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Operation of The Hybrid Energy Resources with Storage System Participation

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Abstract: This paper focused on the optimal operation of the hybrid energy resources in the off-grid state considering energy storage participation. The hybrid energy resources consist of wind turbine (WT), photovoltaic (PV), diesel generator (DG), and energy storage system for supplying energy to DC and AC load demand with maximum reliability. The operation of the proposed energy system based on energy control and energy optimization is modeled. The energy optimization and energy control are implemented by heuristic and nonlinear quadratic programming approaches via optimal power flow on the resources side. The energy control is done based on the weight sum method in different operation states of the system. Also, the impact of the energy storage system on the hybrid energy resources is considered as backup resources. The energy control modeling is implemented via mathematical simulation and numerical analysis in the two operation states in the summer and winter seasons for verifying the proposed approaches. Finally, the results of the energy control show optimal states of the energy system in supplying demand with considering the energy storage system.

Keywords: Hybrid energy resources, energy storage system, energy control, energy optimization, weight sum method

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1. Introduction

1.1 Aims

In recent years, growing demand for energy and increasing global warming leads to an increase in the use of clean energy technologies to meet the demand [1]. Deploying clean energy technologies requires resource location and size, optimal energy distribution, and operating the energy system with minimal emissions and costs [2]. Wind turbine (WT) and photovoltaic (PV) are the leading clean energy technologies in power systems [3]. The energy production of wind and photovoltaic systems, on the other hand, depends on the meteorological conditions and is associated with uncertainties in most cases. Therefore, storage systems such as batteries can store energy generated by PV and WT [4]. Batteries are one of the major resources in power systems. These resources can have optimal participation in power systems by storing extra energy of the other resources in themselves. On the other side, power discharges of the batteries can inject into the system in the event of emergency times [5]. So, employing these resources in the energy system can be affordable to ensure economical operation under all conditions and over a long period of time [6].

1.2 Literature Review

The energy flow in energy systems has been proposed with various strategies in recent years. In [7], the energy optimization of the microgrid is examined with the conditions of the uncertainty of the PV system and the power price. The authors in [8] present the modeling of electrical systems in seasons as well as energy-saving strategies and local energy generation in smart buildings. The optimal power flow in energy hub system with demand sharing has been suggested in [9]. In [10] the genetic algorithm is used to optimize the energy scheduling with demand-response models. The extension of the battery service life through optimal demand planning with WT is presented in [11]. Also in [12] a load management strategy was proposed to maximize battery liftime and energy storage system efficiency. The economic operation and planning of WT, PV and storage systems is examined in [13]. The energy planning in a hybrid energy system was proposed in [14] by using memetic models. In [15], the reconfiguration modeling is used to maximize the energy efficiency and reliability of the power system with load demand uncertainty. A strategy for planning peak power demand with optimal resource design is studied in [16]. In terms of pricing for residential consumers, a distributed algorithm was proposed in [17] to coordinate the demand scheduling of household loads and an adaptive diffusion strategy-based distributed algorithm was proposed in [18] to optimize the aggregated cost and utility of consumers and the profit of the retailer simultaneously. In [19], linear equations based on changing point model [20] and parameter estimation were used to model the responses of thermostatically controlled loads to prices. Although the above studies have presented the successful applications of data-driven modeling, the mentioned methods are not applicable for our problem for the following reasons. On the on hand, because of the privacy of industrial production, it is difficult to obtain even the model framework of the responses of industrial consumers to prices. On the other hand, the complex industrial production requires its learning model to have high capability of modeling nonlinear behaviors. In [21], stacked auto-encoders and adaptive neuro-fuzzy inference systems were combined to extract the reaction patterns of reactive consumers, but the proposed method was not applied to industrial data. Moreover, the involved complex network structure brings challenges to the solution of the problem. The used intelligent optimization algorithm cannot guarantee the quality of the solution in theory.

1.3 Novelties

This study proposes the optimal power generation of hybrid resources in an off-grid status for the supply of both AC and DC loads. With the help of the proposed heuristic algorithm, the optimal energy distribution to cover the demand is realized. On the other hand, the proposed heuristic algorithm is solved by nonlinear quadratic programming as a robust energy modeling. The operation of the proposed energy system based on energy control and energy optimization is modeled. The energy optimization and energy control are implemented by heuristic and nonlinear quadratic programming approaches via optimal power flow on the resources side. Battery storage systems will also be used to meet energy needs, subject to uncertainties regarding WT and PV energy. The novelties of this study can therefore be listed as follows:

1) The load requirement is covered in an off-grid system with an uncertain approach.
2) A heuristic algorithm based on optimal energy production has been proposed.
3) Nonlinear quadratic programming was proposed as the solution for solving problems.
4) Battery storage system is used to cover PV and WT energy production.

2. Overview of The Hybrid Energy System

The structure of the proposed hybrid energy system is shown by Figure.1. The proposed energy system consists of diesel generator (DG), WT, AC load, PV, battery and DC load. The energy dispatch of the system is considered for optimal meet to AC load and DC load. In Figure.1. energy dispatch to P_1, P_2 and P_3 are energy generated by DG, energy exchange between AC and DC buses and energy exchange of battery in charge and discharge modes, respectively. The inverter is used to P_2 exchange in two modes in order to meet AC and DC loads. In the following subsections modelling components are given.

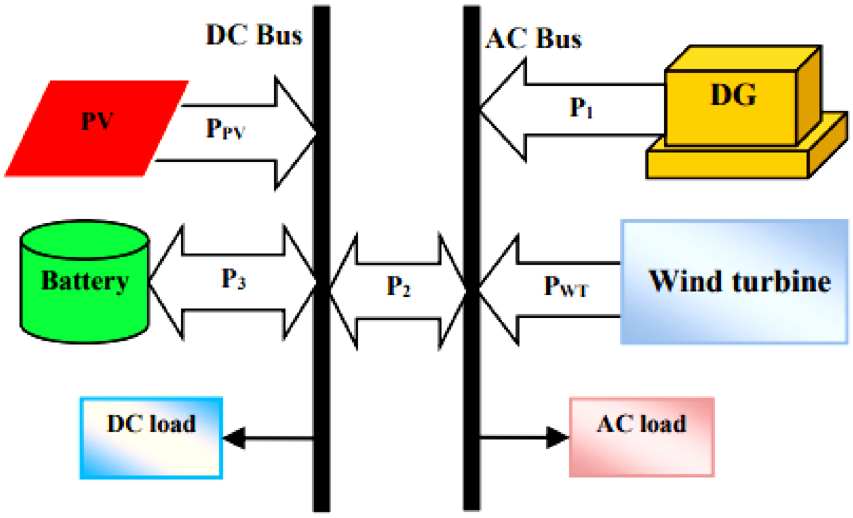


Fig. 1 - Structure of the proposed hybrid energy system

2.1 PV Modelling

The mathematical modelling of the PV is formulated as follow [22]:

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

Here $P_{PV}(t)$, η_{PV}, A_C and $I_s(t)$ are power output of the PV at time t, efficiency of PV, area of solar panels and solar irradiance at time t, respectively.

2.2 WT Modelling

The power generation of the WT is modelled by equation (2) [23]:

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

Where $P_{WT}(t)$, η_t, η_g, ρ_{air}, C_p, A and $Vr(t)$ are WT power generated at time t, efficiency of the turbine, efficiency of the generator in WT, air density , factor of power generation, area of the WT rotor and wind speed at time t, respectively.

2.3 DG Modelling

The power generation of the DG is depended on injected fuel and power capacity of the DG. Hence, energy generation by DG can be modelled as fuel cost than power generation [24]:

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

Here C_{DG} and $P_{DG}(t)$ are DG fuel cost and power generation of the DG in time t, respectively. And a and b are cost factors of fuel.

2.4 Battery Modelling

The battery is used to feed demand, when energy generation by resources is less than demand. The battery is charged at low demand by WTs and PVs, and it's discharged at shortcoming energy generation in generation side. The modelling battery based on technical and economic indices is as follow [25]:

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

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

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

Here equations (4) -(6) are power discharge limit, power charge limit and operation cost of the battery, respectively. As well, P^{DIS}_B and P^{CH}_B are discharge and charge powers, respectively. The binary variable (u_B) is used in order to that discharging and charging are not done same time. The c^{DIS}_B and c^{CH}_B are degradation cost of the battery in discharging and charging modes, respectively.

3. Objective Function

The modelling objective function is formulated based on minimization of the energy generation cost of the DG and battery in Figure.1. The optimization interval is implemented at 24-ahead and power forecast of the PV and WT. The optimization approach is solved by integrated Quadratic programming with weight sum method in MATLAB software. The objective function is modelled by (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_1 to w_4 are weights of decision variables, which sum of them is equal to 1. In objective function (7), plus sign is considered to C_{DG} and C_B^{OP} in order to minimizing the generation costs of the DG and battery, respectively. On the other side, in order to maximizing PV and WT penetration, minus sign is used in objective function. The objective function is optimized subject to optimal energy dispatch of resource by following equations:

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

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

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

Where P_{LAC} and P_{LDC} are energy demand of AC load and DC load, respectively. As well, equations (8) -(10) are energy dispatch in AC bus, DC bus and limit of the DG energy generation, respectively.

4. Solution Method

As mentioned before, Quadratic programming is employed to solving optimization problem. Using Quadratic programming, optimal power dispatch can be done to each load demand. Hence, to implementing optimal energy dispatch in any time; equations (8) -(10) should be satisfaction with minimum cost and high penetration of PV and WT. The Quadratic programming modelling for objective function is as follow [26]-[28]:

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

And modelling for equations (8) -(10) are as follow:

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

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

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

Where H and f are matrix of the second- and first-degree coefficients, respectively. And A, and b are unequal equations; also A_{eq} and b_{eq} are equal equations. Finally, Lb and Ub are lower and upper of the decision variable, respectively.

5. Numerical Simulation

In this section, heuristic algorithm for optimal energy dispatch of the resources is implemented in Figure.2. The energy demand, power forecasted of the PV and WT is shown in Figure.3. It should be mentioned, power forecast of the PV in winter and summer is assumed. Also, data of the system are extracted from Refs [26]-[28].

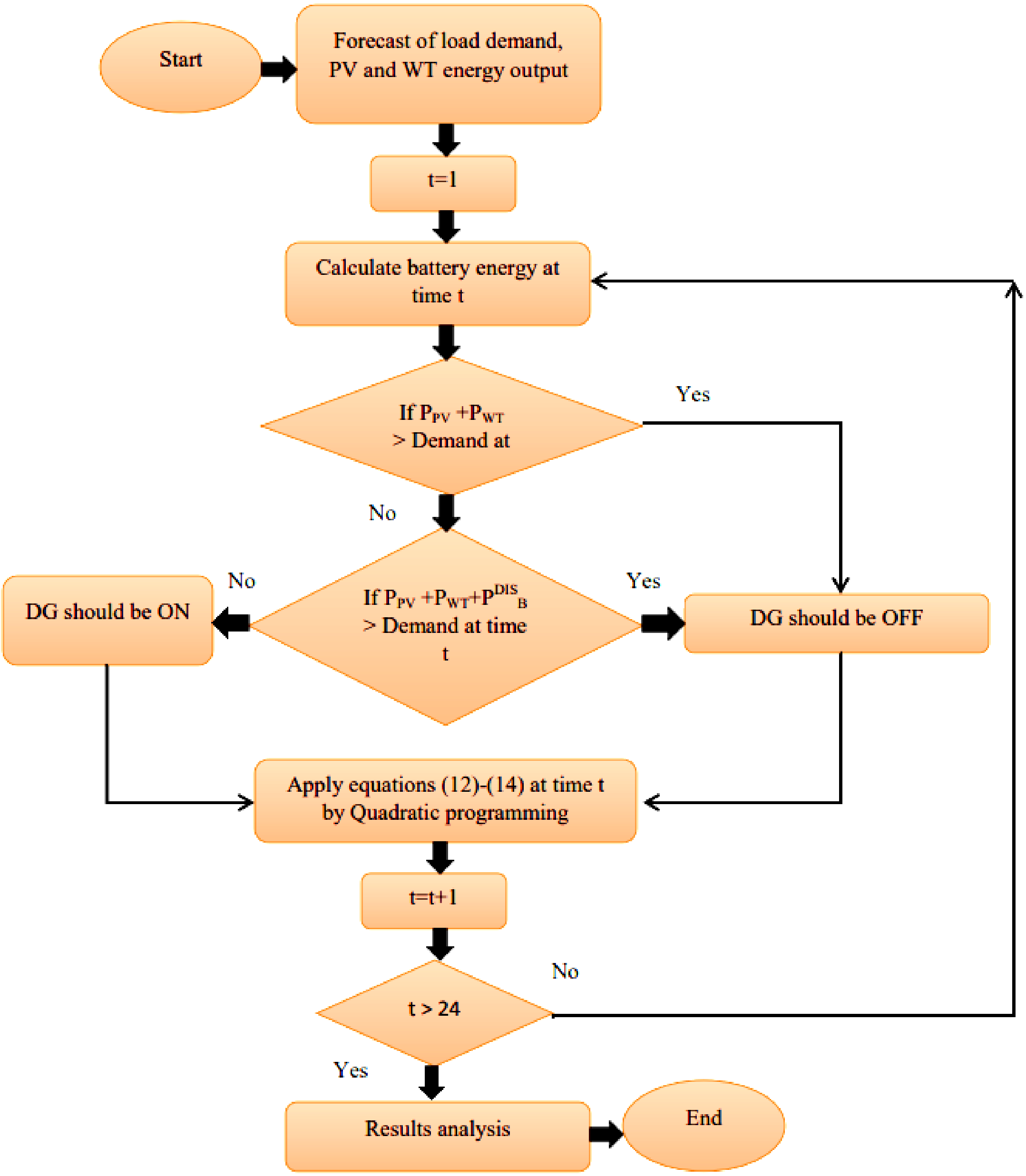
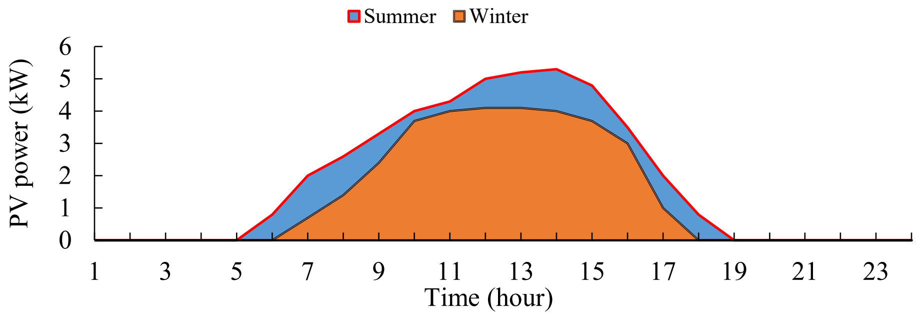
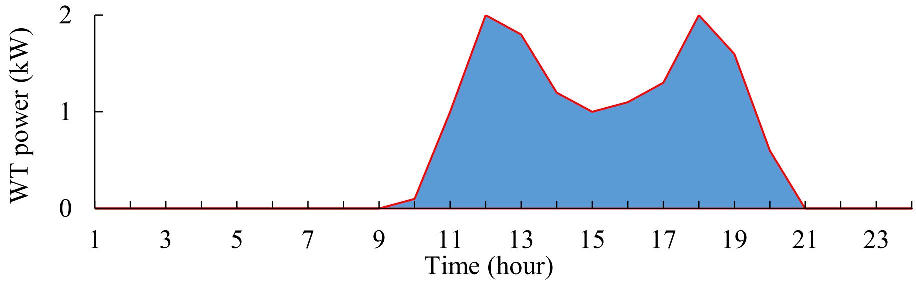


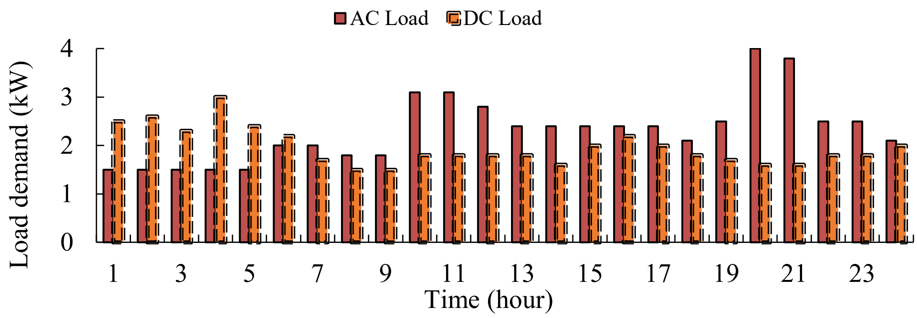
Fig. 2 - Heuristic algorithm for optimal energy generation



(a)



(b)



(c)

Fig. 3 - Power forecast PV, WT and load demand

5.1 Results and Discussion

In this subsection, results of the energy system are provided as two operations modes (two cases) in Table.1. In this table, operation of the PV and WT penetration (weights w_3 and w_4) in both case is considered as equal. However, to shown performance of the battery, the weight w_2 in case 2 is more than case 1. Thus, DG due to having high cost factors of fuel, the weight related to DG in case 2 is less than case 1. In Figures 4 and 5, energy dispatch of energy system in cases 1 and 2 for summer season are depicted. With comparing Figure 4 with 5, power generation of the DG in case 1 at hours 1 and 2 is more than case 2. The generation cost in cases 1 and 2 for summer are $ 283.3 and $ 253.6, respectively. Hence, with increasing weight of the battery in case 2 and meet AC and DC demands at peak hours; generation cost is reduced by % 10.4 in comparison to case 1. In case 2, power exchange (P_2), because of the high DC demand at hours 1-4 has been decreased than case 1. The power dispatch in Figure 5, represent DC demand is more meet by battery than Figure 4.

In Figures 6 and 7, power dispatch in winter season for both case is shown. In Figure.6. due to reduction of the PV energy in winter, power generation of the DG has been increased than Figure.4, with same weights in case.1. Also, in Figure.7. DG has more contribution in feed demand, because of the low power production by PV and unavailable power discharge of battery at hours 1-11 and 21-24. The value of the generation cost for winter season in cases 1 and 2 is $ 298.3 and $ 297.4, respectively.

According to obtained results for summer and winter seasons, it can be concluded that the battery system is depended on PV power and is has positive impact on generation costs in summer and winter. The battery in both case is used at peak demand, to minimizing power generation by DG with high cost factors of fuel. As well, power exchange (P2) between AC load and DC load at peak demand is done for battery charging and meet demand.

Table 1 - Operation modes in energy system

Operation modes	w_1	w_2	w_3	w_4
Case 1	0.4	0.4	0.1	0.1
Case 2	0.2	0.6	0.1	0.1

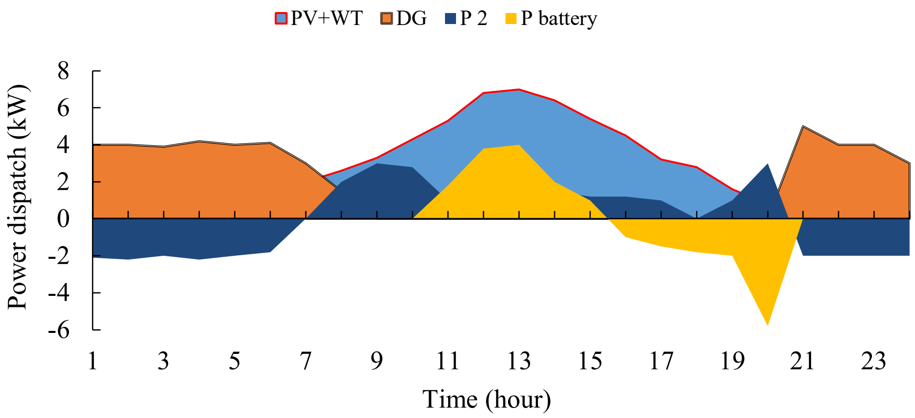


Fig. 4 - Energy dispatch in case 1 for summer

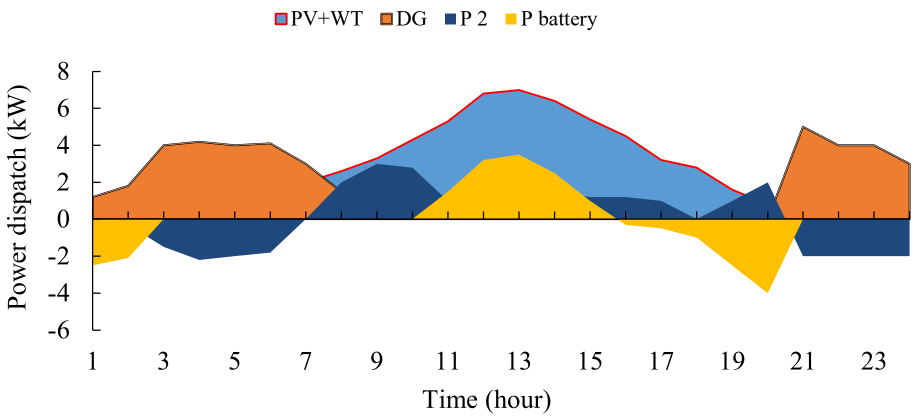


Fig. 5 - Energy dispatch in case 2 for summer

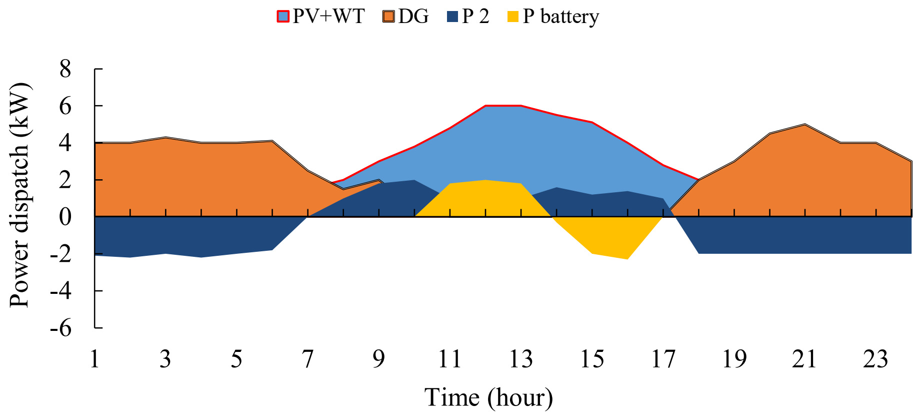


Fig. 6 - Energy dispatch in case 1 for winter

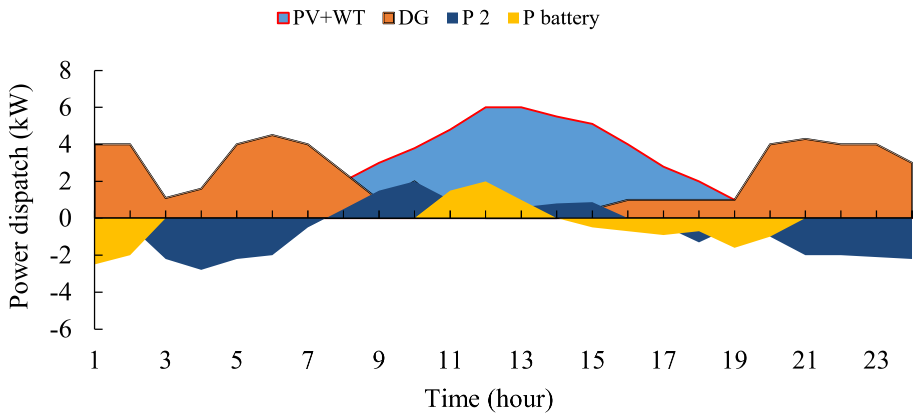


Fig. 7 - Energy dispatch in case 2 for winter

6. Conclusion

This paper focused on the optimal operation of the hybrid energy resources in the off-grid state considering energy storage participation. The operation of the proposed energy system based on energy control and energy optimization is modeled. The energy optimization and energy control are implemented by heuristic and nonlinear quadratic programming approaches via optimal power flow on the resources side. The energy control is done based on the weight sum method in different operation states of the system. Also, the impact of the energy storage system on hybrid energy resources is considered as backup resources. The results of the numerical simulation for case studies represented effective and optimal role of the battery system in meet energy demand at peak time and minimizing generation costs.

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