



Energy Management Strategy and Efficient Fuel Use for a Hybrid System with Pumped Storage Integration

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ABSTRACT

Photovoltaic panels sometimes produce excess power and at other times insufficient energy. To address this uncontrolled production, a storage system is essential. In this paper, pumped hydroelectric storage (PHS) is preferred as an energy storage system due to its ecological benefits and relevance to the context. Managing the energy of a PV/DG/PHS hybrid system requires specific control that considers the temporal availability of solar energy, optimizing diesel fuel consumption in real-time, and accommodating pumping constraints. The proposal showcases the efficiency of the PHS double effect system in terms of irrigation and electricity generation, while also highlighting fuel savings and a decrease in CO₂ emissions. This research validates the new, precise method for calculating online fuel consumption per kWh, outperforming previous studies, and successfully tested within the suggested energy management system. The approach can be utilized in similar future research efforts.

استراتيجية إدارة الطاقة وكفاءة استخدام الوقود لنظام هجين متكامل مع التخزين بالضخ

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الكلمات المفتاحية:

الألواح الكهروضوئية
التخزين الكهرومائي بالضخ
الطاقة المتجددة
انبعاثات الكربون
نظام هجين.

الملخص

تنتج الألواح الكهروضوئية أحياناً طاقة فائضة وأحياناً أخرى طاقة غير كافية. لمواجهة هذا الإنتاج غير المنتظم، يُعد نظام التخزين أمراً ضرورياً. في هذه الورقة، تم تفضيل نظام التخزين الكهرومائي بالضخ نظراً لفوائده البيئية وملاءمته للسياق. يتطلب إدارة طاقة النظام الهجين تحكماً دقيقاً يأخذ بعين الاعتبار التوفر الزمني للطاقة الشمسية، مع تحسين استهلاك الوقود في الوقت الفعلي واستيعاب قيود الضخ. تعرض الورقة كفاءة نظام التخزين الكهرومائي ذو التأثير المزدوج من حيث الري وتوليد الكهرباء، مع إبراز توفير الوقود وتقليل انبعاثات ثاني أكسيد الكربون. تثبت هذه الدراسة صحة طريقة جديدة ودقيقة لحساب استهلاك الوقود لكل كيلوواط/ساعة بشكل مباشر، متفوقة على الدراسات السابقة، وتم اختبارها بنجاح في إطار نظام إدارة الطاقة المقترح. يمكن اعتماد هذا النهج في أبحاث مماثلة مستقبلية.

1. Introduction

The hybrid microgrid system (HMGS) with renewable energy, as shown in Figure 1, is a compelling option for remote sites, ensuring continuous supply, cohesion, and energy reliability. The HMGS consists of a diesel generator and photovoltaic source combined with a storage system, providing enhanced performance. This system is particularly favorable for isolated areas as it not only reduces the carbon oxides environmental emissions (CO_x), nitrogen oxides (NO_x), and sulfur oxides (SO_x), but also offers cost-effective maintenance and operation.

The HMGS technology is derived from the concept of smart systems, employing an optimal strategy to minimize energy losses, thus ensuring efficient resource use, reducing energy transmission losses,

and maintaining the quality and reliability of energy services. Furthermore, the energy management control (EMC) strategy in the HMGS is advanced, optimizing the use of both photovoltaic (PV) and pumped storage hydroelectric (PSH) sources. This EMC strategy functions intelligently and efficiently to meet energy needs in a range of different conditions.

2. Model Description

For long-term investment, the project must meet both financial and technical criteria while genuinely addressing the energy demands of the load. Two key factors primarily influence this: the consumers and the diverse energy sources (PV, DG, PSH). The core purpose of hybridization is demonstrated in Eq(1) and Fig 1.

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$$(1) \quad P_{LOAD}(t) = P_{DG}(t) + P_{PV}(t) + P_{PHS}(t)$$

The hybrid microgrid system combines photovoltaic (PV) panels, diesel generators (DG), and pumped storage hydroelectric (PSH) systems to guarantee a stable and uninterrupted energy supply. Each element contributes significantly to the system's overall efficiency and performance. PV panels capture solar energy, diesel generators serve as backup during periods of low solar output, and the PSH system stores surplus energy for future use.

The goal is to achieve an optimal balance between these sources, ensuring that the energy supply meets the demand while minimizing costs and environmental impact. The mathematical model, represented by Eq(1), and the system configuration, depicted in Fig 1, provide a comprehensive framework for analyzing and optimizing the hybrid system's performance.

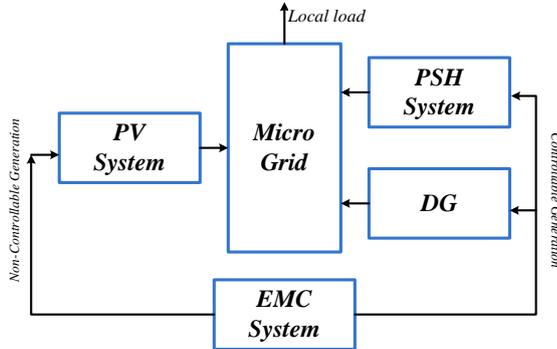


Fig. 1: the studied hybrid microgrid system

a. PV Array

The PV array is a crucial part of the HMGES, supplying power to meet load demands. When excess power is generated, it is used to pump water to the upper tank. The PV output power (PPV) is determined using Eq(2), which factors in the incident irradiance (GIIR). In this study, the SunPower SPR-305-WHT module is employed for the PV system.

$$(2) \quad P_{PV} = P_{STC} \frac{G_{IIR}}{G_{STC}} (1 + k(T_c - T_a))$$

Calculation of PV Output Power

The PV output power can be determined using the following equation:

$$(3) \quad P_{PV} = P_{rated} \times \frac{G_{IIR}}{G_{STC}}$$

where:

(P_{PV}) is the PV output power.

(P_{rated}) is the rated power of the PV module (305 W for the SunPower SPR-305-WHT).

(G_{IIR}) is the incident irradiance.

(G_{STC}) is the standard test condition irradiance (typically 1000 W/m²). This equation allows us to estimate the power output of the PV array based on the available solar irradiance, enabling efficient energy management within the hybrid system.

b. Generator

When the solar and the storage system (ESS) sources cannot fulfill the energy requirements, the diesel generator (DG) serves as a backup to improve the reliability of power generation. The selection of the appropriate DG depends on factors like peak load, fuel consumption (FC), and transportation expenses. The DG's key attributes include its efficiency and fuel consumption rate.

Calculation of Diesel Generator Fuel Consumption

The fuel consumption (FC) of the DG can be calculated using Eq(3), which is the traditional method:

$$(4) \quad FC = a.P_{DG} + b$$

where:

(FC) is the fuel consumption in liters per hour (liter/h).

(P_{DG}) is the power output of the diesel generator in kilowatts (kW).

(a) and (b) are coefficients that depend on the specific DG model and its efficiency.

This equation allows for the estimation of the DG's fuel consumption based on its power output, which is crucial for optimizing the overall energy management and ensuring cost-effective operation within the hybrid system.

This method involves using Matlab to model the DG's performance and obtain a more accurate equation for fuel consumption based on various operational parameters. This approach aims to improve the precision of fuel consumption estimates, thereby optimizing energy

management and reducing operational costs in the hybrid system. The resulting equation, Eq(4), provides a detailed and specific relationship between the DG's power output and its fuel consumption, tailored to the particular characteristics of the DG used in the system.

$$(5) \quad FC_2 = a(e^{(b.P_{DG}(t))}) + c(e^{(d.P_{DG}(t))})$$

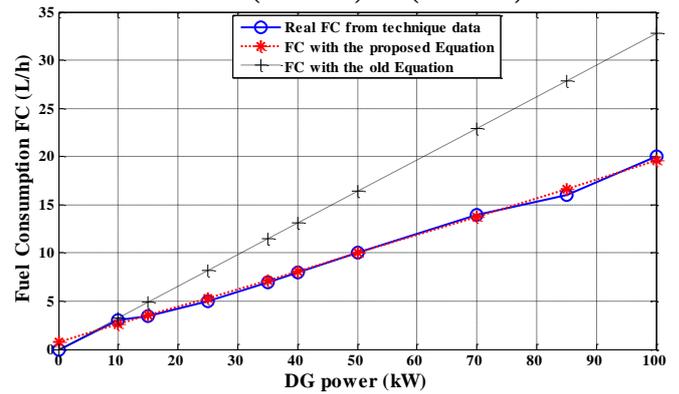


Fig. 2: different power of DG Fuel Consumption

c. Energy Storage System

The pumped storage hydroelectric (PSH) system can function as an efficient energy storage solution (ESS) in remote regions, with a state of charge (SOC) efficiency of up to 80%. It works by converting surplus energy into gravitational potential energy. When required, water is released from an upper reservoir, flowing through pipes to power a turbine generator. The pump and turbine output power are described by Eq(5) and Eq(6), respectively.

Pump and Turbine Output Power Equations

$$(6) \quad P_{pump} = \rho \cdot g \cdot Q \cdot h$$

where:

(P_{pump}) is the pump output power.

(ρ) is the density of the fluid.

(g) is the acceleration due to gravity.

(Q) is the flow rate of the fluid.

(h) is the height difference between the upper and lower reservoirs.

$$(7) \quad P_{turbine} = \eta \cdot \rho \cdot g \cdot Q \cdot h$$

where:

($P_{turbine}$) is the turbine output power.

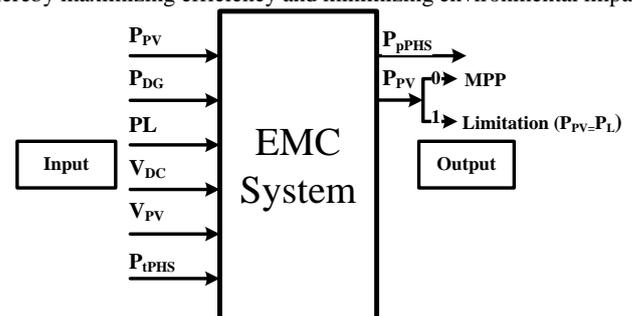
(η) is the efficiency of the turbine.

These equations describe the power generation process in the PSH system, illustrating how excess energy is stored and later utilized to generate electricity when needed.

d. Energy Management Control (EMC) Strategy

The EMC collects data from the hybrid microgrid energy system (HMGES) to determine an economically accurate strategy, such as starting the diesel generator (DG) or utilizing the energy stored in the pumped storage hydroelectric (PSH) system. It aims to increase the reliability of the entire system by providing uninterrupted energy to customers under different climate conditions. The EMC strategy guarantees the performance and effectiveness of the HMG by reducing both the economic costs and the CO₂ emissions associated with DG fuel consumption.

The control strategy procedure is summarized in a flowchart depicted in Fig. 3. This flowchart outlines the steps involved in decision-making and ensures the optimal operation of the hybrid system, thereby maximizing efficiency and minimizing environmental impact.



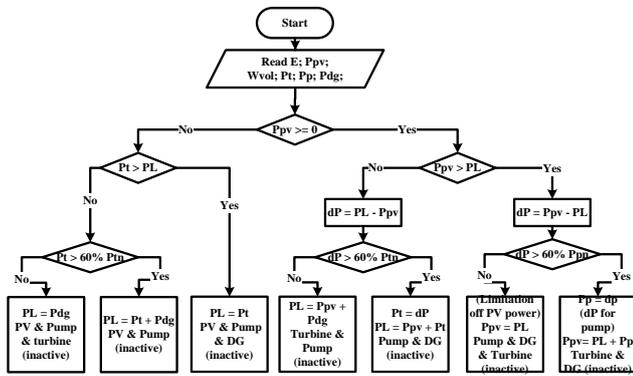


Fig. 3: strategy EMC flowchart

3. Results and Discussion

a. Solar Irradiation Profiles

Figure 4.a displays various solar irradiation profiles collected from the site. The data includes three chosen days: the first day features high solar irradiation density (rich), the second day shows moderate solar irradiation (normal), and the third day records the lowest solar irradiation density (poor). These profiles were obtained from the Renewable Energy weather station of the Research Unit-Medium Saharan (URER-MS).

PV Power Output:

The corresponding output PV power is depicted in Figure 4.b, derived from the available solar irradiation data. It illustrates the variation in PV power generation based on the solar irradiation levels throughout the selected days.

Power Requirements Profile:

Figure 4.c illustrates the power requirements profile for supplying domestic loads, as well as additional power for agricultural demands. This profile reflects the energy needs of the system under consideration, encompassing both residential and agricultural consumption patterns.

Analyzing these results provides a thorough understanding of the performance and dynamics of the hybrid microgrid energy system. This insight facilitates informed decision-making and optimization strategies to effectively meet energy demands while enhancing both efficiency and reliability.

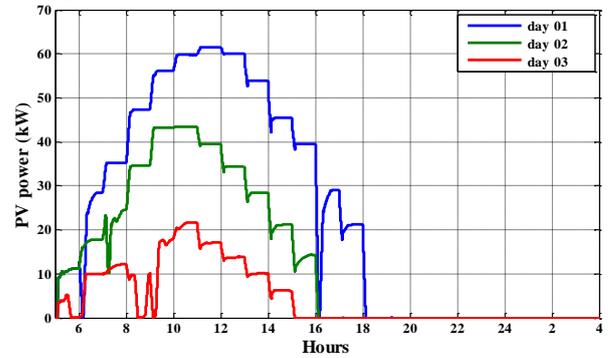
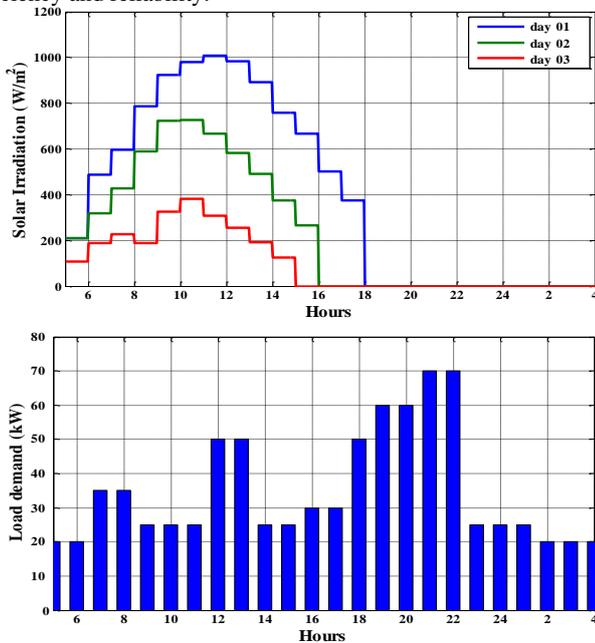


Fig. 4: The selected three days of solar irradiation data, The load demands profile, The PV output Power during 24 hours

b. Integration of Pumped Storage Hydroelectric (PSH) System

The pumped hydroelectric storage (PSH) system is incorporated into the available resources of the hybrid microgrid energy system (HMGES) to improve production flexibility. When the results show that the PV source alone cannot satisfy energy demands, the PSH turbine is activated.

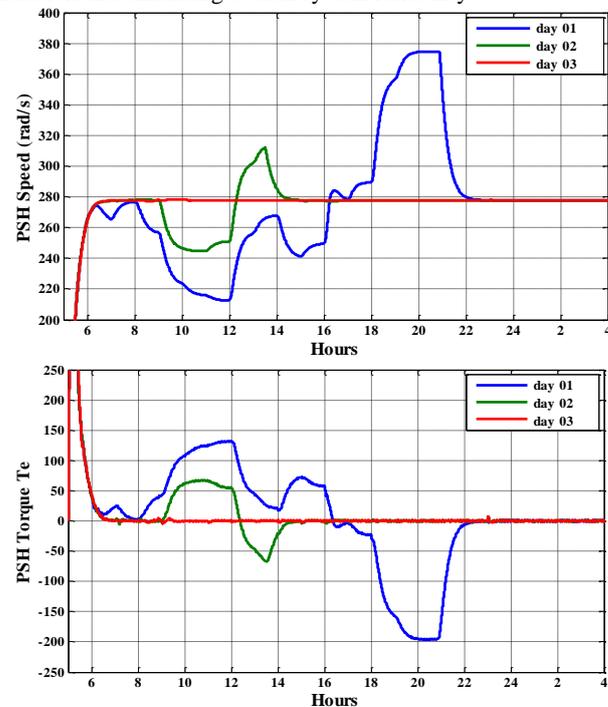
PSH Operation Modes:

Figure 5 demonstrates the characteristics of the PSH system in both charging and discharging modes. In discharge mode, indicated by the output PSH power, the system supplies the necessary energy, keeping the diesel generator (DG) inactive. However, if the PSH system is unable to fulfill the supply requirements, the DG is activated to bridge the gap, thereby reducing dependence on the DG and mitigating its associated drawbacks.

Output Power Comparison:

Figure 6 presents the output power of both the PSH system and the DG. It demonstrates the interplay between these two energy sources, highlighting the dynamic adjustment of the system to optimize energy production while minimizing reliance on conventional diesel generation.

This integrated approach ensures a more resilient and efficient energy supply, with the PSH system acting as a complementary resource to the PV source, thereby reducing reliance on fossil fuel-based generation and enhancing overall system reliability.



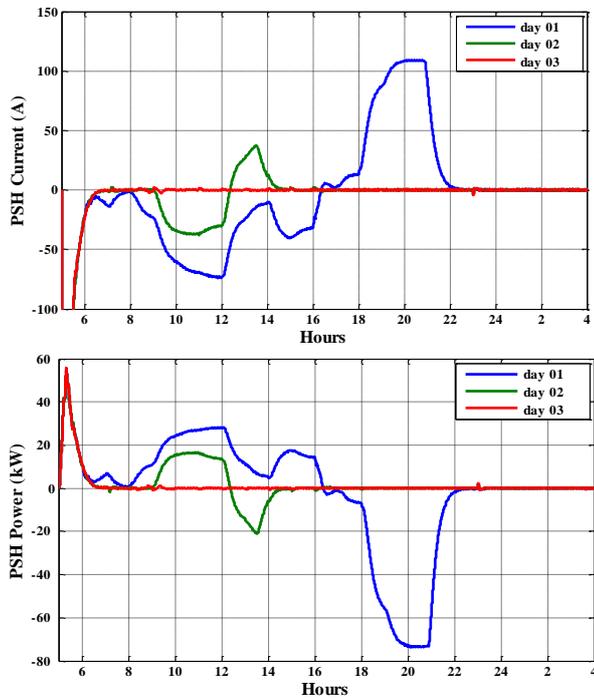


Fig. 5: (a) The Speed (rad/s), (b) Torque, (c) Current, and (d) the output PHS power of the system characteristics.

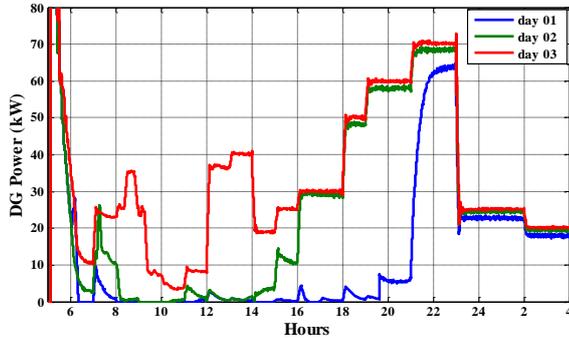


Fig. 6: The output power produced by DG during the selected days.

c. CO₂ Gas Emission Analysis

The emission of CO₂ gas (Figure 7.a) is directly proportional to the output energy of the diesel generator (DG), its running time, and its fuel consumption (FC) (Figure 7.b). Consequently, both the DG output power and the FC are influenced by factors such as the solar penetration of the site, the state of charge (SOC) of the pumped storage hydroelectric (PSH) system, and the effectiveness of the energy management control (EMC) strategy.

d. Impact of EMC Strategy

The EMC strategy plays a crucial role in minimizing CO₂ emissions and reducing FC costs (Figure 7.c). By optimizing the operation of the hybrid microgrid energy system (HMGES), the EMC strategy effectively regulates the usage of the DG and coordinates its operation with other available energy sources, such as the PV array and the PSH system. This results in reduced reliance on the DG, leading to lower CO₂ emissions and decreased FC costs, ultimately contributing to a more sustainable and cost-effective energy production process. Through the integration of renewable energy sources, efficient energy storage systems, and intelligent control strategies, the HMGES demonstrates its potential to mitigate environmental impacts and optimize economic performance, paving the way for a more sustainable energy future.

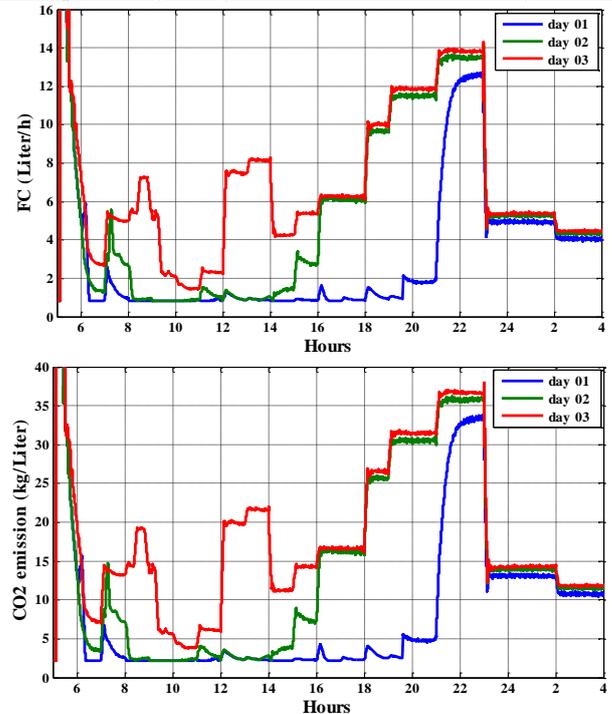


Fig. 7: (a) FC (Liter/h), (b) CO₂ emission (kg/L), and (c) The FC cost (€/L) of DG during the selected days.

e. Optimal Power Generation by HMGES

Figure 8 illustrates the optimal power generation by the hybrid microgrid energy system (HMGES) over a 24-hour period under different profiles of solar irradiation.

Power Generation Strategy

- **Daytime Operation (Sunrise to Sunset):** During daytime hours, the PV array takes the lead in supplying energy, harnessing solar irradiation from sunrise to sunset. This reduces reliance on the diesel generator (DG) and minimizes fuel consumption and CO₂ emissions during daylight hours.
- **Nighttime Operation:** As solar irradiation decreases at night, the PV array's output diminishes, and the pumped hydroelectric storage (PHS) turbine covers the demands of energy. The PHS system helps to minimize DG fuel consumption and CO₂ emissions by providing energy storage and discharge capabilities during periods of low solar generation.
- **DG Backup:** In cases where neither the PV array nor the PSH system can meet the energy demands, especially during nighttime, the diesel generator (DG) takes the lead to ensure uninterrupted energy supply. However, its operation is minimized to reduce fuel consumption and CO₂ emissions, with preference given to renewable energy sources whenever possible.

This optimized power generation strategy ensures efficient utilization of available energy resources, minimizes environmental impact, and maintains reliable energy supply throughout the day and night.

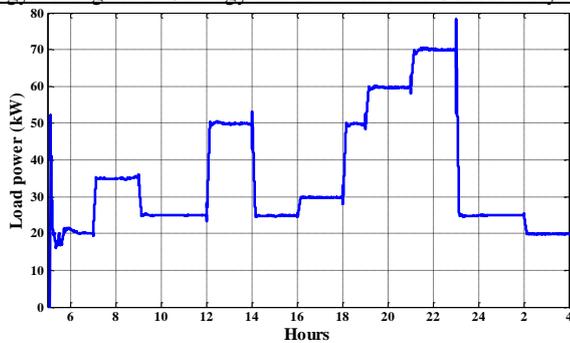


Fig. 8: The total power produced by the HMGS for the different profiles of solar Irradiations

4. Conclusion

In conclusion, the hybrid microgrid energy system (HMGES) coupled with the proposed energy management control (EMC) strategy emerges as a reliable, economical, and eco-friendly solution for remote areas. Unlike conventional systems, it significantly reduces total fuel consumption (FC) to 78.4768 liters per day, FC costs to 1020.2 euros, and CO₂ emissions to 208.2774 kilograms per liter.

Moreover, the HMGES offers the remote area access to clean and renewable energy sources, thereby promoting sustainability and reducing dependence on fossil fuels. By integrating renewable energy generation, energy storage, and intelligent control strategies, the HMGES demonstrates its potential to address the energy needs of remote communities while minimizing environmental impact and maximizing economic efficiency.

Overall, the findings presented in this paper underscore the viability and benefits of deploying HMGES with advanced EMC strategies in remote areas, paving the way for a more sustainable and resilient energy future.

References

- [1]- T. Khatib, A. Mohamed, K. Sopian, and M. Mahmoud, "Optimal sizing of building integrated hybrid PV / diesel generator system for zero load rejection for Malaysia," *Energy Build.*, vol. 43, no. 12, pp. 3430–3435,
- [2]- S. Yilmaz and F. Dincer, "Optimal design of hybrid PV-Diesel-Battery systems for isolated lands: A case study for Kilis, Turkey," *Renew. Sustain. Energy Rev.*, vol. 77, no. May 2016, pp. 344–352, 2017.

- [3]- M. Gökçek, "Integration of hybrid power (wind-photovoltaic-diesel-battery) and seawater reverse osmosis systems for small-scale desalination applications," *Desalination*, no. April, pp. 1–11, 2017.
- [4]- T. Ma, H. Yang, L. Lu, and J. Peng, "Technical feasibility study on a standalone hybrid solar-wind system with pumped hydro storage for a remote island in Hong Kong," *Renew. Energy*, vol. 69, pp. 7–15, 2014
- [5]- S. Wen et al., "Optimal sizing of hybrid energy storage subsystems in PV/Diesel ship power system using frequency analysis," *Energy*, 2017.
- [6]- L. M. Al-hadhrami and M. Alam, "Pumped hydro energy storage system : A technological review," vol. 44, pp. 586–598, 2015.
- [7]- G. Prinsloo, R. Dobson, and A. Mammoli, "Synthesis of an intelligent rural village microgrid control strategy based on smartgrid multi-agent modelling and transactive energy management principles," *Energy*, vol. 147, pp. 263–278, 2018.
- [8]- Yahiaoui, F. Fodhil, K. Benmansour, M. Tadjine, and N. Cheggaga, "Grey wolf optimizer for optimal design of hybrid renewable energy system PV-Diesel Generator-Battery : Application to the case of Djanet city of Algeria," *Sol. Energy*, vol. 158, no. August, pp. 941–951, 2017.
- [9]- M. Junaid, A. Kumar, and L. Mathew, "Techno economic feasibility analysis of different combinations of PV-Wind-Diesel-Battery hybrid system for telecommunication applications in different cities of Punjab , India," *Renew. Sustain. Energy Rev.*, vol. 76, no. January, pp. 577–607, 2017.