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Research on complementarity of multi-energy power systems: A review

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ABSTRACT

In the background of the large-scale development and utilization of renewable energy, the joint operation of a variety of heterogeneous energy sources has become an inevitable development trend. However, the physical characteristics of different power sources and the inherent uncertainties of renewable energy power generation have brought difficulties to the planning, operation and control of power systems. For now, the utilization of multi-energy complementarity to promote energy transformation and improve the consumption of renewable energy has become a common understanding among researchers and the engineering community. This paper makes a review of the research on complementarity of new energy high proportion multi-energy systems from uncertainty modeling, complementary characteristics, planning and operation. We summarize the characteristics of the existing research and provide a reference for the further work.

KEYWORDS

Complementarity, multi-energy systems, operation, planning, uncertainty.

At present, in order to solve the environmental pollution and ecological damage caused by the massive use of fossil energy, countries around the world have formulated energy transformation strategies to realize an energy supply system mainly with renewable energy as soon as possible. Europe, the United States and China have proposed blueprints for power systems that will achieve 100%[1], 80%[2] and 60%[3] of renewable energy in 2050. Recently, President Xi Jinping pointed out that China will enhance the state's independent contribution and adopt more effective policies and measures in the general debate of the seventy-fifth UN General Assembly. The carbon dioxide emissions will strive to reach the peak by 2030, and strive to achieve carbon neutralization by 2060. Therefore, the proportion of renewable energy access is significantly increased in recent years, and the large-scale centralized gird connection has become an important way of renewable energy generation. Meanwhile, the uncertainty and uncontrollability of renewable energy make the operational characteristics of power systems more complex, which has a negative impact on the security and economy of the multi-energy power system. In this situation, the utilization of the complementarity between multiple energy sources is a feasible and economical way to ensure the coordinated operation of power systems.

Complementarity is not a new concept in the energy field. People have long realized that the integration of different energy sources can achieve better overall results. Ref. [4] evaluated an integrated renewable energy system with wind, micro-hydraulic and biomass, which can achieve economic benefits. The opposite availability of solar radiation or wind makes the wind-solar integrated systems attractive during the development of renewable energy[5]. However, in the past, many researches about the planning and operation of multi-energy focused on distribution networks or small isolated energy systems. Ref. [6] optimized the capacities of energy devices in a distributed energy system with the multi-objective of economy, environment and energy. Ref. [7] studied the integrated performance of wind and solar in energy production. The results proved that the complementarity can improve the renewable energy capacity and the energy export for the network. Ref. [8] analyzed the optimal operation strategy of multi-energy distributed systems. The application of a commercial building shows the improvement of operation performance from complementarity. In general, the research about distribution network mainly focuses on the problem of power balancing, power quality, voltage stability, etc. after the placement of distribution generation[9].

With the improvement of renewable energy construction level and penetration rate, large-scale centralized gird-connected renewable energy has been the hotspot of engineering and research. In USA, the energy consumption from renewable energy in 2019 exceeded coal consumption for the first time since before 1885. There are many renewable energy projects in construction. Dominion Energy has proposed the world's largest offshore wind project of 2.64 GW in Virginia. Portland General Electric and Nextera Energy Resources decided to build the nation's first multi-energy complementary project of wind, solar and battery storage. In China, the development of multi-energy complementary systems has been the government policy[10]. It is promoting the development of large-scale renewable in the regions. For example, there are abundant renewable energy resources of wind and solar in the Yalong River Basin in Southwest China. And there will be a world class clean energy base with 30000 MW hydropower, 12000 MW wind power and 1800 photovoltaic (PV). However, the uncertainty of renewable energy output greatly increases the difficulty of power system planning and operation, which may lead to power accidents in severe cases. Recent studies have shown that the complementarity of wind power and photovoltaic in the operation

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process can greatly reduce the impact of renewable energy output uncertainty and increase the reliability of multi-energy system operation.To meet the needs of renewable energy development and operation, there are many researchers studied the corresponding planning and operation methods of large-scale multi-energy systems based on complementarity. They cared about the utilization of the combined advantages of different power sources to improve the overall performance of the system.

This article makes a review of the research on complementarity of new energy high proportion multi-energy system. We first describe the uncertainty modeling methods of renewable energy power sources. Then we summarize the domestic and international progress in the research of multi-energy complementary characteristics. Finally, we give an overview of the planning and operation of multi-energy power systems. Through the overview, we summarize the main issues of the research on multi-energy systems and provide a reference for future research.

1 Uncertainty modeling of renewable energy sources

Uncertainty is the main characteristic of multi-energy power systems due to the high penetration of renewable energy such as wind power and PV. Therefore, the uncertainty modeling becomes an important part of complementary research. This section introduces uncertain models of renewable energy, which lays a foundation for the subsequent analysis of multi-energy system complementarity.

As the representative of variable renewable energy, the wind power and PV have great uncertainty and volatility during the daily operation. In long-term analysis such as production simulation, the common modeling method for wind power output is to use the probability distribution to describe the wind speed, and then carry out the conversion of wind speed and wind power[11]. There are two methods to simulate wind speed: autoregressive moving average (ARMA) model and Weibull. The ARMA model simulates wind from the linear correlation of historical values. The Weibull model adjusts the density function to generate random values based on historical values[12]. The statistical results of a large number of measured data show that the probability distribution characteristics of wind speed approximately obey Weibull function, and its probability density function is as follows:

$$\phi(u) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} \exp\left[-\left(\frac{v}{c}\right)^{k}\right] \tag{1}$$

where v represents the wind speed, k is the shape coefficient and ranges from 1.8 to 2.3 and generally be 2, and parameter c reflects the annual average wind speed of the corresponding area. The common methods of parameter fitting of Weibull function include: minimum error approximation method, least square method, moment estimation method and maximum likelihood method. Ref. [13] estimated the Weibull parameters of wind energy utilization by power density method, then the wind power active output can be obtained by using the wind turbine output power conversion formula.

$$P_{\mathrm{w}}(v) = \begin{cases} 0 & v \leqslant v_{\mathrm{ci}}, v \geqslant v_{\mathrm{co}} \\ \dfrac{v^3 - v_{\mathrm{ci}}^3}{v_{\mathrm{R}}^3 - v_{\mathrm{ci}}^3} P_{\mathrm{R}} & v_{\mathrm{ci}} \leqslant v \leqslant v_{\mathrm{R}} \\ P_{\mathrm{R}} & v \geqslant v_{\mathrm{R}} \end{cases} \tag{2}$$

where v_{ci} is the cut-in wind speed, v_{co} is the cut-out wind speed, v_{R} is the rated wind speed, and P_{R} is the rated output power of the wind turbine.

The common modeling method of photovoltaic power generation output is also to obtain the solar radiation intensity and other variables first, and then calculate the photovoltaic power output. In general, it can be considered that the solar radiation follows Beta distribution[14], and its probability density function is as follows:

$$\phi_{\mathrm{v}}(r) = \frac{\Gamma(k_1 + k_2)}{\Gamma(k_1)\Gamma(k_2)} \left(\frac{r}{r_{\max}}\right)^{k_1 - 1} \left(1 - \frac{r}{r_{\max}}\right)^{k_2 - 1} \tag{3}$$

where k_1 and k_2 are the control parameters of beta distribution, $\Gamma(\cdot)$ is the gamma function, r is the solar radiation intensity, and $r_{\max}$ is the maximum value of solar radiation intensity. The active power output of photovoltaic power generation is usually obtained by conversion formula (4) based on solar radiation intensity and temperature.

$$P_t = P_{\mathrm{stc}} \frac{I_{\mathrm{r},t}}{I_{\mathrm{stc}}} [1 + \alpha_T (T_t - T_{\mathrm{stc}})] \tag{4}$$

where P_{stc}, I_{stc} and T_{stc} are the rated value of active power, solar radiation intensity and temperature of the photovoltaic power station, respectively. The reference value of active power is adjusted according to the solar radiation intensity $I_{\mathrm{r},t}$ and temperature T_t of the corresponding period t to obtain the active power of the period P_t. α_T is the adjustment coefficient, usually –0.47.

In short-term analysis such as daily operation, the uncertainty always refers to the errors of wind power and PV based on the forecast results. Many researches have done a lot of work in determining the types of error distribution. Gaussian distribution is common to describe the errors of wind power and PV[15]. Ref. [16] pointed out that the symmetrical Gaussian distribution cannot reflect the influence of nonlinearity from wind turbine on the distortion degree of prediction error distribution and the Beta distribution is more suitable because its skewness[17]. The results of Ref. [18] show that only when the weather is relatively clear, the forecast error of PV is close to the Gaussian distribution. Ref. [19] purposed a versatile probability which can well represent forecast errors for all forecast timescales and magnitudes and easily applied into the economic dispatch problem.

The existing uncertainty methods are model-driven. However, it is hard to find generalized marginal distributions in the modeling process, and the complex nonlinear correlations are hard to describe. With the wide application of machine learning algorithm in the fields of computer vision and natural language processing, researchers have begun to explore the application potential of related algorithms in uncertainty modeling of power system. Among these methods, the generative model can establish the relationship between hidden variables and target variables so that to model the distributions of target variables. Compared to traditional method, it can complete the description of complex relationships through artificial neural network (ANN), so it has a good application prospect. For now, the common generative models are variational auto-encoder (VAE) and generative adversarial network (GAN).

In Ref. [20], the GAN was first applied to the generation of active power scenarios of renewable energy. The results show that the generation model has a better effect in describing the temporal and spatial correlation of wind power and PV compared with Gaussian copula. Ref. [21] focuses on the performance improvement of GAN, which uses gradient penalty to add Lipschitz constraint to the discriminator of GAN to improve the training speed. In Ref. [22], GAN is used to simulate the scenarios of wind power and solar power for the capacity configuration of micro grid. Ref. [23] used VAE to model the joint distribution of wind and PV, and generated scenarios for short-term optimal operation problem. In Ref. [24], the de-noising VAE is adopted, and the generated scenarios set can reflect the difference of different weather conditions through the modular method. Despite the success application of generative model, it still has the problem of long training time, convergence difficulty, overfitting, mode collapse, etc.

2 Complementary characteristics analysis

Uncertainty is for a single renewable energy source, and multiple energy sources are complementary. Complementarity can greatly reduce the impact of the uncertainty of energy operation alone. Due to the spatio-temporal correlation between wind speed, sunshine, and other factors, further research focuses on the correlation description between different power sources, and complementarity can be embedded into the uncertainty modeling process. This chapter determines the marginal distribution of uncertain factors and sorts out the commonly used complementary evaluation indicators in current research.

Despite the generous studies of complementarity, there is not a unified definition of complementarity. Ref. [25] explained the complementarity through the explanation in the Oxford dictionary, and it understood the complementarity of energy sources as "the capability of working in a complementary way". Comparing to economy, reliability, stability and flexibility power systems, and complementarity is not an inherent characteristic. It is more like a way or approach to solve problems. The complementarity has different meanings and expressions in the power system depending on the specific indicator we want to improve. In general, it is always connected to the power system flexibility, renewable energy consumption, the fluctuation of power output, etc. Therefore, we do not discuss the concept of complementarity and focus on the detailed application.

At present, Copula function is widely used in the fitting and generation of joint distribution function of multivariate random variables. It can "glue" the marginal distributions of multiple correlated random variables into a high-dimensional joint distribution. Copula functions mainly include elliptical copula and Archimedean copula[26]. Elliptical copula includes Gaussian copula and t-copula, and the marginal distribution function needs to meet the given premise hypothesis. Archimedean copula is obtained through the generator function, including Gumbel copula, Clay copula and Frank copula. Because they can fit the marginal distribution functions of different distribution characteristics, Archimedean copula is more commonly used. For example, Frank copula can measure the negative correlation between different variables, so it is very suitable to analyze the complementary characteristics of wind and solar resources[27]. Ref. [28] applied Frank copula to model the interactions of wind power, solar power and demand in Davarzan area in Iran. However, Archimedean copula is not ideal for the "glue" effect of high-dimensional marginal distribution functions. In Ref. [29], Vine-copula is proposed to model the high-dimensional joint distribution of multiple random variables more than two. By combining the random variables in pairs, the joint distribution of each two random variables can be fitted by using the appropriate Archimedean copula. At present, the most common types of Vine-copula includes regular vines (R-vine), canonical vines (C-vine) and drawable vines (D-vine)[30]. R-vine can describe a large number of correlation relationships, but the large amount of calculation will make it very difficult to solve the fitting process. C-vine and D-vine have greater advantages than R-vine in calculation time and structure complexity, but they also lose the fitting accuracy of high-dimensional distribution to a certain extent[31]. Ref. [27] proposed a D-vine copula with truncation to model the spatial and temporal correlations between forecast errors of wind power and PV to reduce the estimation of large numbers of pair-copula parameters.

In the current research, the analysis and evaluation of the complementary characteristics of various power sources are mainly based on the complementary situation of the active power of different power sources. And the power sources are mainly the uncontrollable energy of wind, solar and hydro[32]. The motivation is to eliminate their respective intermittency and uncertainty driven by the variability of climate factors through the aggregation of different energy sources.

Many researches use the correlation analysis method to study the complementarity. The analyzed variable contains wind speed, solar irradiance, water flow or the power data directly of wind, solar and hydro. Generally, the complementarity of variable renewable energy can be divided into spatial complementarity, temporal complementarity and joint complementarity[25]. The correlation indicators of Pearson correlation coefficient, Kendall's rank correlation and Spearman's rank correlation are applied to evaluate the complementarity. Qualitatively, the negative correlation between different sources means complementarity.

Ref. [33] calculated the Pearson correlation coefficient of wind and solar resources for Mexico to evaluate their temporal energetic complementarity. The heat map of the whole country gives a better overview of the complementarity. The case studies compare the complementarity in different scale. Considering the practical cost, the paper also analyzes the proximity of the areas with good complementarity with transmission systems. Ref. [34] assessed spatial and temporal the complementarity of wind and solar resources in China through the calculation of Kendall's correlation and extreme value analysis. It find the wind power and PV power have negative correlation in offshore regions while the coefficients are variable from different onshore regions due to the local terrain conditions and weather patterns. Ref. [35] analyzed the complementarity of wind and solar in Italy in the same geographical point and in different locations. And the complementarity is more significant in larger time scale (hourly, daily, and monthly). Ref. [36] used Pearson and Spearman's coefficients to make a correlation map of wind speed and stream flow over Brazilian. And the highest complementarity is in the Northeastern basins and the weather stations near the power plants of Sao Francisco River.

In essence, correlation coefficients are used to describe the fluctuation of overall output of complementary power supplies. However, the coefficient mentioned cannot reflect the local changes of the active power curves of different power sources so they cannot be directly used as the actual indicators in the operation of the power system. And they can only judge the complementarity between two power sources.

From the perspective of power system operation, there are some indicators to describe the power output of the integrated system. Ref. [37] proposed an impact-increment-based hybrid reliability assessment approach for power transmission systems. The proposed method combines impact-increment-based state enumeration method and impact-increment- based Monte Carlo simulation. It could be used to balance the accuracy and efficiency under various scenarios. Ref. [38] used power stability indicator to evaluate the fluctuation of the power output:

$$I_S = \frac{1}{n-1}\sum_{k=1}^{n-1}\left|\delta_i^k\right| \; k = 1, 2, \cdots, n-1 \tag{5}$$

where δ_i^k is the power variation in adjacent time points, n is the number of total time points.

Power supply fluctuation smoothness, which is used to evaluate the improvement of the stability of power after the integration of different power sources.

$$k = \frac{\sigma_A - \sigma_B}{\sigma_A} \tag{6}$$

Where σ_A is the maximum standard deviation of single power supply output, and σ_B is the standard deviation of the integrated system output.

Load tracking indicator, which is used to evaluate the similarity of the power curve and load curve[39]:

$$D_t = \frac{1}{\bar{P}_L}\sqrt{\frac{1}{T}\sum_{i=1}^{T}\left(P_{v,t} - P_{L,t}\right)^2} \tag{7}$$

where $\bar{P}_L$ is the mean value of load demand, T is the operation period, and $P_{v,t}$ and $P_{L,t}$ are the power output and load value in time point t, respectively.

Some indicators of power system reliability are transformed to analyze the complementarity. Ref. [40] proposed two indicators of the ratio of expected energy not supplied (EENS) (8) and the ratio of loss of load hours (LOLH) (9), which are used to evaluate the improvement of the EENS and LOLH after the integration of different sources. These indicators are applied into the evaluation of the daily operation performance of wind-solar-hydro system.

$$K = \frac{EENS_{sys}}{EENS_1 + EENS_2 + \cdots + EENS_i} \tag{8}$$

$$B = \frac{LOLH_{sys}}{\max\left\{LOLH_1, LOLH_2, \cdots, LOLH_i\right\}} \tag{9}$$

Where $EENS_i$ and $LOLH_i$ are the EENS and LOLH of single power source system i, respectively, and $EENS_{sys}$ and $LOLH_{sys}$ are the EENS and LOLH of complementary system, respectively.

There also some other indicators to evaluate the complementarity in different aspects. In Ref. [41], two new indicators of consistency and complementarity are proposed to assess the local variation characteristics of the active power of different power sources. The effect is better than the correlation coefficient, but the limitation is that only the complementarity between the two power sources can be evaluated. Ref. [42] used the relative coefficient of variation (RCoV) (10) and the inter-quartile range (IQR) as main metrics to analyze the variability and intermittency of wind and solar resources in Australia. The RCoV is computed with reference to the median instead of mean, which is more suitable for long-tail distribution. The IQR is an evaluation for the possible variability of resources. A lower IQR means a higher potential in energy production.

$$RCoV = \frac{\text{median(absolute deviation about the mdeian)}}{\text{median}} \tag{10}$$

As we mentioned above, the analysis of complementarity depends on the research question itself including the statistical analysis, operation, planning, reliability, flexibility, etc. Therefore, the future research should give a unified definition of complementarity as a leadership to establish the research system of complementarity. For the study of complementary characteristics, they should be classified strictly according to their fields of concern. And the indicators of the same type should be compared based on the same database to explain its advantages and shortages so that to establish complementary metric system. Meanwhile, the existing research focus on the wind, solar and hydro. The objects should be expanded to more kinds of power sources such as waves and they should be divided more detail such as mountain wind power, plain wind power, offshore photovoltaic, etc.

3 Planning of multi-energy power systems

This section introduces the application of complementarity in electrical system. Planning is the base of optimal operation of multi-energy power systems, which determines the upper limit of operation benefits. The problem of power system planning is to seek a reliable construction scheme according to the load results in a long-term period. The planning model always consists of two stages of planning decision and operation simulation. The operation simulation examines the reliability of the planning scheme and evaluates the performance of the planned power systems in economy, security, environment, etc.

Traditional operation simulation methods are mainly based on the load duration curve[43] or single-period scenarios[44], which only evaluate the reliability of the system by electric quantity balance. With the increase of renewable energy access, the variability of renewable power sources make it necessary to consider the flexibility constraints of peak shaving, ramping and the startup and shut down of power sources.

Therefore, more researches use the sequential curves to simulate the operation situation. Ref. [45] studied the optimal sizing of photovoltaic-wind turbine. The optimal sizing model took wind speed, solar irradiation, temperature and load demand profiles of 8760 hours as input data to check the performance of the planned system. Ref. [46] purposed a sequential simulation method to evaluate the wind power accommodation capacity of the system. The case study is simulated by the hourly data of load demand, tie line power, wind power, etc., in 2015 of a China province. Due to the rapid increase of the calculation complexity with the increase of simulation periods and unit numbers, some research tries to reduce the period length. Ref. [47] used hourly load of 7 days to represent each month in the optimal sizing for wind, PV and pumped-hydro storage system. More generally, some research used typical days as an abbreviated representation. Ref. [48] studied the planning and operation of European power system in 2050. In capacity expansion model, it used the scenario tree to formulate the uncertainties of investment costs and demand growth in planning period, which took 2030 and 2050 as the tree nodes. Ref. [49] optimized the size of a photovoltaic–wind energy system. The case study used average hourly demand and power data as the typical day scenario. Obviously, the simulation results based on typical days lose accuracy and are greatly influenced by the boundary conditions such as the reservoir capacity at the beginning and end of daily scenarios. Aiming at the minimum network loss and minimum voltage fluctuation, Ref. [50] used particle swarm optimization algorithm to optimize the multi-objective to obtain the optimal location of photovoltaic.

From the concept of planning, research put more emphasis on flexibility and complementarity to ensure the security of power supply, promote the renewable energy consumption and reduce the investment cost. Ref. [51] purposed the generation and transmission co-planning model in the power system with high renewable energy penetration by VRE and CSP. Because the traditional model ignores the start-up and shutdown process of thermal power units to reduce the binary variables in the optimization problem, which may lead to the lack of flexibility in the planning results, the paper purposed an aggregated model for thermal units to formulate the flexibility limits. Ref. [52] explained the necessity of considering flexibility in power system planning, and summarized the current progress of flexibility planning. It pointed out that the challenge of flexibility planning lies in the quantitative evaluation of flexibility and the coordination of planning methods. Ref. [53] studied the sizing and operation of complementary hydro-wind-PV power systems. It first purposed a complementary coefficient of the system power output, which evaluate the level of the system meeting the load. Then it optimize the capacities and locations of wind and PV integrated with hydropower. The case study showed the critical influence of the location of wind and power on their planned capacities. Ref. [54] studied generation expansion planning in Brazil of 100% renewable energy with complementarity and flexibility. The utilization of complementarity can reduce the reservoir requirements. Ref. [55] purposed complementary indices from fluctuation and ramp, and the indices can guide the ratio of wind and PV. Ref. [56] considered the influence of building thermal storage on the penetration ability of renewable energy in the distribution network and provided an optimal planning framework for soft open point and distributed energy resources based on building thermal dynamics differential equation model.

Due to the contradiction between the proportion of renewable energy sources and the flexibility demands of the power grid, CSP becomes a hotspot in the construction of future multi-energy systems[57]. Compared to PV, the output of CSP is more stable because of the thermal inertia. In addition, it can be equipped with large-scale thermal storage, which makes it a controllable renewable power sources. Therefore, many research concerns the CSP construction from the system level for its operational flexibility. The results in Ref. [51] showed that CSP has operational and investment benefits compared with thermal units and electric storage and provides firm capacity compared to VRE. Ref. [58] studied the planning of CSP and battery. The results showed that CSP is not competitive compared with PV and batterers in the cost, but it can meet the constraints of minimum solar generation and flexibility. Ref. [57] used typical scenarios and error scenarios to evaluate the flexibility benefits of CSP comprehensively. The results showed the complementarity between CSP and other power sources in the planning process. Ref. [59] studied the configuration of thermal storage of CSP. The model calculated the optimal results in each day in a year according to the operation cost and find a balanced scheme considering the investment cost.

In summary, multi-energy planning adds flexibility and complementarity to reliability in response to the variability and uncertainty of renewable energy. There are more specific planning objects and evaluation indicators. In addition, the quality of planning results depends on the accuracy of production simulation. Therefore, it is necessary to balance the complexity of the model with the calculation time.

4 Operation of multi-energy power systems

With the access of renewable energy, the traditional scheduling strategy based on thermal power is not suitable for the real structure of multi energy power system. Many research hopes to achieve wide area coordination and competition complementarity of multi-energy systems in multi time and space scale through reasonable scheduling. Compared with the high cost of power system construction, it is a more economical way to improve the flexibility and controllability of the system through complementary operation. Therefore, this section summarizes the research on the optimal operation of multi-energy power systems in recent years.

The complementarity between different power sources in operation is explained in Figure 1. For renewable power sources (without hydropower), they should reduce the uncertainty and volatility of the overall output through the complementarity between wind and PV, and the controllability of CSP. For traditional power sources of thermal power and hydropower, they should meet the load demand after the renewable energy generation, and reduce the uncertainty of VRE. In addition, the complementarity is also shown in a long-term. For example, the wind, solar and thermal power provide electric quantity and regulation capacity for hydropower in dry season.

At the level of station operation, according to the type of power aggregation, many complementary generation systems are formed as wind-solar, wind-solar-storage, wind-solar-hydro, wind-thermal, wind-CSP, etc. The purpose of these complementary power generation systems is to provide stable output, improve the capacity of renewable energy consumption, and get better generation income. Ref. [60] based on the blind number theory, the flexibility margin model of wind power and photovoltaic is presented to consider the uncertainty of renewable energy. Combined with the characteristics of multiple energy generation, the flexibility resource margin quantification model of complex power supply is established, which can quickly and accurately quantify the adjustable range of flexibility margin of each power supply in different periods to achieve optimal operation. Ref. [27] studied the mid-term and short-term operation of wind-solar-hydro integrated system. The results proved the potential of the system to provide

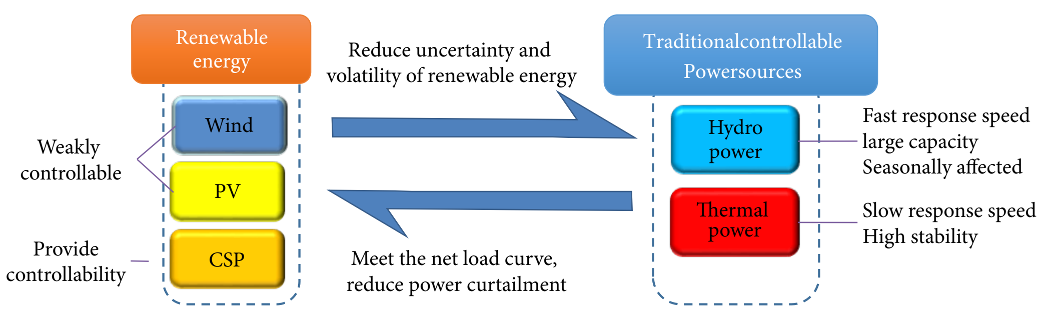

Fig. 1 Explanation of complementarity between different power sources in operation.

stable power supply. It also optimized the installed capacities of wind and PV. Ref. [61] studied the operation of regional wind and hydro power integration in Zambezi basin and South Africa. The target is to maximize the 90% power generation. The simulation based on the data in 2010 proved that the complementary operation can increase the wind power penetration and reduce coal power utilization. Ref. [62] integrated wind power and CSP with an electric heater. The optimal objects are to maximize the generation, reduce the deviation from the generation plan, and reduce the renewable energy curtailment. Ref. [63] proposed a fast rule-based adjustment capacity determination method for pumped storage hydropower to achieve its adjustment of fast power and voltage fluctuations caused by real-time photovoltaic fluctuations.

At the level of the whole entire operation, the earliest research on multi-energy operation was the dispatch of power systems with wind power. The improvement of its control strategy includes leaving sufficient reserves to deal with wind power access[64] and designing a multi-time scale dispatch model[65]. With the continuous construction of the power grid, the consideration of different types of power sources is expanding. Ref. [66] studied the short-term operation of interconnected power systems with hydro, thermal, wind, and PV. The complementary optimization model is solved hierarchically to maximum the new energy consumption and minimum the fluctuation of thermal power and its results show that wide-area complementary scheduling is beneficial to the improvement of system operational benefits. Ref. [67] studied the short-term operation of power systems with CSP. The model contains three stages of day-ahead, real-time and look-ahead, which can consider the uncertainty factors and coordinate the scheduling results within two days. The results analyzed the benefits of CSP compared with PV. Ref. [68] studied the combined system, and established a joint optimization scheduling strategy to ensure the security of the power system operation while maximizing economic benefits and renewable energy consumption. The three-stage algorithm based on Benders decomposition realizes the rapid solution of the scheduling strategy. Ref. [69] proposed a distributed energy automatic generation control combining multi-step greedy attributes and multi-level allocation strategies to achieve optimal coordinated control and power allocation, which can solve the problem of strong random interference caused by large-scale distributed energy access to the power grid.

Energy storage balances fluctuations well during operation. Ref. [70] proposed a heuristic energy storage system operation scheduling strategy based on inverse proportional technology, which can take into account the difference of electricity load demand.

These studies provide references for the optimal operation of multi-energy power systems, and constantly make improvements in strategy formulation, power system uncertainty description, and calculation efficiency.

For the optimization models, since the deterministic scheduling model can no longer satisfy the actual power operation, stochastic programming methods are widely used, including scenario analysis method, fuzzy programming method, chance constraint method and robust optimization method. The scenario analysis method[27] can clearly reflect the probabilistic characteristics of the uncertainty, which represents the distribution of random variables by typical scenarios. The optimization effect depends on the quality of the generated scenarios. So it has a contradiction between the choice of scenario number and the calculation efficiency. The fuzzy programming method[71] introduces fuzzy mathematics to model the uncertainty of random variables. However, the determination of its membership function relies on experts' experience, which introduce some human factors. Chance constraints[72] loose the strict constraints in the optimization problem, and the confidence of the constraints satisfies the tolerance of the optimization results for uncertainties. In Ref. [73], a leader-follower distributed group cooperative control strategy is presented to improve the control of active distribution network and realize multiple operation task control. Robust optimization[74] uses uncertain sets to describe uncertainty factors. The optimal solution requires that any element in the uncertain set must be feasible for constraints, so the economics of the results are poor. The choice of optimization model depends on the available data, optimization objectives, calculation time, etc.

In general, the current research on multi-energy operation focuses on the balance of energy, power and flexibility. There are few studies on the security and stability of power systems, wide-area coordination, and gird-generation coordination.

5 Conclusions

The continuous evolution of the power system structure has prompted us to study it from a new perspective. Aiming at the outstanding situation of the limited capacity of renewable energy consumption, the comprehensive use of the complementary characteristics of new energy high proportion multiple power sources is an effective means to reduce uncertainty and improve control flexibility. Through analysis of existing research, we have the following conclusions:

(1) For modeling of different power sources, we only discussed the uncertainty modeling of renewable power sources. At present, there is a lack of research on unified modeling of heterogeneous energy. Renewable energy model is not compatible with traditional power model. Future research should establish a homogeneous energy/power model of multiple heterogeneous energy sources on multiple time scales.

(2) The study of complementary characteristics should establish a system. There should be a clear definition of complementarity, which explains the relationship between complementarity with the conventional properties of power systems such as flexibility, security, and stability. On this basis, the research should establish an indicator system. Research should not only establish indicators on data analysis and statistics, but should establish practical complementary indicators for specific application areas.

(3) For modeling of different power sources, we only discussed the uncertainty modeling of renewable power sources. At present, there is a lack of research on unified modeling of heterogeneous energy. Renewable energy model is not compatible with traditional power model. Future research should establish a homogeneous energy/power model of multiple heterogeneous energy sources on multiple time scales.

(4) For planning of multi-energy power systems, the planning of the power sources should be coordinated with the planning of the network. The planning model should focus on the balance between flexible demand and supply. Production simulation of planning results should be as precise as possible.

(5) For operation of multi-energy power systems, research should take into account both time and space scales. The coordination and complementarity of the wide-area power grid is conducive to enhancing renewable energy consumption through mutual support. Multi-time scale optimal operation model is helpful to eliminate the influence of uncertain factors, so that the

scheduling plan can be smoothly implemented. In addition, most research studied the complementarity based on historical data, while some research has noticed the impact of future climate change on renewable energy power generation and power systems.

As the proportion of renewable energy in the future power system continues to increase, the problems caused by its uncertainty will be significantly prominent. Rational use of the complementarity between multiple energy sources to reduce the impact of uncertainty will be a research hotspot in the future.

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Declaration of competing interest

The authors have no competing interests to declare that are relevant to the content of this article.

References

[1] Schellekens, G., Battaglini, A., Lilliestam, J., Patt, A. (2010). *100% Renewable Electricity: A Roadmap to 2050 for Europe and North Africa*. London, UK: PricewaterhouseCoopers.

[2] Hand, M. M., Baldwin, S., DeMeo, E., (2012). Renewable electricity futures study. Volume 1: Exploration of high-penetration renewable electricity futures, office of scientific & technical information technical reports. Available at https://www.nrel.gov/analysis/re-futures.html.

[3] Energy Research Institute National Development and Reform Commission (2015), China 2050 high renewable energy penetration scenario and roadmap study. Available at https://www.efchina.org/Reports-zh/china-2050-high-renewable-energy-penetration-scenario-and-roadmap-study-zh. (in Chinese).

[4] Rozakis, S., Soldatos, P. G., Papadakis, G., Kyritsis, S., Papantonis, D. (1997). Evaluation of an integrated renewable energy system for electricity generation in rural areas. *Energy Policy*, 25: 337–347.

[5] Al-Ashwal, A. M., Moghram, I. S. (1997). Proportion assessment of combined PV-wind generating systems. *Renewable Energy*, 10: 43–51.

[6] Luo, Z., Yang, S., Xie, N., Xie, W., Liu, J., Souley Agbodjan, Y., Liu, Z. (2019). Multi-objective capacity optimization of a distributed energy system considering economy, environment and energy. *Energy Conversion and Management*, 200: 112081.

[7] Sun, W., Harrison, G. P. (2019). Wind-solar complementarity and effective use of distribution network capacity. *Applied Energy*, 247: 89–101.

[8] Wang, Q., Liu, J., Hu, Y., Zhang, X. (2019). Optimal operation strategy of multi-energy complementary distributed CCHP system and its application on commercial building. *IEEE Access*, 7: 127839–127849.

[9] Yadav, A., Srivastava, L. (2014). Optimal placement of distributed generation: An overview and key issues. In: Proceedings of the 2014 International Conference on Power Signals Control and Computations (EPSCICON), Thrissur, India.

[10] NDRC, NEA (2016). 13th five-year plan for electric power development. National Development and Reform Commission (NDRC), National Energy Administration (NEA). Available at https://www.gov.cn/xinwen/2016-12/22/content_5151549.htm. (in Chinese)

[11] Li, J., Guo, B., Niu, M., Xiu, X., Tian, L. (2018). Optimal configuration strategy of energy storage capacity in wind/PV/storage hybrid system. *Transactions of China Electrotechnical Society*, 33(6): 1189–1196. (in Chinese)

[12] Salgado Duarte, Y., Szpytko, J., del Castillo Serpa, A. M. (2020). Monte Carlo simulation model to coordinate the preventive maintenance scheduling of generating units in isolated distributed power systems. *Electric Power Systems Research*, 182: 106237.

[13] Akdağ, S. A., Dinler, A. (2009). A new method to estimate Weibull parameters for wind energy applications. *Energy Conversion and Management*, 50: 1761–1766.

[14] Youcef Ettoumi, F., Mefti, A., Adane, A., Bouroubi, M. Y. (2002). Statistical analysis of solar measurements in Algeria using beta distributions. *Renewable Energy*, 26: 47–67.

[15] Holttinen, H. (2005). Impact of hourly wind power variations on the system operation in the Nordic countries. *Wind Energy*, 8: 197–218.

[16] Lange, M. (2005). On the uncertainty of wind power predictions—Analysis of the forecast accuracy and statistical distribution of errors. *Journal of Solar Energy Engineering*, 127: 177–184.

[17] Bludszuweit, H., Dominguez-Navarro, J. A., Llombart, A. (2008). Statistical analysis of wind power forecast error. *IEEE Transactions on Power Systems*, 23: 983–991.

[18] Zhao, W., Zhang, N., Kang, C., Wang, Y., Li, P., Ma, S. (2015). A method of probabilistic distribution estimation of conditional forecast error for photovoltaic power generation. *Automation of Electric Power Systems*, 39(16): 8–15. (in Chinese)

[19] Zhang, Z. S., Sun, Y. Z., Gao, D. W., Lin, J., Cheng, L. (2013). A method of probabilistic distribution estimation of conditional forecast error for photovoltaic power generation. *IEEE Transactions on Power Systems*, 28, 3114–312539.

[20] Chen, Y., Wang, Y., Kirschen, D., Zhang, B. (2019). Model-free renewable scenario generation using generative adversarial networks. In: Proceedings of the 2019 IEEE Power & Energy Society General Meeting (PESGM), Atlanta, GA, USA.

[21] Jiang, C., Mao, Y., Chai, Y., Yu, M., Tao, S. (2018). Scenario generation for wind power using improved generative adversarial networks. *IEEE Access*, 6: 62193–62203.

[22] Li, K. P., Zhang, Z. Y., Wang, F., Jiang, L. H., Zhang, J. J., Yu, Y. L., Mi, Z. Q. (2019). Stochastic optimization model of capacity configuration for stand-alone microgrid based on scenario simulation using GAN and conditional value at risk. *Power System Technology*, 43(5): 1717–1725.

[23] Zhanga, H., Hua, W., Yub, R., Tangb, M., Dingc, L. (2018). Optimized operation of cascade reservoirs considering complementary characteristics between wind and photovoltaic based on variational auto-encoder. *MATEC Web of Conferences*, 246: 01077.

[24] Huang, N. T., Wang, W. T., Cai, G. W., Yang, D. F., Huang, D. W., Song, X. (2019). The joint scenario generation of multi source-load by modular denoising variational autoencoder considering the complex coupling characteristics of meteorology. *Proceedings of the CSEE*, 39(10): 2924–2934.

[25] Jurasz, J., Canales, F. A., Kies, A., Guezgouz, M., Beluco, A. (2020). A review on the complementarity of renewable energy sources: Concept, metrics, application and future research directions. *Solar Energy*, 195: 703–724.

[26] Patton, A. J. (2012). A review of copula models for economic time

series. *Journal of Multivariate Analysis*, 110: 4–18.
[27] Zhang, H., Lu, Z., Hu, W., Wang, Y., Dong, L., Zhang, J. (2019). Coordinated optimal operation of hydro-wind-solar integrated systems. *Applied Energy*, 242: 883–896.
[28] Ávila R, L., Mine, M. R. M., Kaviski, E., Detzel, D. H. M., Fill, H. D., Bessa, M. R., Pereira, G. A. A. (2020). Complementarity modeling of monthly stream flow and wind speed regimes based on a copula-entropy approach: A Brazilian case study. *Applied Energy*, 259: 114127.
[29] Bedford, T., Cooke, R. M. (2002). Vines—A new graphical model for dependent random variables. *The Annals of Statistics*, 30: 1031–1068.
[30] Aas, K., Czado, C., Frigessi, A., Bakken, H. (2009). Pair-copula constructions of multiple dependence. *Insurance: Mathematics and Economics*, 44: 182–198.
[31] Brechmann, E. C., Czado, C., Aas, K. (2012). Truncated regular vines in high dimensions with application to financial data. *Canadian Journal of Statistics*, 40: 68–85.
[32] Engeland, K., Borga, M., Creutin, J. D., François, B., Ramos, M. H., Vidal, J. P. (2017). Space-time variability of climate variables and intermittent renewable electricity production–A review. *Renewable and Sustainable Energy Reviews*, 79: 600–617.
[33] Gallardo, R. P., Ríos, A. M., Ramírez, J. S. (2020). Analysis of the solar and wind energetic complementarity in Mexico. *Journal of Cleaner Production*, 268: 122323.
[34] Ren, G., Wan, J., Liu, J., Yu, D. (2019). Spatial and temporal assessments of complementarity for renewable energy resources in China. *Energy*, 177: 262–275.
[35] Monforti, F., Huld, T., Bódis, K., Vitali, L., D'Isidoro, M., Lacal-Arántegui, R. (2014). Assessing complementarity of wind and solar resources for energy production in Italy. A Monte Carlo approach. *Renewable Energy*, 63: 576–586.
[36] Cantão, M. P., Bessa, M. R., Bettega, R., Detzel, D. H. M., Lima, J. M. (2017). Evaluation of hydro-wind complementarity in the Brazilian territory by means of correlation maps. *Renewable Energy*, 101: 1215–1225.
[37] Lei, Y., Sun, Y., Hou, K., Zhang, P., Zhu, L., Yang, X., Liu, X. (2022). An impact-increment-based hybrid reliability assessment method for transmission systems. *CSEE Journal of Power and Energy Systems*, 8: 317–328.
[38] Li, J. L., Guo, B. Q., Niu, M., Xiu, X. Q., Tian, L. T. (2018). Optimal configuration strategy of energy storage capacity in wind/PV/storage hybrid system. *Transactions of China Electrotechnical Society*, 33(6): 1189–1196. (in Chinese)
[39] Liu, Q., Xie, P., Ouyang, J., Zhu, J., Xiong, X., Xuan, P. (2018). Dynamic economic dispatch strategy based on multi-time scale complementarity of heterogeneous energy sources. *Electric Power Automation Equipment*, 38(06): 55–64. (in Chinese)
[40] Ye, L., Qu, X., Yao, Y., Zhang, J., Wang, Y., Huang, Y., Wang, W. S. (2018). Analysis on intraday operation characteristics of hybrid wind-solar-hydro power generation system. *Automation of Electric Power Systems*, 42(4): 158–164. (in Chinese)
[41] Qu, Z., Yu, J. (2013). Quantitative evaluation on consistency and complementarity of wind power variability. *Power System Technology*, 37(2): 507–513. (in Chinese)
[42] Prasad, A. A., Taylor, R. A., Kay, M. (2017). Assessment of solar and wind resource synergy in Australia. *Applied Energy*, 190: 354–367.
[43] Booth, R. (1972). Power system simulation model based on probability analysis. *IEEE Transactions on Power Apparatus and Systems*, PAS-91: 62–69.
[44] Dominguez, R., Conejo, A. J., Carrion, M. (2015). Toward fully renewable electric energy systems. *IEEE Transactions on Power Systems*, 30: 316–326.
[45] Alsayed, M., Cacciato, M., Scarcella, G., Scelba, G. (2013). Multi-criteria optimal sizing of photovoltaic-wind turbine grid connected systems. *IEEE Transactions on Energy Conversion*, 28: 370–379.
[46] Zhao, D., Yan, W., Luo, C., Luo, T. (2019). MILP model for annual power and energy balance of hydro-thermal-wind power system considering RPS mechanism. In: Proceedings of the 8th Renewable Power Generation Conference (RPG 2019), Shanghai, China.
[47] Waiwong, S., Damrongkulkamjorn, P. (2016). Optimal sizing for stand alone power generating system with wind-PV-hydro storage by mixed-integer linear programming. In: Proceedings of the 2016 IEEE International Conference on Renewable Energy Research and Applications (ICRERA), Birmingham, UK.
[48] Askarzadeh, A. (2013). Developing a discrete harmony search algorithm for size optimization of wind-photovoltaic hybrid energy system. *Solar Energy*, 98: 190–195.
[49] Domínguez, R., Carrión, M., Oggioni, G. (2020). Planning and operating a renewable-dominated European power system under uncertainty. *Applied Energy*, 258: 113989.
[50] Wang, P., Liang, F., Song, J., Jiang, N., Zhang, X. P., Guo, L., Gu, X. (2020). Impact of the PV location in distribution networks on network power losses and voltage fluctuations with pso analysis. *CSEE Journal of Power and Energy Systems*, 8: 523–534.
[51] Du, E., Zhang, N., Hodge, B. M., Wang, Q., Kang, C., Kroposki, B., Xia, Q. (2018). The role of concentrating solar power toward high renewable energy penetrated power systems. *IEEE Transactions on Power Systems*, 33: 6630–6641.
[52] Lu, Z., Li, H., Qiao, Y. (2016). Power system flexibility planning and challenges considering high proportion of renewable energy. *Automation of Electric Power Systems, 40*(13): 147–158. (in Chinese)
[53] Tang, Y., Fang, G., Tan, Q., Wen, X., Lei, X., Ding, Z. (2020). Optimizing the sizes of wind and photovoltaic power plants integrated into a hydropower station based on power output complementarity. *Energy Conversion and Management*, 206: 112465.
[54] Luz, T., Moura, P. (2019). 100% Renewable energy planning with complementarity and flexibility based on a multi-objective assessment. *Applied Energy*, 255: 113819.
[55] Han, S., Zhang, L. N., Liu, Y. Q., Zhang, H., Yan, J., Li, L., Lei, X. H., Wang, X. (2019). Quantitative evaluation method for the complementarity of wind-solar-hydro power and optimization of wind-solar ratio. *Applied Energy*, 236: 973–984.
[56] Zhang, T., Wang, J., Zhong, H., Li, G., Zhou, M., Zhao, D. (2023). Soft open point planning in renewable-dominated distribution grids with building thermal storage. *CSEE Journal of Power and Energy Systems*, 9: 244–253.
[57] Qi, Y., Hu, W., Dong, Y., Fan, Y., Dong, L., Xiao, M. (2020). Optimal configuration of concentrating solar power in multienergy power systems with an improved variational autoencoder. *Applied Energy*, 274: 115124.
[58] Chattopadhyay, D., Bankuti, M., Bazilian, M. D., de Sisternes, F., Oguah, S., Sanchez, M. J. M. (2018). Capacity planning model with CSP and battery. In: Proceedings of the 2018 IEEE Power & Energy Society General Meeting (PESGM), Portland, OR, USA.
[59] Su, C., Cheng, C., Wang, P., Shen, J., Wu, X. (2019). Optimization model for long-distance integrated transmission of wind farms and pumped-storage hydropower plants. *Applied Energy*, 242: 285–293.
[60] Xiao, B., Wang, J., Xiao, Z., Yan, G., Dong, L., Wang, M., Yang, H. (2023). Power source flexibility margin quantification method for multi-energy power system based on blind number theory. *CSEE Journal of Power and Energy Systems*, 9: 2321–233.
[61] Gebretsadik, Y., Fant, C., Strzepek, K., Arndt, C. (2016). Optimized reservoir operation model of regional wind and hydro power integration case study: Zambezi Basin and South Africa. *Applied Energy*, 161: 574–582.
[62] Yang, Y., Guo, S., Liu, Q., Li, R. (2019). Day-ahead scheduling for a new wind-CSP hybrid system. *Energy Procedia*, 158: 6254–6259.

[63] Zhang, S., Xiang, Y., Liu, J., Liu, J., Yang, J., Zhao, X., Jawad, S., Wang, J. (2022). A regulating capacity determination method for pumped storage hydropower to restrain PV generation fluctuations. *CSEE Journal of Power and Energy Systems*, 8: 304–316.
[64] Hetzer, J., Yu, D. C., Bhattarai, K. (2008). An economic dispatch model incorporating wind power. *IEEE Transactions on Energy Conversion*, 23: 603–611.
[65] Zhang, B., Wu, W., Zheng, T., Sun, H. (2011). Design of a multi-time scale coordinated active power dispatching system for accommodating large scale wind power penetration. *Automation of Electric Power Systems*, 35(1): 1–6. (in Chinese)
[66] Wang, X., Chang, J., Meng, X., Wang, Y. (2018). Short-term hydro-thermal-wind-photovoltaic complementary operation of interconnected power systems. *Applied Energy*, 229: 945–962.
[67] Du, E., Zhang, N., Hodge, B. M., Wang, Q., Lu, Z., Kang, C., Kroposki, B., Xia, Q. (2019). Operation of a high renewable penetrated power system with CSP plants: A look-ahead stochastic unit commitment model. *IEEE Transactions on Power Systems*, 34: 140–151.
[68] Fu, Y., Lu, Z., Hu, W., Wu, S., Wang, Y., Dong, L., Zhang, J. (2019). Research on joint optimal dispatching method for hybrid power system considering system security. *Applied Energy*, 238: 147–163.
[69] Xi, L., Zhang, L., Xu, Y., Wang, S., Yang, C. (2020). Automatic generation control based on multiple-step greedy attribute and multiple-level allocation strategy. *CSEE Journal of Power and Energy Systems*, 8: 281–292.
[70] Yang, H., Hao, Z., Zhang, D., Ma, Y. (2020). An inverse proportion technique based scheduling strategy of energy storage system considering electrical load demand difference. *CSEE Journal of Power and Energy Systems*, 8: 1487–1496.
[71] Zhou, H., Chen, C. (2010). Fuzzy programming based daily dispatch of power system with wind power. In: Proceedings of the 2010 Conference Proceedings IPEC, Singapore.
[72] Elshahed, M., Elmarsafawy, M. M., El-din, H. Z. (2015). Stochastic chance constraint with discrete probabilities of wind sources in economic dispatch. In: Proceedings of the International Conference on Renewable Power Generation (RPG 2015), Beijing, China.
[73] Le, J., Zhao, L., Wang, C., Zhou Q., Wang, Y. (2020). Leader optimal selection method for the distributed control system of active distribution networks. *CSEE Journal of Power and Energy Systems*, https://doi.org/10.17775/CSEEJPES.2020.02410.
[74] Li, H., Liu, P., Guo, S., Ming, B., Cheng, L., Yang, Z. (2019). Long-term complementary operation of a large-scale hydro-photovoltaic hybrid power plant using explicit stochastic optimization. *Applied Energy*, 238: 863–875.