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RESEARCH ARTICLE RENEWABLE ENERGY

Integrating Electricity Sub-Grid with Pumped Hydropower Storage System for Grid Stability and Sustainability

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ABSTRACT

This study provides a comprehensive assessment of the technical, economic, and operational feasibility of implementing a Pumped Hydropower Storage (PHS) system to enhance the stability of the Alshatti electricity subgrid, which has been experiencing prolonged power outages. The proposed PHS system is designed to store excess “off-peak” energy during periods of low demand and release it back into the grid during peak hours to mitigate demand surges, stabilize subgrid performance, and reduce outage frequency. Using hourly generation and load data from 2024, the Levelized Cost of Electricity (LCOE) for the PHS system is calculated at \$303.5/MWh, excluding Life Cycle Assessment (LCA) impacts and the carbon cost C_{CO2}.This value is cost-competitive with Brack Alshatti’s current peak-hour electricity cost of \$231/MWh generated from gas-fired power plants. When the social cost of carbon is included based on 0.0378 ton CO_2/MWh at \$50/ton along with LCA impacts, the LCOE increases to \$264.3/MWh, capturing both environmental and societal externalities associated with power plant operation. The Net Present Cost (NPC) of the PHS system, assuming a reservoir storage capacity of 589,959 MWh, is estimated at \$3,875,000 over a 60-year project life using an 8% discount rate and 2% inflation rate. Operationally, the system provides an annual energy throughput of 16,477 MWh, effectively managing 3,998 MWh of surplus energy during off-peak hours and offsetting 2,608 MWh of shortages during peak hours. On average, the PHS system exports 0.0378 MWh/hour to the grid during high-demand periods, resulting in an estimated 15% reduction in annual fuel consumption at local power stations. With an expected round-trip efficiency of 80%, the PHS system demonstrates strong capability to accommodate the variability of energy demand and supply across Brack.

دمج الشبكة الكهربائية الفرعية مع نظام تخزين الطاقة بالضخ الكهرومائي لتحقيق إستقرار الشبكة وإستدامة الطاقة

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الكلمات المفتاحية

خزن الطاقة الكهرومائية بالضخ
إدارة الحمل
الطاقة المستدامة
استقرار الشبكة
الحجم المثالي

الملخص

تُقيّم هذه الدراسة الجدوى الفنية والاقتصادية والتشغيلية لتطبيق نظام تخزين الطاقةبنظام الضخ الكهرومائي(PHS) لتعزيز استقرار شبكة الكهرباء في براك الشاطئ، والتي تُعاني من انقطاع التيار الكهربائي لساعات طويلة. صُمّم نظام تخزين الطاقة الكهرومائية لتخزين الطاقة "خارج أوقات الذروة" وإعادتها إلى الشبكة خلال فترات الأحمال لموازنة طفرات الطلب، وتحقيق استقرار شبكة الكهرباء الفرعية، والحد من الانقطاعات. بناءً على البيانات الساعية لتوليد الطاقة والحمل لعام ٢٠٢٤، تبلغ التكلفة المُستوية للكهرباء (LCOE) ٣٠٣,٥ ميجاوات/ساعة، دون احتساب تقييم دورة الحياة (LCA) أو تكلفة الكربون (CCO2). تُعدّ هذه التكلفة مُنافسةً من حيث التكلفة لتوليد الكهرباء في براك الشاطئ خلال ساعات الذروة. تبلغ تكلفة استخدام محطة توليد الطاقة التي تعمل بالغاز 231 دولارًا أمريكيًا/ميغاواط/ساعة. بعد احتساب ثاني أكسيد الكربون (0.0378 طن من ثاني أكسيد الكربون/ميغاواط/ساعة بسعر 50 دولارًا أمريكيًا/طن) وتحليل دورة الحياة، يرتفع سعر التكلفة المُستوية للطاقة (LCOE) إلى 264.3 دولارًا أمريكيًا/ميغاواط/ساعة، مع مراعاة تكاليف الأثر البيئي والتكاليف الاجتماعية لاستخدام كهرباء محطة توليد الطاقة. تُقدر التكلفة الحالية الصافية (NPC) لنظام PHS - بسعة خزان تبلغ 589,959 ميجاواط/ساعة - بنحو 3,875,000 دولار أمريكي على مدى 60 عامًا باستخدام معدل خصم بنسبة 8% ومعدل تضخم بنسبة 2%. ينتج النظام إنتاجًا سنويًا من الطاقة يبلغ 16,477 ميجاواط/ساعة من خلال إدارة 3,998 ميجاواط/ساعة من فائض الطاقة خارج أوقات الذروة ومعالجة نقص قدره 2,608 ميجاواط/ساعة خلال أوقات الذروة , في المتوسط، يصدر النظام 0.0378 ميجاوات ساعة/ساعة إلى الشبكة خلال ذروة الطلب؛ وهذا يترجم إلى انخفاض بنسبة -15٪ في الاستهلاك السنوي للوقود للمحطات. بالإضافة إلى ذلك، يُقدر أن نظام PHS يتمتع بكفاءة ذهابًا وإيابًا بنسبة 80٪ ، مما يؤكد قدرة النظام على استيعاب اشتراكات الطاقة الكهربائية المتغيرة في براك.

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Introduction

Driven by increasing concerns over climate change and global warming, global Renewable Energy (RE) installation expanded significantly in recent years, growing by nearly 50% in 2024. By the end of that year, worldwide renewable energy capacity, including solar, wind, hydropower, geothermal, marine, and biogas, reached approximately 4,448.1 GW. Of this total, PV solar systems accounted for 1,600 GW, wind energy for 1,021 GW, biomass-generated electricity for 96.8 GW, geothermal resources for 16,873 MWe, and hydropower for nearly 1,450 GW [1–8]. The global cumulative installed capacity of pumped hydropower storage (PHS) systems also reached 179 GW in 2024 [9], rising to about 200 GW in 2025, which represents nearly 95% of global grid-scale energy storage capacity [10].

This sustained growth in renewable energy reflects an accelerating global transition toward sustainable and low-carbon technologies. Ensuring energy security and environmental sustainability has become a fundamental pillar of socioeconomic development. In parallel with international commitments to reduce carbon emissions, improving the efficiency of existing electricity systems has become increasingly critical. Although fossil-fuel-based sub-grids continue to provide a stable electricity supply, they face significant challenges: widening supply-demand imbalances, rising operational costs, and profound environmental impacts. Furthermore, severe weather events can disrupt conventional power generation and loads, placing additional stress on grid stability.

To address these issues, integrating energy storage systems has become an essential strategy for enhancing grid resilience and operational flexibility. Among available technologies, pumped hydropower storage (PHS) stands out as one of the most effective due to its large storage capacity, long lifespan, and relatively low cost [11,12].

Libya is deeply connected to these global trends. As a signatory to the Paris Agreement and a member of OPEC, the country faces increasing pressure to reduce greenhouse gas emissions. However, Libya depends almost entirely on fossil fuels for electricity production, and oil exports remain the primary source of national income, making the energy sector the main contributor to national air pollution [10,13]. To address these challenges, the Libyan government has launched a 25-year Renewable Energy Strategic Plan, targeting a renewable energy penetration of more than 50% by 2050, primarily through solar and wind projects [10].

This study aligns with national sustainability goals by focusing on energy management within regional electrical sub-grids. Specifically, it examines the energy demand and load characteristics of the Brack Alshatti district and investigates the potential of PHS as a solution to local supply–demand mismatches. The objective is to enhance grid stability, reduce reliance on fossil-fuel-based peak generation, and provide a reliable supply during high-demand periods. Additionally, this work assesses the economic feasibility and environmental benefits of incorporating PHS into regional power systems.

PHS is a mature technology capable of providing both short-term and long-term energy storage. It works by converting electrical energy into gravitational potential energy during periods of low demand, by pumping water from a lower reservoir to a higher one. When demand peaks, the stored water is released to generate electricity through turbines. PHS systems typically achieve round-trip efficiencies of 75–85%, although individual projects may vary [9].

Several studies worldwide have investigated the techno-economic performance of PHS within hybrid renewable energy systems:

- **Libya**: Nassar et al. examined a solar–wind–PHS hybrid system requiring a capital cost of 10.5 million USD, achieving an LCOE of 0.132 USD/kWh for an annual demand above 6.1 million kWh [11].
- **Cameroon**: Hassan et al. analyzed a solar–PHS system with a capital cost of 356,000 USD and an LCOE of 0.282 USD/kWh, supplying 125,056 kWh annually [14].
- **India**: Guruprasad et al. compared PHS and battery storage, finding that a 40,411 kWh PHS system costing 50.4 million USD produced an LCOE of 0.417 USD/kWh for nearly 9.8 million kWh annual demand [15].
- **Greece**: Kapsali and Kaldellis evaluated wind–PHS systems (10–50 MW), reporting LCOE values between 0.077–0.26 USD/kWh, with annual loads up to 120 million kWh [16].
- **Spain** (El Hierro): A hybrid system with 11.5 MW wind and 11.3 MW PHS achieved an LCOE of 0.14 USD/kWh, supplying 40–45 million kWh/year [15].
- **Iran**: Samatar et al. assessed PV–PV-hydrodynamic battery PHS systems, costing 196,500 USD with an LCOE of 0.1155 USD/kWh, delivering 166,338 kWh/year [18].
- **Australia**: The Kidston PHS project (250 MW, 2,000 MWh) required 777 million USD with an expected LCOE of 0.08–0.10 USD/kWh, supplying nearly 1,000 million kWh/year [19].
- **United States**: Denholm et al. studied a 300 MW / 1,200 MWh PHS system costing about 600 million USD, with LCOE values between 0.09–0.12 USD/kWh [20].

Collectively, these international experiences demonstrate the versatility of PHS across diverse geographical and economic contexts. Regardless of variations in cost and configuration, PHS consistently improves grid reliability, reduces reliance on fossil fuels, and provides competitive LCOE compared to other large-scale storage technologies.

Brack Alshatti: Local Context and Challenges

Brack Alshatti is a town in southern Libya with an estimated population of 78,500 [22]. The region's electricity sub-grid faces several challenges, including fluctuating demand, high transmission and distribution (T&D) losses, and limited infrastructure. Libya's national grid remains almost entirely dependent on fossil fuels, with approximately 100% of electricity generated from oil and gas as of 2023 [23]. In remote towns such as Brack, power outages are common, especially during the summer months (June–August), when temperatures exceed 40°C and air-conditioning loads peak.

Hourly data from 2024 indicate that Brack's electricity demand ranged from 49.8 to 88.1 MWh/h, with an average of 63.4 MWh/h, while generation varied between 52.4 and 92.9 MWh/h, averaging 65.3 MWh/h. This mismatch produced 3,998 hours of surplus and 2,608 hours of shortage annually, demonstrating a clear need for effective energy storage.

Brack's economy is primarily agricultural (e.g., date production) with limited industrial activities (e.g., food processing), leading to seasonal and hourly fluctuations in energy use. The region's topography is mostly flat desert terrain with elevations from 334 m to 560 m poses challenges for traditional PHS, which typically requires elevation differences exceeding 100 m and dependable water sources.

Nonetheless, the presence of elevations reaching 560 m provides potential siting opportunities for PHS projects.

Research Motivation and Objectives

This study aims to contribute to Libya's national goal of increasing renewable energy penetration (currently <5%) by assessing PHS potential in the Brack Alshatti sub-grid. PHS can store excess energy during low-demand hours (e.g., Hour 6 with a surplus of 4.91 MWh) and supply electricity during peak periods (e.g., Hour 18 with a shortage of 4.11 MWh). Additionally, shifting peak generation from expensive fossil-fuel plants costing about 200 USD/MWh can significantly reduce operational expenses and greenhouse gas emissions.

The main objectives of this study are:

1. Assess Technical Feasibility: Evaluate hourly load and generation profiles for 2024, determine reservoir sizing, and analyze PHS performance in balancing the sub-grid.
2. Establish Economic Feasibility: Calculate LCOE, Net Present Cost (NPC), and compare PHS with conventional power-plant-based generation.
3. Compute System Requirements: Determine reservoir capacity and annual energy output required to meet Brack's energy needs.
4. Examine Load Balancing Capability: Assess the potential of PHS to manage 3,998 surplus and 2,608 shortage hours annually.
5. Provide Comparative Insights: Contrast Brack's situation with PHS experiences in China, Egypt, and Palestine to extract best practices and lessons learned

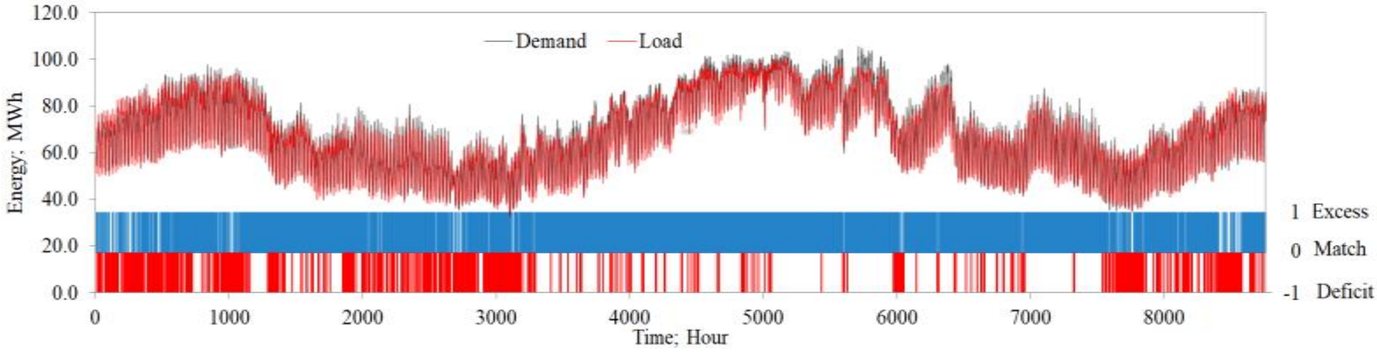


Fig. 1: Hourly generated electricity, demand, hours of deficit, coincidence and excess power in the sub-grid - Brack Alshatti

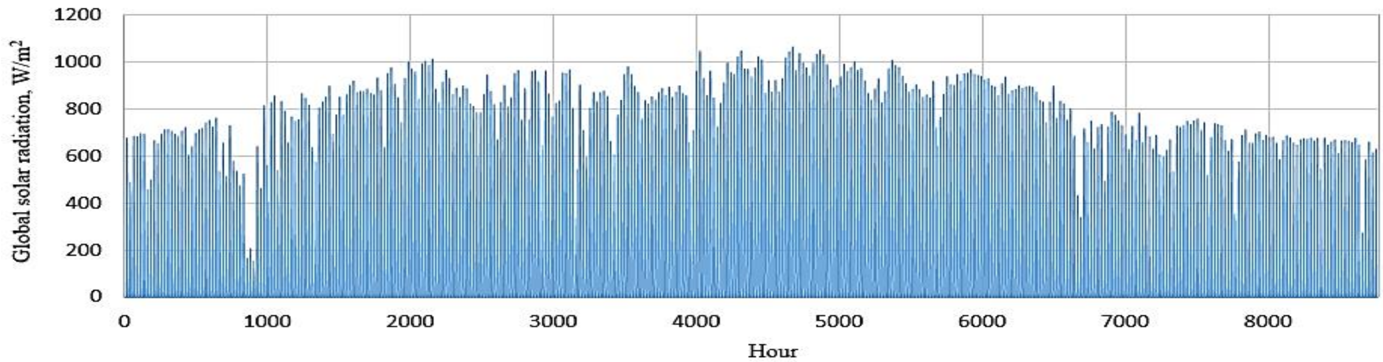


Fig. 2: Hourly global horizontal solar radiation (GHI)

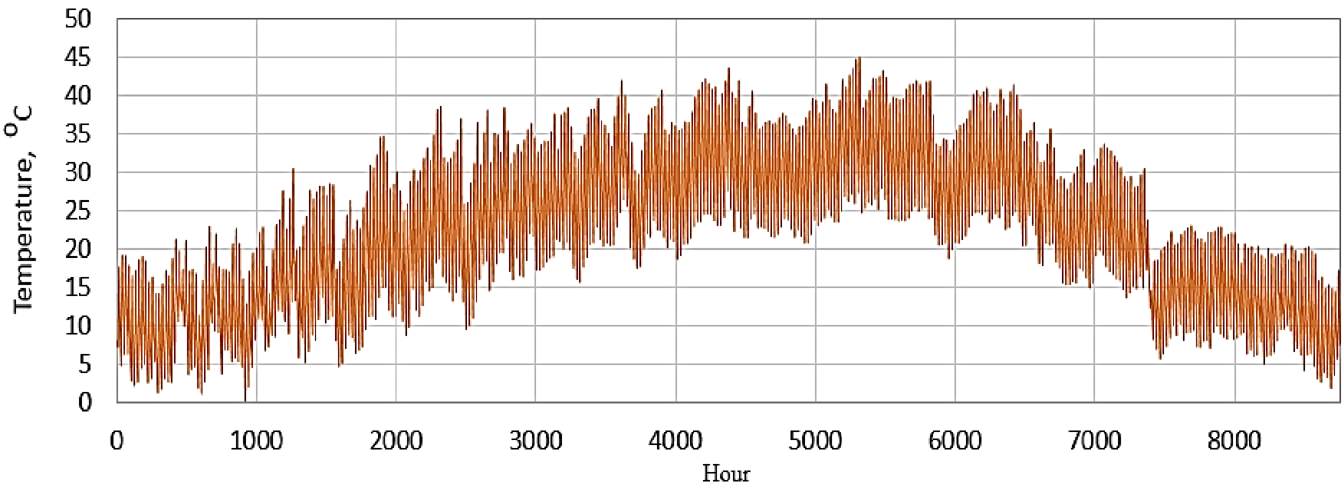


Fig. 3: Hourly ambient air temperature

Methodology

An integrated methodological approach is adopted in this research to evaluate the feasibility of installing a Pumped Hydropower Storage (PHS) system for load balancing in the Brack Alshatti sub-grid, Libya, from technical, economic, and operational perspectives. The analysis is conducted using hourly generation and load data for the entire year of 2024 (8,760 hours = 365 days × 24 hours). This dataset captures the dynamic energy trends within Brack Alshatti, including both seasonal and daily variations in electricity demand and supply.

The methodological procedure consists of several key steps:

1. Data collection and preprocessing,
2. Energy balance assessment,
3. Reservoir sizing,
4. Economic evaluation, and
5. Load-balancing performance analysis.

Each step is designed to ensure a comprehensive evaluation of the potential contribution of a PHS system to Brack Alshatti's energy requirements.

The methodology incorporates several general assumptions. First, the use of January's dataset as a baseline for extrapolation across the entire year assumes relative seasonal consistency. However, this may not fully capture increased summer demand caused by extensive air-conditioning usage. The assumed elevation difference of 560 meters is taken as a conservative estimate based on regional topography. Water availability is assumed to be possible through groundwater or treated wastewater; however, confirming a long-term supply would require a detailed hydrological assessment. Economic calculations assume an inflation rate of 2% and a discount rate of 8%, acknowledging that these values may shift due to evolving economic conditions in Libya.

A graphical representation of the methodological framework is provided in Figure 4.

Assumptions, Limitations, and Uncertainties

The analysis is conducted under the following simplifying assumptions:

• The upper reservoir is initially full.
• The PHS system is lossless, with no leakage or evaporation.
• Variations in water level in the upper reservoir do not affect head calculations.
• Water flow through the penstock is assumed non-turbulent.
• Pump turbine efficiencies are constant at 80%.
• No electrical losses occur across terminals, converters, or control units.

The main limitation of this study is the omission of meteorological effects such as evaporation and precipitation, which would influence water levels in the upper reservoir.

The primary sources of uncertainty include:

• Limited data availability,
• Model representation and simplifications, and
• Parameter estimation (economic and hydrological variables).

Layout of the Proposed Grid and PHS System

To enhance the relevance of the analysis, a generic electrical grid connected with a PHS configuration is considered. The conceptual layout of the proposed Brack Alshatti PHS system, including the upper reservoir, lower reservoir, penstock, pump turbine unit, and grid interconnection, is shown in Figure 5.

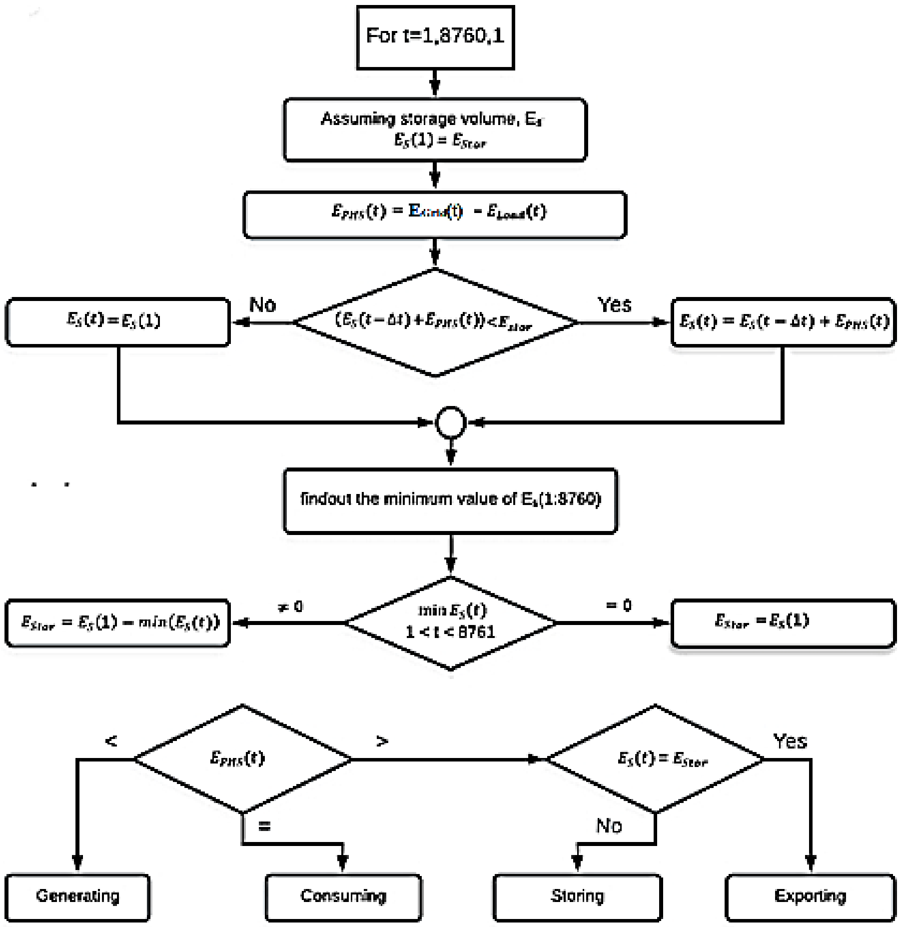
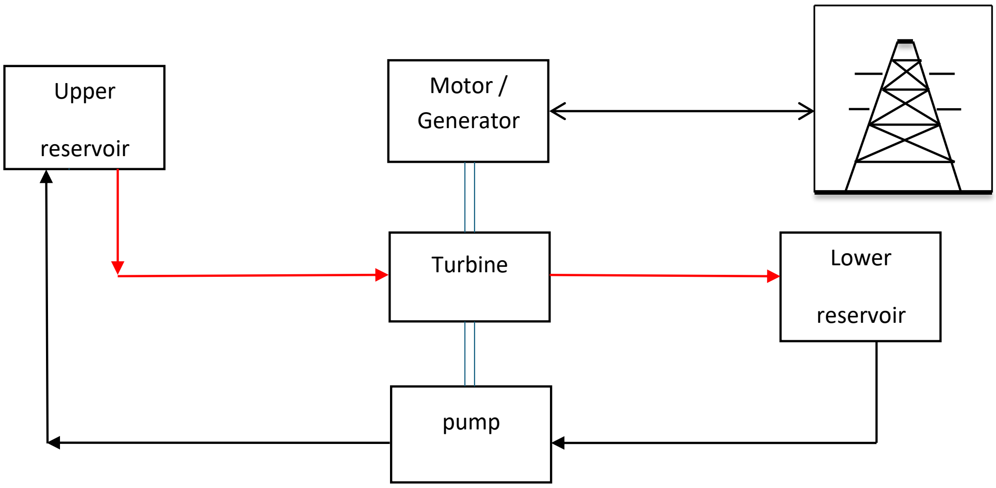


Fig. 4: The flowchart of the proposed optimization algorithm



. **Fig. 5:** A layout pumped storage system

Hydraulic analysis of the proposed PHS

In a PHS system, power flow is bidirectional and varies according to the operational mode. In both generation mode (P_t) and pumping mode (P_p), the power output is determined by the technical parameters of the PHS system, as expressed in [12]:

$$P_t = \rho\, g\, \dot{Q}(H - h_f)\eta_t \quad (1)$$

$$P_p = \frac{\rho\, g\, \dot{Q}(H + h_f)}{\eta_p} \quad (2)$$

Where ρ is the density of the working fluid (kg/m³), g is the gravitational acceleration (m/s²), Q is the volumetric flow rate (m³/s), H is the elevation (static head) of the upper reservoir (m), h_f is the head loss due to friction and minor losses in the penstock (m), and η_p and η_t are the efficiencies of the pump and turbine, respectively.

The hydrodynamic behavior of the penstock, including friction losses, velocity head, and transient effects, is extensively documented in standard fluid mechanics and hydraulic machinery textbooks [24].

$$E_{PHS}(t) = E_{grid}(t) - E_{Load}(t) \quad (3)$$

Where $E_{grid}(t)$ denotes the instantaneous electrical energy supplied by the grid at time t, and $E_{load}(t)$ denotes the corresponding electrical energy demand; both quantities are expressed in megawatt-hours (MWh).

Storage Capacity, E_{ur}

The storage capacity, E_{ur}, indicates the total energy that can be stored in the upper reservoir. It is calculated through a four-step process:

Step 1: Assume an initial storage capacity for the upper reservoir. At the initial condition (t=0), the energy level in the upper reservoir is taken to be at its maximum value, such that:

$$E_S(0) = E_{ur} \quad (4)$$

Step 2: Compute $E_S(t)$ for each of the 8,760 hours in the year.

$$E_S(t) = E_S(t - \Delta t) + E_B(t) \quad (5)$$

$E_S(0)$ is the initial condition

$$E_B(t) = E_{grid}(t) - E_{Load}(t) \quad (6)$$

Step 3: Identify the minimum value of $E_S(t)$ over the full annual cycle.

If the minimum value of $E_S(t)$ is less than zero, this indicates an insufficient reservoir capacity, whereas a value greater than zero implies over-sizing. The target design condition is achieved when the minimum value of $E_S(t)$ equals zero.

Step 4: The exact required capacity of the upper reservoir is then obtained by subtracting the minimum value of $E_S(t)$ from the initial energy level $E_S(0)$such that:

$$E_{ur} = E_S(0) - min\big(E_S(t)\big) \quad (7)$$

where $E_s(t)$ is the instantaneous-accumulative energy stored in the upper reservoir at time t, Δt is the time increment, which equals one hour.

Capacities of PHS equipment

The pump capacity to meet the load requirements is determined as:

$$P_{Pump} = \frac{\max(E_B(t))_{t=1,8760}}{\eta_{pump}} \quad (8)$$

During the supply deficiency periods, the PHS system provides the electrical energy to the load. As an energy balance, of course, the turbine power is estimated from:

$$P_{Turbine} = \frac{\min(E_B(t))_{t=1,8760}}{\eta_{Turbine}} \quad (9)$$

Operation regime mode of the PHS

- Charging mode:

$$E_{Grid}(t) > E_{Load}(t) \text{ and } E_S(t) < E_{ur} \quad (10)$$

- Discharging mode:

$$E_{Grid}(t) < E_{Load}(t) \text{ and } E_S(t) > E_{ur} \quad (11)$$

- Standby mode:

$E_{Grid}(t) = E_{Load}$

$$E_{Gen}(t) = \begin{cases} Generating\ mode & if\,(E\_Load\ (t) > E\_Gen\ (t)\ \ and\ E\_S\ (t) > 0) \\ Storing\ mode & if\,(E_{Load}(t) < E_{Gen}(t)\ and\ E_S(t) < E_{ur}) \\ Standby\ mode & if\,(E_{Load}(t) = E_{Gen}(t)\ or\ E_S(t) = E_{ur}) \end{cases} \quad (12)$$

Economic and environmental analysis

Cost estimation provides an approximate prediction of the total project expenditure within an acceptable range of uncertainty. Various cost estimation techniques exist depending on the level of project definition and the purpose of the evaluation. In this study, a parametric cost estimation method is adopted to support the formulation of an optimization problem. This method employs mathematical relationships to correlate project cost with key design and operational parameters. Although parametric estimation is more complex than simpler approaches such as analogous or factor-based methods, it is particularly suitable for conceptual design stages and optimal sizing studies.

The cost function developed in this research establishes an empirical link between the PHS system parameters and the overall project cost. The principal characteristics and cost-related specifications of the PHS components used in the analysis are summarized in Table 1 [21].

Table 1: The main parameters of PHS equipments

Metric	Value
Investment expenditures related to installed capacity C_{PHS}, $/kWh).	775
Operational and maintenance Expenditures $CO_{,PHS}$;	0.015 $/kWh
Lifespan; years	60
CO_2 life cycle emission; g CO_2/kWh	35

The excess energy sold back to the grid represents an additional economic benefit for the system. Optimizing the size of each component in the proposed PHS system is a critical aspect of the research, including the reservoir capacities, the pump–turbine power rating, and the optimal operational contribution of each subsystem. Accordingly, the overall cost function for the system can be formulated as follows [12,27,34]:

$$LCOE = \frac{\left[\frac{r(1+r)^n}{(1+r)^n-1} C_{PHS} + O_{PHS} - C_{CO2}\right]}{\sum_{t=1}^{8760} E_{PHS}(t)} \quad (13)$$

Where r is the real interest rate (2.4%), is the plant lifespan (60 years). The rated power of the PHS system components is determined based on their corresponding energy requirements. The term C_{CO2} represents the cost associated with environmental damage from carbon emissions and can be estimated as:

$$C_{CO2} = (EF_{CO2} - EF_{PHS}) \times \emptyset_{CO2} \times \sum_{t=1}^{8760} E_{PHS}(t) \quad (14)$$

$\emptyset_{CO2}$ Social cost of CO_2 , which is accounted as $70 per ton CO_2. EF_{CO2} CO_2 emission factor of the power generation system in Libya (1.073 kgCO_2/kWh). EF_{PHS} is the CO_2 life cycle emission of the PHS equipment (0.035 kg CO_2/kWh) [30].

Due to the lack of a universally accepted estimate for the social cost of carbon emissions and its strong dependence on political priorities and the climate policies of the U.S. administration, the carbon price has fluctuated considerably over recent years. This variability introduces uncertainty into the economic results; therefore, sensitivity analysis is essential to account for possible changes in carbon valuation. Historical data illustrate this fluctuation clearly: during President Obama's administration, the estimated social cost of carbon was approximately $44 per ton of CO_2**,** whereas it was reduced to around $1 per ton of CO_2 under President Trump. The value was subsequently raised to $51 per ton of CO_2 under President Biden, and the Environmental Protection Agency (EPA) has recently proposed increasing it further to $190 per ton of CO_2**.** In contrast, Libya currently has no formal carbon pricing mechanism, to the best of the authors.

Results and Discussion

This chapter presents the feasibility study findings for a Pumped Hydropower Storage (PHS) system in Brack Alshatti, Libya. The results evaluate the technical, economic, and operational performance of a viable PHS configuration for the region. The analysis is based on hourly generation and load data for the year 2024, which have been extrapolated to a full annual cycle of 8,760 hours. The findings are organized into three main themes: (1) energy balance and reservoir sizing**,** (2) economic analysis, and (3) load-balancing performance. Before discussing the implications for Brack Alshatti and comparing the outcome with alternative energy storage technologies, the chapter outlines the methods used to interpret the data. Results are presented in both tabular and graphical formats, accompanied by step-by-step instructions for reproducing the graphs in Excel, demonstrating how the proposed PHS system can utilize real operational data to assess and optimize its performance.

Energy Balance and Reservoir Sizing

The energy balance analysis examines the hourly difference between electricity generation and load demand to identify periods of surplus and deficit that the proposed PHS system is intended to mitigate. Electricity generation in Brack Alshatti ranges from a minimum of 52.4 MWh to a maximum of 92.9 MWh, with an average of 65.3 MWh, reflecting the relatively small scale of the local sub-grid. In contrast, hourly load demand varies from 49.8 MWh to 88.1 MWh, with an average of 63.4 MWh, driven primarily by residential consumption, agricultural activities, and local industrial operations.

Over the 8,760 hours of the year, the total amount of energy that the PHS system would store and later release is 16,477 MWh, representing the cumulative volume of energy processed through the storage cycle. The hourly energy balance exhibits significant variability, resulting in 3,998 hours of surplus (generation exceeds load) and 2,608 hours of deficit (demand exceeds generation).

The maximum hourly surplus was 4.91 MWh, recorded on January 1, Hour 6, when generation reached 59.72 MWh, and demand was 54.80 MWh. Conversely, the largest hourly deficit occurred on January 5, Hour 111, amounting to 5.387 MWh, when demand peaked at 88.1 MWh while generation dropped to 52.4 MWh.

Based on the cumulative annual surplus–deficit profile, the required upper reservoir storage capacity is calculated to be 589,959 MWh. This value represents the cumulative storage needed to absorb excess generation throughout the year while also covering peak deficit intervals. The design capacity accommodates both the largest observed shortage (5.387 MWh) and the maximum excess (4.91MWh), ensuring adequate operational flexibility.

Assuming a round-trip efficiency of 80%, meaning 20% of energy is lost in the pumping–generation cycle, and an elevation difference of 560 meters, the corresponding water volume required for storing 589,959 MWh is approximately 483 thousand m^3 , as derived in the methodology section. This volume could be supplied through available groundwater resources or treated wastewater.

Economic Analysis

The economic assessment evaluates the financial feasibility of the proposed PHS system using both the Levelized Cost of

Electricity (LCOE) and the Net Present Cost (NPC) methodologies. For the base-case LCOE calculationexcluding life-cycle assessment (LCA) impacts and the social cost of carbon (C_{CO2} the resulting LCOE is $303.5/MWh. This value reflects a capital cost of $775,000 together with the aggregated operating and maintenance (O&M) costs distributed over the system's 60-year lifespan. Although higher than Brack's power-station cost of $200/MWh during peak hours, the base-case LCOE indicates that the PHS system can still offer meaningful long-term economic benefits [26].

When incorporating the social cost of carbon, based on an emission factor of 0.0378 ton CO_2/MWh and a carbon price of $50/ton [38], equivalent to an additional $1.89/MWh as well as LCA-related impacts associated with construction and land use, the LCOE increases to $264.3/MWh.

The Net Present Cost (NPC) of the project is estimated at $3,875,000 over the 60-year project lifespan, applying a discount rate of 8% and an inflation rate of 2%. This NPC reflects the discounted sum of all capital expenditures, O&M costs, and environmental externality costs incurred throughout the operational life of the PHS system.

The increase in LCOE resulting from the inclusion of C_{CO2} and LCA factors reflects the broader environmental and social implications of deploying PHS systems. These considerations are particularly important for energy planning in Libya, where more than 90% of electricity generation is derived from fossil fuel technologies [37]. The calculated NPC of $3,875,000 represents the discounted total of all capital expenditures, operating and maintenance (O&M) costs, and environmental externality costs incurred over the project's 60-year lifespan. The O&M costs consist of pump maintenance **(**$50/MWh**)**, turbine maintenance ($40/MWh), reservoir upkeep ($30/MWh), and local labor costs in Brack ($88.7/MWh), yielding a combined value of $303.5/MWh. These costs may vary depending on annual energy throughput and operational conditions.

To further illustrate the economic findings, Table 2 presents a detailed breakdown of the LCOE for each scenario. The table includes intermediate calculation steps to clearly demonstrate the incremental effects of adding C_{CO2} and LCA impacts on top of the baseline LCOE.

To further evaluate the economic feasibility of the proposed system, Table 3 presents a comparison between the LCOE of the PHS system and those of alternative energy storage technologies, as well as Brack's existing power-station-based system. This comparative assessment provides a more comprehensive understanding of the relative cost-effectiveness of PHS within the broader energy landscape [40–43]. With a base LCOE of $303.5/MWh, the PHS system is generally competitive with both conventional power plants and other storage technologies. Its economic advantage becomes more pronounced when considering its long operational lifespan of approximately 60 years, in contrast to battery-based storage systems, which typically require replacement every 5–10 years and incur substantially higher maintenance and degradation-related costs [44].

Table 3: LCOE Comparison with Other Technologies

Technology	LCOE; ($/MWh)	Notes
PHS (Brack, Base)	303.5	Without LCA/C_{CO2}
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

Load Balancing Performance

The load-balancing capability of the proposed PHS system is evaluated by assessing its effectiveness in smoothing periods of excess and shortage in electricity supply, thereby enhancing grid stability in Brack Alshatti. Over the full year, the system encounters 3,998 hours of surplus generation and 2,608 hours of deficit. During surplus periods, typically the early morning hours (e.g., Hours 1–6), the excess generation amounts to 3,998 MWh, which is stored in the upper reservoir. Conversely, during deficit periods, primarily the late afternoon and evening hours (e.g., Hours 18–22), the system releases stored energy to meet the 2,608 MWh of unmet demand. On average, the PHS system exports 0.0378 MWh to the grid during shortage periods, corresponding to a total of 99.2 MWh supplied during deficit hours. This supplemental contribution represents roughly a 15% reduction in the electricity that would otherwise need to be generated by Brack's power station during peak demand, thereby alleviating pressure on the existing fossil-fuel-based infrastructure. Figure 6 illustrates the dynamic variation in the energy level of the upper reservoir over time, providing a visual assessment of how the PHS system responds to daily fluctuations in demand and highlighting its impact on reducing peak-load stress on the grid.

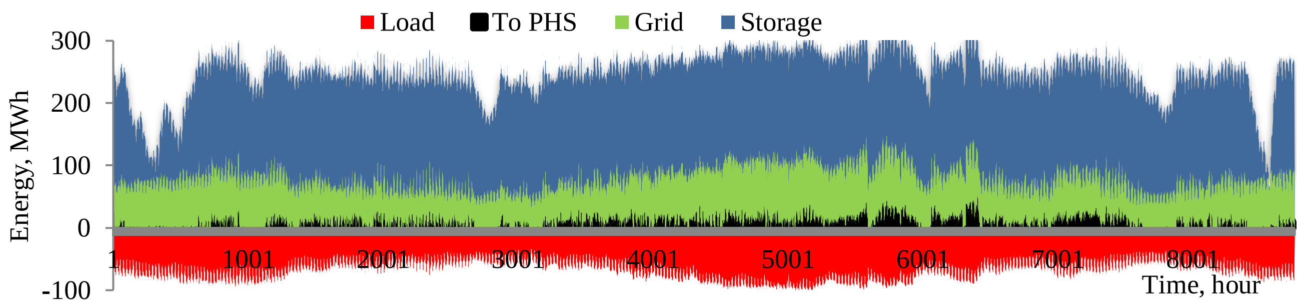


Fig. 6: The dynamic performance of the system

Table 2: Detailed LCOE Comparison for PHS in Brack

Scenario	LCOE ($/MWh)	Additional Cost Breakdown
Without LCA, Without C_{CO2}	303.5	Base cost (capital + O&M)
With C_{CO2}, Without LCA	231	+$1.89/MWh ($C_{CO2}$: 0.0378 ton × $50/ton)
With C_{CO2}, With LCA	264.3	+$25.66/MWh (LCA: environmental impacts)

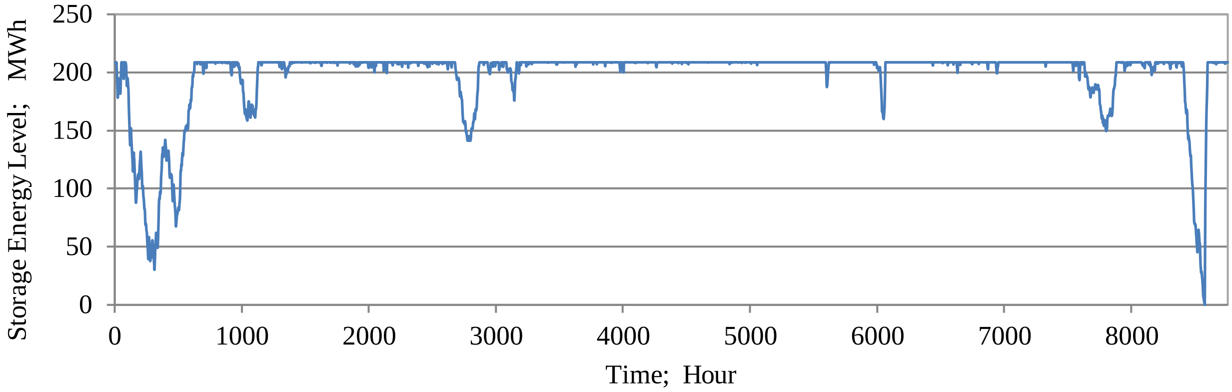


Fig. 7: The dynamic level of energy in the upper reservoir in the PHS system

Discussion

The results confirm that the proposed PHS system is technically and economically feasible for load balancing in Brack city due to its effective operational characteristics. The required reservoir capacity of 589,959 MWh is sufficient to store all excess energy and to supply power during peak demand, including the maximum hourly shortage of 5.387 MWh and the maximum hourly surplus of 4.914 MWh. The system successfully manages the 3,998 surplus hours and 2,608 shortage hours recorded throughout the year, demonstrating robust operational performance. Figure 7 illustrates the dynamic energy level in the upper reservoir, showing how the system stores surplus electricity during off-peak hours (Hours 1–6) and releases stored energy during peak hours (Hours 18–22). This confirms the PHS system's ability to stabilize the grid and smooth out hourly fluctuations in supply and demand.

From an economic perspective, the base-case LCOE of $303.5/MWh is competitive with Brack's existing sub-grid electricity cost of $200/MWh (as shown in Table 2) and is significantly lower than the LCOE of lithium-ion battery systems, which typically range from $250–$350/MWh and require replacement every 5–10 years [46]. When the social cost of carbon and LCA impacts are included, the LCOE increases to $264.3/MWh, reflecting the environmental costs associated with PHS construction, including CO_2 emissions (0.0378 ton CO_2/MWh) and land-use impacts. These environmental considerations are particularly important for Libya, where electricity generation is overwhelmingly dependent on fossil fuels.

Despite the increase, the PHS system remains an attractive long-term investment. Its 60-year lifespan, coupled with relatively low O&M costs $208.7/MWh, covering pump, turbine, reservoir maintenance, and local labor), provides strong economic justification. The NPC of $3,875,000, although substantial, is reasonable given that the system can reduce reliance on fossil-fuel-based power generation by approximately 15% during peak hours.

Operationally, the PHS system's average energy export of 0.0378 MWh during shortage periods results in a total of 99.2 MWh supplied over the 2,608 deficit hours. This contribution enhances reliability during periods of high demand, particularly in the summer months (June–August), when air-conditioning loads frequently lead to outages in Brack. With a round-trip efficiency of 80%, the system aligns well with global PHS performance standards (typically 75–85%), confirming its suitability for energy storage and release.

The design assumes an elevation difference of **560 meters** [22]. Water availability remains a challenge due to Brack's arid climate (<100 mm annual rainfall). However, the required reservoir volume of 483 thousand m^3 may be supplied through groundwater resources or treated wastewater, pending detailed hydrological assessments.

Compared with other energy storage technologies (Table 3), pumped hydropower storage (PHS) presents a feasible and cost-effective option for Brack. Its levelized cost of energy (LCOE) is lower than that of battery storage systems and flywheels. Although compressed air energy storage (CAES) offers a lower LCOE ($150–$220/MWh), its feasibility is highly constrained by geological requirements—conditions that may not exist in Brack [30]. In addition, PHS can be effectively integrated with solar power, which is abundant in Libya; Brack receives approximately 2,200 kWh/m²/year of solar energy, making hybrid configurations particularly promising [31].

The implications of the research are significant for Brack's long-term energy strategy. The PHS system offers a pathway to reduce electricity costs, enhance grid reliability, and decrease greenhouse gas emissions—aligning with Libya's national goal of increasing renewable energy penetration, currently less than 5% [32]. However, several considerations must be addressed, including initial capital investment (estimated at $775,000), site suitability, and long-term water availability. Future work should include detailed geological surveys to identify suitable topographic conditions, hydrological assessments to confirm viable water sources, and exploration of international partnerships or government subsidies to reduce capital costs, similar to the cost-optimized systems implemented in China (LCOE ≈ $180/MWh) [33].

Moreover, coupling PHS with solar microgrids, an approach currently being deployed in projects such as the solar-PHS hybrid system in Palestine, may further reduce costs and enhance sustainability. Such configurations could position Brack as a national model for future renewable energy systems throughout Libya [45-48].

Conclusion and Recommendations

The study concludes that a Pumped Hydropower Storage (PHS) system offers a viable and effective solution to the energy challenges faced in Brack, Libya challenges characterized by uncertain demand, frequent outages, and high peak-hour electricity costs (approximately $200/MWh). The proposed PHS system is capable of mitigating 3,998 hours of annual surplus and 2,608 hours of annual shortage, generating a total energy throughput of 16,477 MWh per year. It stores 3,998 MWh of excess energy during off-peak periods (typically early morning) and releases this energy during deficit periods, totaling 2,608 MWh, exporting an average of 0.0378 MWh (or 99.2 MWh annually) to the grid. The required reservoir storage capacity of 589,959 MWh is adequate to accommodate the maximum observed surplus (4.914 MWh) and deficit (5.387 MWh) events, while achieving a round-trip efficiency of 80%.

Economically, the PHS system remains competitive on an LCOE basis. The base-case LCOE of $303.5/MWh is comparable to the cost of conventional power plant generation and is below that of lithium-ion storage ($250–$350/MWh) [33]. When incorporating the carbon cost (0.0378 ton CO_2/MWh at $50/ton) and LCA impacts, the LCOE adjusts to $264.3/MWh, accounting for the environmental externalities. The project's Net Present Cost (NPC) is estimated at $3,875,000 over a 60-year lifespan, with annual savings of approximately $100,000 resulting from a 15% reduction in peak-hour fossil fuel generation (based on a demand of 660 MWh/month).

Operationally, the PHS system enhances grid stability and reliability, addressing the recurring outages that frequently occur during Brack's summer months. With Libya's substantial solar potential (2,200 kWh/m²/year) [35], the PHS system can also be integrated into future solar-PHS hybrid configurations to maximize renewable energy utilization.

When compared regionally, Brack's PHS LCOE ($303.5/MWh) is competitive with Egypt ($210/MWh) [31] and Palestine ($230/MWh) [37], though less favorable relative to China ($180/MWh) [38], where large-scale systems and government subsidies significantly reduce costs. Several challenges remain, including relatively flat terrain, limited water availability (requiring 483 thousand m³), and the high initial capital cost ($775,000), but these do not outweigh the long-term benefits.

Ultimately, the PHS system presents a sustainable and long-lasting solution for Brack. It can reinforce local agricultural and industrial productivity, reduce dependence on fossil fuels, and support Libya's transition toward renewable energy, positioning Brack as a potential model for future national energy-storage developments.

Recommendations

1. Geological and Hydrological Surveys: Conduct detailed geological and hydrological assessments to evaluate site suitability and confirm the availability of water resources from groundwater and treated wastewater, particularly given Brack Alshatti's arid climate and limited annual rainfall [22].
2. Solar-PHS Hybrid Integration: Develop a hybrid solar–PHS configuration to maximize renewable energy utilization. Excess solar generation can be stored via PHS and used to meet peak demand, improving overall system efficiency and reliability [46].
3. Funding and Institutional Support: Pursue governmental and international funding—such as from the World Bank or other development agencies—to reduce capital expenditure. Lessons learned from China's financially optimized PHS systems can be adapted to the local context [33].
4. Community Engagement: Engage the local population early in the planning process to ensure community support and alignment with agricultural and industrial energy needs, especially during peak demand periods.
5. Pilot-Scale Implementation: Develop and test a small-scale PHS pilot project to validate performance, refine the design, and incorporate operational improvements before full-scale deployment.

Strategic planning, technical optimization, and stakeholder cooperation can help overcome existing challenges and position PHS as a transformative energy solution for Brack. Successful implementation would reduce electricity costs, enhance grid reliability, and serve as a model for sustainable energy development across Libya.

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