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REVIEW ARTICLE **RENEWABLE ENERGY**

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

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ABSTRACT

The sporadic characteristics of adjustable renewable energy sources, along with fluctuating energy consumption, require an effective long-term energy storage solution. Pumped Hydroelectric Storage (PHS) has demonstrated its economic feasibility as an electricity storage technology and its compatibility with Renewable Energy Systems (RESs). The present study proposes a straightforward and effective methodology for the optimal size of a pumped hydro storage-integrated combined photovoltaic solar energy system (PV) for ensuring a sustainable energy supply for an urban population in Brack, Libya. A constrained optimization problem is used to formulate the sizing process. The limitations are meant to provide for the operational conditions and output uncertainty of RESs. Both the optimization procedure and the sizing technique are explained in detail. Several operational scenarios were studied to establish the ideal size of the hybrid PV energy system and the PHS. The proposed system consists of 500 MW of PV solar field and 5,770 MWh of storage capacity, generating enough energy to meet an estimated load of 590,019 MWh while preventing the emission of 611 tons of CO_2. Energy exported to the grid, levelized cost of electricity (LCOE), and system investment are also discussed.

مراجعة مختصرة في منظومات الطاقات البديلة الهجينة وتحليل منظومة الخلايا الشمسية المتصلة مع منظومة تخزين الطاقة الكهربائة بالضخ المائي لتغطية الحمل الكهربائي الكلي لمدينة براك الشاطئ-ليبيا

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الكلمات المفتاحية

تخزين الطاقة الكهرومائية
الطاقات المتجددة الهجينة
الطاقة الشمسية
الحجم المثالي
ليبيا.

الملخص

تتطلب الخصائص المتقطعة لمصادر الطاقة المتجددة القابلة للتعديل وتقلبات استهلاك الطاقة حلاً فعالاً لتخزين الطاقة على المدى الطويل. وقد أثبت تخزين الطاقة الكهرومائية بالضخ (PHS) جدواه الاقتصادية كتقنية لتخزين الكهرباء وتوافقه مع أنظمة الطاقة المتجددة. تقترح هذه الدراسة منهجية واضحة وفعالة لتحديد الحجم الأمثل لنظام طاقة كهروضوئية مدمج مع تخزين الطاقة الكهرومائية بالضخ، وذلك لضمان إمدادات طاقة مستدامة لسكان المناطق الحضرية في براك، ليبيا. تم استُخدام صيغة مقيدة مع تحسينات عليها لتحديد هذا الحجم. تهدف القيود إلى مراعاة الظروف التشغيلية وعدم اليقين في مخرجات أنظمة الطاقة المتجددة. حيث تم شرح كل من إجراء التحسين وتقنية تحديد الحجم بالتفصيل. تمت دراسة العديد من السيناريوهات التشغيلية لتحديد الحجم الأمثل لنظام الطاقة الكهروضوئية الهجين ونظام PHS. يتكون النظام المقترح من 500 ميجاوات من الخلايا الكهروضوئية و5770 ميجاوات ساعة من سعة التخزين، مما يُولّد طاقة كافية لتلبية حمل يُقدّر بـ 590,019 ميجاوات/ساعة ويمنع انبعاثات 611 طنًا من ثاني أكسيد الكربون. كما تمت مناقشة الطاقة المُصدّرة إلى الشبكة، مستوى تكلفة الكهرباء المُوَحَّد (LCOE)، والاستثمار في النظام.

Introduction

Driven by concerns about climate change and global warming, Global installed capacity of solar PV has grown continuously since 2000. In 2023, the global installed capacity of solar photovoltaic energy will reach 1,177 GW. This growth in the solar photovoltaic market reflects a global shift towards renewable and sustainable energy technologies. China and the United States lead the global PV market, with 307 and 122 GW of installed solar PV capacity, respectively. On the other hand, Chile and Honduras had the highest share of photovoltaic energy mix in total energy produced in 2023 [1]. The potential and viability of renewable energy resources as reliable and sustainable electrical energy sources have recently been world widely researched by the academic community and industry [2-20]. Nevertheless, Renewable Energy Systems (RESs) do not provide the same level of load-following flexibility compared to traditional fossil fuel power plants [21,22]. Additionally, the use of RESs, principally PV, decreases active /instantaneous power reserves, that are largely used for primary frequency management in the wake of abnormal operating conditions [23]. These RES shortfalls might be reduced by installing an

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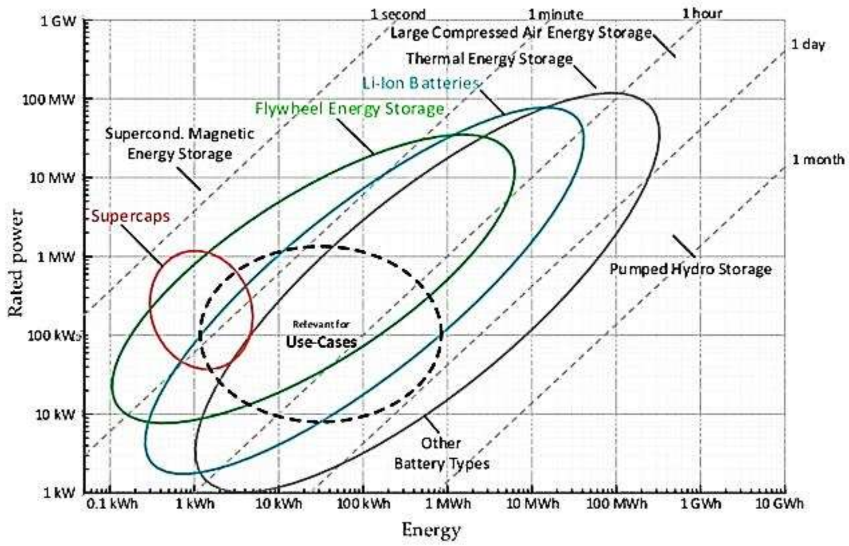

Fig. 1: Rated energy capacity versus power rating at different discharge times for different ESS
[Source: https://www.sciencedirect.com/science/article/pii/S0306261914010290]

efficient energy storage system (ESS). The ESS is capable of bidirectional power flow, allowing energy surplus to be stored during periods of generation shortcoming. Also, ESS systems, especially PHS, offer the essential synchronous inertia level needed to perform controlling the frequency [22]. In this regard, many works investigate several combinations of hybrid renewable energy systems integrated different energy storage technologies, such as: PV-Battery [24], PV-Generator-Battery [25]. PV-Batter-Fuel cell [26], PV-Wind-PHS-Battery [27], CSP-Wind-PHS [28], Wind-Battery [29], Wind-PHS, Wind-H_2, PV-Wind-Battery [30], PV-Wind-Battery [31], PV-Wind-PHS [32], PV-Biomass-Fuel Cell [33], PV-Grid [34] [35], PV-Wind [36]. More literature is summarized in Table A1, which shows the energy supply system, the storage system, the grid connection mode, and the key findings of the study. The global energy storage market experienced substantial growth, with 175.4 GWh of installed capacity added in 2024 [37]. There are several techniques of electrical energy storage such as but not only: Kinetic [38], potential [39], Electrical [40], Chemical [41] and Thermal [42] energy storages which are described in literature. However, pumped hydropower storage remains a significant technology, reaching 139.85 GW worldwide by 2023. Major markets include China and the Americas [39].

The ESS systems tend to offer multiple advantages, such as more effectively RES reliability and safety in both on-grid and off-grid operating modes, higher stability margins, less operating costs for utility grids, and facilitating switching from tradi1tional grids to smart grids. Many ESS technologies are depicted in Figure 1, which is reproduced here to emphasize the many obstacles and constraints while demonstrating the promise of various ESS techniques.

Figure 2 indicates the increasing global curiosity with Pumped Hydroelectric Storage (PHS) technology. In the Middle East and North Africa (MENA) region, still there are noticeably fewer confirmed PHS installations. Despite MENA's enormous potential for renewable energy sources (RESs), the region's distinct topography and the inclusion of PHS might result in major advantages. Libya, as a prominent MENA a performer, has developed an ambitious strategy to

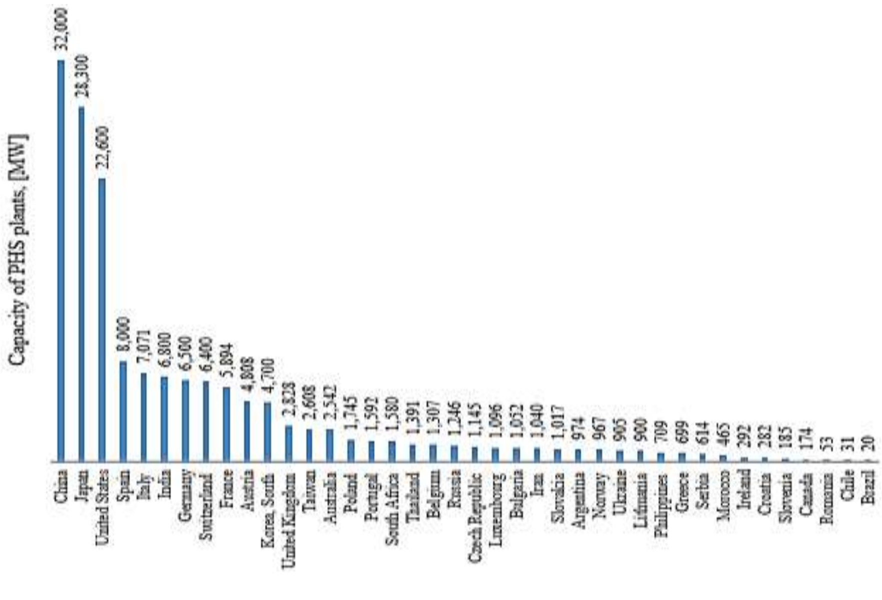

Fig.2: Capacity of PHS plants worldwide
[Source: https://www.hydroworld.com/industry-news/pumped-storage-hydro.html]

integrate PHS into its national energy framework, particularly in its southern metropolitan regions. The national grid is sensitive to voltage fluctuations, power sags, and general instability, which is a common problem. Considering Libya's abundant solar and wind energy resources, the integration of RESs without a reliable energy storage method may escalate these concerns. As a result, the deployment of a durable and economically feasible Energy Storage System (ESS) is critical. Fortunately, Libya's geographical characteristics allow for the reduction of capital expenditures associated with PHS initiatives.

For the purpose of fulfill Brack City, Libya's electricity demands, this study provides optimization sizing model for an isolated photovoltaic (PV) system integrating Pumped Hydroelectric Storage (PHS). Objective functions and constraint were applied to find the optimal size for the isolated PV-PHS system. In order to maintain costs that are equivalent to those of fossil fuel power plants while ensuring system security and stability, this strategy chooses objective functions such the Levelized Cost of Energy (LCOE) and the minimum Payback time money (PBTM), while the constraint is setup as zero value for Loss Power Supply Probability (LPSP). The System Advisor Model (SAM) is used to estimate the real productivity of the PV solar field under real time climatic data, which provided as hourly time series data by the renewable energy laboratory in Wadi Alshatti University for the year 2023.

The rest of the article is arranged as: Section 2: Discusses the methodology and attributes of the study site, including its geographic orientation, latitude, electrical characteristics, and climatological data. Also, outlines the unpredictable optimization procedure and presents the study hypothesis. Section3: Presents the results and analysis. While the drawn conclusion was provided in section 4.

Methodology

Layout of the Proposed Site

According to the hypothesis of the study the site has been selected near a 70-meter-high mountain and near the local electricity grid in Brack City, Libya (27°32′N, 14°17′E). In the near future, this site is a good option for constructing the appropriate power plant. An illustration of this location may be shown in Figure 3 in the appendix.

Key Information on the Study Area

Energy Situation

The hourly load distribution for the year of 2023 is presented in Figure 4. Behavioural analysis of the Alshatti district sub-grid for the year 2024 reveals that the total annual generated power was 605,879.5 MWh, while the load was 590,018.7 MWh. The total energy outage hours are 1573 hours.

Global Horizontal Solar Radiation (GHI)

The average hourly Global Horizontal Solar Radiation (GHI) data recorded for the study site during the year 2023 is also shown in Figure 5, which were collected from the meteorological station at the Solar Energy Laboratory of the Faculty of Engineering and Technical Science in Brack City.

Temperature

Temperature is an important climatic component since it directly affects both the electrical load and the performance of PV modules. Figure 6 depicts the average temperature of Brack City, which is roughly 22°C, with a range of 5°C to 40°C.

Topographer of the site

Mohammed et al., in [43] revealed that approximately 25% of Libya's land area is suitable for the construction of hydroelectric power storage stations, as it illustrated in Figure 7. The most promising sites have been identified throughout the country, with Brack Alshatti standing out as a particularly

Fig.3: Map of the site under consideration
[Source: https://www.istanbul-city-guide.com/map/libya/map-of-libya.gif]

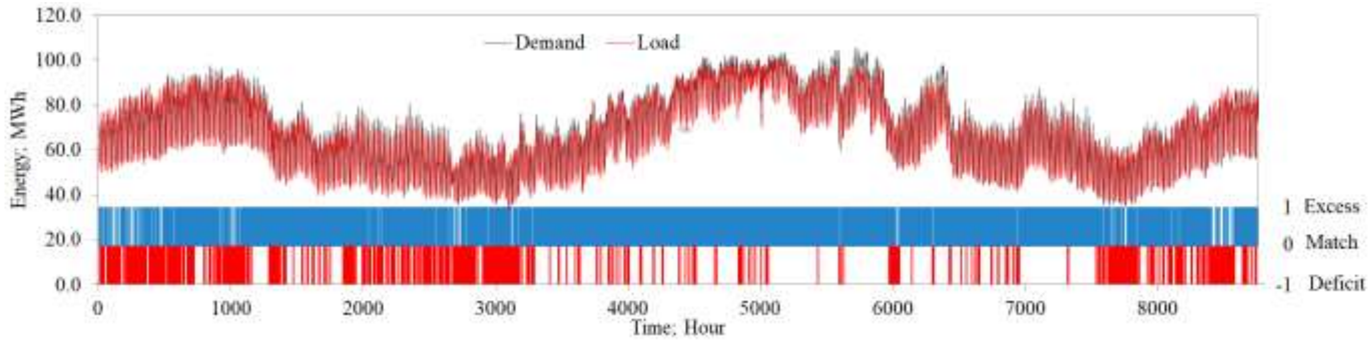

Fig.4: Hourly generated power, demand, hours of deficit, coincidence and surplus power in the sub-grid - Alshatti

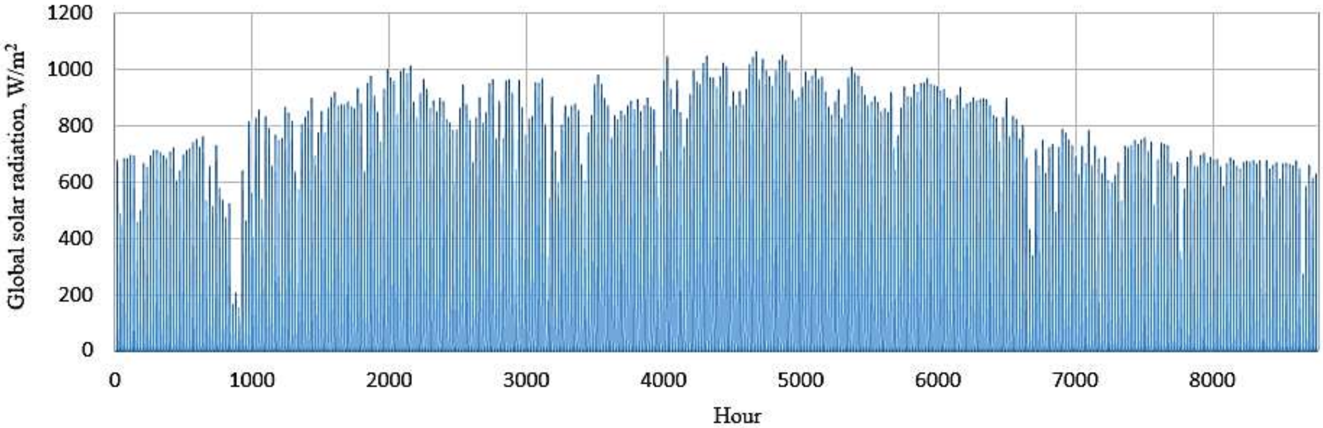

Fig.5: Hourly global horizontal solar radiation (GHI)

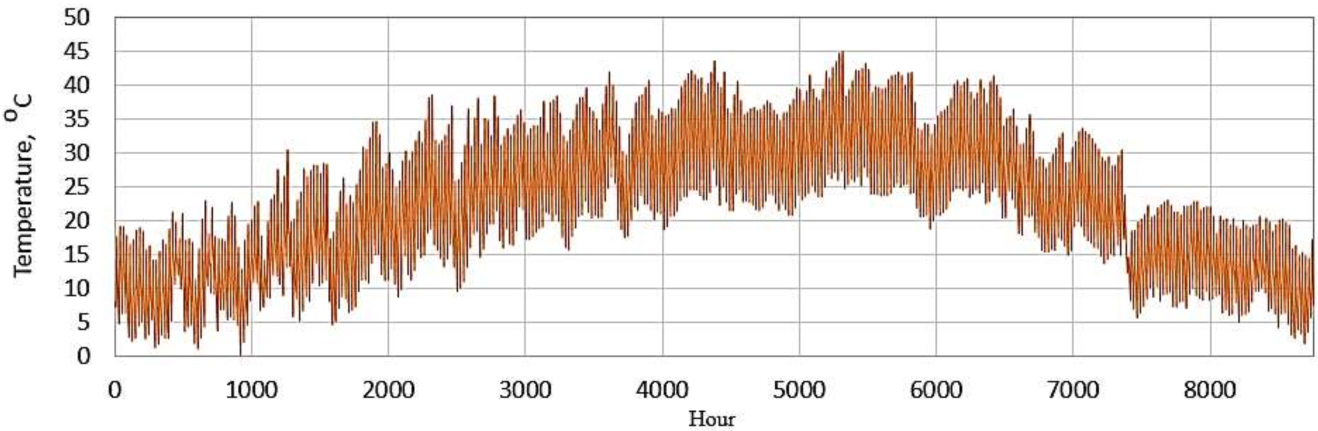

Fig.6: Hourly ambient air temperature

desirable location, one of its mountains (27.54^0 '14.260) rises approximately 650 meters from its base, making it ideal for such projects.

Layout of Proposed hybrid renewable power and PHS system

The research's utility has been enhanced by investigating a photovoltaic power system (PV) combined with pumped hydro storage (PHS). The suggested system's structure is illustrated in Figure 8.

The renewable energy sources (RESs) have intrinsic intermittency and uncertainty. To deal with these issues, control systems for photovoltaic (PV) panels are intended to optimize power extraction under changing climatic circumstances, as shown in Figure 8. Furthermore, the suggested system utilizes DC distribution to mitigate energy losses and enhance voltage management.

Figure 8 depicts the Pumped Hydroelectric Storage (PHS) system, which comprises of two naturally occurring reservoirs at the research site. This geographical advantage has the potential to significantly reduce the capital costs of the proposed hybrid power and PHS system.

PHS works in three different modes: zero, positive, and negative. In positive mode, turbine engines transform waterpower into mechanical energy, which powers electrical generators. In negative mode, the power flow reverses, and the generators act as motors, pumping water back into the upper reservoir for storage. The quantity of energy stored is determined by the elevation difference between reservoirs and the total volume of water.

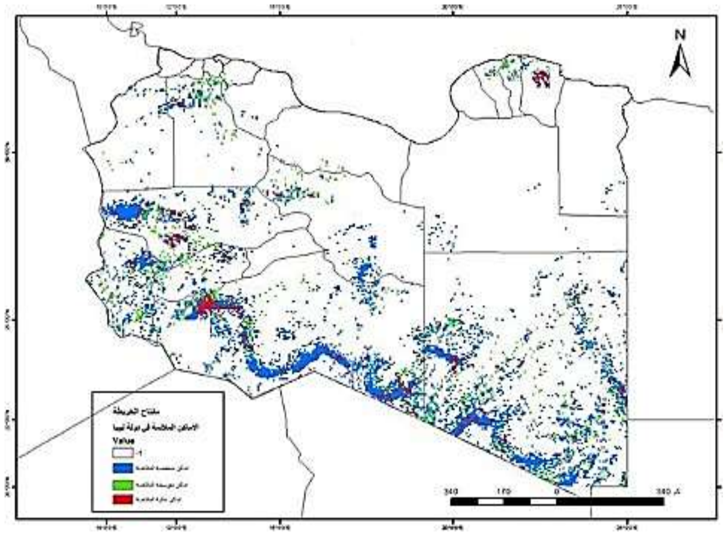

Fig.7: Promising Locations for the Consumption of Pumped Hydro Energy Storage Plants
[Source: https://www.waujpas.com/index.php/journal/article/view/128]

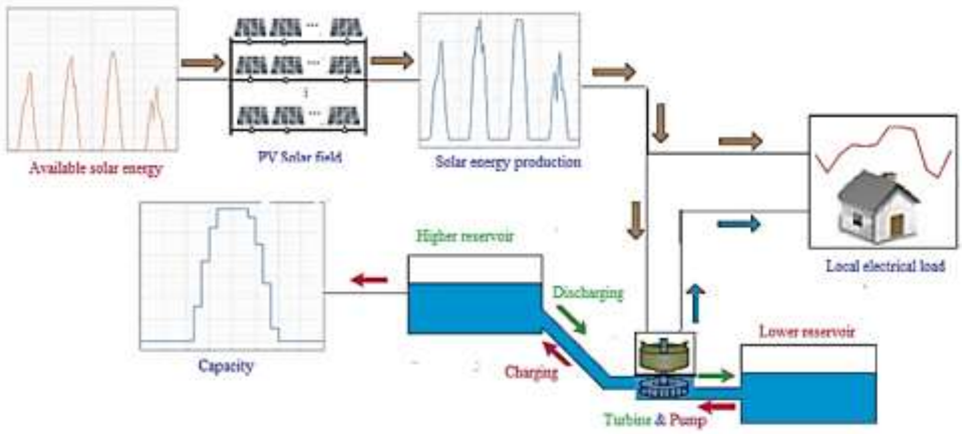

Fig.8: Photovoltaic complementary power generation system with PHS and operating performance curves

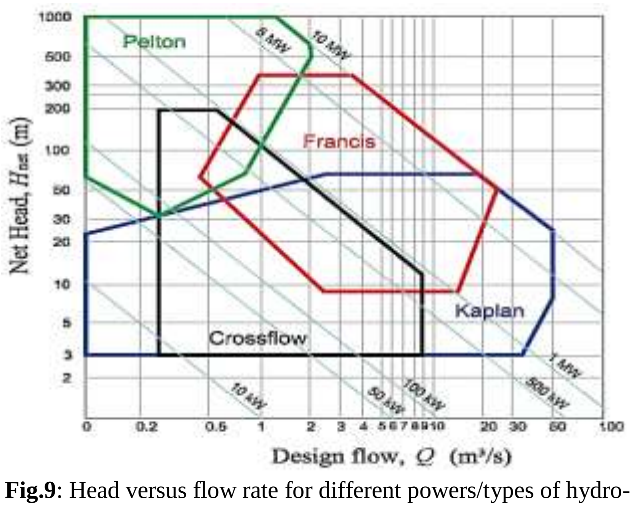

Fig.9: Head versus flow rate for different powers/types of hydro-power turbines
[Source: https://www.researchgate.net/publication/282819109]

The rated power of PHS plants depends on the water flows rate through the turbines and the total system efficiency. The power ratings for various PHS plants range from 1 kW to 3,000 MW, with a cycle efficiency of around 70-90%. Furthermore, PHS systems have a lifespan typically approaching 60 years. Figure 9 shows operation zones to different types of turbines at a given head and volumetric flow rate.

Static sizing of proposed PHS

PHS power flow is directional subject to the mode of operation. However, the power regardless of generating, Pt, or pumping modes, Pp, is defined by the PHS mechanism's attributes. This is given by [23],

$$P_t = \rho\ g\ \dot{Q}(H + h_f)\eta_t \qquad (1)$$

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

where ρ is the working fluid density (kg/m^3), g is the ground gravity (m/s^2), $\dot{Q}$is the volumetric flow rate (m^3/s), H is the elevation of the higher reservoir (m), η_p and η_t are the efficiency of the pump and the turbine respectively, and h_f is the head loss (m) which is given by the Darcy-Welsbach formula [23] as:

$$h_f = \frac{8\ L\ f\ Q^2}{\pi^2\ g\ D^5} \qquad (3)$$

where D is the diameter of the penstock (m),

$$D = 0.72\ Q^{0.5} \qquad (4)$$

while f is friction factor, and L is the penstock length (m). The value of 0.2 could be set for f in the Darcy-Welsbach formula to get an initial estimation of head loss. Then, the friction factor value f is updated. Generally, the friction factor value f could be estimated directly from the theoretical Moody diagram or by [18],

$$f = \left\{1.8\ log\left[\frac{6.9}{Re} + \left(\frac{\varepsilon}{3.7\ D}\right)^{1.11}\right]\right\}^{-2} \quad (5)$$

where ϵ is the roughness of the penstock, and Re is the Reynold's number that could be calculated in terms of flow rate as:

$$Re = \frac{4\ Q}{\pi D \nu} \quad (6)$$

where: ν is the kinematics viscosity *(m^2/s)*

Dynamic sizing of proposed system

PV solar energy

The productivity of the PV solar panel is affected with the solar radiation incident on the surface of the panel and the temperature of the cell's PV panel, as [44.45]:

$$P_{PV} = P_{STC} \times \frac{H_t}{H_{STC}}[1 + \beta_P(T_{cell} - T_\infty)] \quad (7)$$

Where $T_{cell} = T_\infty + 0.078 H_t$

The choice of TF solar cell type was based on recommendations from local researchers [46.47]. The same is true for inclination and orientation angles and calculations of the total solar radiation incident on the solar field.

Table 1: Technical characteristic of the PV and inverter [Source: https://www.principalsolarinstitute.org/psi_ratings_query_stion/]

Solar module	Country	Technology	η	Pmax	V_{mp}	Imp	Bp	βv	βI
			%	W	Volt	Amp	%/°C	%/°C	%/°C
Stion SN-115	USA	T-F	11.40	125	41.0	3.0	-0.400	-0.360	0.007

Instantaneous PHS energy, E_{PHS}

The instantaneous PHS energy E_{PHS} is given by,

$$E_{PHS}(t) = E_{PV}(t) - E_L(t) \quad (8)$$

Where $E_b(t)$ represents the energy balance of the system

Storage Capacity, E_{PHS}

The storage capacity represents the energy level in the upper reservoir and is determined through the following three-step process:

1. **Initial Assumption:**
   - Assume an initial storage capacity, denoted as $E^i_{S,1}$ where the superscript (i) represents different capacity variations in the electrical supply, and the subscript (1) indicates the first assumption of the reservoir capacity.
2. **Minimum Value Evaluation:**
   - Assess the minimum storage capacity over a full year (8,760 hours).
   - If the minimum value falls below zero, it indicates a shortage in the upper reservoir's capacity. Conversely, a non-negative value suggests that the assumed capacity is sufficient.
3. **Adjustment and Iteration:**
   - Based on the results of Step 2, refine the storage capacity estimate.
   - The second iteration will determine the exact required storage capacity.

$$E^i_S(t) = E^i_S(t - \Delta t) + B_E(t), \text{t = 1, 8760 , 1}$$
$$E^i_S(0) = E^1_S \qquad \text{Initial condition} \quad (9)$$

Therefore, the storage capacity $E_S(V)$ will be found as:

$$E_S(V) = E^1_S(0) - \min\left(E^1_S(t)\right)_{t=1-8760}\text{, MWh} \quad (10)$$

Pump capacity, E_{Pump}

The energy required to pump the water from the lower reservoir to the upper one is calculated by,

$$E_{Pump} = \min(B_E(t))_{t=1-8760} \quad (11)$$

Turbine capacity , $E_{Turbine}$

The PHS system supplies electrical energy to the power grid to meet load demands during periods of supply deficiency. In accordance with the principle of energy balance, the energy generated is equal to the energy used for pumping.

$$\mathbf{E_{Turbine}} = \max(B_E(t))_{t=1-8760} \quad (12)$$

Assumptions, limitations, of the research and the uncertainties of the results

The following assumptions are considered in this study to facilitate the analysis:

- The upper reservoir is initially full.
- The PHS system is considered to be lossless, without leaks or evaporation.
- The head calculates neglects to take into account the water level in the upper reservoir.
- Water flow through the penstock is considered turbulent.
- Pump and turbine efficiencies are assumed to be constant, regardless of flow rate.
- All PV modules receive uniform solar irradiance and temperature.

Optimization process

Objective functions

This research aims to determine the optimal configuration of a PV/PHS system for Brack City, Libya, while minimizing the Levelized Cost of Energy (LCOE) and the minimum Payback Time Money (PBTM). Accordingly, the objective function (*OF*) is expressed in Eqn. (13).

$$OF = w_1(\text{LCOE}) + w_2(\text{PBTM}) \quad (13)$$

$$LOCE = \frac{\left[\frac{r(1+r)^{n_{PHS}}}{(1+r)^{n_{PHS}-1}} C_{PHS} + \frac{r(1+r)^{n_{PV}}}{(1+r)^{n_{PV}-1}} C_{PV} + O_{PV} + O_{PHS}\right]}{E_L} \quad (14)$$

where C_{PHS} and C_{PV} are the capital costs of the PHS and PV system; O_{PHS} and O_{PV} are PHS and PV operation & maintenance costs respectively. r states for the discount rate (2.5%). n_{PHS} and n_{PV} are the PHS and PV system lifespans.
TB, the total benefits of the hybrid system over the project lifespan [26] is given by,

$$TB = \left\{\frac{(1+r)^n - 1}{r(1+r)^n}\right\} I_S \qquad (15)$$

The average annual benefits TB_{av} is given by [26],

$$TB_{av} = \frac{TB}{n} \qquad (16)$$

The average annual benefit gives indication on the economic feasibility of the project. Another economic indicator is the Payback Time Money, *PBTM* depends on the project total cost, C_s, and average annual benefit TB_{av}. *PBTM* is given by,

$$PBTM = \frac{C_S}{TB_{av}} \qquad (17)$$

The Economic, technical and environmental data of the HRES components are tabulated in Table 2.

Table 2: Economic, technical and environmental data of the HRES components

Metric	Value
PV solar field	
Capital cost of PV solar field; C_{PV}	\$876/kW
Operation and maintenance; O_{PV}	\$20/kW/year
Life time; n_{pv}	25 years
PHS Energy	
Capital cost of PHS; C_{PHS}	\$1,982/kWh
Operation and maintenance; O_{PHS}	\$3.88/kW/year
Elevation; H	650 m
Life time; n_{PHS}	60 years
Environmental aspects	
EF_{CO2} for solar PV energy	52 kg CO_2/MWh
EF_{CO2} for PHS energy	35 kg CO_2/MWh
EF_{CO2} of electricity generation in Libya	1,037 kg CO_2/MWh
Social cost of CO_2	\$ 70/ton CO_2

Constraint

The proposed hybrid renewable power system must be reliable and capable of sustaining an independent energy supply, as it serves as the sole source for meeting the site's load demand. Therefore, the objective function in Equation (14) is subject to the Loss of Power Supply Probability (LPSP) constraint.

$$LPSP = \frac{\sum_{t=1}^{8760}[E_L(t) - (E_{PV}(t) + (-1)^m E_{PHS}(t))]}{\sum_{t=1}^{8760} E_L(t)} \qquad (18)$$

where $E_L(t)$, $E_{PV}(t)$, $E_{PHS}(t)$ are instantaneous load, PV and PHS energy respectively. The acceptable LPSP For the system under consideration, the LPSP is set between 1% and 5%, balancing high reliability with power supply security in the proposed hybrid system. The LPSP value ranges from 0 to 1, where **0.0** indicates full load fulfillment, while **1.0** signifies a complete sizing deficiency. However, achieving an LPSP of zero requires a significantly costly renewable power system.
An LPSP of 1% corresponds to approximately 87.6 hours of load disruption per year. Therefore, in the proposed sizing procedure, LPSP is incorporated as a constraint on the generated power. In this study, LPSP is set to **zero**, ensuring full load fulfillment.

Results and discussion

Sizing the PV solar filed

The temporal results of the photovoltaic solar field with a capacity of 500 MW are illustrated in Figure 10. The diagram depicts that the overall productivity of the solar field has variations throughout the year, with temporary drops at certain times. The further drop in productivity of solar field is mainly due to hot climate which affects the performance of photovoltaic solar energy which is temperature sensitive
Figure 11 shows the energy levels in the pumped hydro storage (PHS) system according to the specified design and operating parameters. It also validates the sizing technique, proving that the system has satisfied the entire load equal to 100% of demands. The two-way direction of PHS power indicates its technical feasibility since it acts as a source as well as a sink for the load, thus ensuring supply continuity and compliance with the operational constraints of the design.

Cost analysis of the hybrid renewable system.

The cost analysis is conducted for the proposed system, which integrates PV and PHS, to ensure it meets the full load requirements while considering the given constraints.
From Figure 12, the Levelized Cost of Energy (LCOE) serves as a reliable economic indicator for comparison. Investing more in the system impacts no matter much to the LCOE. The general finding is that a capacity of 500 MW and of 5770 MW storage is the optimal system size. This setup guarantees effective energy performance for the suggested system.
Figure 13 illustrates hourly energy produced, Stored and consumed in the proposed HRES.

Sizing PHS for the proposed PV

The best option based on economic assessment is the one with the minimum Levelized Cost of Energy (LCOE). According to Figure 12, the lowest LCOE is achieved using a 500 MWh PV Solar field and 5770 MWh from the PHS system, which is the most economical option.
Designing a Pumped Hydro Storage (PHS) system for a Photovoltaic (PV) power plant requires careful consideration of storage capacity, power rating, and reservoir volume to achieve a steady equilibrium of energy production and load demand. The following structured approach outlines the process for sizing a PHS system for a 5000 MW PV solar field with a 5770 MWh storage capacity. By following this step-by-step methodology, a reliable PHS system can be designed while considering energy storage demands, system constraints, and operational requirements.

Conclusions

An optimization approach was developed and implemented to find the appropriate capacity of a PHS-integrated hybrid PV power system for powering a southern Libyan urban area. The system's capacity was optimized while maintaining the lowest Levelized Cost of Energy (LCOE) and attaining 100% load demand coverage within the specified limits. A hybrid Renewable Energy System (RES) with a 5000 MWh solar PV field and a 5770 MWh PHS (equal to 343,373 m³ of storage volume) was demonstrated to be an appropriate

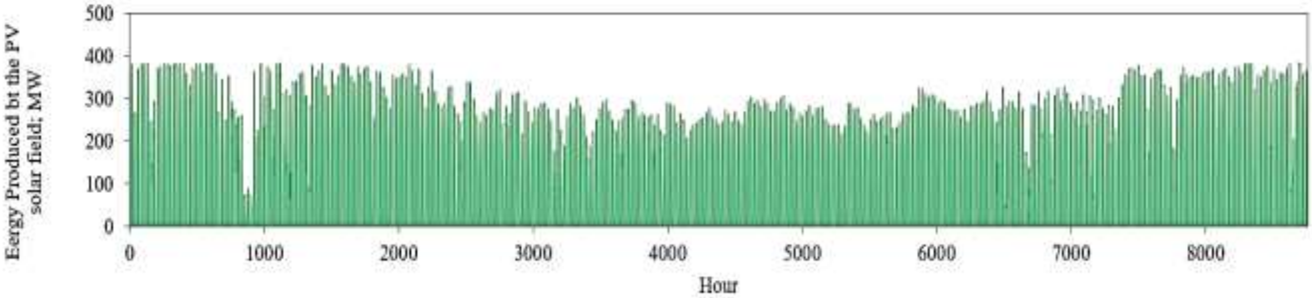

Fig.10: Energy Produced by the PV solar field; MWh

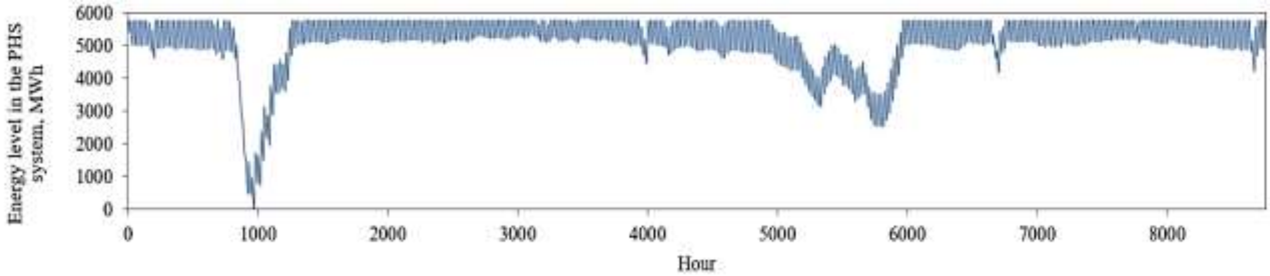

Fig.11: Energy Level in the PHS system; MWh

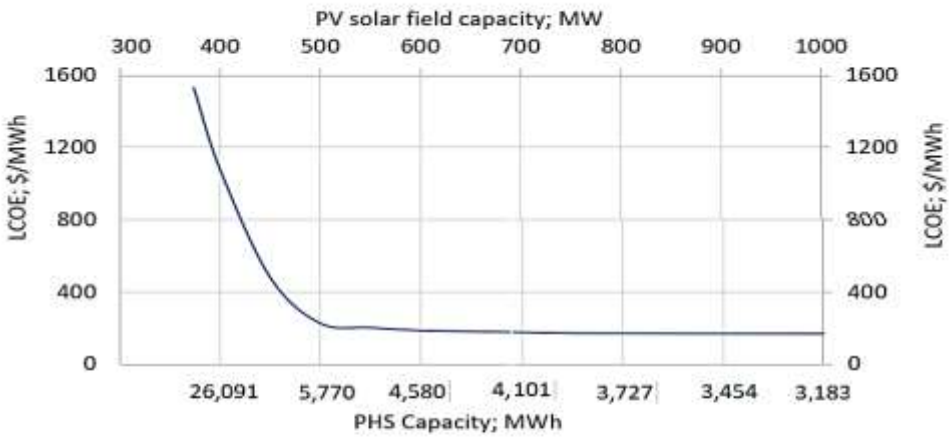

Fig.12: Sizing optimization process on the Pac LCOE

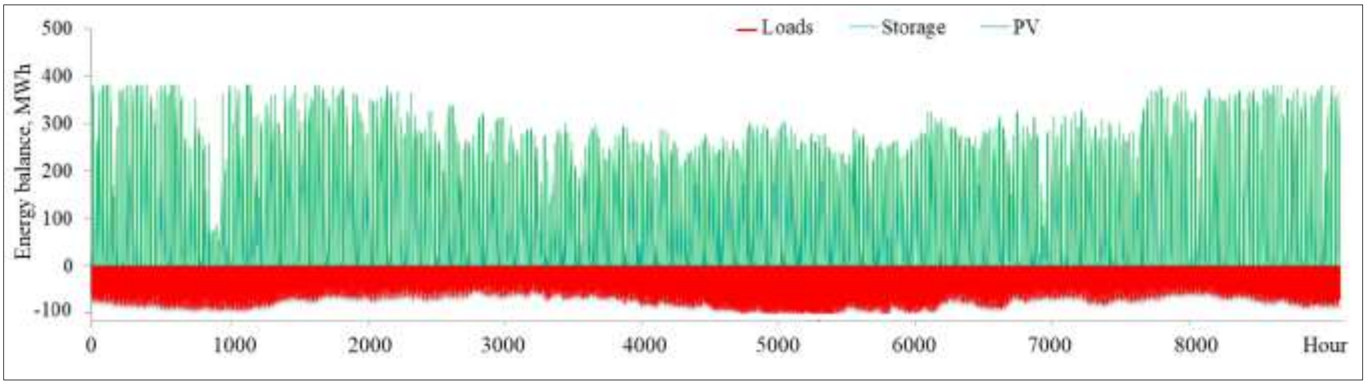

Fig.13: Stacked Energy balance of the PV/PHS

option for ensuring a reliable source of energy to an electric load with a peak power demand of 100.8 MW. The system directly delivers approximately 55% of the energy demand from the hybrid RES, while the remaining 45% is absorbed by the PHS. The established system, which includes 500 MW of solar PV and 5770 MW of storage, is intended to provide enough energy to fully meet the annual expected load of 590,019 MWh. While, about 248386.5 MWh estimated as an energy surplus from the HRES, which can be exported to the utility grid to make an additional economic profit to the proposed system. By depending on renewable energy sources, the system helps to reduce carbon dioxide emissions by about 611,850 tons CO2 per year (according to the emission factor of the power generation system in Libya is about 1,037 kg CO_2/MWh [48-52]), helping to environmental conservation. The annual cost of CO_2 damage was estimated as US$ 42,829,480 (as the cost of CO_2 is $70/ton CO_2 [53-55]). The successful execution of such efforts shortage a supportive environment that includes suitable financing sources and legal frameworks for associated studies. Furthermore, it is vital to plan for the transition to environmentally friendly power generation and to encourage private sector participation in renewable energy applications.

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Appendix

Table A1: Literature review on the hybrid renewable energy systems

Design	Storage	Grid	Country	Key findings	Ref.
PV/WT/BG	=	On/Off	China	Off-grid and on-grid modes are analyzed through simulations, optimizations and sensitivity analysis. In off-grid mode, the optimal system comprises PV panels of 29 kW, 5 Wind turbines of 10 kW, 30 kW BDG, 89 Batteries of Generic 1 kWh Lead Acid, and 26 kW converter. The initial capital and LCOE of $142,220 and $0.131/kWh, respectively. While in on-grid mode, the optimal system comprises PV panels of 64 kW, 6 Wind turbines of 10 kW, 30 kW, and 42 kW converter, with initial capital and LCOE of $311,634 and $0.084/kWh, respectively.	[56]
PV/WT/ BG/DG	B	On/Off	Turkey	Biomass-based hybrid power system with solar energy reduced net present cost by around 12% and increased renewable fraction by 7%, and grid-connected options can provide 88.9% renewable fraction. In addition, the energy storage integration increased renewable fraction by around 10% and reduced excess energy by 16%.	[57]
PV/BG	B	Off	Bengal	The CO2 emission avoided is about 140 ton. The LCOE in the range of 0.101 $/kWh-0.105 $/kWh	[58]
HCPV	B	Off	Kuwait	The yearly average efficiency of integrated HCPV-battery system is 39.1 % compared to 40.2 % for the normal HCPV system. So, for one year period operation, the loss in energy resulted from temperature rise in integrated HCPV-battery system is about 2.7 % in comparison to normal HCPV battery installation system.	[59]
PV/WT	PHS	Off	Libya	A hybrid RES of 1000 kWp solar PV array and 5000 kW wind turbines farm coupled with PHS of 27,954 kWh capacity (equivalent to 166,532 m3 volume capacity) was found eligible to fulfil the requirements for the sustainable energy supply for an electric load of 1.2 MW peak power and 6.14 GWh annual energy consumption. The system supplies the load with about 85% of its energy demand directly from the hybrid RES and the rest (about 15%) is covered by the PHS. The avoided CO2 is about 4385 ton/year. The LCOE $0.132/kWh	[60]
PV/WT/DG	B	Off	Palestine	It found that the PV-Wind-Diesel generators HES is able to cover 100% of the load with LCOE of $0.348/kWh	[61]
PV/BG	-	On	India	The LCOE of the proposed hybrid system is about $0.099/kWh. The optimal system is estimated to save 27.8 Mt CO2/year (w.r.t diesel-only system).	[62]
PV/WT	-	On	Djibouti	The study showed that the contribution of RE can be as much as 77 % with 47 % of solar and 30% of Wind energy. The LCOE $0.02/kWh compared with the average cost of grid of $0.32/kWh.	[63]
PV/WT	B	Off	Algeria	The cost of the batteries represented for this combination is 52% of the total investment cost, the WT accounted for 42%, the PV panels for only 3% and 4% for the inverter. The LCOE of 0.2388€/kWh	[64]
PV	B/FC	On	Japan	The research proposed a state machine-based energy management strategy, combined with a hysteresis band control strategy that aims to achieve the system’s power balancing state while also being able to maintain the battery’s state of charge and level of stored hydrogen.	[65]
CSP	PHS	Off	Egypt	LCOE 4.45 ₡/kWh, Net capital cost, $150E6, Annual energy 131E6kWh. Capacity 50MW	[66]
PV/DG	B	Off	Sudan	The LCOE 0.328$/kWh	[67]
PV/WT	B	Off	Botswana	The offered hybrid system employs 100% renewable energy, resulting in zero carbon emissions. Solar generates 53.7% of production, while wind generates 46.3%. The system has a 25-year lifespan with a 7.6% return on investment and an 11.4% internal rate of return.	[68]
CSP/WT	B/FC	Off	Morocco	The NPC/ LCOE of 3.391 M€/ 0.126 €/kWh, respectively. The LCOH value of 21.4 €/kg	[69]
PV/HT/DG	B	Off	Iraq	Techno-economic and environmental performance of different systems are discussed. Sensitivity analysis considering variations in several parameters is conducted.	[70]
PV	B	Off	Brazil	Provided a new method for managing the power battery and improving (MPPT) performance and the battery lifetime.	[71]
PV/WT	B/FC	Off	Canada	The results show that wind resources along with solar and storage technologies can play a key role in satisfying RC electricity demand, while significantly reducing costs and Greenhouse Gas Emissions (GHG). In addition, insights on sustainable and affordable policies for	[72]

				RC MGs are provided.	
PV/WT/DG	B	On	Nigeria	It is shown from the simulation result that the incorporation of solar PV and battery storage into the existing system reduces the NPC by 32.3% and decreases the annual diesel fuel usage by 48.9%.	[73]
PV/WT	B/FC	Off	Saudi Arabia	The results demonstrated that the "best-optimized system has 270 kW of photovoltaic (PV), 1 unit of 300 kW of wind turbine (WT), 500 kW of electrolyzer, 100 kg/L of the hydrogen tank, 70 units of 1 kWh lithium-ion battery, and 472 kW of the converter. The selected hybrid energy system has the lowest LCOE, LCOH, and NPC of $/kWh 0.6208, $/kg 9.34, and $ 484,360.00 respectively	[74]
PV	B/FC	On/Off	Oman	The analysis has shown that a 3 MWp grid-connected PV system represents a promising green hydrogen production at an LHC of 5.5 €/kg. The system produces 58 615 kg of green hydrogen per year reducing carbon dioxide emission by 8209 kg per year. The LHC in the stand-alone PV system with batteries, and stand-alone PV system with fuel cells are 5.74 €/kg and 7.38 €/kg, respectively.	[75]
PV/WT/BG	B/PHS	On	Cyprus	The HRS is designed for a university camps, it consists of 1.79 MW PV, 2 MW wind and 0.92 MW biomass systems with 24.39 MWh pumped hydro storage system and 148.64 kWh batteries. The LCOE equals to 0.1626 $/kWh.	[76]
CSP/TPP	-	Off	Vietnam	According to the calculations performed for the basic case with no solar radiation, the efficiency of the 4.6MW power station was η = 0.345, the fuel consumption mF = 0.056 kg/s, and for the 11.86 MW station η = 0.317 and mF =0.72 kg/s. The highest intensity of solar radiation is achieved in February and April. At that time the efficiency is increased by 13.3% compared to the basic case, while fuel consumption is reduced by11.7% (for a 4.6 MW station). For a more powerful station, efficiency is increased by 12.3% and fuel is reduced by 11.1%. Thus, due to the use of solar energy, substantial fuel savings are achieved.	[77]
PV	B	On	Poland	For a properly designed photovoltaic system, the energy self-consumption can be up to 90.19%, while self-sufficiency can be up to 82.55% for analysed cases.	[78]
PVT/CSP/HE	FC	Off	Russia	In the present study, a hybrid renewable system to supply the electricity, heating and fresh water demands of a near zero energy building (NZEB) is proposed.	[79]
PV/WT	-	On	USA	comprehensive assessment of temporal complementarity for co-located wind-PV hybrid systems at greater than 1.7 million locations across the contiguous United States. We model hourly variation in potential wind and solar generation for a period spanning 2007–2013 and evaluate robust evidence for complementarity using multiple metrics to assess correlations and stabilization benefits achieved via hybridization.	[80]
PV/WT/CSP	TS/B/PHS	Off	Chile	The main results indicate that by 2050, and considering a baseline scenario defined for 2016, for most of the scenarios studied the renewable electricity generation would be at least a 90 % and CO_2 emissions would be 75 % lower.	[81]
PV/WT	B	Off	Botswana	The results show that the PV/wind/battery system generates the most economic and technical benefits, as measured by the Net Present Cost (NPC). Due to the high initial expenditures on renewable energy systems, the Levelized Cost of Energy (LCOE) of the system is 65 percent higher than the present energy cost in Botswana for households and 57 percent higher for companies.	[82]
PV/TS	B/FC	Off	Spain	This study shows that the use of microgrids for a single-family home is a technically viable solution, not only in terms of energy demand, but also in terms of power demand which is not study in any other literature to the best of our knowledge. For this scale, the use of hydrogen technologies is technically possible, but economically unfeasible, because of the high investment costs of the necessary equipment.	[83]
PV/WT/HT/BG	-	-	South Korea	The results show that a convolutional neural network can efficiently predict sequential demand electricity (R^2 = 98.79%), with respective Bio, solar, hydro, and wind energies optimally supplied 45.7, 34.52, 14, and 5.78%. under optimal conditions in S. Korea.	[84]
PV/HT	-	Off	Indonesia	This combined power plant can service the electrical load of 962 households. The production of electricity to supply the domestic housing load is 3273 kWh per day. In addition to meeting the needs of the local area, excess electrical power from micro-hydro and solar photovoltaic plants can also be sold to available grid systems. Based on the analysis, the excess electricity that can be sold every year is 4,263,951 kWh.	[85]
PV/WT/DG	B	Off	Malaysia	Results show that scenario B, with the net present cost (NPC) of 188,814$ and the cost of energy (COE) of 0.198$/kWh, is reliable in delivering the electricity required while having a reasonable cost relatively low emission. Sensitivity analysis is also carried out with different parameters to examine its effects on the system's sustainability throughout its lifetime.	[86]

PV/BG	-	On	Argentina	The optimum hybrid system size was the installation of biomass plant with 2.4 kW capacity, and 16 solar panels with a capacity of 5.2 kW. The initial investment required is 17,042 USD, with a payback of 3.4 years and a GHG reduction of 275.9 tons of CO_2 eq per year.	[87]
PV/DG	B	Off	Ethiopia	The proposed microgrid configuration is capable to meet an average daily load of 3,596 kWh/day with 405 kW peak power demand. The NPC of $4.13M and at LCOE of $0.149.	[88]
PV/WT/CSP	PHS	Off	Qatar	The results show that increasing the share of RES in electricity production is possible by as much as 80%. The optimum cases for the deployment of wind, PV, and CSP with storage technologies presented a 28.3%, 23.4%, and 38.2% share to electricity produced, respectively. The market economic simulation shows that the total annual cost for some of the scenarios that integrated renewable energy was lower than that of the reference case currently deployed in the country.	[89]
PV/DG	B/FC	Off	UAE	The LCOE was found 0.34 $/kWh after including the capital, recourses, operation and maintenance, and replacement cost for the lifetime of the project which is 25 years. The unmet electrical load and shortage capacity were 0.0102 % and 0.0912 %, respectively. Furthermore, the environmental impact of the system was compared with the diesel energy system based on the carbon footprint and emission as in carbon dioxide, carbon monoxide, unburn hydrocarbon, sulfur dioxide, and nitrogen oxide. The carbon footprint was 90.1 which equivalent to 1000 saving diesel gallons.	[90]
CSP/BG	-	Off	Jordan	Hybrid system of waste incineration — parabolic trough plant was investigated to generate power and desalinate water. Around 34 MWe power can be generated and 13,824 m3/day of water desalinated. Superheated steam temperature can be fixed at 550 °C due to continuous waste loading. Minimum treatment cost of each Ton of MSW is found to be 11.5 US$ in the 15th year of operation. Around 2,450 tons/month of CO_2 emissions were reduced due to solar field performance.	[91]
PV/WT	B	On	Chile	The evaluation of the potential of on-site 1MWh steady electricity generation from a hybrid renewable energy system consisting of photovoltaic micro-generation, wind turbines and battery systems shows mixed results for Chile. Only specific regions possess weather conditions where complementarity between solar and wind resources would be an advantage. In regions with very high solar radiation and low cloudiness, such as in the Atacama Desert, there is no apparent advantage of combining PV and wind power. Under those climatic conditions, systems consisting only of PV and Battery would be able to constantly provide 1 MWh of energy at the lowest cost.	[92]
PV/WT	B	Off	Kenya	The techno-economic modelling shows that PV/wind hybrids have both technical and economic potential at average wind speeds above 4.5 m/s but little relevance below. The capacities of the components are PV, WT and bakeries are 72.5 kW, 5.4 kW and 242 kWh, the NPC is $ 440,000 and he LCOE of $0.676 for kWh	[93]
PV/DG	-	Off	Burkina Faso	The results revealed that the hybrid configuration PV/Diesel leads to about 54% decrease of the LCOE when compared to conventional diesel generator stand-alone configuration. Furthermore, it has been shown that the discount rate and fuel prices have a sharp impact on the LCOE. A decline of the interest rate from 9% to 0% results in 83% decrease of electricity cost while an increase of fuel cost from $1.2/L to $3/L results in a staggering 110% increase of the LCOE.	[94]
PV/W/BG	B	On	Bulgaria	One tonne MSW can potentially produce up to 1000 kWh of electricity. Biogas generator is found to make the most substantial share of electricity generation (up to 60–65% of total)	[95]
PV/WT	FC	OF	Chad	The results showed that in the electricity generation scenario, the average total NPC for the studied stations was $ 48164 and the average LCOE was $0.573. The lowest LCOE was related to Aouzou station with 0.507 $/kWh and the highest LCOE was obtained for Bol station with 0.604 $/kWh. In the simultaneous electricity and hydrogen generation scenario, the cheapest hydrogen ($4.695/kg) was produced in the "Grid" scenario, which was the same for all of the stations, with a total NPC of $2413770. The most expensive hydrogen ($4.707/kg) was generated in the "Grid-Wind" scenario and Bol stations with a total NPC of $2420186. The paper develops cost effective	[96]
PV/WT	B/FC	Off	UK	The cost of electricity (COE) of the new system was £0.776 per kilowatt hour.	[97]
PV/DG	B	On	Lebanon	The optimization approach offers an efficient methodology to evaluate alternative designs in order to select the best source sizes that minimize the LCOE of the system.	[98]
PV/WT/DG	B	Off	Syria	The system consists of photovoltaic (PV) panels and a wind turbine as renewable power sources, a diesel generator for back-up power and batteries to store excess energy and to improve the system reliability. The optimization results show that using a power supply	[99]

				system consisting only of batteries, PV and wind generators may be applicable as well to satisfy the power demand.	
PV/WT/DG	FC	Off	Tunisia	It is shown that the system guarantees a dumped energy of only 4.7%, less than 0.05% of unmet power and reduced power losses resulting from converting procedure of 1.02% from the total production. From a financial perspective, the proposed model presents a competitive LCOE of $0.0492/kWh and a renewable fraction of 35.52% with further diminished carbon dioxide emission.	[100]
PV/WT	B/FC	On	Bahrain	The annual renewable energy production of the HRES was 3,518 kWh, where 3,285 kWh was produced by the 4.0-kWp PV system with an annual yield of 821 kWh/kWp and 348 kWh was produced by the 1.7-kW WT system with an annual yield of 205 kWh/kW. the HRES reduced the annual CO_2 emission from an expected value of 3,800 kg of CO_2 – in case of powering the station using the public grid only – to 1,990 kg, a 48%-reduction.	[101]
WT/DG	B	On	Mauritania	Analysis shows that the optimum combination of the hybrid system is (wind /diesel / batteries): 4 wind turbines of 100 kW each, two generators of 100 kW each, 400 batteries of 4 V / 1900 Ah / 7.6 kWh each and a converter of 150 kW. This configuration records a total NPC of 3, 151,076 $, a cost per kWh of 0.199 $ with a renewable energy fraction of 0.77 (77%) and finally, the diesel generator runs 2,937 h.	[102]
PV/WT	FC	Off	South Africa	The capital cost of the hybrid system was found to be $177,600 with a NPC of $206,323. The LCOE of the system was determined to be 2.34 $/kWh.	[103]
PV/WT/DG	-	Off	Scotland	The research focused on seeking the optimal size of the batteries and the diesel generator usage in small sizes systems.	[104]
PV/WT		Off	Bangladesh	The work presented a feasibility and sensitivity analysis of on/off grid mode hybrid renewable energy by estimating the potentials of solar and wind energies at different areas in Bangladesh - a country that experiences a tropical climate.	[105]
PV	B	On	Cameroon	The system is designed and optimized for household energy supply in three different locations in Cameroon. The monthly PV/Battery energy represents 58.371% to 74.160% of the load consumed.	[106]
PV/WT/DG	-	Off	Comoros	A study of PV-Wind-Diesel system for energy supply in remote areas applied for telecommunications towers in Comoros was conducted using HOMER software tool. The LCOE of the energy generated by the offered system (0.198 $/kWh) is cheaper of the Comoros energy (0.31 $/kWh).	[107]
PV/WT/DG	B	Off	Peru	Technical aspects of implementation, operation, and social impact of a hybrid microgrid installed in Peru has been studied, a rural fishing community composed of about 35 families who have no access to electricity. The wind speed average of 8 m/s and annual average irradiation of 6 kWh/m^2/day. The designed hybrid system is composed of a 6 kWp PV system and two wind turbines of 3 kW each, 4 kW inverters, and a battery bank of 800 Ah, 48 V, which is designed to work at 50% DOD.	[108]

Abbreviations: B- Battery, PV- Photovoltaic solar panel, WT- Wind turbine, BG- Biogas electrical generator, DG- Diesel electrical generator, FC- Fuel cell, HT- Hydro-turbine, GE-geothermal energy, PHS-pumped hydro storage system, TPP- thermal power plant, HE- Hydrogen engine, CSP- concentrated solar power, TS- thermal storage.