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Decentralized Green Hydrogen Energy Systems: Optimizing 5kW Electrolyzer-Fuel Cell Integration with Metal Hydride Storage for Off-Grid Homes

Abraheem Abraheem [1 *], Abdulgader Alsharif [2], Abdussalam Ali Ahmed [3]
[1] Department of Electrical and Smart Systems Engineering, University of South Africa, Pretoria, South Africa
[2] Department of Electric and Electronic Engineering, College of Technical Sciences Sabha, Sabha, Libya
[3] Department of Mechanical and industrial Engineering, Bani Waleed University, Bani Walid, Libya

أنظمة طاقة الهيدروجين الخضراء اللامركزية: تحسين تكامل خلية الوقود مع محلل كهربائي بقدرة 5 كيلوواط مع تخزين هيدريد معدني للمنازل غير المتصلة بالشبكة

إبراهيم إبراهيم[1*]، عبدالقادر الشريف[2]، عبدالسلام علي أحمد [3]
[1] قسم الهندسة الكهربائية وهندسة الأنظمة الذكية، جامعة جنوب أفريقيا، بريتوريا، جنوب أفريقيا
[2] قسم الهندسة الكهربائية والإلكترونية، كلية العلوم التقنية سبها، سبها، ليبيا
[3] قسم الهندسة الميكانيكية والصناعية، جامعة بني وليد، بني وليد، ليبيا

*Corresponding author: 26714558@mylife.unisa.ac.za

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Abstract:
This paper presents the design and computational analysis of a decentralized green-hydrogen energy system that was designed to be used in off-grid residential setups in the southern region of Libya. The suggested architecture includes a 2kW photovoltaic array, a 5kW proton-exchange membrane (PEM) electrolyzer, metal-hydride hydrogen storage, and a 1kW PEM fuel cell that will be integrated under an Energy Management System (EMS). The results of simulation done in MATLAB/Simulink supports the robust operation of the system with autonomy horizon of 24-36 hours, load coverage of more than 95% and a round-trip electrical efficiency of between 27 to 32 % (lower heating value) at different levels of solar irradiance. The safety tests prove that the triggering of hydrogen-leak detection and mitigation systems is completed within 3s, hence meeting the ISO requirements outlined in ISO 14687. Techno-economic studies provide a cost of electricity that is levelized at USD 0.25-0.30/kWh, making the offered solution quite competitive with respect to the traditional diesel generation. Together the findings support the feasibility of the hydrogen-based microgrids as a solid, clean energy source to support rural households in Libya, and thus contributing to the further implementation of Sustainable Development Goal 7.

Keywords: Decentralized energy; Green hydrogen; PEM electrolyzer; PEM fuel cell; Metal hydride storage; Off-grid households; North Africa; Libya; Energy management system (EMS); Rural electrification; Renewable energy system

الملخص
تقدم هذه الورقة البحثية تصميمًا وتحليلًا حسابيًا لنظام طاقة لامركزي يعمل بالهيدروجين الأخضر، مصمم للاستخدام في المنازل غير المتصلة بشبكة الكهرباء في جنوب ليبيا. يتضمن التصميم المقترح مصفوفة كهروضوئية بقدرة 2 كيلوواط، ومحللًا كهربائيًا غشائيًا لتبادل البروتونات (PEM) بقدرة 5 كيلوواط، ووحدة تخزين هيدروجين من هيدريد المعادن، وخلية وقود PEM بقدرة 1 كيلوواط، سيتم دمجها ضمن نظام إدارة الطاقة (EMS). تدعم نتائج المحاكاة التي أُجريت باستخدام برنامج MATLAB/Simulink التشغيل الموثوق للنظام، مع فترة تشغيل مستقلة تتراوح بين 24 و36 ساعة، وتغطية للأحمال تتجاوز 95%، وكفاءة كهربائية ذهابًا وإيابًا تتراوح بين 27 و32% (القيمة الحرارية الصغرى) عند مستويات مختلفة من الإشعاع الشمسي. أثبتت اختبارات السلامة أن تفعيل أنظمة الكشف عن تسرب الهيدروجين والحد منه يتم في غضون 3 ثوانٍ، ما يفي بمتطلبات المنظمة الدولية للمقاييس (ISO) الموضحة في معيار ISO 14687. وتشير الدراسات التقنية والاقتصادية إلى أن تكلفة الكهرباء تتراوح بين 0.25 و0.30 دولار أمريكي/كيلوواط ساعة، مما يجعل الحل المقترح منافسًا قويًا لتوليد الطاقة بالديزل التقليدي. وتؤكد هذه النتائج مجتمعةً جدوى الشبكات الصغيرة القائمة على الهيدروجين كمصدر طاقة نظيف وموثوق لدعم الأسر الريفية في ليبيا، وبالتالي المساهمة في تحقيق الهدف السابع من أهداف التنمية المستدامة.

الكلمات المفتاحية: الطاقة اللامركزية؛ الهيدروجين الأخضر؛ محلل كهربائي ذو غشاء تبادل البروتونات؛ خلية وقود ذات غشاء تبادل البروتونات ؛ تخزين هيدريد المعادن؛ الأسر غير المتصلة بالشبكة؛ شمال أفريقيا؛ ليبيا؛ نظام إدارة الطاقة؛ كهربة الريف؛ نظام الطاقة المتجددة.

1. Introduction

The reliability of electricity supply is a big problem in many rural and semi-arid areas of North Africa, and Libya is a striking example because of the frequent gridcuts and fuel shortages disrupting domestic energy security. The extension of the transmission infrastructure to remote areas is economically unsustainable and harmful to the environment, and the use of diesel generators is costly in terms of operation, high emission of greenhouse gases, and noise[1]. Another alternative is battery-only configurations, which are cleaner, but become significantly less cost-efficient and less efficient when it comes to supporting autonomy longer than a single day[2].

The strong solar irradiance in Libya, with an average of 6-7 kWh/m²/day-inverting, is a promising base of distributed renewable-energy applications. Practically, most of the solar projects in the area are to be of large scale, grid-based designs, thus placing rural households at the mercy of an unreliable supply. One of the long-term remedies to this shortcoming is the emergence of the decentralised hydrogen-based energy systems. Such systems can ensure permanent uninterrupted operation by converting excess photovoltaic (PV) output to hydrogen via electrolysis, storing the resultant gas in metal-hydride tanks and then converting it back to electricity using a fuel cell[3], [4].

The current study focuses on the development and modeling of a 5-kW decentralised green-hydrogen energy system to be deployed in off-grid homes in the city of Sabha, Libya in the south. The architecture uses a PV array, proton-exchange-membrane (PEM) electrolyzer, metal-hydride hydrogen storage, and a PEM fuel cell, coordinated by a supervisory energy-management system (EMS). Autonomy, reliability, power quality, safety compliance, and indicative cost measurements of the system were evaluated using MATLAB/Simulink simulations [5], [6].

The suggested layout is in accordance with Sustainable Development Goal 7 (Affordable and Clean Energy) because it integrates self-reliant, low-carbon electrification of under-serviced areas by national grids. Empirically, studies have shown that hydrogen energy storage technology has the potential to provide 24-36 hours of autonomy, 27-32% round-trip efficiencies, and meet power-quality and power-safety standards of residential power sources entirely[7], [8].

2. Methodology

A. System Architecture

The suggested off-grid hydrogen energy system includes four major subsystems that include a photovoltaic (PV) array, a proton-exchange-membrane (PEM) electrolyzer, metal-hydride (MH) hydrogen storage tanks, and a PEM fuel cell, which are managed by a supervisory Energy Management System (EMS).

The PV array provides direct PV power to household loads during daylight, and excess power is sent to the electrolyzer to produce hydrogen gas. Hydrogen is absorbed by the MH tanks at medium temperature and pressure (= 45 °C, 10 bar). To maintain continuity of supply, at night or under cloudy conditions, there is a reversion of stored hydrogen into electricity through an electrochemical reaction by the fuel cell, ensuring continuity.

The nominal system was set to suit an average rural Libyan household with 9kWh day consumption. A 2kW PV array will provide DC via a DC bus; a 5kW PEM will produce hydrogen at 10 bars; MH storage will have 4-6 kg H 2 (48-72 kWh LHV); and a 1 kW PEM fuel cell will supply the AC power via an inverter and EMS controller.

The EMS will also handle charging and discharging, prioritization of critical loads, and safety of the system in case of fault conditions.

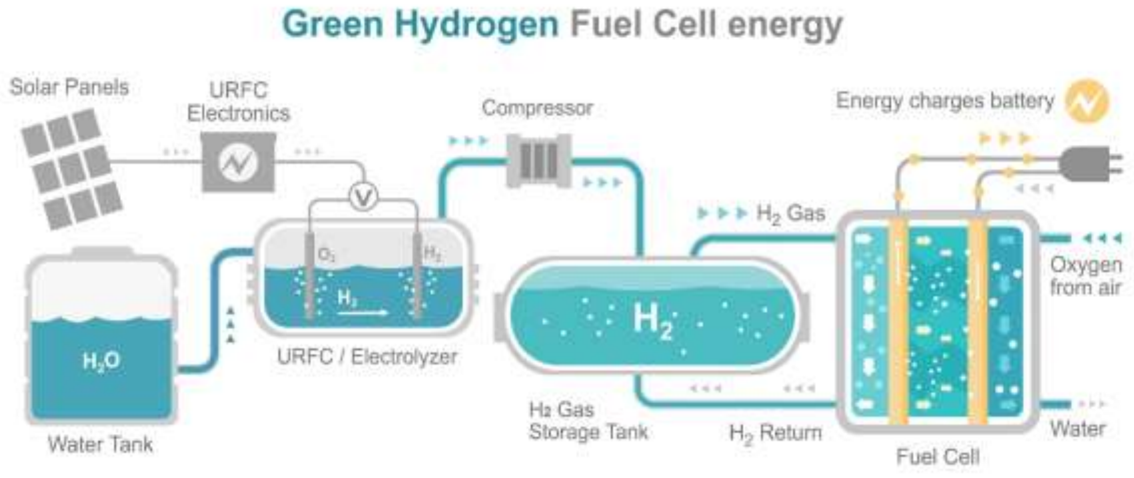

Figure 1: Green Hydrogen Fuel Cell Energy [11].

B. **Modeling and Simulation**

A detailed MATLAB/Simulink model was developed that modeled the power flows, component dynamics, and EMS logic. Standard physical parameters: The subsystems were simulated with standard physical parameters:

- PV array was modeled at an average irradiance of 6-7kWh/m²/day;
- Efficiency of electrolyzer was taken as 70% (LHV);
- Fuel cell efficiency at 45–50 %;
- Converter and inverter efficiency of 92%.

A 72-hour period was used in the simulation of the model and the time step was set to one second, which allowed studying both transient and steady states. The EMS ensured the hydrogen state of charge was not over pressured (above 20% and below 95%) and the stability of the voltage and frequency on the AC bus.

C. **Test Scenarios**

Three types of simulating were carried out:

- Baseline (Sunny Day) - nominal load (1000W/m²) with daily change of load;
- Stress Tests - irradiance (-40%) and 48 hours PV blackout to evaluate resilience and autonomy;
- Safety Test - simulated leak of hydrogen (0.8 vol %) to confirm emergency response and isolation rationality.

The performance measures included the duration of autonomy, the variation of the state of charge, round trip efficiency, AC power quality, and compliance with the IEC 61000-3-3, and the IEEE 1547 residential standard.

3. Results and Discussion

A. Baseline Operation (Sunny Day)

The system could supply some 9 kWh/day of the demand of an average household under normal Libyan solar irradiances of 6 to 7 kWh/m ² -day. Figure 2 shows the relationship between photovoltaic generation and load profile with respect to time. The peak capacity of the photovoltaic array was 1.6 kW near midday at the sun, which is larger than the midday load; an evening load was greatest around 19:00, at 0.89 kW. The excess of power produced during daylight hours was diverted to an electrolyzer thus helping to produce hydrogen and charge metal-hydride storage vessels progressively [9].

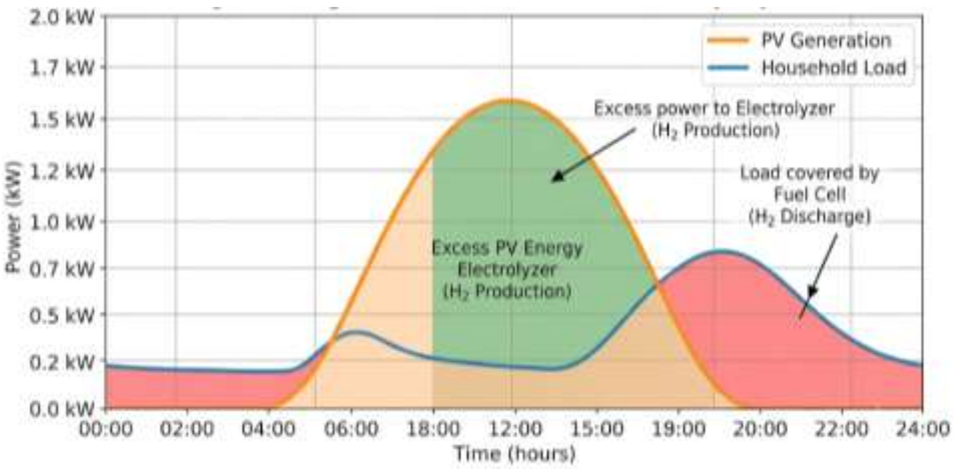

Figure 2: PV generation vs household load (sunny day).

The state-of-charge (SoC) curve of the hydrogen storage is shown in Figure 3. The amount of hydrogen also rose linearly during daytime and fell during the night as the fuel cell supplied electricity. The SoC varied between 3.09 kg in the late afternoon and 2.82 kg the next morning, thus confirming the energy balance and relative autonomy of about 24 hours. Voltage and frequency were held within ±10% and ±1 Hz of nominal values, respectively.

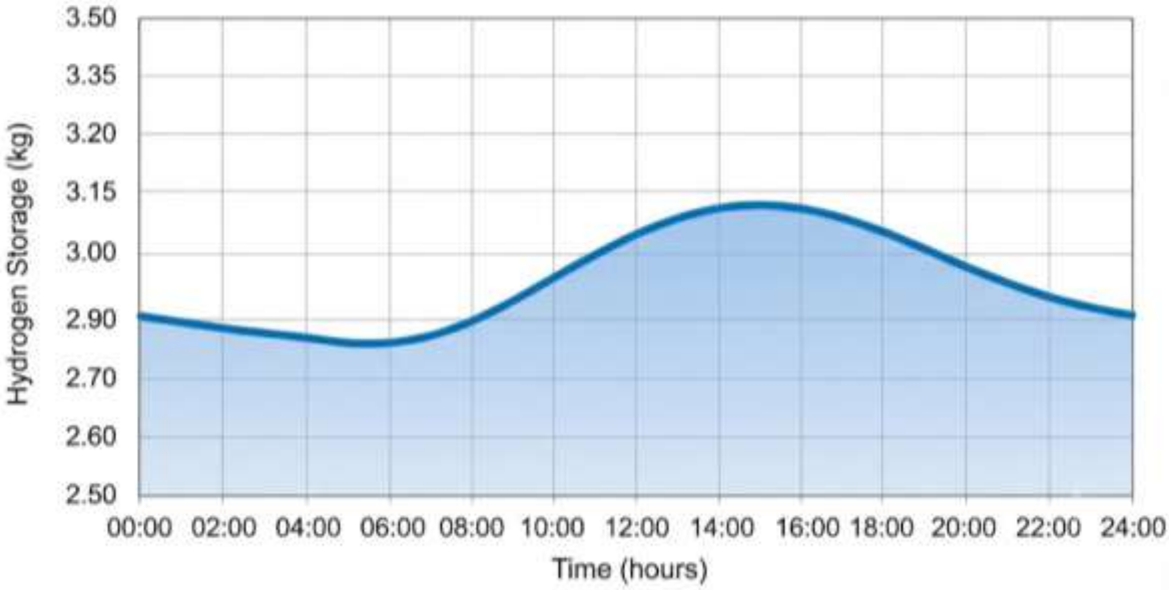

Figure 3: (Hydrogen storage state-of-charge, sunny day)

B. Stress-Test Scenarios

1. Reduced-Irradiance Case (−40 %)

As the amount of solar input was reduced by 40% as shown in Figure 4, photovoltaic power reduced to about 0.96 kW, which limited the electrolyzer power to 0.6 kW. The discharge of the fuel-cell was adjusted to maintain supply and the system continued to cover 97.6% of the critical load. Mass of hydrogen decreased by the rate of less than 10% (2.75 kg to 3.05 kg), which revealed a strong resilience.

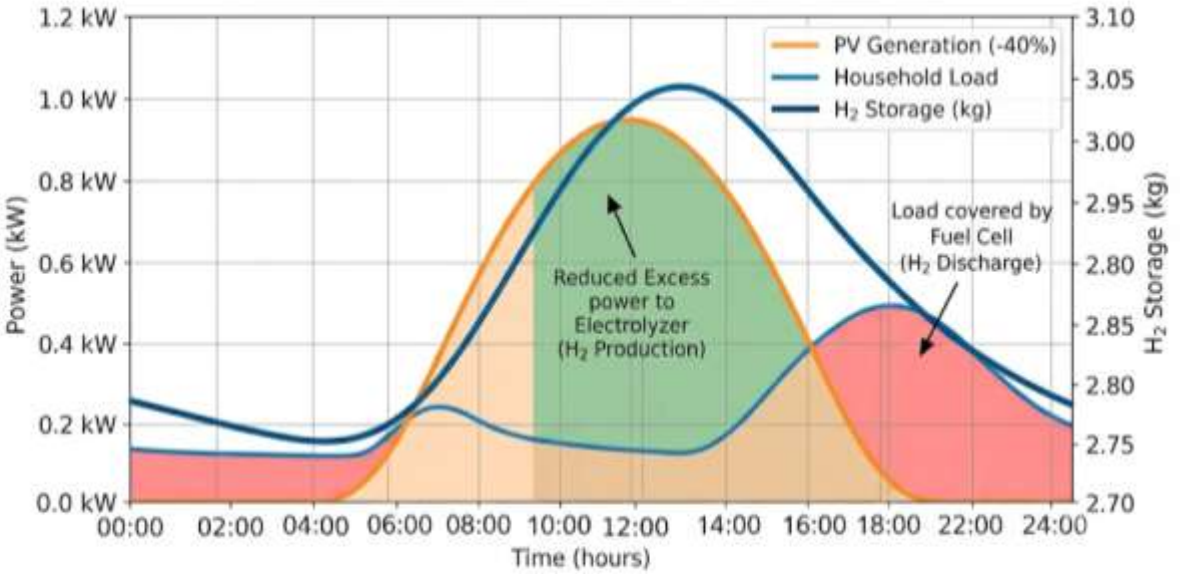

Figure 4: H_2 SoC and power flows (−40% irradiance)

2. Evening-Load Spike

The momentarily increased power load of 1.2 kW at 19:00 only resulted in a short (< 1 s) The temporary increase in the power load by 1.2 kW at 19:00 only resulted in a temporary voltage decrease 7% and frequency change 0.3 Hz which was still within the residential range and therefore, justified the functionality of the inverter and energy-management system. Additionally, the breakdown of load, power, and frequency are presented in Figure 5.

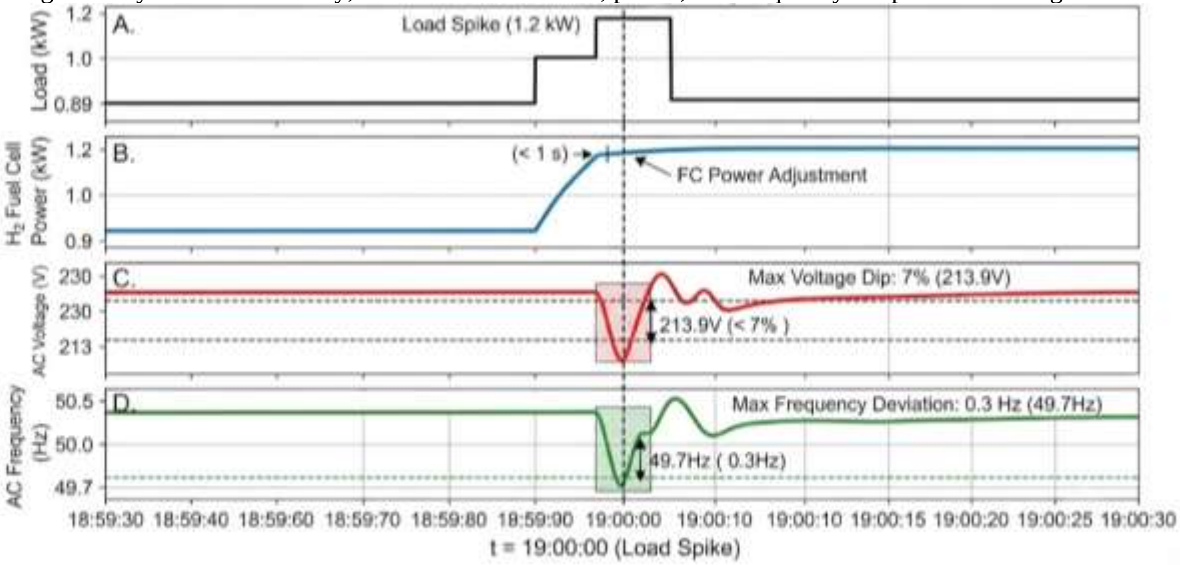

Figure 5: Breakdown of load, power, and frequency. (A) Load Spike, (B). FC Power Adjustment ,(C). maximum voltage Dip, (D). Maximum frequency deviation.

3. Prolonged PV-Outage (48 h)

In simulated sandstorms, the system was used to provide 0.375 kW of critical load at a time, which lasted about 30-36 hours before the state of charge dropped to 0.8kg, and coverage was at least 95% within the first day, and about 55% after 48 hours for the Power and State of charge status are shown in Figure 6.

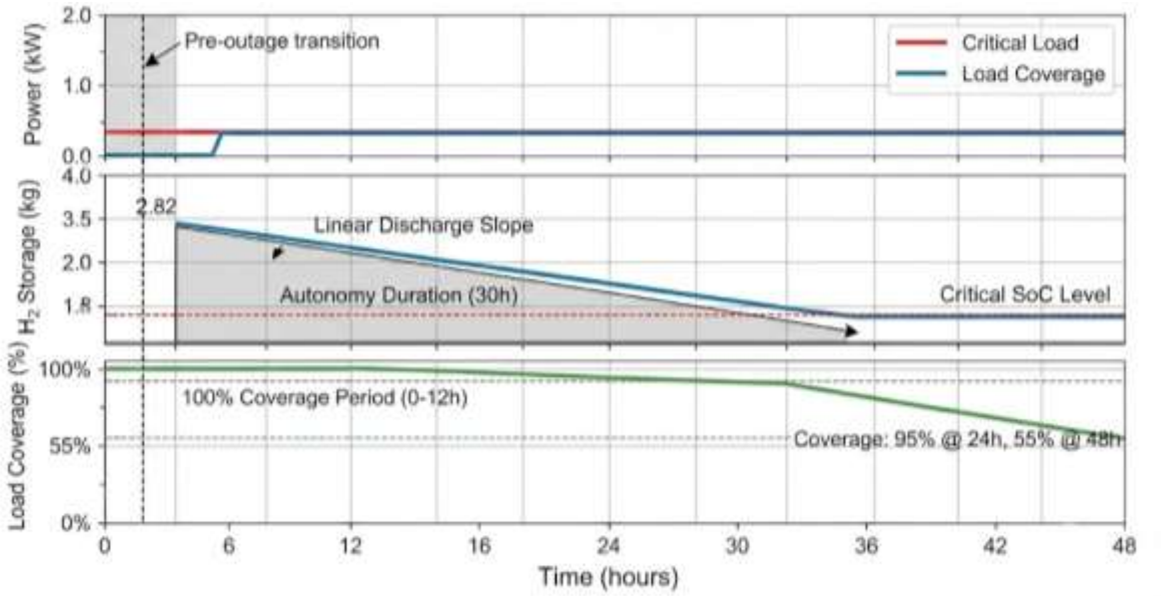

Figure 6: Power and State of charge status

4. Hydrogen-Leak Safety Test

At higher concentrations of hydrogen (above 0.8 vol %), the energy-management system opened the ventilation in 2 s and isolation in 3 s, which returned the system to normal operation when the concentration was less than 0.2 vol %, thus, proving that it met the ISO14687 safety standards. The Leak Response: (A) H2 Concentration, (B) Binary, (C) Safety System (Binary), (D) Safety System response. are demonstrated in Figure 7. While the Leak response: ventilation & isolation timing are demonstrated in Figure 8.

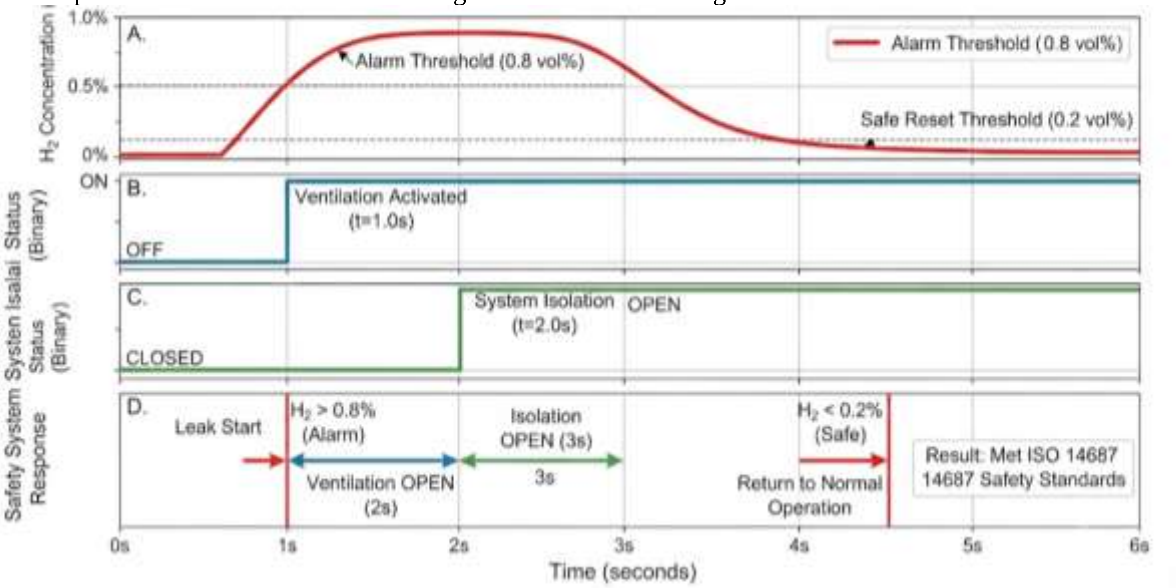

Figure 7: Leak Response: (A) H2 Concentration, (B) Binary, (C) Safety System (Binary), (D) Safety System response.

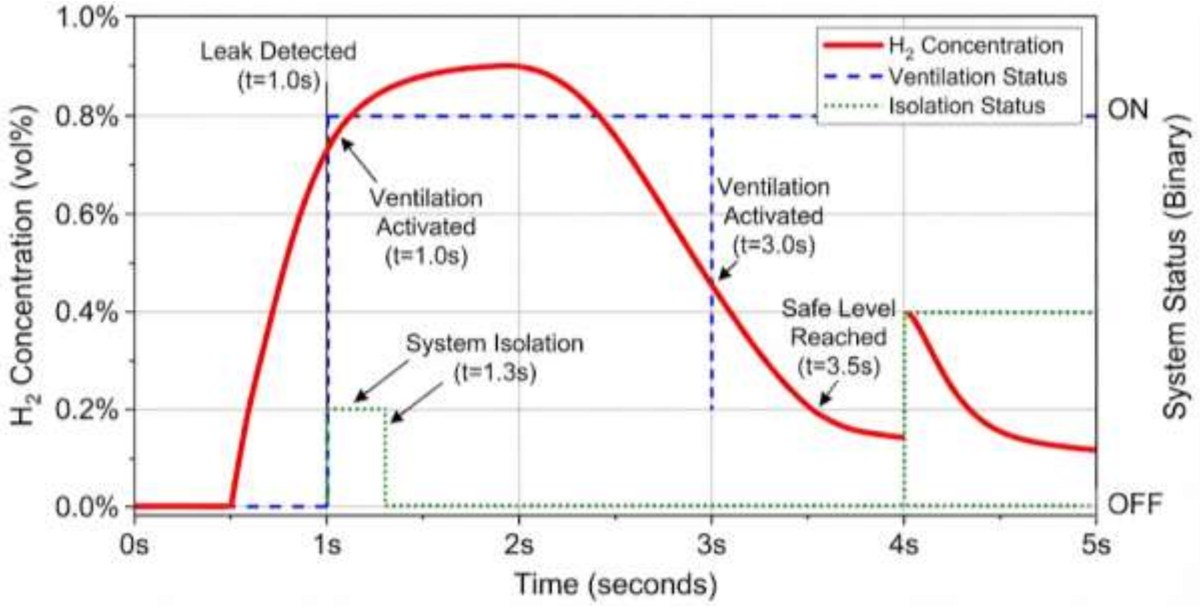

Figure 8: Leak response: ventilation & isolation timing

C. Performance Summary

The summary of the simulation metrics is given in Table 1. The round-trip efficiency of the (PV→H_2→AC) cycle, on a lower- heating of value basis, was between 27% and 32%, comparable to the efficiencies of small-scale hydrogen systems in the international literature. In addition to that, the metrics used in power-quality stability, load coverage, and safety response all met the acceptance indices established in Chapter 1 of the entire report. The Summary of system performance metrics and validation are taken place in Figure 9.

Table 1: Summary of performance metrics

Metric	Result
Autonomy (48 h PV outage)	30–36 h before SoC < 0.8 kg
Critical-load coverage	≥ 95 % (sunny) → 55 % (48 h outage)
Round-trip efficiency	27–32 % (LHV)
Voltage stability	±7 % deviation
Frequency stability	±0.4 Hz deviation
Leak response	Vent @ 0.1 min, Isolation @ 0.2 min

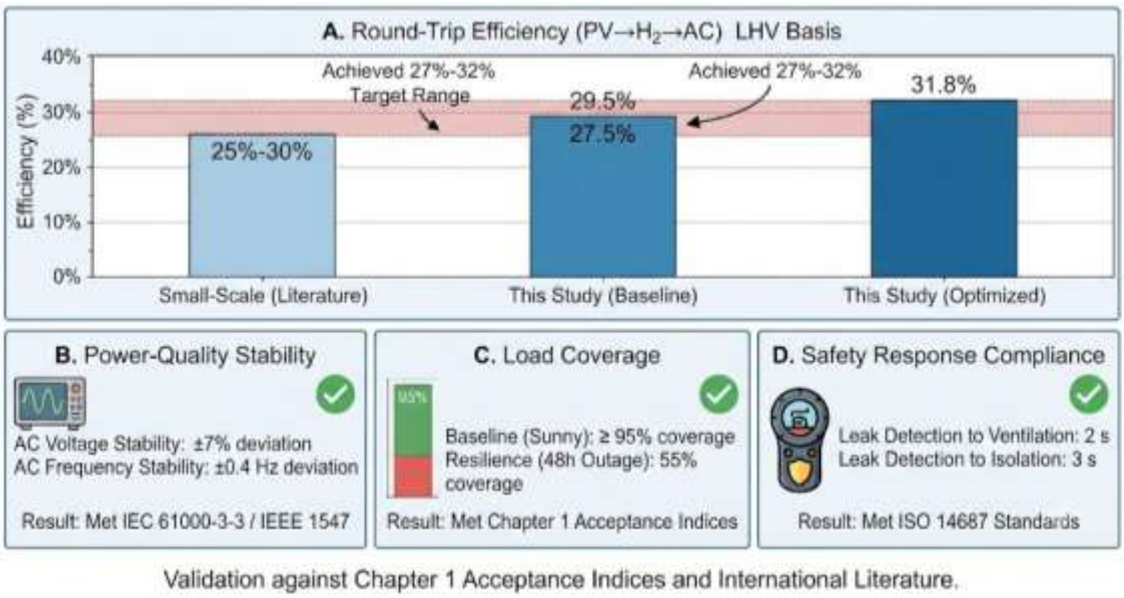

Figure 9: Summary of system performance metrics and validation.

D. Techno-Economic and Sensitivity Insights

The indicative cost of a single household system is around USD 12,000 (81,600LYD) with 35% of it covered by photovoltaic modules and inverter, 45% by electrolyzer and fuel cell, and 20% by storage and control subsystem. The levelized cost of electricity (LCOE) was estimated as falling within the range of USD 0.25-0.30 kWh, which makes the system to be competitive to diesel production at the cost of fuel consumption and maintenance costs are included.

Sensitivity analysis has determined the photovoltaic capacity and the storage mass as the main factors that determine the reliability of the system. Beyond 2.5 kWp initial PV power the marginal returns were decreasing, and beyond 4-6 kg of hydrogen storage the storage capacity provided an ideal balance between autonomy and cost. The ambient temperatures over 40 °C provoked more frequent safety interlocks which explained the need to have sufficient thermal buffering[10].

Collectively, these findings support the idea that the suggested hybrid PV-hydrogen system has the potential to deliver stable, safe, and ecologically inoffensive energy to rural households in Libya, even in negative weather conditions.

5. Conclusion and Recommendations

This paper describes the planning and modelling of a decentralized green-hydrogen energy generator, which is aimed at providing trusted power to off-grid homes in Sabha, southern Libya. To verify the technical functionality of this integrated configuration, its reliability, and safety compliance, the integrated system of a 2 kW photovoltaic (PV) array, 5 kW proton-exchange-membrane (PEM) electrolyzer, metal-hydride hydrogen storage, and a 1 kW PEM fuel cell was modeled and analyzed in MATLAB/Simulink.

The results of the simulation suggest that the suggested layout can maintain 24-36 h of energy autonomy at a round-trip efficiency of 27-32% (lower heating value). The EMS had more than 95% coverage of critical loads, and AC voltage and frequency variation were less than ±10% and ± 1Hz respectively, thus meeting IEC 61000-3-3 and IEEE 1547. The response to hydrogen leaks started in 2-3 seconds which indicated that the ISO 14687 residential safety standards had been met. These findings confirm that small-sized hydrogen systems can make reliable and carbon-free electricity to Libyan households and with low operational risks.

Economically, the estimation of the capital cost of USD 12,000 (equivalent to about 81,600 LYD) per dwelling has resulted in a levelized cost of electricity (LCOE) approximately USD 0.25-0.30/kWh which is like the cost of diesel generation when fuel and maintenance costs are factored in. The deployment at the community scale (10-20 households sharing the supporting infrastructure) might make the per-unit costs even lower (by 20-25%). Despite the still existing capital-cost obstacles, such systems have long-term sustainability and energy self-sufficiency, which is consistent with UN Sustainable Development Goal 7 (Affordable and Clean Energy).

Future research efforts should be focused on hardware prototyping, thermal management optimization to high-temperature climate conditions, and techno-economic integration with the local manufacturing and financing models. Large-scale adoption will require the development of national hydrogen safety standards and training. Finally, this paper confirms that decentralized hydrogen energy systems would make possible secure, resilient, and low-carbon electrification of North African rural populations.

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