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Nonlinear Quadratic Programming Algorithm Modelling for Operation of The Off-Grid Energy Resources System with Backup Storage System

Abdeljelil Chammam[1], Harikumar Pallathadka[2]*, Nada Qasim Mohammed[3], Shavan Askar [4], Naseer Ali Hussien[5], Saif Hameed Hlail[6]

[1] *College of Engineering, Department of Electrical Engineering, Prince Sattam Bin Abdulaziz University Alkharj, 11942, SAUDI ARABIA*
[2] *Manipur International University, Imphal, Manipur, INDIA*
[3] *Department of Medical Laboratories Technology, AL-Nisour University College, Baghdad, IRAQ*
[4] *Erbil Technical engineering college, Erbil polytechnic University Erbil, IRAQ*
[5] *Information and Communication Technology Research Group, Scientific Research Center, Al-Ayen University, Thi- Qar, IRAQ*
[6] *College of Technical Engineering, National University of Science and Technology, Dhi Qar, IRAQ*

*Corresponding Author: *harikumarpallathadka@gmail.com*
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Keywords

Renewable energy sources; off-grid state; nonlinear quadratic programming algorithm, minimize costs, maximizing reliability

Abstract

This study aims to investigate and optimize the energy usage of multiple electrical systems operating off-grid. The focus is on maximizing the utilization of storage systems to ensure a reliable power supply. This is achieved by harnessing renewable energy sources such as backup storage systems, wind turbines, solar cells, and diesel generators. To meet the energy demand, both DC and AC loads on the consumer side are considered. The research employs a mathematical approach known as nonlinear quadratic programming to ascertain the most efficient energy generation for both producers and consumers. The primary aim is to minimize expenses the system. The study also evaluates the impact of battery storage systems on achieving the operational level. By analyzing the performance of these storage systems, the researchers can assess their contribution to the overall energy optimization. To validate the proposed optimization algorithm, the study implements it in Matlab software. This enables numerical simulations in various case studies of energy systems demonstrates the optimal energy generation and offers valuable insights into the performance of the proposed algorithm. Overall, this study contributes to the field of energy optimization in off-grid systems by considering multiple electrical systems, energy sources, and storage systems. The findings can help in designing and operating off-grid systems more efficiently, ensuring a reliable and cost-effective power supply.

1. Introduction

As the world's demand for electricity continues to grow, environmental and social issues have become major issues around the world [1]. In conventional power plants, combustion fossil fuels has resulted in significant environmental pollution, while the conventional power grid suffers from high costs and low performance [2]. As a result, energy storage systems that promote clean energy production through the use of renewable electricity have been widely adopted around the globe [3]. A energy system (also known as a small grid) is a system that generates and distributes electricity using Renewable energy sources and storage systems. It is an important part of power systems due to its high security, high renewable energy utilisation rate, and low operating cost [4]. However, intermittency and volatility of renewable energy supply and demand present significant obstacles to the supply and demand balances of the microgrid, as well as to the safe and cost-effective dispatch of the system [5]. As a result, energy storage systems can be incorporated into the microgrid scheduling process as a key distributed power supply solution [6].

Previous research on energy dispatching has mostly focused on several objective functions to maximize the dispatching's outcomes [7]. The environmental cost and the generation cost are typical examples of multi-objective functions. The complete life cycle expenses and wind desertion rate of a grid-connected microgrid as well as operating costs and reliability, are provided [8]. The distribution network's assistance has considerably increased the microgrid's operational reliability [9]. However, a microgrid's distribution network is primarily powered by fossil fuels, which seriously pollutes the environment. Consequently, fuel-powered and renewable energy devices make up microgrids [10]. By incorporating renewable energy sources, the microgrid's environmental performance is enhanced as fuel consumption is decreased. These sustainable energy gadgets are pricey, albeit [11]. Therefore, the main objective functions of the microgrid are economic and environmental protection [12]. The system's environmental protection is enhanced by the optimal unit output, which also raises the rate at which renewable energy sources are used [13].

The loads in energy systems are usually random variables, but they can be regulated by offering economic incentives, it considerably affects the stability of energy systems [14]. Therefore, in order to maximize the benefits of load on energy systems, demand response mechanisms must be developed [15]. The main challenge faced by these resources is the uncertainty in their power output because natural parameters are naturally random [16]. Predicting the output values of these resources can become inaccurate if the ambiguity around microgrid energy management is ignored. Consequently, scholars have put forth a range of techniques, encompassing both deterministic and non-deterministic methodologies [17]. Power system management now faces additional difficulties as a result of the grid's integration of energy storage systems. Having efficient ways to enhance grid management is crucial, particularly when there are a lot of renewable energy sources available [18]. The inclination of earlier techniques to converge towards local spots and the lack of a strong global search engine in these algorithms are two of their drawbacks [19].

The research presented in this study focuses on developing a method to achieve optimal energy generation in an off-grid energy system. This is particularly important as off-grid systems often need to cater to both AC and DC load requirements. To address this challenge, the researchers propose the use of a heuristic algorithm. This algorithm ensures that the energy dispatch is optimized to meet the demand, taking into consideration the specific requirements of both AC and DC loads. By employing this algorithm, the researchers aim to maximize the efficiency and effectiveness of the energy generation process. To solve the proposed heuristic algorithm, a nonlinear quadratic programming approach is utilized. This approach allows for the optimization of the energy dispatch by considering various factors such as the availability of renewable energy sources, the energy storage capacity, and the load demand. By using this approach, the researchers aim to enhance the robustness of the energy optimization process, ensuring that the system can adapt to changing conditions and uncertainties. In addition to the optimization techniques mentioned above, the researchers also integrate battery storage systems into the off-grid energy system. This integration is crucial in addressing demand fluctuations that may arise due to uncertainties in the energy generation from WTs and PVs. By utilizing battery storage systems, excess energy generated during periods of high generation can be stored and used during periods of low generation, ensuring a consistent and reliable energy supply. Overall, this research proposes a comprehensive approach to achieve optimal energy generation in an off-grid energy system. By employing a heuristic algorithm, utilizing a nonlinear quadratic programming approach, and integrating battery storage systems, the researchers aim to enhance the efficiency, reliability, and robustness of the energy optimization process. This research has the potential to contribute to the development of sustainable and reliable off-grid energy systems that can cater to both AC and DC load requirements.

2. Energy System Modeling

In Figure 1, an overview of the proposed system is presented. This system includes a diesel generator (DG), wind turbine (WT), AC load, photovoltaic (PV) system, battery, and DC load. The energy flow is optimized to meet the requirements of demands like DC and AC loads. The energy flow for P1, P2, and P3, representing the power flow

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of DG, the power exchange between the buses, and the power exchange of the battery, respectively. An inverter is utilized for the P2 in two states to fulfill the load demands. The subsequent subsections provide detailed modeling of the system components [20][21].

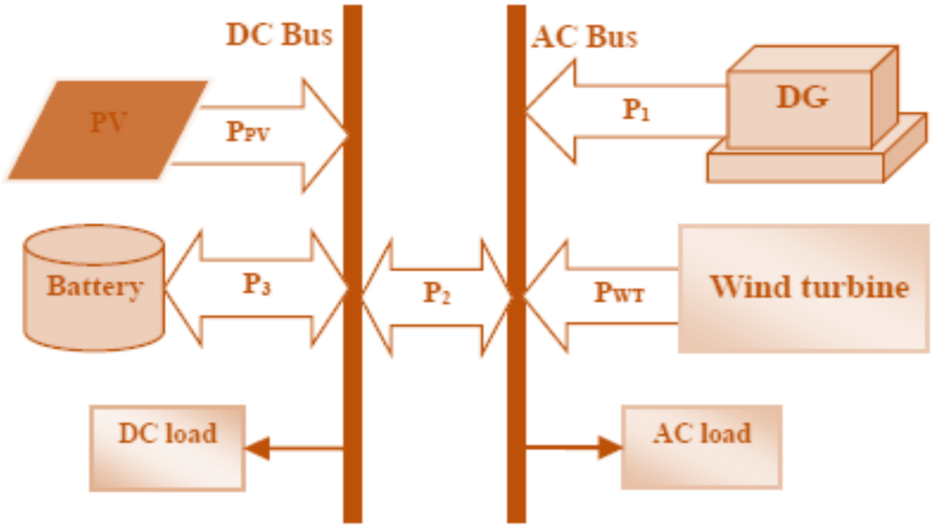


Fig.1 *Energy system and power flow*

2.1 PV System Model

The formulation of the PV system is as follows [22]:

$$P_{PV}(t) = \eta_{PV} \times A_C \times I_s(t) \tag{1}$$

Where $P_{PV}(t)$ is PV power at time t. A_C is area of PV. $I_s(t)$ is area of PV. η_{PV} *is* efficiency of PV.

1.2. WT System Model

Equation (2) represents the mathematical model used to simulate the power generation of the wind turbine [23][24].

$$P_{WT}(t) = \frac{1}{2} \times \eta_t \times \eta_g \times \rho_{air} \times C_p \times A \times V_r^3(t) \tag{2}$$

Where $P_{WT}(t)$ is WT power output. The η_t is efficiency of the WT. The η_g is generator's efficiency. The ρ_{air} is air density. The C_p is power generation factor. The A is area of rotor in WT. And $Vr(t)$ is wind speed.

2.3. DG System Model

The power output of the DG relies on both the amount of fuel injected and the power bound of the generator. Therefore, the generation of energy by the DG is represented more accurately as a function of fuel costs rather than power generation [25][26]:

$$C_{DG} = \sum_{t=1}^{24} \left\{ \left(a.P_1^2(t) \right) + \left(b.P_1(t) \right) \right\} \tag{3}$$

Where $P_{DG}(t)$ is DG power generation. The factors *a* and *b* are fuel cost.

2.4. Battery System Model

The primary function of the battery is to provide power in situations where the energy produced by resources is insufficient to meet the demand. When there is a decrease in energy demand, the battery is recharged using WTs and PVs. Conversely, it is discharged when there is a deficit in energy generation on the production side. The modeling of the battery incorporates both technical and economic factors, and it is structured as follows [27][28]:

$$0 \le P_B^{DIS}(t) \le u_B(t) \times P_3^{\max} \tag{4}$$

$$0 \le P_B^{CH}(t) \le [1 - u_B(t)] \times P_3^{\max} \tag{5}$$

$$C_B^{OP} = \sum_{t=1}^{24} \left\{ \left(c_B^{DIS} \times P_B^{DIS}(t) \right) + \left(c_B^{CH} \times P_B^{CH}(t) \right) \right\} \tag{6}$$

Where equation (4) is limit of discharged power. Equation (5) is limit of charged power. Equation (6) is battery cost. Where $P^{DIS}{}_B$ is discharge energy. And $P^{CH}{}_B$ is charge energy. The u_B is binary variable in charge and discharge modes [29][30].

3. Objective Function

The objective of the modeling function is to minimize the cost of energy generation for the DG and battery shown in Figure 1. To solve this optimization problem, an integrated programming approach with a weight sum method is employed. The objective function is represented by equation (7).

$$\min f = \sum_{t=1}^{24} w_1.C_{DG}(t) + w_2.C_B^{OP}(t) - w_3.P_{PV}(t) - w_4.P_{WT}(t) \tag{7}$$

Where w is weight of decision variables, and $w_1+w_2+w_3+w_4=1$.

$$P_1(t) + P_2(t) = P_{LAC}(t) - P_{WT}(t) \tag{8}$$

$$P_2(t) + P_3(t) \le P_{PV}(t) - P_{LDC}(t) \tag{9}$$

$$0 \le P_1(t) \le P_1^{\max} \tag{10}$$

Where P_{LAC} is AC load demand. The P_{LDC} is DC load demand. The energy flow in energy system is formulated by equations (8)-(10).

4. Methodology

Quadratic programming is utilized for solving optimization problems, as previously stated. By employing Quadratic programming, it becomes possible to achieve optimal power dispatch for each load demand. Therefore, optimal energy flow at any given time by equations (8)-(10) must be satisfied with the least cost and a maximum generation of WT and PV. The objective function for Quadratic programming modeling is represented as follows [31]-[33]:

$$\min \left\{ \frac{1}{2} x.Hx + fx \right\} \tag{11}$$

The equations (8)-(10) are modeled as follows [34][35]:

$$Ax \le b \tag{12}$$

$$A_{eq}x = b_{eq} \tag{13}$$

$$Lb \le x \le Ub \tag{14}$$

Where H is second degree coefficients and f is first-degree coefficients. The Ub and Lb are bounds of decision variable. The b_{eq} and A_{eq} are equal limitations. And A, and b are unequal equations [36][37].

5. Numerical simulation

Figure 2 illustrates the implementation of algorithm for achieving energy flowof the available resources. The loads and the power of PV and WT are depicted in Figure 3. It is important to note that the power for the PV during summer and winter is assumed.

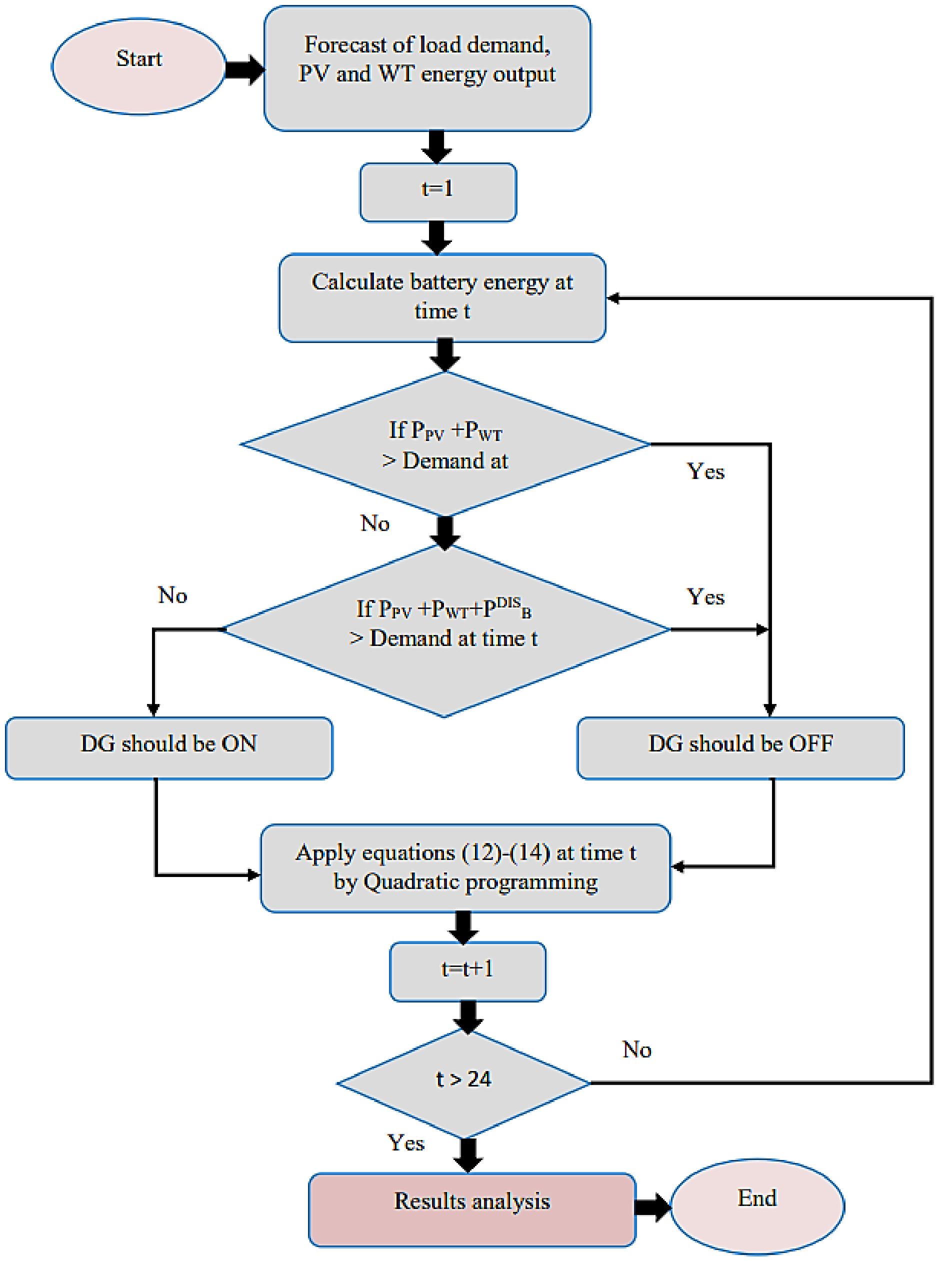
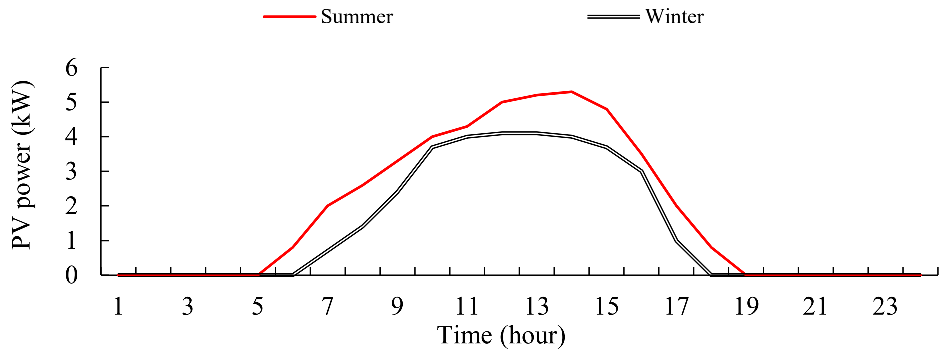
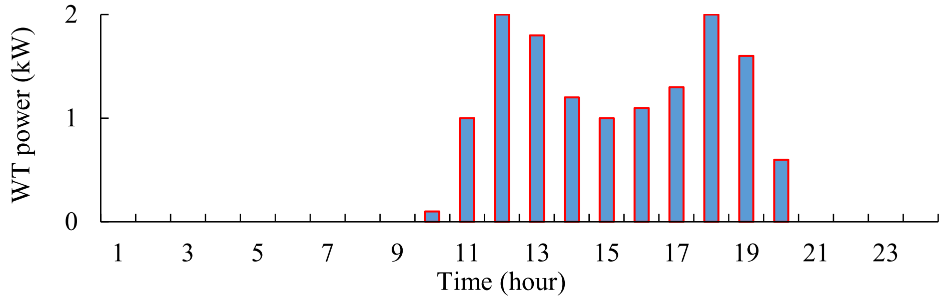


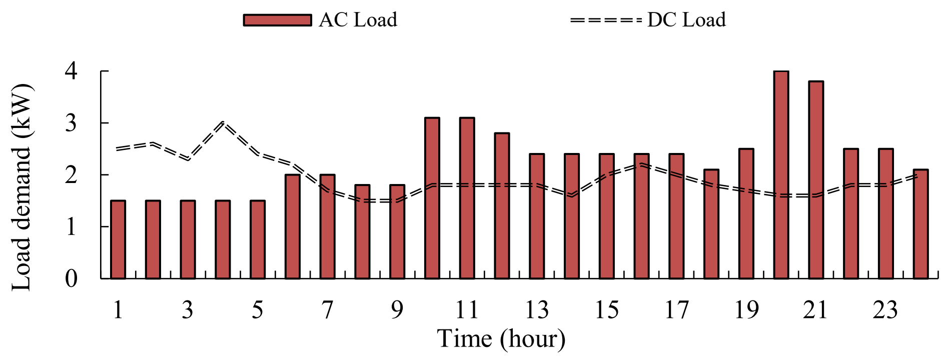
Fig. 2 *Flowchart of energy optimization*



(a)



(b)



(c)

Fig. 3 *Data of system like PV power generation, WT power generation and Load demand*

5.1. Results

In this section, the outcomes of the energy flow are presented in this section. The table 2 illustrates the using of PV and WT in both cases as equal. In order to demonstrate the battery's performance, the weight w2 in the second case surpasses that of the case 1. As a result of the expensive fuel costs, the weight attributed to DG in case 2 is less than that in case 1. Figures 4 and 5 illustrate the energy flow in cases 1 and 2 throughout the summer. Upon examining Figure 4 and Figure 5, it is evident that the power generation of the DG in case1 exceeds that of case 2 during hours 1 and 2. The costs in cases 2 and 1 for the summer are $253.6 and $283.3. By augmenting the weight of the battery in case 2 to fulfill requirements during peak periods, the production expense experiences a decrease of 10.4%. In the second case, there has been a decline in P2 as a result of the increased demand for DC power between hours 1 and 4, in contrast to the first case. The power flow depicted in Figure 5 demonstrates that the battery is more efficient in meeting the DC demand compared to Figure 4.

The power flows in the winter for the two cases in depicted in Figures 6 and 7. Figure 6 illustrates a rise in power generation from the DG in comparison to Figure 4, attributed to a decrease in PV energy output during the winter season, while maintaining consistent weights in case 1. Additionally, the DG plays a more significant role

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in meeting demand, as a result of the low PV power and the unavailability of discharge from the battery in Figure 7. The costs for the winter season in cases 2 and 1 are $297.4 and $298.3, respectively.

Based on the findings from the winter and summer; it can be inferred that the battery relies on PV power and has a positive impact on generation costs during both seasons. The battery in all cases is utilized during high demand to minimize generation by DG, which has high fuel costs. Furthermore, P2 among loads like AC and DC buses during high demand is carried out for charging and to supply loads.

Table 1 *Case studies*

Cases Weight	Case 1	Case 2
W_1	0.4	0.2
W_2	0.4	0.6
W_3	0.1	0.1
W_4	0.1	0.1

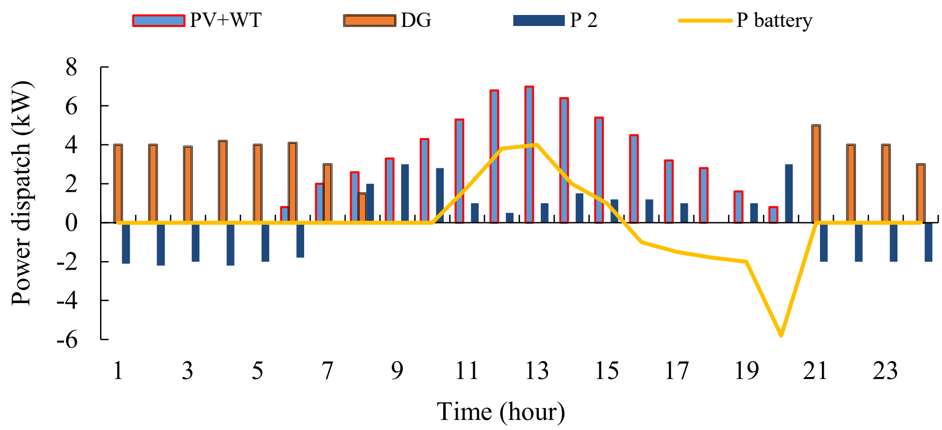

Fig. 4 *Power flow in Case 1 in summer*

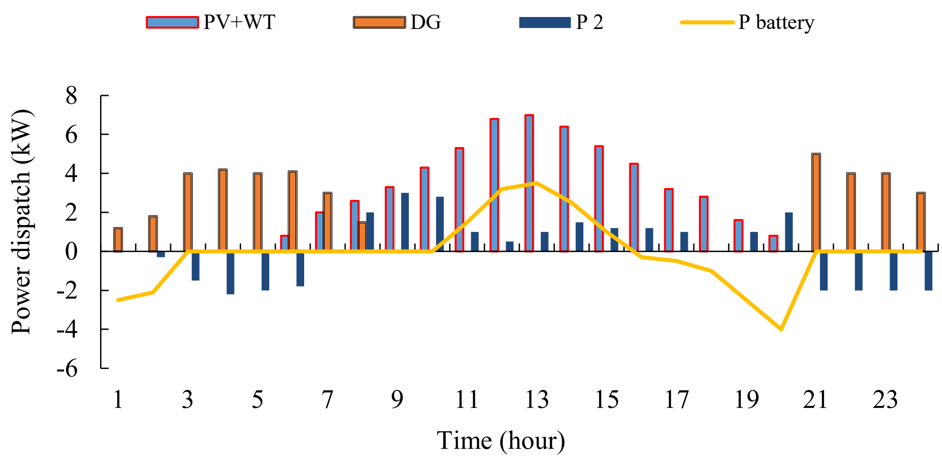

Fig. 5 *Power flow in Case 2 in summer*

Penerbit UTHM

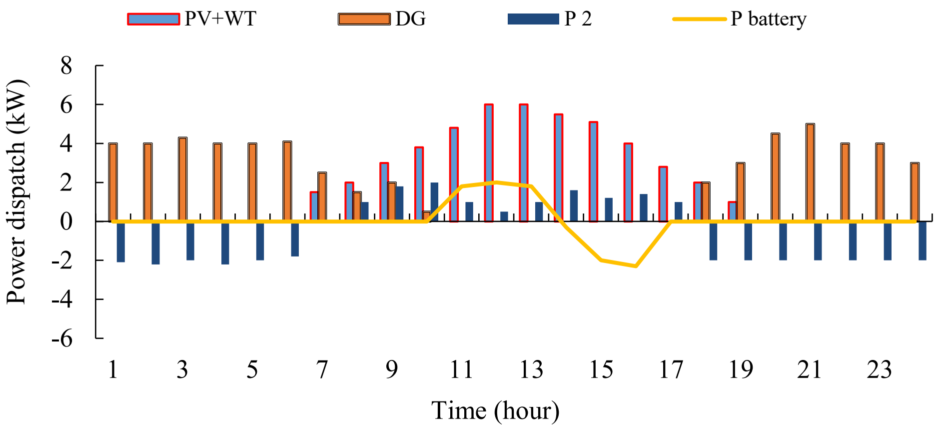

Fig. 6 *Power flow in Case 1 in winter*

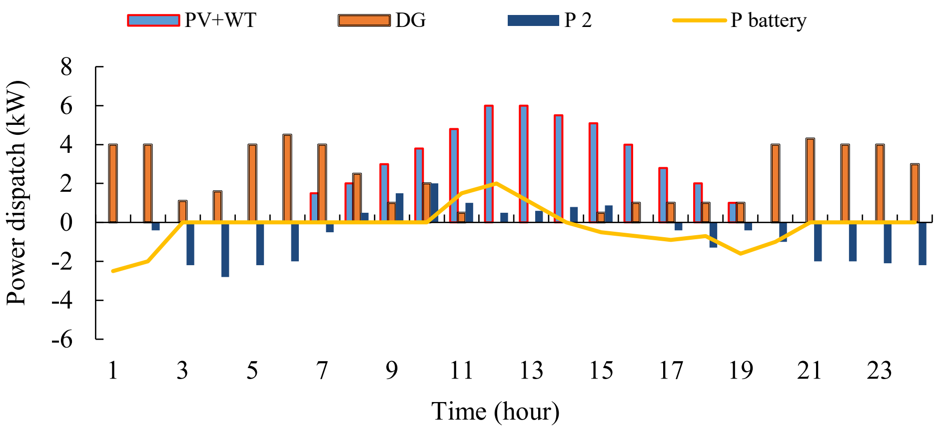

Fig. 7 *Power flow in Case 1 in winter*

6. Conclusion

In this paper, we focus on studying the optimal power flow of resources. Off-grid energy systems are becoming increasingly popular as they provide a sustainable and reliable source of energy for remote areas or areas with unreliable grid connections. However, optimizing the energy dispatch in such systems is crucial to ensure efficient utilization of resources and minimize costs. To achieve this, we employ Quadratic programming, a mathematical optimization technique, and the weight sum method. Quadratic programming allows us to model and solve the optimization problem by considering various constraints and objectives. The weight sum method is used to assign weights to different objectives, such as minimizing costs and maximizing the participation of renewable energy resources. One key component of our off-grid energy system is the battery system. Batteries are employed as a means of storing excess energy during periods of low demand and supplying it during peak demand. This helps in balancing the energy supply and demand and ensures a reliable energy supply even during high-demand periods. The primary objective of our study is to minimize energy generation costs while maximizing the utilization of renewable energy resources. Renewable energy resources, such as solar and wind, are crucial for sustainable energy systems. By maximizing their participation, we aim to reduce the reliance on non-renewable energy sources and decrease the environmental impact of the off-grid energy system. To evaluate the effectiveness of our proposed approach, we conduct two case studies for each season, summer and winter. We assume equal system operation for both cases to ensure a fair comparison. Through the simulation of numerical data, we showcase the efficiency and effectiveness of the battery system in fulfilling energy requirements during peak periods while also reducing expenses. In general, our research offers important perspectives on the most efficient energy distribution in off-grid energy networks. By utilizing Quadratic programming and the weight sum method, we are able to optimize the energy dispatch and achieve a balance between cost minimization and renewable energy utilization. The results of our case studies highlight the effectiveness of the battery in meeting peak demand and reducing costs. This research contributes to the development of sustainable and efficient off-grid energy systems.

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Conflict of Interest

The authors declare that they have no known competing financial interests.

Author Contribution

All authors have made equal contributions in terms of conceptualization, methodology, software development, data curation, formal analysis, and both reviewing and editing the writing, as well as the creation of the original draft.

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