

## Leveraging Hydrogen for Covering Energy Shortage in an Electricity Subgrid

Abduallah Abdulllah<sup>1,2,\*</sup>  , Massoud Fakher<sup>2</sup>  , Elsadic Salim<sup>2</sup>  , Ibrahim Latiwash<sup>2</sup>  ,  
Suliman Ahmad<sup>2</sup>  , Mukhtar Irhoma<sup>2</sup>  , Muetaz Mohammed<sup>3,4</sup>  , Hala El-Khozondar<sup>5,6</sup>  ,  
Ibrahim Imbayah<sup>7</sup>  , Monaem Elmnifi<sup>8</sup>  , Yasser Nassar<sup>2</sup>  

<sup>1</sup>Higher Institute of Sciences and Technology, Tamezawa, Brack-Libya

<sup>2</sup>Mechanical and Renewable Energy Eng. Dept., Faculty of Eng., Wadi Alshatti University, Libya

<sup>3</sup>Department of Mechanical Engineering, King Fahd University of Petroleum & Minerals, Dhahran, Saudi Arabia

<sup>4</sup>Department of Sustainable and Renewable Energy Engineering, Omar Al-Mukhtar University, Al-Byda, Libya

<sup>5</sup>Department of Materials and London Centre for Nanotechnology, Imperial College, LondonSW7 2AZ, UK

<sup>6</sup>Electrical Engineering and Smart Systems Departments, Islamic University of Gaza, Gaza, Palestine

<sup>7</sup>Department of Energy Engineering, College of Renewable Energy, Tajoura, Libya

<sup>8</sup>Department of Mechanical Engineering Technology, Belgorod State Technological University, Belgorod, Russia

### ARTICLE HISTORY

Received 17 January 2026

Revised 20 February 2026

Accepted 26 February 2026

Online 01 March 2026

### KEYWORDS

Electricity;  
Hydrogen;  
Fuel-Cell;  
Electrolyser;  
Libya.

### ABSTRACT

This study explores a sustainable solution for addressing the electricity supply-demand imbalance in Brack Ashatti by utilizing excess electricity during off-peak hours for hydrogen production through electrolysis, and subsequently employing fuel cells to generate electricity during peak periods. The research evaluates the feasibility of using a hydrogen-based system to stabilize the national grid without the need for additional power generation units. Based on the calculations, the electrolyzer can produce up to 271.8 cubic meters of hydrogen per hour, requiring approximately 9.1 MW of electricity, which is sufficient to cover the network's 6.1 MW energy deficit during off-peak hours. With a hydrogen storage capacity of 421,255 cubic meters, this system can store hydrogen for later use in fuel cells to meet the 1689 MW deficit in the national grid during peak times. The results indicate that by optimizing hydrogen production through electrolysis and utilizing fuel cells for electricity generation, the proposed system can provide 8,424 MW of power, effectively covering the network's deficit. This method not only resolves the supply-demand gap but also proves to be a cost-effective and efficient solution for achieving grid stability, without requiring additional power plants.

## الاستفادة من الهيدروجين لتغطية عجز امداد الطاقة في شبكة كهربائية فرعية

عبد الله عبد الله<sup>1,2,\*</sup>، مسعود فاخر<sup>2</sup>، السادق سالم<sup>2</sup>، إبراهيم لطياوش<sup>2</sup>، سليمان أحمد<sup>2</sup>، مختار إرحومة<sup>2</sup>، معتز محمد<sup>3,4</sup>، هالة الخزندار<sup>5,6</sup>،  
إبراهيم إمبية<sup>7</sup>، منعم المنفي<sup>8</sup>، ياسر نصار<sup>2</sup>

### الكلمات المفتاحية

الكهرباء  
الهيدروجين  
خلايا الوقود  
المحلول الكهربائي  
لبنيا

### المخلص

تستكشف هذه الدراسة حلاً مستداماً لمعالجة عدم التوافق الزمني بين العرض والطلب على الكهرباء في منطقة براك الشاطئ من خلال استغلال فائض الكهرباء خلال ساعات انخفاض الطلب لإنتاج الهيدروجين عبر التحليل الكهربائي، ثم استخدام خلايا الوقود لتوليد الكهرباء خلال فترات الذروة. تقيم الدراسة جدوى استخدام نظام يعتمد على الهيدروجين لتحقيق استقرار الشبكة الفرعية دون الحاجة إلى وحدات توليد كهرباء إضافية. ووفقاً للنتائج، يمكن للمحلول الكهربائي إنتاج ما يصل إلى 271.8 متر مكعب من الهيدروجين في الساعة، ويتطلب ذلك حوالي 9.1 ميغواط من الكهرباء، وهو ما يكفي لتغطية العجز في الطاقة البالغ 6.1 ميغواط في الشبكة. وبسعة تخزين للهيدروجين تبلغ 421,255 متر مكعب، يمكن لهذا النظام تخزين الهيدروجين لاستخدامه لاحقاً في خلايا الوقود لتغطية العجز البالغ 1689 ميغواط في الشبكة الفرعية خلال أوقات الذروة. وتشير النتائج إلى أنه من خلال تحسين إنتاج الهيدروجين بالتحليل الكهربائي واستخدام خلايا الوقود لتوليد الكهرباء، يمكن للنظام المقترح توفير 8,424 ميغواط من الطاقة، مما يغطي فعلياً عجز الشبكة. ولا يقتصر هذا الأسلوب على سد الفجوة بين العرض والطلب بحسب، بل يثبت أيضاً أنه حل فعال من حيث التكلفة والكفاءة لتحقيق استقرار الشبكة دون الحاجة إلى محطات توليد كهرباء إضافية.

## Introduction

Stability issues in electrical grids, especially with increasing loads during peak times, have become one of the major

challenges facing modern energy systems. Today's electrical grids struggle to adapt to rapid fluctuations in energy demand, leading to imbalances that affect system stability and reliability. During peak times, grids experience

\*Corresponding author

[https://doi.org/10.63318/waujpasv4i1\\_26](https://doi.org/10.63318/waujpasv4i1_26)

This work is licensed under a Creative Commons Attribution-NonCommercial 4.0 International License (CC BY-NC 4.0).



significant pressure due to high electricity demand, while during off-peak periods, it is difficult to effectively utilize surplus energy. These challenges require innovative solutions to ensure sustainable electricity supply, particularly given the growing need to meet the increasing demand for energy while maintaining a balance between production and consumption. In this context, hydrogen emerges as an effective solution, due to its unique characteristics that make it ideal for long-term energy storage. Hydrogen is the lightest element in the periodic table and one of the most abundant elements in nature, accounting for 75% of the atomic mass of the universe. Additionally, hydrogen has properties that make it a clean fuel, as it only produces water as a by-product when used in fuel cells, making it an environmentally friendly solution. It also has a very high energy density compared to many other fuels; the energy density of hydrogen is 33.6 kWh/kg, allowing it to store large amounts of energy in relatively small volumes. Furthermore, hydrogen technology enjoys a high availability rate of up to 99% in modern energy storage systems [1-3] making it ideal for use in electrical grids that require effective storage solutions. The integration of Hydrogen energy storage in hybrid energy systems is increasing in many applications [4-9].

Singh et al. [4] analyzed the feasibility of a hybrid hydrogen fuel cell and solar photovoltaic system for academic research building in India. A fuzzy logic computing program has been performed for this purpose. The obtained results have shown that, hydrogen fuel cell and battery storage, are the most important components of the hybrid renewable energy systems to meet the load demand, especially at late night and early morning hours. Shifting to practical applications of hydrogen in energy systems, we refer to the study by Yue et al. , which analyzed Power-to-Hydrogen-to-Power systems. In this study, electrolyzers were used to convert surplus electricity into hydrogen, which was then converted back into electricity using fuel cells. The study showed that PEM and Alkaline electrolyzers typically consume 48–55 kWh to produce 1 kg of hydrogen, while PEMFC fuel cells generate 16–20 kWh/kg H<sub>2</sub> of electricity, with an overall efficiency ranging from 32% to 40%. The researchers also noted that the LCOE of electricity produced from hydrogen in the grids ranges from 0.30 to 0.45 USD/kWh, which is relatively high but acceptable for long-term energy storage applications and grid support [10].

Nassar *et al.* designed and analyzed a multi-generation hybrid system based on wind energy and hydrogen to address electricity shortages in resource-constrained urban areas such as the Gaza Strip. The proposed system consists of a 1000 MW wind farm integrated with a 750 MW electrolyzer, 338 MW fuel cells, a hydrogen storage tank with a capacity of 5617 m<sup>3</sup>, and a seawater desalination unit. The results demonstrated that the system is capable of covering the annual electricity deficit and supplying energy to the transportation sector, with an LCOE of 0.124 \$/kWh when environmental and social impacts are considered. The study also confirmed the economic feasibility of the system, with a payback period of approximately 9 years and a significant reduction in carbon dioxide emissions [11]. In another study conducted by Pera et al. (2025) in Spain, a hydrogen storage system was applied in a solar-powered energy community. The researchers used a PEM Electrolyzer with a capacity of 250 kW to produce approximately 4.8 kg H<sub>2</sub>/day during off-peak periods, while a PEM Fuel Cell with a capacity of 100 kW was used to generate 80–90 kWh/day of electricity during peak periods. The study showed that the

LCOE of electricity produced from hydrogen was 0.34 \$/kWh, and the NPC was estimated at 1.42 million euros over 20 years, reflecting the feasibility of these systems in distributed environments [12]. In a different context, Kharel and Shabani (2018) analyzed a hydrogen storage system in Australia to support renewable energy grids. The system used an Alkaline Electrolyzer to produce 1,200 kg H<sub>2</sub> annually, which was then converted into electricity using PEM fuel cells, producing 22 MWh annually during peak periods. The study showed that the LCOE was 0.626 USD/kWh, which is lower compared to other storage systems, reinforcing hydrogen's effectiveness as a sustainable energy storage solution for long-term storage[13]. In Greece, Tziritas et al. (2023) conducted a study on a hydrogen-based backup support system for service buildings. The system used a PEM Electrolyzer with a capacity of 60 kW to produce 1.1 kg H<sub>2</sub>/day, and a PEM Fuel Cell with a capacity of 30 kW to generate 18–20 kWh/day of electricity during peak periods. The results showed that the LCOE was 0.41 \$/kWh, with a 18% reduction in the NPC compared to traditional diesel generators over a 25-year operational period [14].

Another study by Wong and Afrouzi focused on enhancing the efficiency of hydrogen storage systems using hybrid systems. The researchers employed SOFC fuel cells in conjunction with PEM Electrolyzers, showing that each kilogram of hydrogen could generate 22 kWh of electricity. The LCOE ranged between 0.28 to 0.40 USD/kWh, reflecting a higher production efficiency compared to other systems [15].

In a separate analysis, Jung examined a hybrid system combining PEM Water Electrolyzers with SOFC. The study showed that producing 1 kg H<sub>2</sub> required approximately 52 kWh, while the fuel cells produced 23 kWh/kg H<sub>2</sub>. The hybrid system was capable of meeting peak load demands of 120 kWh/day, with a notable reduction in NPC compared to conventional storage systems[16]. In a comparative study by Pellow et al. (2015), the differences between battery-based and hydrogen-based storage systems at the grid level were analyzed. The study showed that each 1 kg H<sub>2</sub> could generate approximately 17–19 kWh of electricity through fuel cells, and while the round-trip efficiency is lower than batteries, hydrogen demonstrated a higher net energy recovery in seasonal storage scenarios. The LCOE ranged from 0.35 to 0.45 USD/kWh[17]. In Europe, Boukhchina et al. (2025) reviewed Power-to-Hydrogen applications at the national grid level, noting that experimental projects in Europe produce 10–50 kg H<sub>2</sub>/day using PEM and Alkaline electrolyzers. This hydrogen was used to generate electricity ranging from 160–900 kWh/day through PEMFC fuel cells. The LCOE was estimated between 0.25 and 0.38 \$/kWh[18].

Azamian (2020) examined a hydrogen storage model for residential buildings. The system produced 2.4 kg H<sub>2</sub>/day using a PEM Electrolyzer, with 5 kW fuel cells generating 40 kWh/day of electricity. The NPC of the system was estimated at 96,000 USD, with an LCOE of 0.39 USD/kWh[19]. The available literature demonstrates that hydrogen is a promising solution for energy storage and addressing load and peak issues in electrical grids, especially for long-term storage and integration with renewable energy sources. Despite the challenges related to efficiency and cost, continuous advancements in electrolyzer and fuel cell technologies, along with legislative and economic support, enhance the feasibility of these systems as a sustainable and future-proof solution for grid stability.

**Key Information on Brack Alshatti City**

**Geographic location**

Brack Alshatti city is located in southwestern Libya, within the Fezzan region, specifically in the eastern part of Wadi al-Shati. It extends southward to the Zallaf Sand Sea. The city lies at approximate geographic coordinates of 27°53' N and 14°28' E. Brack is a large oasis in the heart of the Libyan desert, combining desert terrain with agricultural fertility due to the availability of groundwater. Its elevation is about 334 meters above sea level, and the topography is generally flat with some hills and limited highlands reaching up to 560 meters. The prevailing climate in the area is continental desert, characterized by high temperatures in the summer and cold winters, with low precipitation and humidity. Studies indicate the presence of various natural resources in the region, including deposits of iron ore and manganese, in addition to groundwater that is considered potable in terms of most physical and chemical properties, except for elevated concentrations of iron in some cases [22].

**Electrical Energy Situation:**

In 2024, the city of Brak al-Shati faces a complex reality in the electrical energy sector. The total electricity generated was approximately 605,879.5 MWh, while the total electrical load during the same period was about 590,018 MWh. Although the available capacity exceeds the required loads throughout the year, the city still suffers from a noticeable shortage during peak periods, when demand rises beyond the grid's immediate response capability, leading to frequent power outages. This imbalance is attributed to the lack of effective energy storage systems, inefficient load distribution, and partial reliance on unstable conventional energy sources.

**Climatology details**

Brack Alshatti is located in southwestern Libya and has a hot desert climate. The region is characterized by extremely high solar radiation, low annual rainfall, and significant

temperature differences between day and night. Summer temperatures often exceed 40°C, while winters are relatively mild. The area receives very limited rainfall, usually less than 50 mm annually, concentrated in sporadic events during the cooler months. It records more than 3,000 hours of sunshine per year. Figures 2 and 3 illustrate the horizontal solar radiation and the temperature variations throughout the year.

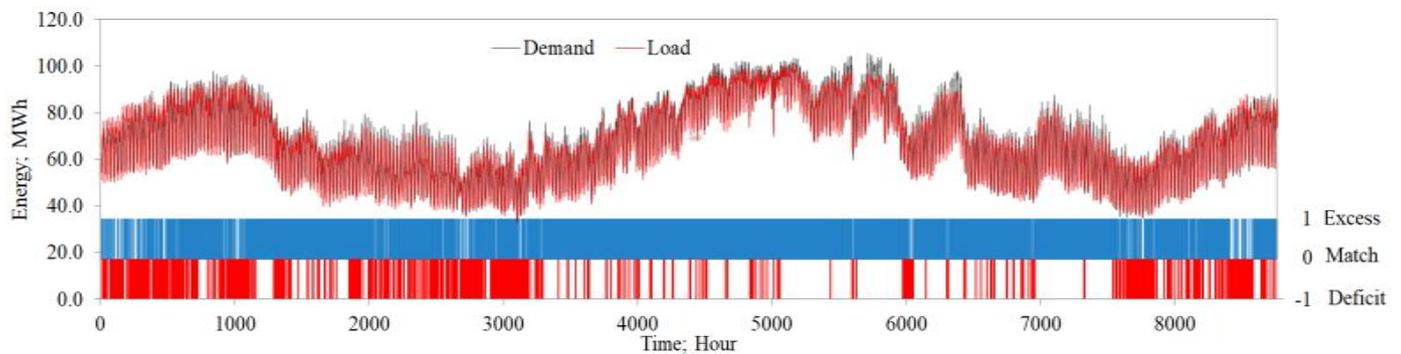
**Methodology**

The followed approach is illustrated by the flowchart depicted in Fig. 4. The research focuses on analyzing the energy, economic and technical performance of the proposed system illustrated in Fig. 5. This system will be compared with conventional fossil-fuel power generation systems in terms of economic and operational efficiency.

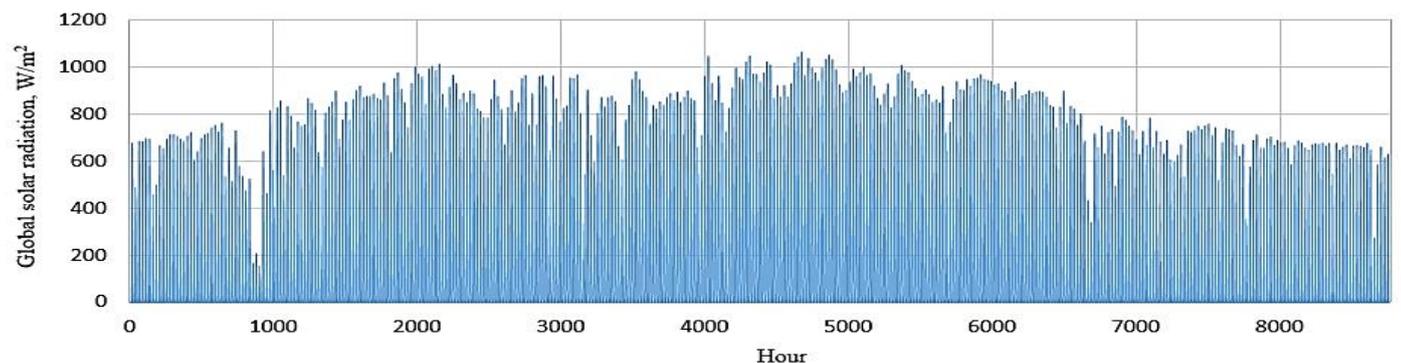
The goal of the study is to balance grid loads during peak demand periods using these new technologies, thus contributing to reducing carbon emissions by improving the use of renewable energy sources and storing hydrogen as an effective means for later use. The analysis is based on hourly generation and load data for all of 2024 (8,760 hours = 365 days × 24 hours). The data reflects dynamic energy trends in Brack Alshatti, illustrating seasonal and daily variations in the demand and supply of electricity. The procedure involves several steps: data collection and preprocessing, energy balance analysis, system sizing, economic analysis, and load balancing performance analysis. Each action is calibrated to allow for a comprehensive assessment of the overall potential of the system towards Brack's energy needs. The methodology incorporates a number of assumptions

**Layout of proposed Grid and Fuel Cell system**

To boost the feasibility of this research work, the analysis is applied for a generic grid and Fuel Cell. The layout of the proposed system is shown in Fig. 4.



**Figure 1:** Hourly generated electricity, demand, hours of deficit, coincidence and excess power in the sub-grid - Brack Alshatti



**Figure 2:** Hourly global horizontal solar radiation (GHI)

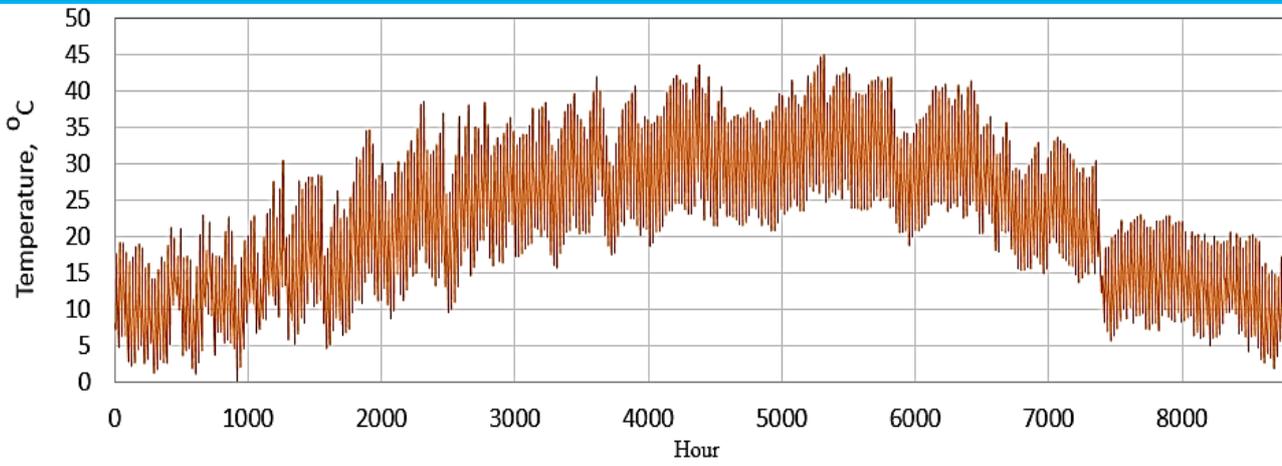


Figure 3: Hourly ambient air temperature

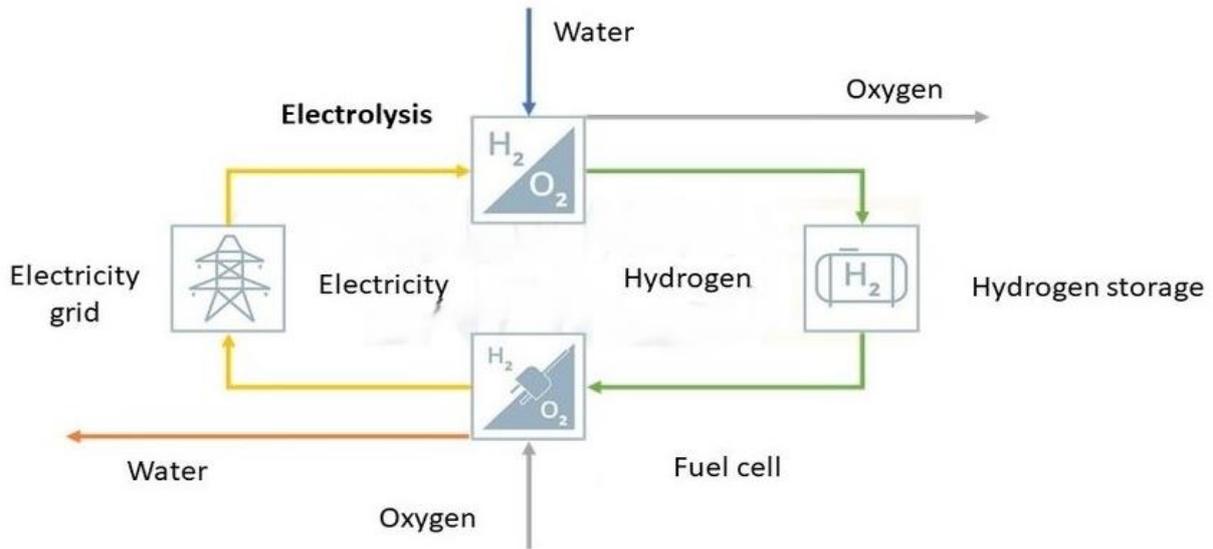


Figure 4: A layout of proposed hydrogen fuel cell system

**Assumptions, limitations and uncertainties of the results:**

To make the analysis easier, the following assumptions were adopted:

- The electrical load is assumed to be constant during one hour.
- hydrogen is considered as an ideal gas.
- The economic evaluation excludes the salvage value of the equipments.
- Neglecting the transmission losses and leaks in electricity transition system and fuel lines.
- Constant efficiency of electrolyzer ( $\eta_E = 80\%$ ) and fuel cell ( $\eta_F = 60\%$ ) systems.

A key limitation of this study is that the influence of parameter variability on the design and performance of the proposed system has not been investigated.

The key sources of uncertainty in this study are mainly the data including climate and electrical load data and physical quantities such as density and low heating value of the H<sub>2</sub>. Furthermore, economic risks occur from volatility in the capital and operating costs of energy technology. Notably, in some cases; the costs of equipments vary by more than 360% [19].

**Hydrogen System**

There are several uses for hydrogen, including energy storage [10], power generation [21], industrial sector [22,13] and fuel for H<sub>2</sub> vehicles [4]. Hence, hydrogen production from green

energy sources is essential to meet sustainable energy targets (SETs) as the globe attempts to move to a low-carbon economy [22]. The hydrogen system consists Electrolyzer for H<sub>2</sub> production, Storage tank, and Fuel cell for electricity production.

The instantaneous H<sub>2</sub> productivity of the electrolyzer ( $\dot{m}_{H_2}(t)$ ) may be estimated as:

$$\dot{m}_{H_2}(t) = \left[ \frac{P_w(t) \times \eta_{EL}}{LHV_{H_2}} \right]_{t=1 \rightarrow 8760} \tag{1}$$

Where,  $\dot{m}_{H_2}(t)$  is the H<sub>2</sub> productivity (ton/hr) powered  $P_w(t)$  (MW),  $LHV_{H_2}$  is the lower heating value of H<sub>2</sub> (33.33 kWh/kg H<sub>2</sub>) and  $\eta_{EL}$  is the electrolyzer efficiency (80%).

While the hourly electrical energy produced by the fuel cell  $P_{FC}$  (MW) is determined as:

$$P_{FC}(t) = [\dot{m}_{H_2}(t) \times LHV_{H_2} \times \eta_{FC}]_{t=1 \rightarrow 8760} \tag{2}$$

Where:  $\eta_{FC}$  represents the fuel cell efficiency (60%).

The produced hydrogen will be stored at 1000 bar, the high pressure compressed gas tank made of composite materials, such as carbon fiber, with a thermoplastic polymer liner [94]. The instantaneous of energy level or volume level of H<sub>2</sub> in the storage tank is estimated as:

$$V_{H_2}(t) = \left[ \frac{m_{H_2}(t)}{\rho_{H_2}} \right]_{t=1 \rightarrow 8760} \tag{3}$$

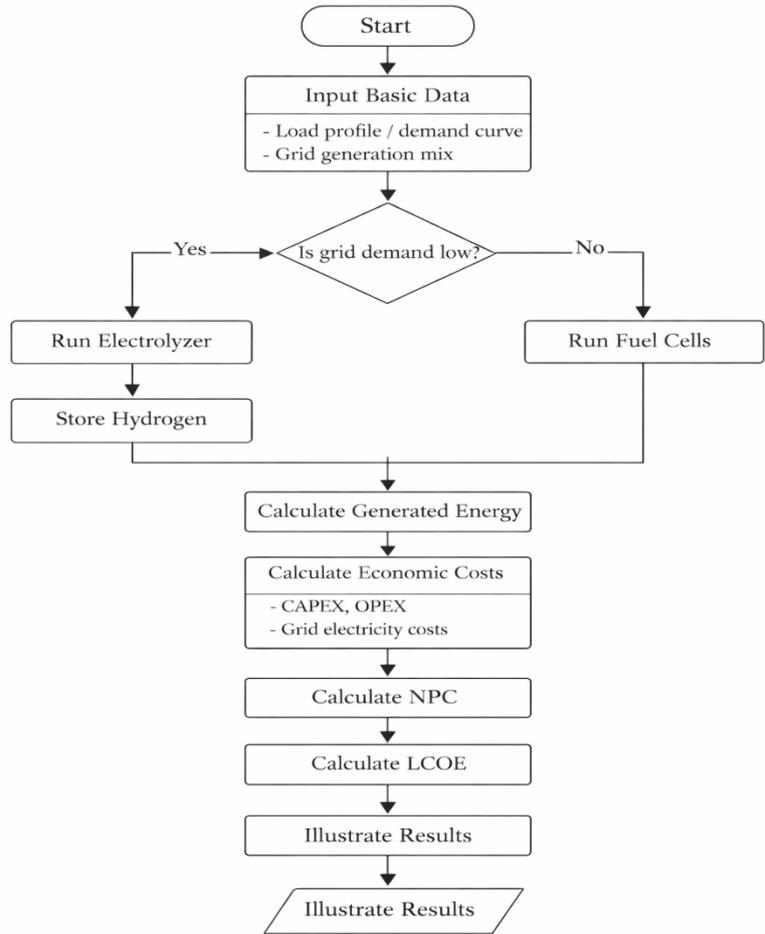


Figure 5: The methodology flowchart

Where:  $\rho_{H_2}$  is the density of the compressed hydrogen at 100 MPa, taking as 71.59 kg/m<sup>3</sup> [30]. Accordingly the volume of the H<sub>2</sub> storage tank we be determined as:

$$V_{H_2} = \max \left[ \frac{m_{H_2}(t)}{\rho_{H_2}} \right]_{t=1 \rightarrow 8760}$$

The energy consumed by the compressors  $P_{Comp}(t)$  in MWh are:

$$P_{Comp}(t) = \frac{m_{H_2}(t)}{\eta_{comp} \times \rho_{H_2}} \Delta p \quad (5)$$

Accordingly, the capacity of the compressor will be:

$$P_{comp} = \max [P_{Comp}(t)]_{t=1 \rightarrow 8760}$$

Where  $\eta_{comp}$  refers to reciprocating compression efficiency and is taken as 95%.

**Water requirement**

It is needed about 11.0 kg of pure water to produce 1.0 kg of H<sub>2</sub>. The energy consumption in Reverse Osmosis plants are in the range of 0.0016 kWh/kg. As such, energy consumption to purify the seawater to meet the feedstock purity requirements for electrolyser ranges roughly from 0.055 to 0.077 kWh/kg H<sub>2</sub> (given assumed water consumption of 11 l H<sub>2</sub>O/kg H<sub>2</sub>).

The cost for water desalination is about \$0.85/m<sup>3</sup> H<sub>2</sub>O, which then adds about \$0.0075/kg H<sub>2</sub> to the production cost H<sub>2</sub> [26].

$$P_{RO}(t) = 11.0 m_{H_2}(t)$$

Accordingly, the capacity of the RO plant will be:

$$P_{RO} = \max [P_{RO}(t)]_{t=1 \rightarrow 8760}$$

Analysis and Design constraints

LPSP=0

**Economic analysis**

Involving the environmental damage cost on the economic analysis enhances the competitiveness of eco-friendly renewable energy in the energy market, even in countries that subsidize energy prices [27-33]. The levelized cost of energy is considered the most important economic and environmental indicator for demonstrating the feasibility of several alternatives of energies. As the proposed system provides two energies; electricity and Hydrogen it is essential to estimate the levelized cost of electricity (LCOE) and the levelized cost of Hydrogen (LCOE). The present research is different from others as there are two energy sources and two consumption sides. This necessitated the development of traditional equations for calculating the levelized cost of energy, and the new equation was formulated in terms of the share of each source in supplying energy to the consumer.

Table 1: The key information on economic and environmental factors related to the components of the system

Equipment	Capital Cost	Operation & Maintenance	Lifespan; year	Ref.
Electrolyzer	\$1800-2,450/kW	\$10-175/kW	10	[13], [15]
Fuel Cell	\$1200-2900/kW	\$49-170/kW	10	[13], [14]
Hydrogen storage tank	\$30-50/kg H <sub>2</sub>	\$0.0162/kg	10	[17]

$$LCOE = \frac{\left[ \frac{r(1+r)^n}{(1+r)^n - 1} (C_{FC} + C_{El} + C_{st}) + (O_{FC} + O_{El} + O_{st}) \right]}{\sum_{t=1}^{8760} E_{FC}(t)} \tag{6}$$

where  $r$  is the real interest rate (2.4%),  $n$  is the plant lifespan (10 years). The rated power of the FC are determined from their corresponding energies.

The net present value NPV is determined as:

$$NPV = \frac{\left[ \frac{r(1+r)^n}{(1+r)^n - 1} (C_{FC} + C_{El} + C_{st}) + (O_{FC} + O_{El} + O_{st}) \right]}{\frac{r(1+r)^n}{(1+r)^n - 1}}$$

## Results and Discussion

### Sizing of proposed hydrogen system

The aforementioned equations were analyzed using Microsoft Excel, which included all of the data supplied in the preceding sections. The results show that the system's energy balance and the answer-stability condition were achieved for a Fuel Cell with an installed capacity of 9.1 MW and an electrolyser with an hourly capacity of 271.8 cubic meters of hydrogen, which corresponds to around 105 MW of electrical production. The needed hydrogen storage capacity was computed as 421255 m<sup>3</sup> at a pressure of 100 MPa by 133KW compressor.

### Load Balancing Performance

The hydrogen fuel cell system's load balancing is assessed through its ability to smooth excess and shortage hours to maintain grid stability in Brack Ashatti.

On an annual basis, it encounters a total of 3,998 excess hours and 2,608 shortage hours, of which excess energy is stored or generated as 8424.2 MWh during the off-peak hours, while energy is released to cover about 1689 MWh of shortage hour.

Figure 6 show the level of energy in the hydrogen storage tank.

### Hourly Hydrogen Productivity from Electrolysis

Fig. 7 shows the hourly productivity of hydrogen (H<sub>2</sub>) from an electrolyzer system with a nominal capacity of 271.8M<sup>3</sup> per hour. This corresponds to a power input of 11.32 MWh. The electrolyser functions under variable power supply circumstances. it also shows considerable changes in hourly hydrogen generation due to the intermittent grid electricity availability. During periods of low load, the electrolyser hits its peak productivity of around 271.8m<sup>3</sup> per hour, indicating that its rated capacity is fully used. In contrast, during high load, hydrogen production decreases dramatically or stops totally.

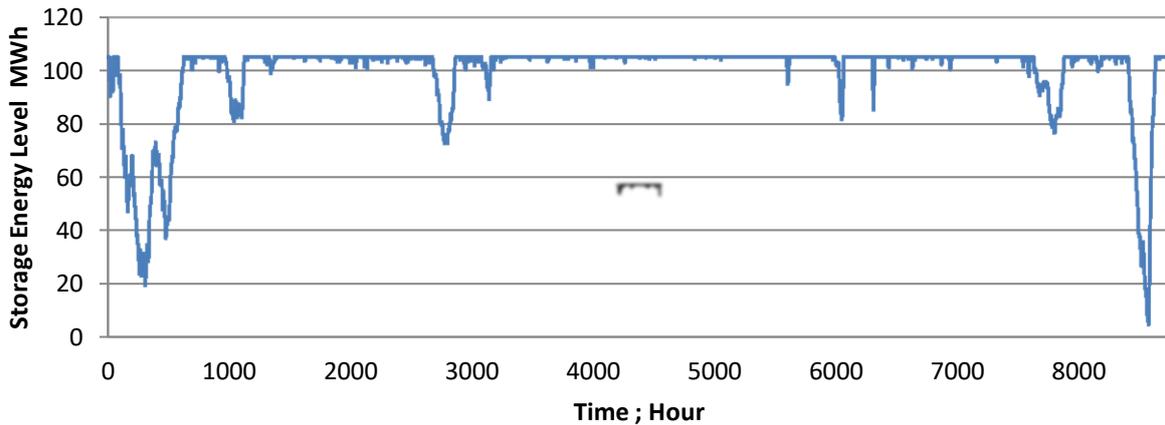


Figure 6: Storage Energy Level MWh

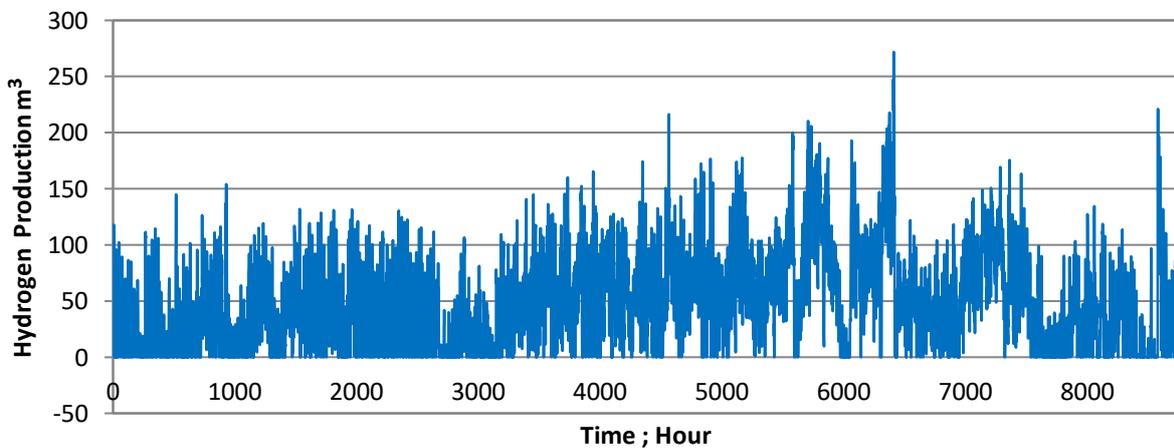


Figure.7: Hydrogen production from Excess Electricity

**Hourly Electricity Generation from Fuel Cell**

Figure 8 depicts the hourly power generation curve of the fuel cell with a capacity of 10.2 MW. The system's operation is inextricably related to the hydrogen storage infrastructure, which buffers the intermittent generation of hydrogen from the electrolyzer and guarantees a more reliable power supply. The hydrogen storage system essentially enables this smoothing effect, which reduces the influence of the inherent fluctuation of grid-based hydrogen generation [46,50]. Nonetheless, the system efficiently maintains baseline power generation, which contributes to grid stability and increases energy security. These findings highlight the crucial importance of combined fuel cell and hydrogen storage systems in accelerating the transition to electrical energy infrastructures. By improving energy generation, such hybrid arrangements provide dependable, dispatchable electricity supply [36].

**The dynamic energy behavior of the Hydrogen system:**

Fig. 9 illustrated the energy behavior of the subgrid under consideration integrating the proposed H2 system. It is clear from Fig. 9 the effect of the power supply capacity on the storage capacity. Also it is clear that the hydrogen fuel cell system capacity the strategic importance of hydrogen and fuel cell systems as a flexible, dispatchable, and scalable energy storage solution for fossil fuel-dominated power grids. By converting surplus electricity into a storable energy carrier and reconverting it during peak demand

**Economic Analysis:**

The economic assessment evaluates the financial feasibility of a Hydrogen Fuel cell system using LCOE and NPC methodologies. For the base LCOE calculation (without LCA and  $C_{CO_2}$ ), the LCOE is \$202.2/MWh, which demonstrates a capital cost of \$27000000, and ongoing operating and maintenance (O&M) costs, inclusive of their combined costs over a 10-year lifespan. The base LCOE is competitive with Brack's (brack's power station-based system.) cost of \$200/MWh at peak hours and can provide meaningful savings. Considering  $C_{CO_2}$ , which is based on the calculation of 0.0378 ton  $CO_2$ /MWh, valued at the social cost of \$50/ton (which adds an additional \$1.89/MWh), and LCA concerns, which take into account the emissions due to environmental construction impacts and land use, the LCOE increases to \$267.1/MWh. The NPC is calculated at \$3,875,000 over 10 years, using a 8% discount rate and a 2% inflation rate. An increase in LCOE with  $C_{CO_2}$  and LCA represents the environmental and social implications of Hydrogen Fuel cell, which are vital for energy planning in Libya where more than 90% of electricity generation is sourced from fossil fuel technologies [27]. The NPC of \$3,875,000 is a discounted aggregated total of capital costs, O&M costs and environmental costs incurred over the lifetime of the project. Table 2 compares the LCOE of the Hydrogen Fuel cell system to other energy storage technologies, as well as brack's power station-based system. This provides a more complete understanding of cost effectiveness [28,46,47].

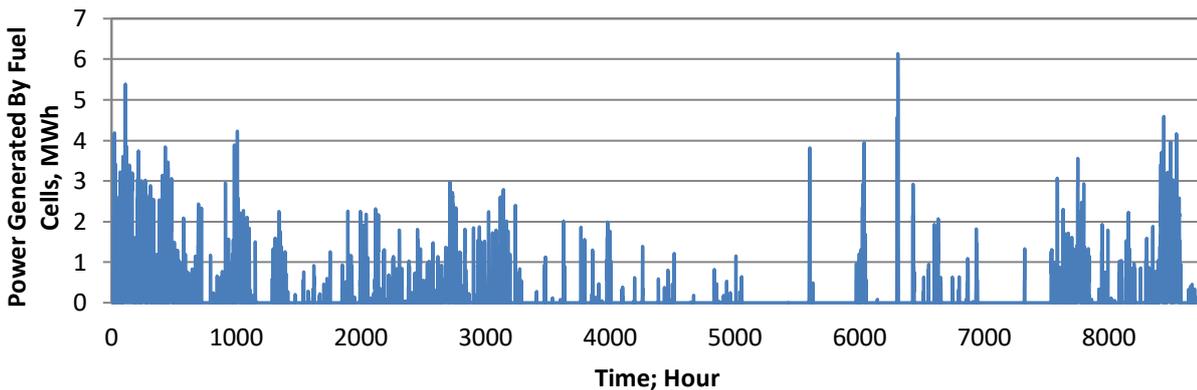


Figure.8: Power Generated by Fuel Cell

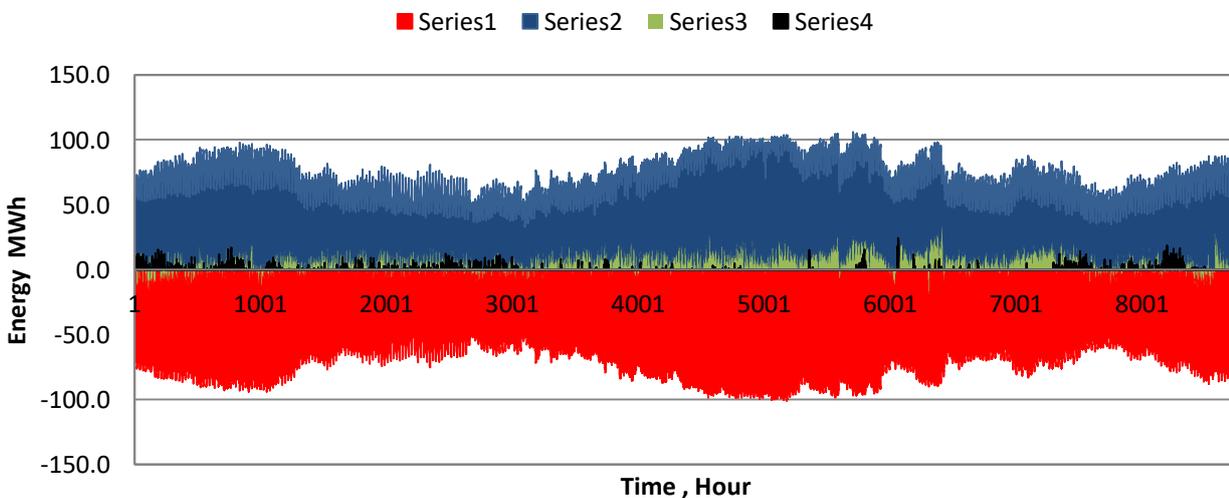


Figure 9: The dynamic performance of the grid including H2 system

**Table 2:** LCOE Comparison with Other Technologies

Technology	LCOE (\$/MWh)	Notes
Hydrogen Fuel cell system (Brack, Base)	202.2	Without LCA/Cco2
Gas power plant	200	High fuel cost, emissions
Lithium-Ion Batteries	250-350	High upfront cost, shorter lifespan
Compr. Air Storage	150-220	Requires specific geology
Flywheels	300-500	High cost, short duration

## Discussion

The results confirm that the hydrogen-based energy storage system, comprising electrolyzers, hydrogen storage tanks, and fuel cells, represents a technically and economically feasible solution for mitigating electricity supply-demand imbalances in Libya's power grid. The system effectively utilizes surplus electricity during off-peak periods to produce hydrogen at a rate of up to 271.8 m<sup>3</sup>/h, requiring approximately 9.1 MW of electrical input, which is sufficient to absorb the 6.1 MW off-peak surplus observed in the network. With a total hydrogen storage capacity of 421,255 m<sup>3</sup>, the system ensures adequate energy availability to compensate for peak-period shortages.

Operationally, the stored hydrogen enables reliable electricity generation through fuel cells, supplying up to 8,424 MW of electrical power and covering the network's peak deficit of 1,689 MW. The integration of hydrogen storage decouples electricity generation from real-time demand and electrolyzer operation, resulting in significantly improved output stability compared to the fluctuating grid conditions. Although short-term reductions in fuel cell output occur when hydrogen storage levels are temporarily insufficient, the system consistently maintains baseline power generation, thereby enhancing grid reliability and energy security during high-demand periods.

From an economic standpoint, the proposed system demonstrates strong competitiveness. The leveled cost of energy (LCOE) is approximately 202 USD/MWh. Moreover, the ability to avoid constructing additional power plants further strengthens the economic justification of the system.

## Conclusion

This research addressed one of the fundamental challenges facing the electricity sector in Libya, namely the imbalance between electricity supply and demand, particularly during peak load periods. By utilizing surplus electricity available during low-load periods to produce hydrogen through electrolyzers, and subsequently using this hydrogen to generate electricity via fuel cells, the study presented a practical and integrated framework for achieving effective energy balancing without the need to construct additional power generation plants. The results demonstrated that the proposed system is capable of converting unused surplus electricity into a storable energy resource that can be deployed when needed, enabling the production of sufficient hydrogen to compensate for power deficits during peak demand periods. The study also showed that integrating electrolyzers with hydrogen storage systems and fuel cells significantly enhances grid stability, improves supply reliability, and reduces reliance on costly and short-term conventional solutions. From an economic perspective, the analysis confirmed that the proposed system exhibits clear economic feasibility, as the leveled cost of energy falls within a competitive range, even when carbon disposal costs are taken into account. This confirms that hydrogen-based solutions are not merely environmentally sustainable options,

but also represent practical and cost-effective pathways for improving the performance of the national electricity grid.

**Authors' Contributions:** Nassar: Conceptualization, Supervision. Abduallah: Writing – original draft. Nassar, Abduallah, El-Khozondar: Methodology, Investigation. Ahmad, Latiwash, Irhouma, Salim, Imbayah, Fakher, Mohammed: Formal analysis, Software, Validation, Data curation, El-Khozondar, Mohammed: Writing – review & editing. All authors have read and agreed to the published version of the manuscript.

**Funding:** "This research received no external funding."

**Data Availability Statement:** "The data are available at request."

**Conflicts of Interest:** "The authors declare no conflict of interest."

## References

- [1] M. Salem, et al. "Technical and environmental cost-benefit analysis of strategies towards a green economy in the electricity sector in Libya." *Economics and Policy of Energy and the Environment*, vol. 2/2025, pp. 1-19, 2025. <https://doi.org/10.3280/EFE2025-002007>
- [2] M. Salem, et al. "Towards Green Economy: Case of Electricity Generation Sector in Libya." *Solar Energy and Sustainable Development Journal*, vol. 14, no. 1, pp. 334–360, 2025.
- [3] Y. Nassar, et al. "Regression Model for Optimum Solar Collectors' Tilt Angles in Libya," in *The 8th International Engineering Conference on Renewable Energy & Sustainability (ieCRES 2023)*, Gaza Strip, Palestine, May 8-9, 2023. <https://ieeexplore.ieee.org/document/10209547>
- [4] A., Garcia-Linares, P., & Martí, A. (2025). Comparative analysis of hydrogen production and economic feasibility: direct versus indirect coupling of photovoltaic systems with electrolyzers. *Advanced Energy and Sustainability Research*, 6(10), 2400210.
- [5] H. El-Khozondar, M., Andeef, N. Fathi, R. El-Khozondar, and H. Awad. "Feasibility of Concentrating Solar Power as a Solar Fuel for Electrical Power Stations: A Case Study of Ubari Gas-Power Station in Libya." *Wadi Alshatti University Journal of Pure and Applied Sciences*, vol. 4, no. 1, pp. 56-69, 2026. [https://doi.org/10.63318/waujpasv4i1\\_06](https://doi.org/10.63318/waujpasv4i1_06)
- [6] A. Alkhazmi, et al.. "Design and Analysis of PV Solar Street Lighting systems in Remote Areas: A Case Study." *Wadi Alshatti University Journal of Pure and Applied Sciences*, vol. 4, no. 1, pp. 1-14. 2026. [https://doi.org/10.63318/waujpasv4i1\\_01](https://doi.org/10.63318/waujpasv4i1_01)
- [7] L. Ben Dalla, Ö. Karal, M. EL-Sseid, and A. Alsharif. "An IoT-Enabled, THD-Based Fault Detection and Predictive Maintenance Framework for Solar PV Systems in Harsh Climates: Integrating DFT and Machine Learning for Enhanced Performance and Resilience." *Wadi Alshatti University Journal of Pure and Applied Sciences*, vol. 4, no. 1, pp. 41-55, 2026. [https://doi.org/10.63318/waujpasv4i1\\_05](https://doi.org/10.63318/waujpasv4i1_05)
- [8] El-Khozondar, et al. "Feasibility of Concentrating Solar Power as a Solar Fuel for Electrical Power Stations: A Case Study of Ubari Gas-Power Station in Libya." *Wadi Alshatti University Journal of Pure and Applied Sciences*, vol. 4, no. 1, pp. 56-69, 2026. [https://doi.org/10.63318/waujpasv4i1\\_06](https://doi.org/10.63318/waujpasv4i1_06)
- [9] A. Mahmoud, et al. "Charging systems/techniques of electric vehicle: A comprehensive review." *Solar Energy and Sustainable Development Journal*, vol. 13, no. 2, pp. 18–44, 2024. <https://doi.org/10.51646/jsesd.v13i2.203>
- [10] A. Pal, P. & Mukherjee, V. (2021). *Off-grid solar photovoltaic/hydrogen fuel cell system...* *Renewable and Sustainable Energy Reviews*, 149. (ideas.repec.org)
- [11] F. Yasser, H. El-Khozondar, M. Khaleel, A. Ahmed, A. Alsharif, M. Elmnifi, M. Salem and I. Mangir, "Design of reliable standalone utility-scale pumped hydroelectric storage

- powered by PV/Wind hybrid renewable system," *Energy Conversion and Management*, vol. 322, p. 119173, 2024. <https://doi.org/10.1016/j.enconman.2024.119173>
- [12] HY Jung (2023). *Techno-Economic Analysis of Hybrid Energy Storage...* Preprints. (preprints. <https://doi.org/10.1002/aesr.202500049>)
- [13] Trapani, D., et al. (2023). *The potential of hydrogen-battery storage systems...* *Energy Storage (Elsevier) (IJEES)*, vol. 3, no. 4, pp. 47–69, 2025. <https://ijeess.org/index.php/ijeess/article/view/150>.
- [14] A. Ahmed, A. Alsharif, and N. Fathi. "Recent Advances in Energy Storage Technologies." *The International Journal of Electrical Engineering and Sustainability (IJEES)*, vol. 1, no. 1, pp. 9–17, 2023. <https://ijeess.org/index.php/ijeess/article/view/11>
- [15] M. Khaleel, I. Imbayah, Y. Fathi, and H. El-Khozondar. "Renewable Energy Transition Pathways and Net-Zero Strategies." *The International Journal of Electrical Engineering and Sustainability (IJEES)*, vol. 3, no. 4, pp. 01–16, 2025. <https://ijeess.org/index.php/ijeess/article/view/145>.
- [16] A. Blakers, B. Lu, K. Anderson and A. Nadolny, "Pumped hydro energy storage to support 100% renewable electricity," in 2018 IEEE 7th World Conference on Photovoltaic Energy Conversion (WCPEC) (A Joint Conference of 45th IEEE PVSC, 28th PVSEC & 34th EU PVSEC), Waikoloa, HI, USA, 2018. <https://ieeexplore.ieee.org/document/8548026>
- [17] D. Bogdanov, O. Koskinen, and C. Breyer, "Integrated renewable energy based power system for Europe, Eurasia and MENA regions," in 2016 International Energy and Sustainability Conference (IESC), Cologne, Germany, 2016. <https://ieeexplore.ieee.org/document/7569508>
- [18] N. Naval, J. Yusta, R. Sánchez and F. Sebastián, "Optimal scheduling and management of pumped hydro storage integrated with grid-connected renewable power plants," *Journal of Energy Storage*, vol. 73, no. 12, p. 108993, 2023. <https://doi.org/10.1016/j.est.2023.108993>
- [19] E. Salim, A. Abubaker, B. Ahmed, and Y. Nassar, "A Brief Overview of Hybrid Renewable Energy Systems and Analysis of Integration of Isolated Hybrid PV Solar System with Pumped Hydropower Storage for Brack city-Libya", *waujpas*, vol. 3, no. 1, pp. 152-167, 2025. [https://doi.org/10.63318/waujpasv3i1\\_22](https://doi.org/10.63318/waujpasv3i1_22)
- [20] S. Ahmed, A. Agrira, and Y. Nassar, "The Impact of Loss of Power Supply Probability on Design and Performance of Wind/Pumped Hydropower Energy Storage Hybrid System ", *waujpas*, vol. 3, no. 2, pp. 52-62, May 2025. [https://doi.org/10.63318/waujpasv3i2\\_06](https://doi.org/10.63318/waujpasv3i2_06)
- [21] Y. Nassar, M. Abdunnabi, M. Sbeta, A. Hafez, K. Ali, A. Hassan and B. Belgasim, "Dynamic analysis and sizing optimization of a pumped hydroelectric storage-integrated hybrid PV/Wind system: A case study," *Energy Conversion and Management*, vol. 229, p. 113744, 2021. <https://doi.org/10.1016/j.enconman.2020.113744>
- [22] S. Mohammed, et al. "Exploring Optimum Sites for Exploitation Hydropower Energy Storage Stations (PHES) Using the Geographic Information System (GIS) in Libya." *Solar Energy and Sustainable Development Journal*, vol. 14, no. 1, pp. 394-409, 2025. <https://doi.org/10.51646/jesd.v14i1.426>
- [23] A. Abduallah, N. Fathi, S. Mohammed, and M. Ghatas. "Integrating Electricity Sub-Grid with Pumped Hydropower Storage System for Grid Stability and Sustainability." *Wadi Alshatti University Journal of Pure and Applied Sciences*, vol. 3, no. 2, pp. 322-332, 2025. [https://doi.org/10.63318/waujpasv3i2\\_40](https://doi.org/10.63318/waujpasv3i2_40)
- [24] M Elmnifi, et al. " Design of an Innovative Wastewater Treatment System Using Photovoltaic-Hydro System Coupled with Reverse Osmosis Technology: Sustainability and Continuous Improvement." In *Proceedings of the 7th International Symposium on Water Resource and Environmental Management*, WREM 2024. Environmental Science and Engineering. Springer, Cham. [https://doi.org/10.1007/978-3-031-88850-2\\_12](https://doi.org/10.1007/978-3-031-88850-2_12)
- [25] M Elmnifi, et al. "Solar and Wind Energy Generation Systems with Pumped Hydro Energy: City of Derna." In *the proceedings of the 7th International Symposium on Water Resource and Environmental Management*, 2025. WREM 2024. Environmental Science and Engineering. Springer, Cham. [https://doi.org/10.1007/978-3-031-88850-2\\_17](https://doi.org/10.1007/978-3-031-88850-2_17)
- [26] M Elmnifi, et al. "Ensuring sustainability in Libya with renewable energy and pumped hydro storage." *Ecological Questions*, vol. 35, no. 3, pp. 1-17, 2024. <https://doi.org/10.12775/EQ.2024.036>
- [27] A Awad, et al. "Energy, economic and environmental feasibility of energy recovery from wastewater treatment plants in mountainous areas: a case study of Gharyan city – Libya." *Acta Innovations*, vol. 50, no. 4, pp. 46-56, 2023. <https://www.ceeol.com/search/article-detail?id=1233304>
- [28] I Mangir, et al. "Feasibility of innovative topography-based hybrid renewable electrical power system: A case study." *Cleaner Engineering and Technology*, vol. 14, p. 100650, 2024. <https://doi.org/10.1016/j.clet.2023.100650>
- [29] A. Ali, E. Karram, Y. Nassar, A. Hafez. "Reliable and economic isolated renewable hybrid power system with pumped hydropower storage." In the 22nd international Middle East power systems conference (MEPCON), 14-16 December 2021, Assiut, Egypt. <https://doi.org/10.1109/MEPCON50283.2021.9686233>
- [30] S Mohammed, et al. "Exploring Optimum Sites for Exploitation Hydropower Energy Storage Stations (PHES) Using the Geographic Information Systems (GIS) in Libya." *Solar Energy and Sustainable Development Journal*, vol. 14, no. 1, pp. 394-409, 2025. <https://doi.org/10.51646/jesd.v14i1.426>
- [31] F. Yasser, et al. "Thermoelectrical analysis of a new hybrid PV-thermal flat plate solar collector." In *the 8th International Engineering Conference on Renewable Energy & Sustainability (ieCRES)*, 08-09 May 2023, Gaza, Palestine, State of. <https://doi.org/10.1109/ieCRES57315.2023.10209472>
- [32] K. Amer, et al. "Economic-Environmental-Energetic (3E) analysis of Photovoltaic Solar Energy Systems: Case Study of Mechanical & Renewable Energy Engineering Departments at Wadi Alshatti University." *Wadi Alshatti University Journal of Pure and Applied Sciences*, vol. 3, no. 1, pp. 51-58, 2025. [https://doi.org/10.63318/waujpasv3i1\\_09](https://doi.org/10.63318/waujpasv3i1_09)
- [33] H. El-Khozondar, et al. "Economic and Environmental Implications of Solar Energy Street Lighting in Urban Regions: A Case Study." *Wadi Alshatti University Journal of Pure and Applied Sciences*, vol. 3, pp. 1, pp. 142-151. [https://doi.org/10.63318/waujpasv3i1\\_21](https://doi.org/10.63318/waujpasv3i1_21)
- [34] I. Imbayah, et al. "Design of a PV solar-covered parking system for the college of renewable energy Tajoura, Libya: A PVsyst-based performance analysis." *University of Zawia Journal of Engineering Sciences and Technology*, vol. 3, no. 2, pp. 288–307, 2025. <https://doi.org/10.26629/uzjest.2025.23>
- [35] I. Latiwash, and A. Abubaker. "Performance Analysis and Sizing Optimization of a Utility Scale Stand-Alone Renewable Energy PV/Battery Storage System for Urban Zones." *University of Zawia Journal of Engineering Sciences and Technology*, vol. 3, no. 2, pp. 261–275, 2025. <https://doi.org/10.26629/uzjest.2025.21>
- [36] J. El-Khozondar, et al. "Sustainable street lighting in Gaza: Solar energy solutions for main street." *Energy 360*, vol. 4, no. 12, p. 100042, 2025. <https://doi.org/10.1016/j.energy.2025.100042>
- [37] A. Aquila, et al. "Real Time Design and Analysis of a Hybrid Renewable Energy System (PV/Wind/Battery) for Self-Consumption Residential Building." In Conference: Engineering for Palestine Conference At: Palestine Polytechnic University, Hebron, Palestine, 2025. <https://www.researchgate.net/publication/396910534>
- [38] B .Ahmed, et al. "Atlas of solar (PV and CSP) and wind energy technologies in Libya." *The North African Journal of Scientific Publishing (NAJSP)*, vol. 1, no. 4, pp. 8-24, 2023. <https://www.researchgate.net/publication/374846048>

- [39] A. Alatrash, et al. "Assessing the Viability of Solar and Wind Energy Technologies in Semi-Arid and Arid Regions: A Case Study of Libya's Climatic Conditions." *Applied Solar Energy*, vol. 60, no. 1, pp. 149–170, 2024. <https://doi.org/10.3103/S0003701X24600218>
- [40] N. Abuhamoud, et al. "Mapping of PV solar module technologies across Libyan territory." *In the Iraqi International Conference on Communication and Information Technologies (IICCIT)*, 07-08 September 2022, Basrah, Iraq, <https://doi.org/10.1109/IICCIT55816.2022.10010476>
- [41] N. Abuhamoud, et al. "Atlas of PV solar systems across Libyan territory." In 2022 International Conference on Engineering & MIS (ICEMIS), 04-06 July 2022, Istanbul, Turkey. <https://doi.org/10.1109/ICEMIS56295.2022.9914355>
- [42] M. Khaleel, et al. "Solar and Wind Atlas for Libya." *International Journal of Electrical Engineering and Sustainability (IJES)*, vol. 1, no. 3, pp. 27–43, 2023. <https://ijees.org/index.php/ijees/article/view/44>
- [43] A. Al-Mathnani, A. Mohammed, S. Al-Hashmi, and E. Geepalla. "Control and Modification of 12-Pulse Static Compensator with PV Cell Using New Control Algorithm." *Wadi Alshatti University Journal of Pure and Applied Sciences*, vol. 3, no. 1, pp. 30-34, 2025. [https://doi.org/10.63318/waujpasv3i1\\_06](https://doi.org/10.63318/waujpasv3i1_06)
- [44] D. Albuzaia, A. Ali, M. Mohmed, and A. Hafez. "Reliable and Robust Optimal Interleaved Boost Converter Interfacing PhotoVoltaic Generator". *Wadi Alshatti University Journal of Pure and Applied Sciences*, vol. 3, no. 2, pp. 192-201, 2025. [https://doi.org/10.63318/waujpasv3i2\\_24](https://doi.org/10.63318/waujpasv3i2_24)
- [45] M. Elnaggar, et al. "Leveraging Wind Energy for Electricity and Hydrogen Production: A Sustainable Solution to Power Shortages and Eco-Friendly Alternative Fuel." *Advanced Energy and Sustainability Research*, e202500049, 2025. <https://doi.org/10.1002/aesr202500049>
- [46] W. El-Osta, et al. "Carbon footprint and energy life cycle assessment of wind energy industry in Libya." *Energy conversion and management*, vol. 300, p. 117846, 2024. <https://doi.org/10.1016/j.enconman.2023.117846>
- [47] A. Amhimmid, W. El-Osta, Y. Nassar, H. El-Khozondar, and M. Salem. "Financial Modeling of Social and Environmental Impacts of Wind Farm in Urban Zones: A Case Study of Zawia-Libya." *International Journal of Energy and Environmental Engineering (IJEEE)*, vol. 15, no. 4, pp. 1-19, 2024. <https://doi.org/10.57647/ijeee.2024.1504.17>
- [48] S Mohammed, et al. "Carbon and Energy Life Cycle Analysis of Wind Energy Industry in Libya." *Solar Energy and Sustainable Development Journal*, vol. 12, no. 1, pp. 50-69, 2023. <https://www.ajol.info/index.php/jsesd/article/view/260868>
- [49] A. Elmariami, et al. "Life Cycle Assessment of 20 MW Wind Farm in Libya." *Appl. Sol. Energy*, vol. 59, pp. 64–78, 2023. <https://doi.org/10.3103/S0003701X22601557>
- [50] M. Elnaggar, et al. "Assessing the techno-enviro-economic viability of wind farms to address electricity shortages and Foster sustainability in Palestine." *Results in Engineering*, vol. 24, p. 103111, 2024. <https://doi.org/10.1016/j.rineng.2024.103111>