.; methodology, H.A.; software, H.A.; validation, H.A. and T.D.; formal analysis, H.A. and B.Ç.; investigation, H.A.; resources, H.A. and T.D.; data curation, H.A.; writing—original draft preparation, H.A. and B.Ç.; writing—review and editing, H.A., B.Ç. and T.D.; visualization, H.A.; supervision, T.D.; project administration, H.A., B.Ç. and T.D.; funding acquisition, B.Ç. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the Kivanç Textile Industry and Commerce Incorporated Company Research and Developing Center Project Number: KTM-25-082. This research was funded by the Scientific Research Project Unit of Adana Alparslan Türkeş Science and Technology University under the project number 23803002.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Acknowledgments: The authors would like to acknowledge the Kıvanç Textile R&D Center for full financial support and the data process. The authors would also like to Kıvanç Textile Industry and Commerce Incorporated Company due to its contribution.

Conflicts of Interest: Authors Büşra Çeltikçi and Hakan Alici are employed by the Kıvanç Textile Industry and Commerce Incorporated Company. The authors declare that this study received funding from the Kıvanç Textile Industry and Commerce Incorporated Company Research and Developing Center. The funder had the following involvement with the study: financial support and the data process. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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