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J. Electrical Systems 17-2 (2021): 171-181

Regular paper

Optimal planning and investment of Multi-renewable power generation and energy storage system capacity

Journal of Electrical Systems

This paper focus on the coordination and optimization of renewable energy power generation capacity and other multiple energy sources in the power grid and the operational efficiency of renewable energy power generation equipment. The detail description of multi-energy system model composed of high proportion of wind power generation, photovoltaic power generation, solid regenerative electric boiler, electricity-generated natural gas, gas energy storage, and thermal energy storage system (ESS), renewable energy based on different scheduling time scales. First, the proposed power generation capacity planning and profit multi-objective optimization model. Second, investigate the energy supply and consumption characteristics of multi-energy supply, transmission, and load equipment in the power grid, and establish a multi-energy grid power balance model based on the uncertainty of high-ratio renewable energy generation. Finally, testing the proposed model using the actual operation data of a multi-energy grid in a region of northeast Pakistan. The simulation results show that the renewable energy capacity and benefit optimization model can achieve a smaller renewable energy capacity allocation on the premise of ensuring higher investment benefits.

Keywords: Rrenewable energy; energy storage investment; supply planning.

1. Introduction

The energy development considering, more and more electricity produced by natural gas, thermal heat, PV, solar thermal and wind are connected to multi-energy conversion and energy storage such as fuel cells, chemical and battery energy storage [1, 2]. Meanwhile, the renewable energy industry has seen a cumulative growth rate of around 26% for the past eighteen years. The total wind power capacity is expected to reach nearly 2000 GW by 2030 in an advanced scenario, and to supply between 16.7% and 18.8% of global electricity demand [1]. Although wind energy is sustainable and emission-free, it is largely intermittent and subject to a high level of uncertainty. The forecast error of renewable energy including wind power can be over 10%, so it is still difficult to efficiently integrate wind power with high penetration.

Many researches focused on multi-energy systems and grid power capacity planning show that the allocation capacity of renewable energy in multi-energy grids determines the coordination and autonomy of multi-energy grids on the one hand and their functional quality. It also greatly affects the efficiency of the multi-energy grid investment returns [3]. To improve the level of collaborative optimization of multi-energy systems and operational efficiency and shorten the investment recovery period [4, 5] based on the relationship between virtual energy storage, coordinated allocation of renewable energy, and time-of-use electricity prices, virtual energy storage is proposed. The coordinated optimization model of capacity and revenue improves the optimal allocation of energy storage in multi-energy systems [6]. In [7], to solve the problem of restricting the utilization of multi-energy

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supply equipment to system capacity planning in comprehensive energy system planning, based on the research of renewable energy supply and uncertainty of various types of loads, proposed a method that can effectively Multi-energy system capacity optimization configuration model to improve equipment utilization hours. In [8], proposed multiple multi-energy system planning and coordination problems, based on the multi-energy linearization model, studied the energy network and energy hub layered coordination planning model, and proposed a multi-energy component and system layered scheduling Energy system planning method. In [9,10] investigate the problem of multi-energy system or power grid capacity planning under the premise of meeting the power demand of multi-energy system or power grid, the system planning or power supply capacity optimization is aimed at the minimum capacity or the maximum investment income. At present, under the constraints of comprehensive factors such as source and load uncertainty, multi-energy conversion coordination, and grid reliability after multi-energy equipment is connected to the grid on a large scale, renewable energy power generation capacity planning is based on renewable energy proportion increase and investment income [11, 12].

This paper first aims at the coordination and autonomous optimization of energy supply, conversion, storage, and consumption of various types of energy sources such as electricity, heat, and gas in the multi-energy grid to maximize the return on investment in power grid construction. The study establishes the optimization model of renewable energy investment income based on energy supply price response and energy quality control cost constraints by period the price response of multi-energy loads under uncertainty in multi-energy grids and other factors to cooperate to optimize the planning method of renewable energy power generation capacity. The collected operation data of a multi-energy power system in a northeast city in Pakistan. Finally, optimize and analyze the system's renewable energy allocation capacity and investment income according to the energy supply and energy storage parameters of the traditional power grid, thermoelectric grid, and gas power grid. The research results show that the renewable energy power generation capacity planning and investment benefit optimization model can better improve the grid's renewable energy capacity allocation and investment return level under the premise of compatible energy supply quality and energy supply price period characteristics.

2. Multi-energy grid structure

Multi-energy grid structure is based on the traditional power system, which is connected to larger-scale renewable energy power generation, electric heating boilers, electric natural gas and natural gas fuel cells, and cogeneration units to form a multi-energy power system that can simultaneously satisfy the load demand of various energy forms such as electricity, heat, natural gas, etc. within a certain geographical area depicted in Figure 1 [13, 14]. The general multi-energy power system is shown in Figure 1. The multi-energy power system can not only realize the efficient autonomous operation of multiple energy sources in the region through energy conversion and storage within the system but also can interact with the upper-level gas grid and power grid to provide a certain amount of energy for the upper-level energy backbone network [15]. The ability to adjust the peak and valley, the multi-energy power system is an important comprehensive energy supply, conversion, and storage and consumption unit to realize the energy internet [12, 16]. The multi-energy power system can generate revenue when it provides energy for internal loads and external networks. The scale of renewable energy power generation in the region largely determines the total operating cost and investment income of the system.

The multi-energy grid is the main energy carrier, and the three energy networks of electricity, heat, and gas pass through the conversion and storage units of the three energy sources to realize the interaction of energy forms between the networks presented in Figure

1. Electricity, heat and gas can be converted, stored and distributed according to the real-time status of the three types of energy consumption in the region [17, 18]. This feature can coordinate the different peak and valley characteristics of various energy supply and consumption, and balance the time characteristics of total energy consumption in the region. Therefore, in the planning of renewable energy power generation in multi-energy grids, full consideration should be given to the coordination of renewable energy power generation characteristics, conversion and storage characteristics of multiple types of energy forms [19, 20]. With the coordination of multiple energy load characteristics within the grid, and multiple energy consumption benefits optimization can effectively improve renewable energy planning and its investment income level [21, 22].

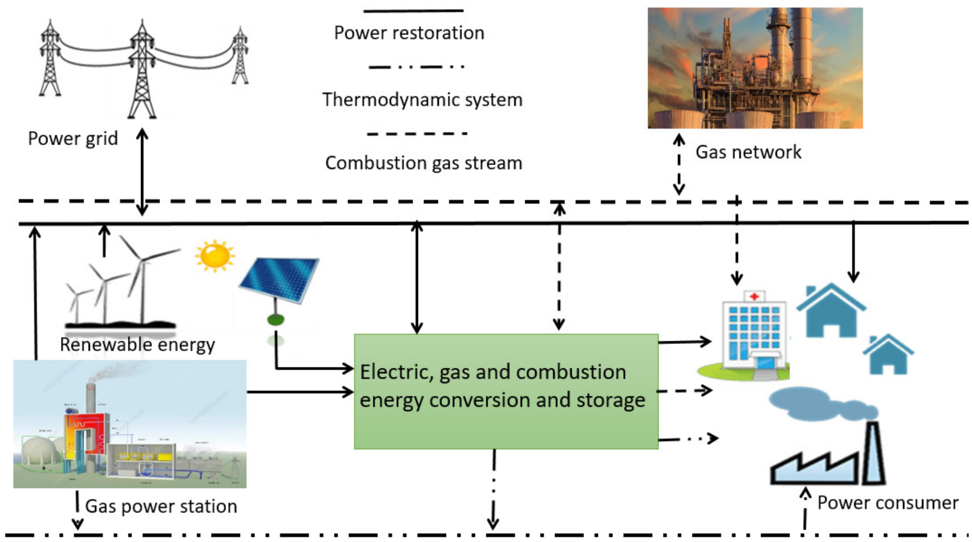

Figure 1 multi-energy electric power system topology model

2.1 Multi-source load uncertainty model

The electric, thermal and gas loads in the multi-energy grid are divided into adjustable and non-adjustable loads. The multi-energy grid load model considering uncertainty is:

$$\begin{cases} P_{M-U} = f_{MU}(\mathrm{t}) \pm \Delta \mathrm{L}_{U,}\ t \in [\mathrm{t}_s, \mathrm{t}_e] \\ P_{M-C} = f_{MC}(\mathrm{t}) \pm \Delta \mathrm{L}_{\mathrm{C},}\ t \in [\mathrm{t}_s, \varsigma] \cup [\xi, \mathrm{t}_e] \end{cases} \tag{1}$$

Where, $P_{M\text{-}U}$ and $P_{M\text{-}C}$ are the uncontrollable load and controllable load demand values in the multi-energy grid; f_{MU} and f_{MC} are the time characteristics of the uncontrollable load and the controllable load in the multi-energy grid， ξ are controllable load adjustment time parameters; ΔL_U, ΔL_C are the uncertainty of uncontrollable load and controllable load; t_s,t_e are the start time and end time of a dispatching cycle of the power grid, respectively.

2.2 Uncertainty model of renewable energy power

The uncertainty considering the output power of renewable energy, the power characteristics of renewable energy in multi-energy systems are:

$$P_{RE} = f_{RE}(\mathrm{t}) \pm \Delta \mathrm{L}_{\mathrm{R},}\ t \in [\mathrm{t}_s, \mathrm{t}_e] \quad (2)$$

Where, P_{RE} is the total renewable energy generation output power in the multi-energy grid; f_{RE} is the renewable energy generation time characteristic in the multi-energy grid; ΔL_R is the uncertainty of the renewable energy power generation output.

2.3 Multi-energy conversion constraint model

Consider that the system includes the upper-level power grid, thermal power unit, thermal power unit, renewable energy generation, upper-level gas network and other electricity, heat and gas supply units and energy conversion and storage units, and multi-energy grid power, heat, gas load and energy supply units [23, 24].
In the planning of renewable energy capacity of multi-energy grids, assuming that the technical and economic parameters of renewable energy equipment remain constant, the system economic dispatch strategy can better meet the optimization of operating costs. At the same time, the objective function of optimizing the capacity of renewable energy and optimizing the revenue of the multi-energy grid is:

$$\begin{cases} \max \mathrm{E}_{RN}(\mathrm{t}) \\ \min \mathrm{C}_{QRE}(\mathrm{t}) \end{cases} \quad (3)$$

The constraint functions of renewable energy capacity optimization and revenue optimization mainly include multi-energy grid real-time power balance constraints and multi-energy grid real-time operating status constraints.

3. Proposed Model

In a multi-energy grid, the power constraint between electricity and heat energy supply and demand is:

$$\sum PME(t) = \sum P_{SUP}(t) + \sum \Delta P_{LOS}(t) \quad (4)$$

Where, $P_{ME}(t)$ is the energy demand of each electricity, heat, and gas energy consumption unit in the multi-energy grid; $P_{SUP}(t)$ is the output of each electricity, heat, and gas energy supply unit in the multi-energy grid; $P_{LOS}(t)$ is the energy loss of electricity, heat, and gas networks in multi-energy grids.
To ensure the reliability and quality of electricity, heat and gas energy supply in the multi-energy grid, the operational constraints that the multi-energy grid should meet are:

$$\begin{cases} P_{EL\min} \le P_{ELSUP}(\mathrm{t}) \le P_{ELmax} \\ P_{\mathrm{CS}\min} \le P_{CSSUP}(\mathrm{t}) \le P_{CSmax} \\ P_{\mathrm{TH}\min} \le P_{THSUP}(\mathrm{t}) \le P_{THmax} \\ U_{\mathrm{EL}\min} \le U_{EL}(\mathrm{t}) \le U_{ELmax} \\ E_{\mathrm{BT}\min} \le E_{BT}(\mathrm{t}) \le E_{BTmax} \end{cases} \quad (5)$$

Where, $P_{ELSUP}(t)$ is the output power function of all power sources in the multi-energy grid at time t; $P_{GSSUP}(t)$ is the output power function of the gas multi-energy grid gas supply equipment at time t; $P_{THSUP}(t)$ is the output power function of the thermal energy supply equipment of the multi-energy grid at time *t*; $U_{EL}(t)$ is the voltage fluctuation function of the grid node at time *t*; $E_{BT}(t)$ is the charge of the energy storage device of the energy storage system in the multi-energy grid at time *t* energy state function.

In a multi-energy grid, the energy supply resources are divided into two categories: One is the energy supply from renewable energy in the area, that is, the renewable energy supply unit; the second is energy supply from other energy supply resources, that is, non-renewable energy supply units. At this time, to ensure the quality of each multi-energy supply in the dispatch cycle, the energy supply cost of the renewable energy supply unit and the non-renewable energy supply unit is:

$$\begin{aligned} &C_{RE} + \vartheta_R C_{QRE}(\mathrm{t}) \\ &C_{URE} + \vartheta_U C_{QURE}(\mathrm{t}) \end{aligned} \tag{6}$$

Where the renewable energy supply unit and the non-renewable energy supply unit, in a scheduling period [t_s, t_e], the price P_{RIRE}(t), P_{RIURE}(t) to supply energy to the load.
These are the basic energy supply costs that are not related to the quality of renewable energy or non-renewable energy. The level of this cost is determined by the development level of renewable energy and non-renewable energy supply equipment, which is an inherent cost and cannot be affected by optimal capacity allocation. R_{CQRE} and U_{CQRRE} are the energy supply costs resulting from the adjustment of the energy supply system with the fluctuations and uncertainties of multiple energy supply, conversion, storage and demand in the system to ensure the energy supply quality of the system. The higher the level of coordinated operation within a multi-energy grid, the lower the corresponding adjustment cost, while ϑ_R, ϑ_U are the unit energy supply adjustment cost parameters. This parameter is related to the input of the total dispatch operation control system of the multi-energy grid and has nothing to do with the installed capacity configuration of renewable energy. When the capacity configuration is performed, it can be considered as a constant. C_{QRE}, and C_{QURE} are the cost of energy supply reliability, that is, the installed capacity cost. The C_{QRE} and C_{QURE} have no relation with the coordinated operation capability of the system, and are related to the installed capacity of renewable energy supply and non-renewable energy supply equipment in the system. The larger the installed capacity will have the higher installation capacity cost, the higher reliability of the system can improve the power supply quality. The installed capacity cost is:

$$\begin{aligned} &C_{QRE}(\mathrm{t}) = \frac{\rho_R}{2} P^2{}_{RE}(\mathrm{t}) \\ &C_{QURE}(\mathrm{t}) = \frac{\rho_U}{2} P^2{}_{URE}(\mathrm{t}) \end{aligned} \tag{7}$$

Where, p_R, p_U are the parameters of unit installed capacity cost. Under the above energy supply quality cost, the load response to the price in the multi-energy grid:

$$P_{LM}(\mathrm{t}) = E_{RN2}(\mathrm{t}) + E_{RN3}(\mathrm{t}) \tag{8}$$

$$\begin{cases} E_{RN2}(\mathrm{t}) = \mathrm{P}_L(0) - \sigma[\mathrm{P}_{PIRE}(\mathrm{t}) - \mathrm{P}_{PIURE}] \\ E_{RN3}(\mathrm{t}) = \gamma[\mathrm{C}_{QRE}(\mathrm{t}) - C_{QURE}] \end{cases} \tag{9}$$

In the formula, σ is the energy supply price response parameter; γ is the energy supply quality response parameter; $P_L(0)$ is the system's initial energy consumption demand.
In a multi-energy grid with a certain renewable energy installed capacity, the revenue from renewable energy supply can be expressed as:

$$E_{RN}(\mathrm{t}) = \int_0^t \mathrm{e}^{-\varphi t}[E_{RN1}(\mathrm{t}) + E_{RN2}(\mathrm{t}) + \mathrm{N}_{ER3}(\mathrm{t}) + C_{QRE}(\mathrm{t})]\,\mathrm{dt} \tag{10}$$

Where $E_{RN1} = P_{RIRE}(t) - C_{RE} - \vartheta_R C_{QRE}(t)$; φ is the discount rate of renewable energy supply income; $e^{-\varphi t}$ represents the current investment quota after the renewable energy power generation equipment is put into operation The energy supply income and the discount rate r have a negative exponential relationship. With time, the energy supply capacity of the equipment invested in the initial investment or the energy supply capacity to ensure a certain quality will decrease exponentially.

Equation (8) shows that higher installed capacity of renewable energy can bring higher reliability of renewable energy supply, and accordingly increase energy supply income; increased installed capacity also brings cost increase, and the improvement of the quality level will increased demand; improved quality will also bring increased investment costs of renewable energy. Therefore, the optimization of renewable energy capacity planning is to find the optimal solution between the revenue and reliability of renewable energy supply.

4. Simulation result and discussion

The actual operating data from a region in the northeast, Pakistan including the electricity price, gas price and heating price, the system operation characteristics and investment income of renewable energy in different configuration scales are simulated and analyzed. The typical daily load curves of electricity, heat, and gas in the multi-energy grid in this area are shown in Figure 2. The multi-energy power system parameters are shown in Table 1.
Table 2, shows the sets of the period characteristics of energy prices in multi-energy grids. At the same time, considering the requirements of comprehensive energy supply quality and the uncertainty of renewable energy on energy supply reliability in multi-energy grids. To analyzes the corresponding renewable energy capacity allocation for different system energy supply reliability index requirements as shown in Table 3.

Table 1 Non-renewable energy supply parameters of the multi-energy grid

Energy supply unit	Capacity
Thermoelectric	2000MW
Thermal Power	5550MW
Electrical conversion	350MW
Gas-electricity	550MW
Conversion	415MW
Gas storage	1150MWh
Thermal storage	1300MWh

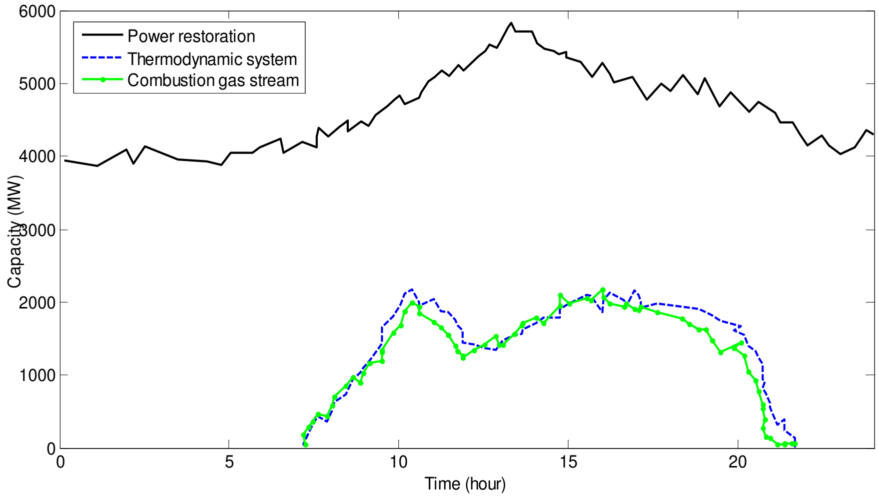

Figure 2 Typical daily load curves of electricity, heat, and gas for multi-energy power systems

Table 2 Prices of multi-energy supply at each time

Time	Price ratio (%)
08:00-12:00 17:00 -21:00	120
12:00-17:00 21:00-24:00	95
00:00-to 08:00	50

Table 3 Configuration of renewable energy devices under different energy supplement quality

Renewable energy power generation equipment	Configuration capacity (MW)			
	0.990	0.992	0.995	0.998
Wind Turbine	2150	2500	3100	4250
Photovoltaic	1590	1910	2150	2750

The estimated daily cost of operations was 1546105.69 US$ and load mitigation could occur in a bus if the single power consumption output is much smaller than expected. After

the multi-power system deployment, there is no load constraint in all chosen scenarios. Thanks to the load shifting capacity of both devices, the average daily cost is considerably lower than with the standalone system to 906397.89 US$. Figure 4 shows a decrease in operational costs, which indicates the estimated hourly cost of operations in all cases for the weekday season. The operating cost of the case of multi-systems was higher than the case with a standalone system during the first 7 hours, where demand is low, indicating that the storage unit is filled with extra power. Operating costs increase dramatically by 9 am during peak hours, then at 9 pm. In the energy storage situation, the energy stored during the previous hours can be used to supply the demand instead of depending on inefficient peak power generators, so the operating costs during this period are much smaller than the operational costs without a multi-system. If storage expenditure expenditures are raised to encourage the scale of storage facilities, we will move larger peak hour loads and thereby reduce operational costs. This is followed by a debate in the next segment.

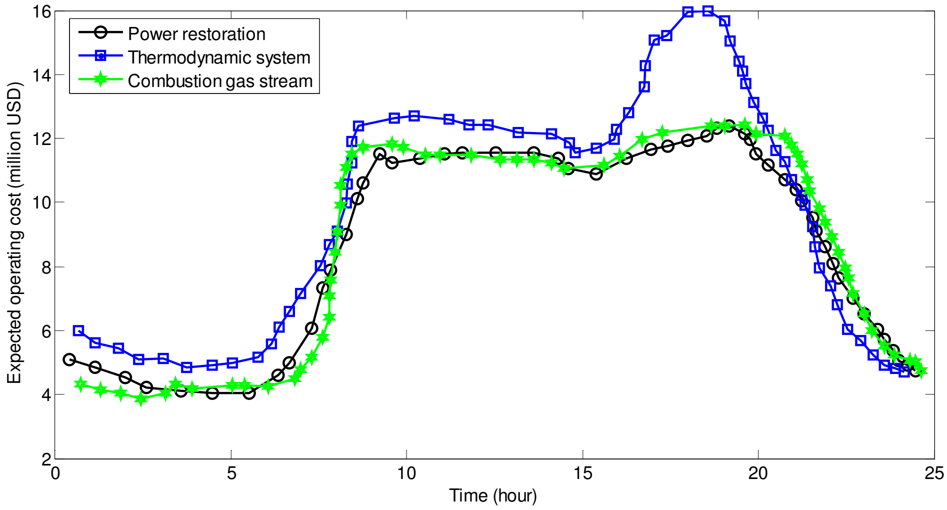

Figure 3 Expected hourly operating cost for multi-energy power systems

A capital/running costs balance indicates the tradeoff between ESS capital spending and day-to-day operating costs, as seen in Figure 4. This cap is reached by addressing financial forecasting challenges from zero to 260 million. The average costs are greatest if without ESS is included in the test method. When the budget rises, operational costs are gradually decreasing, mostly due to the expanded ability for ESS to transfer load. This expense curve is seen to be "square" when the budget is very high, suggesting a reduction in everyday running costs as spending in the ESS increases. In the following, the best possible balance between ESS capital expenditure and maintenance costs is calculated based on the average daily expense of the power network over the lifetime of storage facilities.

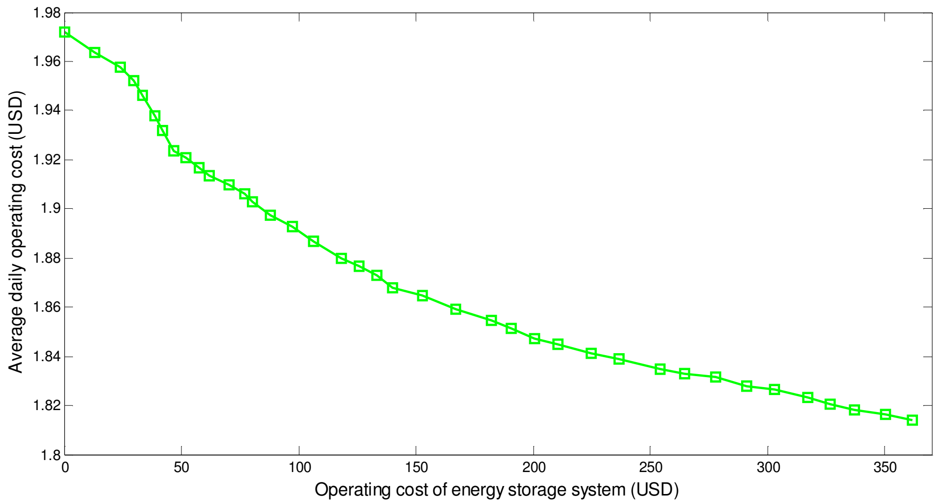

Figure 4 Energy storage system operating cost

$$\delta + \frac{1}{365} \frac{\eta(1+\eta)^{NS}}{(1+\eta)^{NS} - 1} . \gamma \tag{11}$$

Where δ refers to the average regular operating cost and the second is the daily cost of ESS adjusted according to the annuity model, where NS is the lifespan of storage units for many years and is the annual interest rate.

The minimum Searching expression value Eq. (12) for all solutions will determine the most effective expenditure budget. For example, assume that the discount rate ± 4 per cent per year is shown in the figure as the best level of ESS investment for the lifetime of storage devices. Case studies suggest that innovation in ESS should be expanded if advances in technology prolong the lifespan of energy storage devices. It can also be shown, even if the lifetime of the storage units is as long as 50 years that the cost should not reach US$ 380 million. Because the ESS investment budget is over US$ 180 million, the increase in everyday quality of service is very negligible. The comparison between the 180 million budget case and the 260 million budget case reveals that the operating cost reduction is just 0.76 per cent, although the investment budget has increased. Nevertheless, even if no spending cap (infinite budget) is set, the actual running daily expenses are US$ 1860510.02, only about 1% less than the case for a budget of US$ 120 million.

There are two reasons why the regular cost reduction may become negligible as the ESS investment increases further: (1) the increasing ESS scale also raises operating cost and (2) it could reduce the ESS load shifting capacity by the transmission limit. That is why it is as important to locate storage devices as the scales. The optimum locations and the optimal ESS scale under different budget constraints. It is found that storage devices are installed around the area where power failure is likely to occur. If the budget is small, the most efficient way to plan is to focus all available resources to construct ESS. Bus two specific busses should be the perfect mix. Since the budget approaches US$ 220 million, the commitment is enough to build ESS in three or even four different locations. Nevertheless, Figure 5 shows that the operating efficiency of the additional storage unit is practically meaningless.

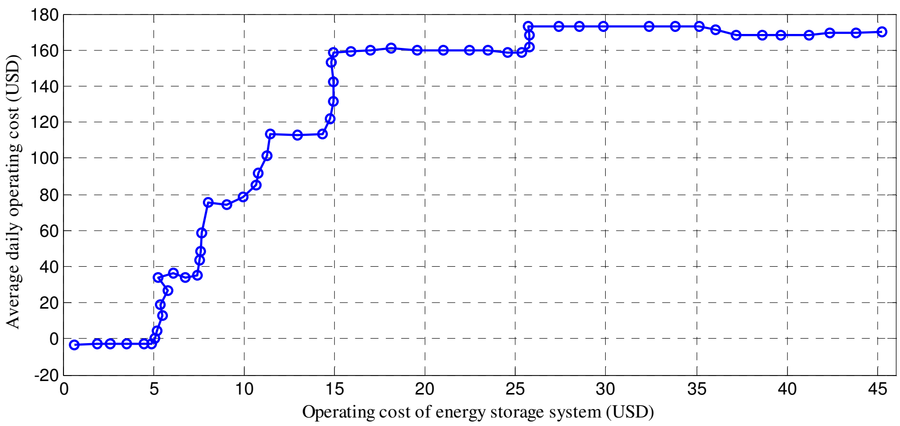

Figure 5 Energy storage system investment

The data of the increase in the demand for energy supply reliability, the demand for renewable energy capacity allocation shows in Table 3 an accelerated upward trend, which will also lead to an increase in initial investment and post-operation and maintenance costs. Considering the income parameter requirements such as renewable energy investment and operation and maintenance costs as shown in Table 4, under the given investment income requirements, set the multi-energy grid energy supply reliability requirements to be more than 0.998, and according to Table 2 to implement the stage supply Energy price mechanism, the optimization results of renewable energy capacity allocation in the multi-energy grid shown in Table 1 and Table 5.

Table 4 Investment income parameters of renewable energy power generation equipment

Investment parameters	Set value
Capacity cost/ten thousand yuan MW	716
Operation and maintenance cost/ton thousand (US$) (MW)	65
Design life (annual)	15
Loan ratio (%)	68
Lending rates (%)	4.78
Loan life (annual)	5
Expected yield (%)	7
Evaluation period (annual)	5

Table 5 Multi-energy grid renewable energy optimal configuration

Equipment	Capacity (MW)	Net present value/ton (US$)	Investment recovery period (annual)	Rate of return (%)
Wind Turbine	3720	41489.361	3.6	23.7
Photovoltaic	2390	26331.914	4.7	21.1

In Table 5 it can be seen from the data that the coordinated optimization method of renewable energy capacity allocation and investment income in this paper can take into account the relationship between the two, and on the premise of ensuring higher energy supply reliability, achieve a smaller capacity allocation and comparative Good investment income.

5. Conclusion

When configuring the capacity of renewable energy in a multi-energy grid, not only the uncertainty of the various types of loads in the energy supply area and the uncertainty of the output of renewable energy affect the energy supply quality, but also need to be considered the cost of energy supply quality control brought about by the coordination of renewable energy supply and non-renewable energy supply can effectively coordinate the technical and economic optimization of uncertainty and energy supply quality control. The multi-energy grid adopts a time-segment energy supply price mechanism, which can not only effectively improve the system's multi-energy supply coordination autonomy level, reduce reliability costs, but also effectively optimize the renewable energy capacity allocation and increase the multi-energy grid energy supply income level. Because of the characteristics of electricity, heat and gas load demand and the parameters of non-renewable energy supply equipment in a specific multi-energy grid, the renewable energy capacity allocation and investment income optimization model proposed in this paper, under the same energy supply quality requirements, the capacity allocation was reduced by 12.4%, and the investment recovery period was shortened by 17%.

Acknowledgment

Authors gratefully acknowledge the support of Huaiyin Institute of Technology for providing the necessary facilities to complete this study.

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