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Multi-object model for the hybrid wind-solar power generation with energy storage and inverter access capacity configuration

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ABSTRACT

Hybridization of multi-RE energy systems present a reliable alternative resource of energy. Optimization model of a multi-objective configuration of hybrid wind-solar energy system is presented in this paper. The minimum annual investment cost is aimed and the optimal configuration scheme and energy storage output range is determined. The impact of configuration strategies considering the stand-alone and grid-connected hybrid energy systems separately, taking actual wind and solar data is established. The energy storage scheduling cost is around 0.518 $/kWh and the cost of the abandonment unit is fixed at 0.97 $/kWh. The simulation results prove the effectiveness and correctness of the proposed optimization configuration strategy, and quantitatively analyzes the optimization of the multi-energy system operation mode.

KEYWORDS

PV power, Wind power, Optimal configuration, Economic dispatch

INTRODUCTION

The use of wind, solar with other renewable energy resource as part of Micro-grid system in the distribution system to optimize power quality which become the development of the distribution system. However, the output of this form DG has problems such as randomness, volatility and intermittency. Micro-grid is a small power supply and distribution system containing a variety of distributed power sources [1]. The impact of the power grid has improved the power grid's ability to absorb distributed power. Hybrid renewable energy systems either grid-connected or off-grid modes can be selected according to operating requirements [2-4]. Hybrid RE energy systems will determine whether the entire system can achieve stable economic operation, so its optimal configuration method has always been an important research issue in this field [5-6]. Many researches and developments trials seek the best of multi-energy systems in terms of economy, power supply, and environmental protection [7 -8]. The volatility of photovoltaic output in independent solar-storage power sources, proposes a typical solar-load scenario generation method that takes into account factors such as seasons and weather, and optimizes the configuration of the solar-storage grid [9]. A scenario analysis method for a certain regional distribution system to determine the timing, periodicity and uncertainty of wind power, photovoltaic output and load changes in the distribution system area has proposed by Cai W. et al. [10]. A performance analysis study of a hybrid solar wind power generation system proposed for water pumping in Iraqi climate [11]. The configuration method of the forecast accuracy of net load forecasting and the profit index of the user micro-grid are used as important parameters. The above-mentioned related researches all use heuristic optimization algorithms [12]. The main problem of this type of algorithm is that its population size is large and the amount of data is large, which leads to a large search space for optimization, which makes its calculation speed often slow. This paper considers the profitability of a hybrid wind-solar energy system taking actual data in a site. The effectiveness and the impact of configuration scheme and strategies of the operation of the hybrid system is discussed.

THE STRUCTURE OF MICRO-GRID POWER SYSTEM

Integrated energy system can include cogeneration equipment such as gas boilers, absorption chillers, power storage equipment, heat storage tanks and wind power. According to the structure of a single-region integrated energy system, a multi-region integrated energy system can be constructed, as shown in Figure 1. The equipment of the random combination of RE system must meet the electrical load requirements fresh water of the system.

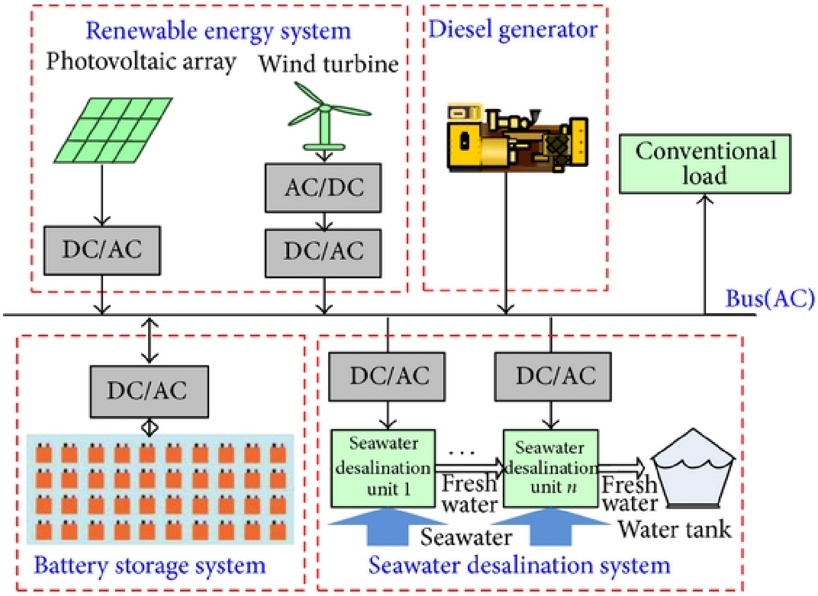


Figure 1. The structure of a typical Micro-grid power system [13]

The aspects of equipment planning, optimized operation, energy distribution and demand side management of multi-energy systems based on the complementary characteristics of energy regionsare essensial tasks [14]. Distributed and centralized energy a regional integrated energy system composed of a network was studied by Z. Liang et al [15]. An intermediate system coupled by cogeneration and clean energy for the coordinated transformation of multiple energy sources is studied by Bruno Canizes et al [16]. A regional integrated energy system heat Network model to coordinate the planning of the supply-demand relationship of various subsystems.is built by Fatemeh Bayatloo [17]. The integrated energy system from the aspects of system model establishment, simulation, operation, optimization, safety, and economy, and introduced suitable recommendations for the development of integrated energy systems was reviewed [18]. In [19], the conversion, storage and distribution of different types of energy, builds corresponding models, and conducts simulation experiments on multi-energy characteristics was sought. Ming Wu et al. [20] runs multi-objective optimization algorithms for the uncertainties in the multi- RE energy system in all seasons. Athanasios S. Dagoumas and Nikolaos E. Koltsaklis [21] studied the model with central energy and the model with multi-energy complementarity to optimize the cost of the integrated energy system; from the perspective of market economy.

COST OPERATION MODE

The grid-connected multi-energy system mainly has two operating modes: "spontaneous self-use" and "uniform purchase and sales" in which the interaction costs of different methods are also different. Further, the multi-energy system should also consider the demand-side response cost when interacting with the distribution system. The interaction cost C_{ex} under the "self-generated and self-use" mode includes the multi-energy system and the main system electricity sales and purchase costs, electricity revenue and renewable energy subsidies, and the expression is as follows:

$$C_{ex} = \sum_{T=1}^{N_T} C_{w,t} P_{bbuy,t} - C_{s,t} \sum_{t=1}^{N_T} P_{sell,t} - C_{pv-bu} \sum_{t=1}^{N_T} P_{pv,t} - \sum_{t=1}^{N_T} C_{w,t} \; P_{load,t} \quad (1)$$

Where P_{buy}, P_{sell} , C_w, C_s represent the power and price of the multi-energy system to buy and sell electricity from the main system respectively; P_{PV}, C_{pv-buy} represent the output power and subsidy price of the photovoltaic array; P_{load} represents the power consumption.

Interactive cost of unified purchase and sales

The interactive cost C_{ex} under the "universal purchase and sales" model includes the cost of renewable energy to sell electricity to the main system, the cost of electricity and the charge and discharge of energy storage, as follows:

$$C_{ex} = C_{PV} \sum_{t=1}^{N_T} P_{PV,t} + C_{WT} \sum_{t=1}^{N_T} P_{WT,t} + \sum_{t=1}^{N_T} C_{w,t} \left(P_{BS-D,t} - P_{BS-C,t}\right) - \sum_{t=1}^{N_T} C_{w,t} P_{load,t} \quad (2)$$

Where C_{PV}, C_{WT} represent the price of renewable energy power generation; P_{WT} represents the output power of the wind turbine, P_{BS_D}, P_{BS_C}, represents the discharge and charging power of the energy storage battery (BESS).

Demand side response cost

The demand-side adopts response model of stepped electricity price, with 24 hours as a dispatch cycle, according to the time-of-use electricity price policy, set compensation fees for different periods, and restrict the number of interruptions, single interruption capacity, and continuous interruption time. The specific model considering the different types of interruptible loads, the unit power compensation cost CDR is different in different time periods. The specific model is as follows [23]:

$$C_{DR} = \sum_{H_1}^{H_4} \xi_{m\_H} \sum_{t=0}^{24} \left[L_{l_d,t} + L_{in,t} - L_{out,t} - L_{MESi,d,t} - L_{G\_t}\right] \quad (3)$$

Where ξ_{m_H} is the cost per unit capacity of m-type loads of different electricity price layer s; L_{in_t}， L_{out_t} are the transfer-in and transfer-out loads; $L_{l\_d,t}$ does not consider the demand response load L_{G_t} is the power output of grid-connected absorbing load, and $L_{MES\_i,b,t}$ is the power output of absorbing load.

PROPOSED METHOD

In order to minimize the total cost of investment in the multi-energy system, the proposed model can be divided into two layers: first-layer optimization model to quantify the construction and operation costs of each power supply, and second layer optimize the capacity configuration of each power sources supply.

First-layer multi-energy system

Construction and operation costs

As an optimization decision variable construction and operation costs include the maintenance and operation and replacement costs of the equipment during the investment period. Select PV □ WT 、 $BESS$ inverter for the equipment used in the system, select the number of WT units N_{wt}, the number of PV groups N_{pv}, the number of BESS units N_{bess}, and the number of INVR units N_{invr}.

$$\begin{cases} C_{init} = C_{wt,in} N_{wt} + C_{pv,in} N_{pv} + C_{bess,in} N_{bess} + C_{invr,in} N_{invr} \\ C_{om} = C_{wt,om} N_{wt} + C_{pv,om} N_{pv} + C_{bess,om} N_{bess} + C_{invr,om} N_{invr} \\ C_{rep} = C_{bess,rep} N_{bess} \end{cases} \quad (4)$$

where， $C_{rep,}C_{om}$， and C_{init} are annual maintenance and operation cost and the total initial investment cost, of the WT 、 PV 、 $BESS$ 、 and $INVR$ operation and maintenance costs; energy storage life is short, there is multiple replacement behaviors during the investment period, so the corresponding replacement cost present value $C_{(bess,rep)}$.

Annual cost of construction and operation

The present value of the cost in the investment period multiplied by the fund recovery coefficient can be converted into the equivalent annual cost, and then sum to obtain the total equivalent annual cost $C_{dev-eav}$, the expression is as follows

$$C_{dev-eav} = \left(C_{init} + C_{rep}\right) \frac{i(1+i)^i}{(1+i)^i - 1} + C_{om} + C_{ex} + C_{DR} \quad (5)$$

Where $\frac{i(1+i)^i}{(1+i)^i-1}$ is the recovery coefficient of funds [22], where i is the discount rate and l is the investment period. Considering the economics of the system by taking the total equivalent annual cost $C_{dev-eav}$ minimum as the goal, the expression is

$$minC_{dev-eav} \quad (6)$$

The optimization decision variables mainly include: the number of WT units N_{wt}, the number of PV groups N_{pv}, the number of BESS monomers N_{bess}, and the number of INVR units N_{invr}. When performing optimization calculations, the above decision variables need to meet certain constraints.

$$\begin{cases} 0 \leq N_{wt} \leq N_{wt-max} \\ 0 \leq N_{pv} \leq N_{pv-max} \\ 0 \leq N_{bess} \leq N_{bess-max} \\ 0 \leq N_{invr} \leq N_{invr-max} \end{cases} \tag{7}$$

Where N_{wt-max}、N_{pv-max}、$N_{bess-max}$、 and $N_{invr-max}$ represent the maximum installation capacity of WT, PV, BESS and INVR respectively, and the value of installation capacity.
The expression of the system power balance condition is as follows [24]

$$Pwt,h + Ppv,h + Pbess - out,h + Pbuy,h = Pbess - in,h + Psell,h + Pload,h \tag{8}$$

Where, $P_{wt,h}$、$P_{pv,h}$ respectively represent the real-time output power of wind power and photovoltaic; $P_{bess-in,h}$、$P_{bess-out,h}$ represent the charging and discharging of energy storage Power; $P_{load,h}$ is the load power; $P_{wt,h}$、$P_{pv,h}$respectively represent the power of the multi-energy system to buy and sell electricity from the main system. The charging and discharging power of BESS shouldn't exceed its maximum margin level as

$$\begin{cases} P_{bess-in,h} \leq \frac{1}{k_{bi}} f_{bi,h} N_{bess} P_{maxcharge} \\ P_{bess-out,h} \leq \frac{1}{k_{bi}} f_{bo,h} N_{bess} P_{maxcharge} \\ f_{bi,h} + f_{bo,h} \leq 1 \end{cases} \tag{9}$$

where, $P_{maxcharge}$and $P_{maxdischarge}$ are the maximum charge and discharge power limits of BESS respectively; $k_{bi}$and k_{bo} are the conversion efficiency of BESS charge and discharge respectively; $f_{bi}$and $f_{bo}$are 0-1 variables, which represent the BESS charge and discharge flags. As an important parameter of BESS operation, the state of charge should be set to a certain range. The expression is as follows

$$\begin{cases} S_{h+\Delta t} = S_h + \frac{k_{bi} P_{bess\_in,h} \Delta t}{k_{bo} B_{cap}} - \frac{P_{bess\_out,h} \Delta t}{k_{bo} B_{cap}} \\ S_{min} \leq S_h \leq S_{max} \end{cases} \tag{10}$$

where, $S_h and\ S_{h+\Delta t}$ are the SOC values at h and B_{cap}, respectively; B_{cap} is the total capacity of BESS.

If the reverse power to the distribution system is too large, it will damage the stability of the distribution system. Excessive power purchase will also have a certain impact on the economic benefits of the micro-grid. Therefore, the power purchased and sold shouldn't exceed the maximum margin level as:

$$\begin{cases} 0 \leq P_{buy,h} \leq P_{buy,max} \\ 0 \leq P_{sell,h} \leq P_{sell,max} \end{cases} \tag{11}$$

Where $P_{buy.max}$ and $P_{sell.max}$ are power limits for power purchase and sale.

Second-layer multi-energy system

The second layer takes the operating cost of the multi-energy system and the utilization rate of renewable energy as the goal. According to the first model, the energy storage output range and the capacity of photovoltaic and wind turbines are given. The second model can optimize the operation and scheduling of the multi-energy system. The objective function expression is as follows:

$$F = min(F_1, F_2) \tag{12}$$

Daily operating cost

$$F_1 = min(\sum_{h=1}^{24}(C_{bess} + C_{\Delta PV} + C_{\Delta WT})) \tag{13}$$

Where C_{bess} is present the cost of energy storage scheduling, considering the costs of its one-time maintenance, operation and configuration which determine by

$$C_{bess} = k_{bess}\left(\frac{P_{bess-out}}{k_{bo}} + P_{bess-in}k_{bi}\right)\Delta t \quad (14)$$

where, k_{bess} is present the dispatch cost of the energy storage system and $C_{\Delta PV}$ is the abandonment cost of photovoltaic which can determine by

$$C_{\Delta PV} = k_{pv}\Delta P_{pv}\Delta t \quad (15)$$

In the formula, ΔP_{pv} represents the abandonment power, and k_{pv} represents the unit abandonment cost.
$C_{\Delta WT}$ is the wind abandonment cost of the wind turbine calculation as

$$C_{\Delta WT} = k_{wt}\Delta P_{wt}\Delta t \quad (16)$$

Where k_{wt} is present the cost of the abandonment wind turbine unit; ΔP_{wt} is present the reeducation in the power of the wind turbine system in the multi-energy system.

Unutilized renewable energy

The percentage of renewable energy utilization is defined as the ratio of curtailed wind and solar energy to the amount of electricity generated by renewable energy as:

$$F_2 = \min\left(\frac{\Delta P_{pv} + \Delta P_{wt}}{P_{PV} + P_{WT}}\ X\ 100\%\right) \quad (17)$$

The scheduling operation, the system operating power should also meet the balance power condition can be determined by:

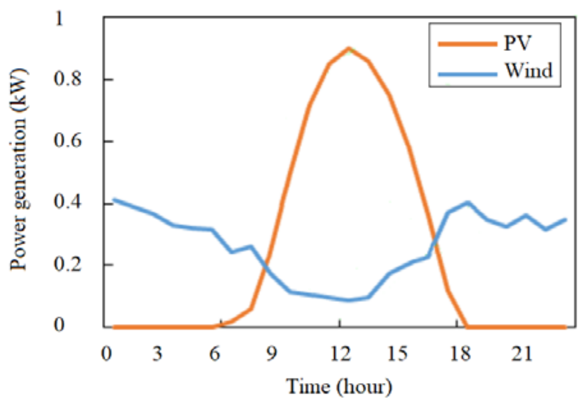
$$P_{load,h} = P_{wt,h} - \Delta P_{wt} + \Delta P_{pv,h} - P_{pv} + P_{bess-out,h} - P_{bess-in,h} - P_{buy,h} + P_{sell,h} \quad (18)$$

Excessive amount of abandoned wind and light will have an adverse effect on the economy and practicability of the multi-energy system. Therefore, its size should be limited to a certain range, which can be expressed as

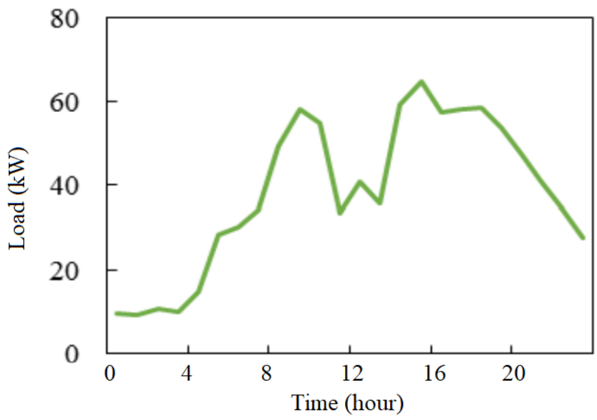
$$\begin{cases} 0 \le \Delta P_{pv} \le P_{PV} \\ 0 \le \Delta P_{wt} \le P_{WT} \end{cases} \quad (19)$$

RESULT AND DISCUSSION

According to the meteorological data of a certain place, the typical daily wind turbine and photovoltaic unit power generation and load power curves are obtained, as shown in Figure 2 (a) and (b). Analyze the dual-layer optimization configuration of independent and grid-connected multi-energy systems respectively. The hybrid sources are BESS, PV, and WT and converter as energy storage annual maintenance and operation costs as shown in Table 1.



(a) Renewable energy unit output



(b) Load power curve

Figure 2. Typical daily power curve

Table 1. Alternate power supply and converter parameters

Types	**Specification (unit)**	**Purchase cost ($)**	**Annual operation and maintenance cost ($)**
WT	50kW	35	1000
PV	45kW	25	20
BESS	3.6V/60Ah	0.02	0.5
WT-inv	20kW	0.8	300
	30kW	1.5	300
	50kW	2.5	300
PV-inv	20kW	0.8	100
	40kW	1.5	100
	60kW	1.8	100
BS-inv	30kW	1.5	400
	50kW	2.8	400
	100kW	4.2	400

The maximum installation capacity of wind and solar storage is set to 20 units, 20 groups, and 3000; the maximum installation number of wind-solar storage inverters is set to 20, 20, and 10 units. The SOC value range is [0.1, 0.9], while the charging and discharging efficiency is 85% and 95% respectively. The energy storage scheduling cost is round 0.518 $/kWh, and the cost of abandonment unit is fixed at 0.97 $/kWh. In the particle swarm optimization algorithm, the population size is 10, the number of iterations is 50, and c_1 and c_2 are 0.6 and 0.01 respectively. The current value of the purchase and sale power range of the multi-energy system is 200kW, and the electricity price characteristic curve is shown in Figure 3.

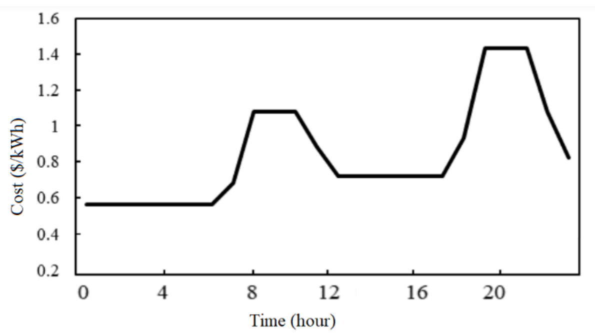


Figure 3. Time-of-use electricity price characteristic curve

Table 2 and Table 3, show the detail of the calculation of a two-layer optimization method including particle swarm optimization algorithm and the large-scale mathematical programming to determine the optimal configuration scheme.

Table 2. The cost benefit of individual power sources

Types	**Nwt (unit)**	**Npv (group)**	**Nbess (uit)**	**Cdev-eav ($)**
Independent	2	1	55	18.681
Grid-connected surplus electricity	5	5	150	-72.696
Grid-connected full access	2	7	389	-8.5295

Table 3. The details of supported invertor for each power sources

Types	Specification	Independent (unit)	Grid-connected type	Grid-connected (full access)
Nwt-inv	20kW	0	0	0
	30kW	0	0	0
	50kW	2	5	2
Npv-inv	20kW	0	0	0
	40kW	0	0	1
	60kW	1	4	5
Nbs-inv	30kW	1	0	1
	50kW	0	0	1
	100kW	1	3	7

From Table 2 and Table 3, it can be seen that the optimal configuration scheme of the independent multi-energy system has selected two 50kW direct-drive wind turbines, a 45kW photovoltaic array, and 55 energy storage batteries; in the converter, photovoltaic One 60kW converter was selected, two 50kW wind converters, and one 30kW and 100kW energy storage bidirectional converter. Under the condition of satisfying the power balance constraints of independent multi-energy systems, although the cost of wind turbines is slightly greater than that of PV, the output of wind turbines is more stable. Therefore, the capacity of wind turbine modules in the optimal solution is more than that of PV . Although the equipment cost of the energy storage module is low, it has multiple replacement costs, which affects the economics of its configuration, which in turn leads to its configuration capacity less than renewable energy, but due to the independent multi-energy system and the large power grid if there is no connection, the excess power generated by the wind needs to be stored in energy storage, so the number of energy storage modules will not be too small as shown in Figure 4.

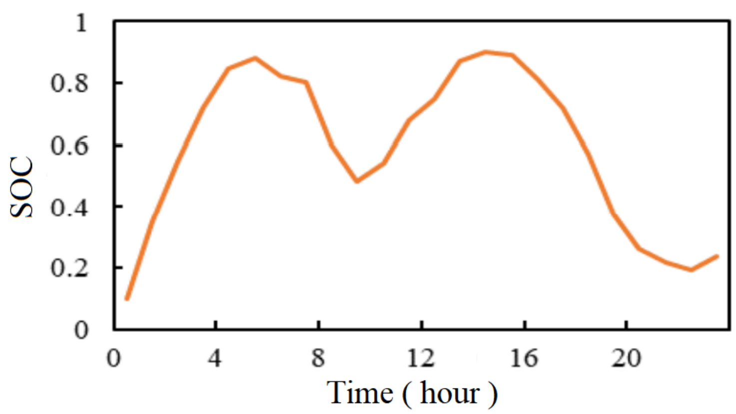


Figure 4. SOC curve of off-grid operation

There are two configuration schemes for the grid-connected multi-energy system. It can be seen that the "spontaneous self-use" model has the lowest overall investment cost and better economy. From the comparison of the economic costs of the two models as shown in Figure 5, the equipment costs of option 1 and option 2 are not much different, but the operating income of scheme 1 is significantly higher. The "self-generation and self-use" mode selected in option 1, the power generated by the power supply in the system meets the power demand of the load, and the surplus power can be exchanged for power sales income; the "uniform purchase and sales" mode feeds all the generated power into the main system, users purchase electricity through normal electricity prices to meet their own needs, and at the same time, the reverse power is limited by interactive power. The excess energy output by renewable energy is charged and stored by BESS, which increases the BESS configuration capacity and reduces the economy of the overall system. At the same time, the energy storage operation status of the two schemes also meets the constraint conditions in which scheme 1 is beneficial to prolong the service life of the energy storage battery as shown in Figure 6.

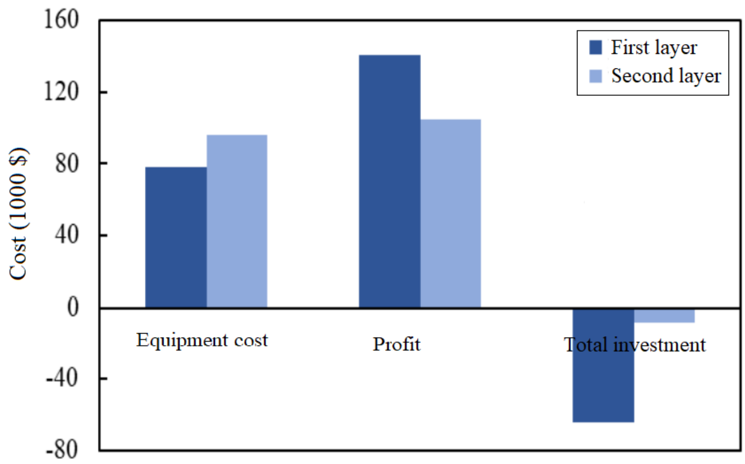


Figure 5. Cost comparison of two grid-connected solutions

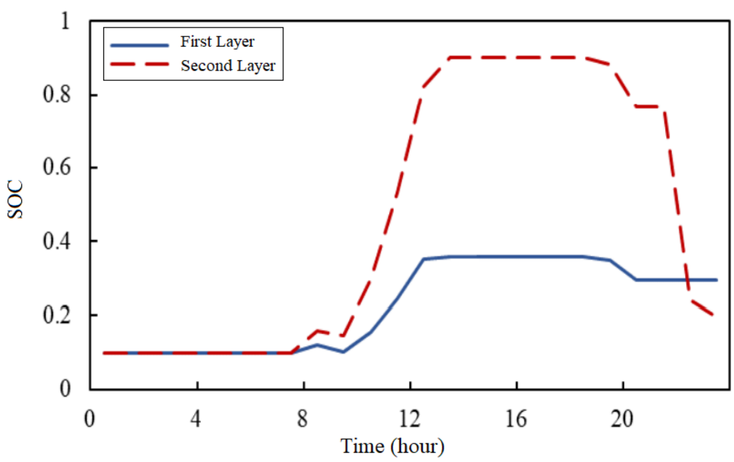


Figure 6. SOC of grid-connected operation

From Figures 7 and 8 are shown the corresponding system operating power with the optimal configuration results of the independent and grid-connected multi-energy systems for one-day economic dispatch

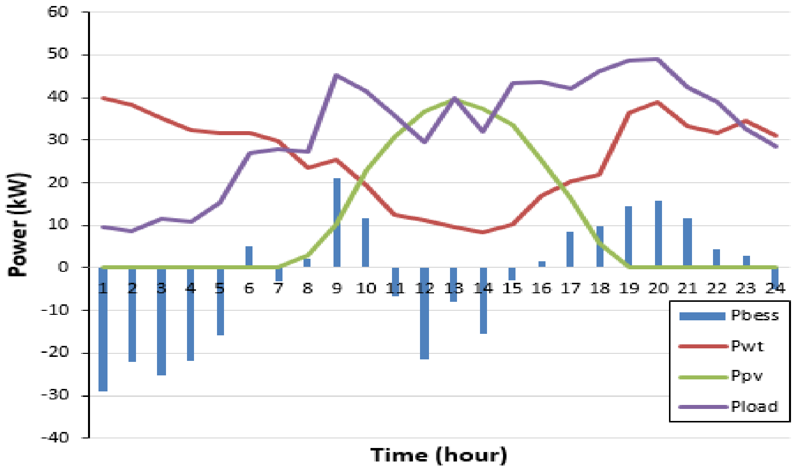


Figure 7. Off-grid operating power

Figures 4 and 7 reflect the daily operation of the multi-energy system island. From midnight to five in the morning, PV has no power output, WT assumes the load power consumption while excess power is charged and stored by BESS, Pbess<0 and the SOC curve is on the rise; from 6 to 9 o'clock, the wind and solar resources are insufficient, and the power demand is determined by WT , PV output and BESS discharge are met together, Pbess >0 and the SOC curve shows a downward trend; from 10 am to 2 pm, there are sufficient sunshine resources, user electricity is met by PV and excess electricity is charged and stored by BESS; 3 pm to night At ten o'clock, the load power consumption reaches the peak of the whole day, and the operating state is similar to the period from 6 to 9 o'clock; after 11 o'clock in the evening, the load demand gradually decreases, and WT once again stores the excess power in the BESS, which is connected to the time between 0 AM and 5 AM .

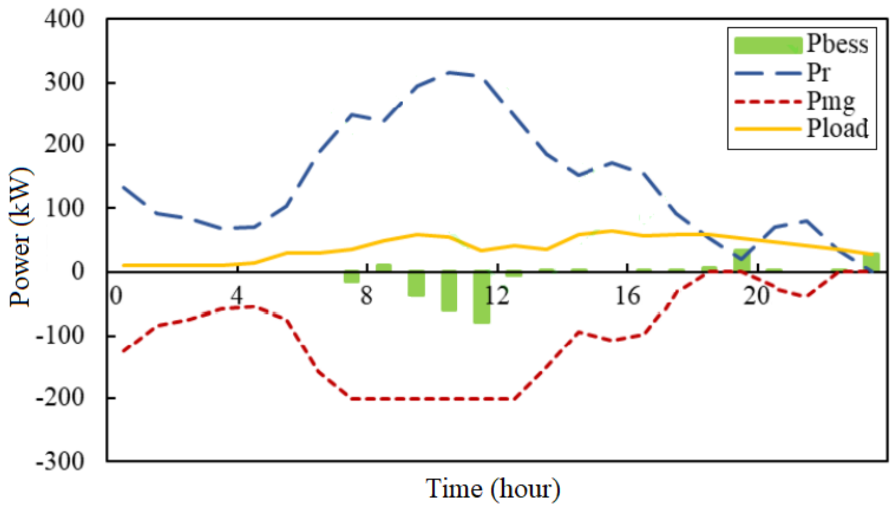


Figure 8. Grid-connected operating power

Figures 6 and 8 reflect the daily operation of the multi-energy system connected to the grid. From midnight to five o'clock in the morning, PV has no power output, WT assumes the load power consumption while the excess power is fed into the main system Pmg<(0) to obtain electricity sales revenue. BESS does not work during this period; daytime hours from 7:00 to 6:00 pm, natural resources. The most sufficient, the load power demand is on the rise. After the wind and solar output power assumes the load power, part of the power is fed into the main system, and part of the power is charged and stored by the BESS $Pbess$<0 and the SOC curve is on the upward trend; at eleven o'clock, the electricity demand has not decreased, but the wind and solar resources are restricted by day and night and climate factors. The electricity demand is met by WT, PV output and BESS discharge $Pbess$ >0 and the SOC curve shows a downward trend.

CONCLUSION

The multi-objective optimization configuration method for wind-solar and solar-storage multi-energy systems is done. The optimal configuration plan with the goal of minimum annual investment cost is determined. The system's daily operating cost and renewable energy utilization rate ae used, the minimum is the goal, and the multi-energy system multi-objective day-ahead economic optimization dispatch model is established. Computations with aid of the data scenery verifies the correctness and effectiveness of the method proposed in this paper. The proposed method takes into account the construction cost of the whole life cycle, and if suitable for the optimized configuration and scheme selection of the grid-connected multi-energy system in the substation station.

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