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A Multi-Source Coordinated Optimal Operation Model Considering the Risk of Nuclear Power Peak Shaving and Wind Power Consumption

JIE ZHAO[1], YUHUI MA[1], (Graduate Student Member, IEEE), QI LIU[2], (Member, IEEE), LIBIN WEN[3], CHENYIYANG JIA[1], AND YUDI FANG[1]

[1]School of Electrical Engineering and Automation, Wuhan University, Wuhan 430072, China
[2]State Grid Xuzhou Power Supply Company, Xuzhou 221000, China
[3]Electric Power Research Institute of Guangxi Power Grid Company Ltd., Nanning 530023, China

Corresponding author: Qi Liu (liuqioscar@gmail.com)

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ABSTRACT In view of the development trend of nuclear power and offshore wind power in China's coastal areas, as well as the current situation of peak shaving pressure brought by reverse peak shaving of wind power to the power grid. In this paper, according to the number of failures and power loss per year in each region, the risk of peak load regulation is calculated comprehensively and quantitatively, and the risk cost increment of nuclear power peak shaving is calculated and evaluated. Optimize and linearize the constraints, and the relatively complete constraint conditions are established. Thus, the traditional peak shaving model of fixed gear nuclear power dispatch is improved, and the peak shaving depth is continuous within the safety regulation range of nuclear power. Then, based on the peak shaving operation model of nuclear power safety constraints, considering the nuclear power risk and wind power consumption, taking into account the operation cost, risk cost, environmental cost and safe operation constraints of various types of power supply, a multi-source optimal scheduling model of wind-nuclear-thermal-storage-gas is established. Based on the calculation example of the actual regional power grid, the security, low carbon and economy of the model are analyzed, and the sensitivity analysis of the risk cost coefficient and wind power reserve coefficient in the dispatching model is carried out. It can be concluded that the nuclear power has a little safety impact on the reactor core and coolant circulation system after participating in the peak shaving operation, and the increase in the probability of man-made misoperation is not obvious. The main source of the risk cost increase is the benefit loss of selling electricity, so that it can properly participate in the peak shaving of the system. When the nuclear safety risk is low and the risk of wind abandonment is high, the nuclear power peak shaving has a stronger economic advantage. The dynamic optimal allocation of wind power reserve capacity can further reduce the abandonment of nuclear power and improve the operation economy of the system.

INDEX TERMS Economic dispatch, linear adjustment, nuclear power peak shaving, nuclear safety risk, security constraint, wind power consumption.

I. INTRODUCTION

In China, with the increasing proportion of nuclear power installed, and the severe peak shaving situation of the system, the power grid requires it to have a certain peak shaving capacity. The NPP is equipped with a radioactive nuclear reactor, which generates a huge amount of heat energy to heat the water supply through nuclear fission reaction. Its safety in the process of power generation and power regulation cannot be ignored. In addition, due to the demand for cooling water sources, nuclear power units are generally built in coastal areas in China [1], [2]. At the same time, offshore wind power and onshore wind power resources in coastal areas are relatively rich. In the foreseeable future, the trend of wind power and nuclear power development is unstoppable. Due to the inverse peak shaving characteristics and random fluctuation of wind power, the peak shaving pressure is increased. The nuclear power units in Hongyanhe, Fuqing and other

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places often operate in an output mode that continuously suppresses the load, which damages the utilization ratio of nuclear power equipment [3], [4]. Therefore, considering the safety risk of nuclear power and the consumption of wind power, the research on regional multi-source optimal scheduling with nuclear power and wind power has become a hot topic.

NOMENCLATURE

i	Number of four risk factors, i = 1,2,3,4
J	Number of nuclear power unit
n^{T}	Number of thermal power units
T	The dispatching period, in this paper, T = 24h
$C^{\mathrm{T}}_{i,\mathrm{start}}/C^{\mathrm{T}}_{i,\mathrm{stop}}$	Start up cost of thermal power unit i
C_i^{repair}	Maintenance cost corresponding to risk factor i
C^{ongird}	Benchmark price of nuclear power on Grid
$C^{\mathrm{G}}_{i,\mathrm{start}}$	The cost of one-time start-up of pumped storage unit i
$C^{\mathrm{P}}_{i,\mathrm{start}}$	The cost of one-time start-up of pumped storage unit i
C^{N}	Operating cost of nuclear power units
C^{T}	Operation cost of thermal power units
C^{PS}	Operation cost of pumped storage units
C^{CC}	Operation cost of combined cycle units
$C^{\mathrm{N}}_{\mathrm{R}}$	Risk cost of peak load regulation in NPP
$C^{\mathrm{W}}_{\mathrm{R}}$	Risk cost of wind power abandonment
C^{ENV}	Environmental cost of the system
$C^{\mathrm{N}}_{\mathrm{PS}}$	Peak load regulation cost coefficient of nuclear power unit
$C^{\mathrm{T}}_{\mathrm{CE}}/C^{\mathrm{CT}}_{\mathrm{CE}}$	Carbon emission cost coefficient of coal and gas, unit: ton / MWh
$c_i^{\mathrm{CC},xy}$	Conversion cost of unit i between different modes
$P^{\mathrm{loss}}_{i,j}$	Annual loss of electricity (MWh / year)
P^{N}_j	Rated output power of nuclear power unit j
$P_{i,t}$	Output power of the i-th nuclear power unit at time t
$P_i^{\max}$	Maximum output power of nuclear power unit
$P^{\mathrm{T}}_{i,\max}/P^{\mathrm{T}}_{i,\min}$	Maximum and minimum technical output of thermal power unit i at time t
$P^{\mathrm{G}}_{i,\max}/P^{\mathrm{P}}_{i,\min}$	Maximum power of pumped storage unit i under generating / pumping conditions
$P^{\mathrm{CC},x}_{i,\max}/P^{\mathrm{CC},x}_{i,\min}$	Maximum / minimum output power of CCGT unit i in mode x
$P^{\mathrm{T}}_{i,t}$	Output of thermal power unit i at time t
$P^{\mathrm{CC},x}_{i,\max}/P^{\mathrm{CC},x}_{i,\min}$	The maximum and minimum output power of CCGT unit i in mode x respectively
$b_i^{\mathrm{CC},x}$	Linear variable cost for each mode of unit i
$a_i^{\mathrm{CC},x}$	No-load cost of unit i for each mode
$a^{\mathrm{N}}_{\mathrm{eq}}/b^{\mathrm{N}}_{\mathrm{eq}}$	Constant term / primary term of operating cost of nuclear power unit
$\alpha^{\mathrm{G}}_{i,t}/\beta^{\mathrm{T}}_{i,t}$ $\alpha^{\mathrm{P}}_{i,t}$	0-1 variable
$a_i^{\mathrm{T}}/b_i^{\mathrm{T}}/c_i^{\mathrm{T}}$	Coefficient of constant term / primary term / quadratic term of generation cost of thermal power unit
$\delta^{\mathrm{T}}_{i,t}$	0-1 variable representing the operation state of thermal power units
$T^{\mathrm{on}}_{i,\min}/T^{\mathrm{off}}_{i,\min}$	The minimum start-up operation / minimum shutdown time of thermal generator group i
T_{b}	Spinning reserve time, in this paper, $T_{\mathrm{b}} = 10$min
$t^{\mathrm{stop}}_{i,j}$	The shutdown time of j-th nuclear power unit caused by risk factor i
$f^{\mathrm{stop}}_{i,j}$	The number of failures caused by risk factor i of the j-th nuclear power unit
$f^{\mathrm{day}}_{\mathrm{PL},i}$	Peak regulation rate of nuclear power unit i
m_{PL}	Number of nuclear power units participating in peak shaving
m_{BL}	Number of nuclear power units operating with base load
$S^{\mathrm{T}}_{i,t}$	Start and stop cost of thermal power unit
R_{PL}	Safety risks caused by peak load operation of nuclear power units
ΔR_{PL}	Safety risk increment caused by peak shaving of NPP
R_{BL}	Safety risk of NPP with base load
$R^{\mathrm{N}}_{i,t}$	Safety risk cost of nuclear power unit i at time t
$R^{\mathrm{N}}_{\mathrm{day}}$	Unit peak shaving safety risk cost converted to daily
$R_{\mathrm{u}\%}/R_{\mathrm{d}\%}$	Positive / negative spinning reserve capacity factor of the system
n_{N}	Number of nuclear power units
n_{PS}	Number of pumped storage units
n_{W}	Number of wind farms
n_{CC}	Number of units in CCGT
k	Peak shaving depth of NPP

D_m^k	Operation status of power down phase
$P_{\text{eq},t}^{\text{N}}$	Output power of nuclear power unit i at time t
$P_{\text{eq,max}}^{\text{N}}$	Rated maximum output power of nuclear power unit i at time t
P^{W}	Penalty cost of wind abandonment risk
$P_{i,t}^{\text{W}}$	The dispatch plan output of wind farm i at time t
$P_{i,t}^{\text{W,pre}}$	Predicted output of wind farm I at time t
$P_{i,t}^{\text{P,S}}$	Output of pumped storage unit i at time t
$P_{i,t}^{\text{CC}}$	Output power of CCGT unit i at time t
P_t^{L}	System load at time t
$P_{i,\min}^{\text{CC},x}$	Minimum output power of unit i in each mode
$\Delta P_{i,t}^{\text{CC},x}$	Power output of unit i higher than its minimum technical output in each mode
$W_{\text{u}}\%/W_{\text{d}}\%$	Positive / negative spinning reserve capacity factor of wind power
$MTTR_i$	The average repair time corresponding to risk i.
$M_k^{\text{F},x}$	The feasible conversion set of unit i between mode x and mode y, where $x \neq y$;
NPP	NPP
U_m^k	Operation status of power up phase
$h_{i,t}$	0-1 variable
k^{W}	Risk coefficient of wind abandonment
ξ_{CE}	Carbon emission cost, unit: \$ / ton
$\mu^{\text{CC},x'}$	Generation proportion factor of CCGT gas unit
E_i^N	Rated power output of unit i during operation
$M_k^{\text{F},x}$	Feasible conversion set of unit i between mode x and mode y
$r_{\text{u},i}^{\text{T}}/r_{\text{d},i}^{\text{T}}$	Ramp rate of power up / down of thermal power unit i
ε	Safety risk factor of nuclear power
$u_{i,t}^{\text{CC},x}$	Binary variables of unit I operation state in each mode
$v_{i,t}^{\text{CC},xy}$	Binary variables for conversion between modes
$x, y \in M_k$	The operation mode of unit, from 0 to M_k
$x', y' \in M_k$	All operation modes different from x = 0 in M_k

At present, the research on safety risk assessment of nuclear power mainly focuses on the comprehensive risk calculation of auxiliary power supply of NPP and the stability of large power grid including nuclear power. There are few reports about the risk calculation and assessment of nuclear power participating in peak shaving. The recent work [5] analyzes the main power supply system, generator system and other aspects of the NPP, and uses fault tree analysis and importance factor decision-making algorithm to carry out qualitative and quantitative reliability evaluation for the operation of NPP. Reference [6] presents a least-squares solution to evaluate the components of parallel systems in NPP. In our recent work [7], a new risk assessment framework combining Monte Carlo method, polymorphic modeling method and network theory is proposed to assess the safety performance of nuclear power generating sets. In reference [8], an improved GO-FLOW model for power supply system of NPP is constructed, which can be used to calculate the failure rate and reliability of power supply system in NPP. It can be seen that at present, the research on safety risk assessment of nuclear power participating in power grid peak shaving is still shallow, which needs in-depth analysis and research.

In the aspect of nuclear power safety output model. Our recent work [9] analyzed and modeled the low-power operation stage of nuclear power. Reference [10] obtained the peak shaving depth of nuclear power through the interior point method, established a multi-objective optimal scheduling calculation model, and realized the equivalent peak shaving of nuclear power. Reference [11] conducted a detailed modeling analysis on the constraint conditions of "12-3-6-3" nuclear power output model, using multiple 0-1 variables to represent the nuclear power in different stages But it fixed the time of power up / down for 3 h. On this basis, the author in [12] considered that the power up and down time of the third generation nuclear power unit can be 1 ∼ 3 h, further established the daily load tracking operation model of the fixed three gear peak shaving depth, and analyzed and calculated the peak shaving cost of the NPP. It can be seen that the output model of NPP is simplified by using fixed peak shaving depth of several gears and fixed high / low power operation time. This output mode may lead to the jump of state variables with different regulating time, which leads to the nonlinear regulation of unit output. Moreover, if the turning point of upward or downward peak shaving is not well constrained, the direction of upward or downward peak shaving may be wrong. It is necessary to further study the safety output model of nuclear power participating in peak load regulation, and further optimize the constraints of peak shaving depth and peak shaving output model, at the same time, solve the nonlinear problem caused by the complex coupling relationship between various operating variables.

Reference [13] proposed a new framework of multi time frame robust scheduling / scheduling system for various types of renewable energy integration systems, which is different from other robust methods. A distributed energy demand scheduling method based on game theory was proposed in [14], which minimizes the interaction between consumers and optimizes the energy demand cost. However, the participation of nuclear power is not considered in the multi-source scheduling model, and the existing literature shows that nuclear power can participate in peak shaving. Reference [15] studied the joint optimal operation strategy of thermal- hydro-nuclear. The peak load operation mode of NPP is set based on daily load characteristics and the ramp rate of thermal power units. In our recent work [16], a multi-source optimal scheduling model of wind- thermal-nuclear storage is established, which considers wind and nuclear abandonment. The simulation results show that nuclear power participating in system peak shaving can effectively relieve the pressure of system peak shaving, but the impact of environmental cost on optimal scheduling is not considered. In addition, in the process of optimal scheduling, priority should be given to the safety of nuclear power operation. How to quantify the safety risk caused by nuclear power participating in peak shaving and add it to the scheduling model needs further analysis. With the large-scale wind power connected to the grid, appropriate wind or nuclear abandonment and their coordination should be considered.

Aiming at the risk assessment of nuclear power peaking and multi-source coordinated dispatching, this paper takes the power system including nuclear power in coastal areas as the research object. Firstly, this paper analyzes the factors and mechanism that affect the safety risk of nuclear power, studies and calculates the comprehensive risk after the operation of nuclear power peaking. Secondly, the constraint optimization, depth optimization and equivalent linearization representation of the model are improved. And a more safe and accurate peak shaving scheduling model is proposed, so that the output power level of nuclear power can be linearly adjusted in terms of technical requirements. Then, based on the principle of economic dispatch, considering the operation cost of various types of units, incremental risk cost of peak shaving of nuclear power, wind power abandonment cost and system environment cost, an optimization model including multi-source coordinated dispatch is constructed. Finally, the effectiveness of the model and strategy is verified by an example analysis.

The contributions of this paper are summarized as follows.

1) Based on the risk assessment of the main power supply and units of NPP in reference [5]–[8], this paper further quantifies the risk of nuclear power participating in peak load regulation, and calculates and analyzes various risk costs after nuclear power participates in peak load regulation.
2) The constraints are supplemented and optimized. The continuous variables are set to represent the peak load regulation depth of nuclear power units, and the equivalent linearization of the model is realized by mathematical methods. Then, a model for nuclear power to participate in peak shaving operation safely, accurately and economically is established. Different from [10], [11] and [12], where the establishment of the peak shaving model of nuclear power is based on the fixed three gear peak shaving depth, and the processing of peak shaving depth is discrete, which is not conducive to the accuracy and economy of nuclear power peak shaving. The model determines the peak shaving depth of nuclear power, that is, the output power level of nuclear power can be linearly adjusted in terms of technical requirements, and reflects the flexible peak shaving depth of nuclear power in the mathematical model.
3) In the multi-source optimal dispatch model, the incremental cost of nuclear safety risk is used to constrain the nuclear abandonment, the wind abandonment risk cost is used to constrain the wind abandonment and the clean energy consumption is further promoted by environmental cost. The coordination and cooperation among the dispatching modes such as wind abandonment, nuclear abandonment and start-up and shutdown of conventional units are analyzed in detail, and the scheduling scheme considering peak load operation of nuclear power plant and allowing a small amount of wind abandonment is optimized and formulated. The model not only makes up for the lack of considering nuclear power participating in peak shaving in reference [13] and [14], but also has more perfect constraints.

II. RISK ANALYSIS AND ASSESSMENT OF NUCLEAR POWER UNIT PEAK SHAVING

A. FACTORS AND MECHANISM AFFECTING NUCLEAR POWER SAFETY RISK

Under the normal operation and maintenance of NPP, nuclear power units can participate in the peak shaving of power grid properly according to the technical specifications and requirements, which generally will not cause nuclear safety accidents of level 2-7. In the process of nuclear power participating in daily load tracking, it is necessary to insert or withdraw control rods to adjust the unit power. This process may cause local disturbance to the nuclear reactor and induce nuclear safety events such as level 0-1 anomalies or deviations, and affect the safe and reliable operation of the nuclear power unit to a certain extent. The mechanism analysis of nuclear safety events caused by nuclear power peaking is shown in Figure 1.

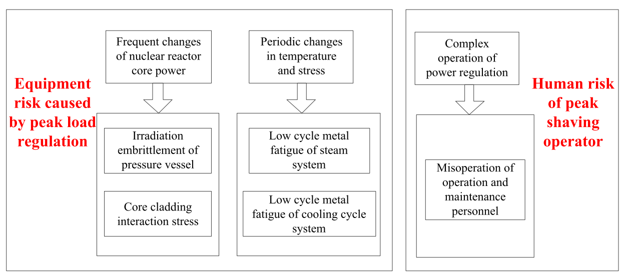


FIGURE 1. Risk mechanism of nuclear power units participating in peak shaving.

It can be seen from Figure 1 that the participation of nuclear power units in peak shaving may cause safety risks of NPP equipment and human factors risks due to complex power regulation operations. The mechanism of each risk is as follows:

1) Frequent change of core power: during the power regulation of the unit, inserting or pulling out the control rod bank will lead to a significant decrease or increase in the power of the surrounding fuel assemblies, resulting in a rapid

decrease or increase in the fuel temperature. The expansion and contraction power of the fuel pellet has a faster response to the power change than the surrounding cladding. Therefore, the rapid change of the core power will cause significant thermal and mechanical stress to the fuel pellet and the surrounding cladding, which may lead to fuel cracking and cladding failure. At the same time, the frequent change of core power will further aggravate the irradiation embrittlement of nuclear reactor pressure vessel and increase the possibility of embrittlement fracture.

2) Periodic change of temperature and stress: the power regulation of nuclear power units will have a certain impact on the temperature change of the coolant system, and the constant change of coolant temperature will affect the temperature of the components of the unit through which it flows, resulting in frequent changes in the temperature of some mechanical components of the unit. The same is true of the steam supply system. Frequent changes over a long period of time will aggravate the fatigue damage of metal parts. Therefore, frequent peak shaving of nuclear power units may lead to equipment damage under long-term alternating stress, which has a certain impact on the operation life of the units.

3) Human risk influence for peak shaving operator: A significant feature of NPP participating in peak load regulation is the continuous and rapid change of power. In the process of peak load regulation, operators mainly use control rods to adjust the rate of reactor power up and down. When the control rod is adjusted, the speed of power up and down is fast, the reactivity fluctuates greatly, and the parameters that the operator needs to monitor increase, which makes the peak shaving task more complex and increases the probability of accidents in the process of peak shaving. When the NPP participates in the peak load regulation of power grid, the operators need to formulate the operation strategy of peak load regulation temporarily according to the actual situation to deal with the sudden peak load regulation task. The peak shaving process will inevitably depend on the skilled operation of operators and years of operation experience. However, the tedious operation steps and the additional work pressure caused by peak load regulation may cause additional psychological burden and work errors of operators. Therefore, the man-made safety risk caused by peak shaving can not be ignored.

B. QUANTITATIVE INDEX OF NUCLEAR POWER PEAK SHAVING COMPREHENSIVE RISK

The comprehensive risk quantification index of nuclear power peak shaving is shown in Figure 2, which can be evaluated by annual failure times and power loss. First, the annual failure times can be used to calculate the additional cost brought by the maintenance of the failed equipment. Second, the loss of electricity can be used to calculate the loss of the benefit of selling electricity in the power market.

The annual failure times triggered by peak shaving can be calculated on the basis of the total downtime and maintenance time caused by various risk factors in a year,which is shown

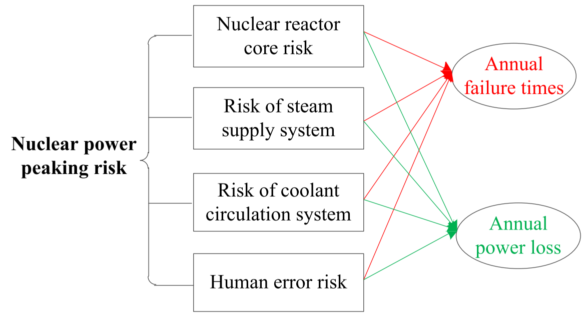


FIGURE 2. Quantitative index of nuclear power peak shaving comprehensive risk.

as follows:

$$f_{i,j}^{\text{stop}} = \frac{t_{i,j}^{\text{stop}}}{MTTR_i} \tag{1}$$

The annual loss of electricity $P_{i,j}^{\text{loss}}$ (MWh / year) caused by risk factor i of peak shaving is shown as follows:

$$P_{i,j}^{\text{loss}} = t_{i,j}^{\text{stop}} P_j^{\text{N}} \tag{2}$$

Therefore, the safety risk quantification caused by nuclear power peak shaving can be expressed by the sum of these two parts, as shown in the following formula:

$$R_{\text{PL}} = \frac{\sum_{j=1}^{m_{\text{PL}}} \sum_{i=1}^{4} \left(f_{i,j}^{\text{stop}} C_i^{\text{repair}} + P_{i,j}^{\text{loss}} C^{\text{ongrid}} \right)}{m_{\text{PL}}} \tag{3}$$

In order to quantify the risk of nuclear power caused by peak shaving more intuitively, compare the safety risk caused by nuclear power operating in daily load tracking mode with that of baseload mode. The peak shaving risk increment can be calculated as follows:

$$R_{\text{BL}} = \frac{\sum_{j=1}^{m_{\text{BL}}} \sum_{i=1}^{4} \left(f_{i,j}^{\text{stop}} C_i^{\text{repair}} + P_{i,j}^{\text{loss}} C^{\text{ongrid}} \right)}{m_{\text{BL}}} \tag{4}$$

$$\Delta R_{\text{PL}} = R_{\text{PL}} - R_{\text{BL}} \tag{5}$$

Taking formula (1) ~ (4) into formula (5), we can get:

$$\Delta R_{\text{PL}} = \sum_{j=1}^{m_{\text{PL}}} \sum_{i=1}^{4} \left(\frac{t_{i,j}^{\text{stop}}}{MTTR_i} C_i^{\text{repair}} + t_{i,j}^{\text{stop}} P_j^{\text{N}} C^{\text{ongrid}} \right) g \frac{1}{m_{\text{PL}}} - \sum_{j=1}^{m_{\text{BL}}} \sum_{i=1}^{4} \left(\frac{t_{i,j}^{\text{stop}}}{MTTR_i} C_i^{\text{repair}} + t_{i,j}^{\text{stop}} P_j^{\text{N}} C^{\text{ongrid}} \right) g \frac{1}{m_{\text{BL}}} \tag{6}$$

It can be seen that the safety risks brought by nuclear power operation in peak shaving mode mainly depend on the failure downtime of units in peak shaving mode and that in baseload operation mode. At the same time, the cost of equipment maintenance and the pool purchase price of nuclear power determine the risk cost of peak load operation of nuclear power units.

To sum up, the flow chart of the comprehensive risk quantitative assessment of nuclear power unit peak shaving is shown in Figure 3.

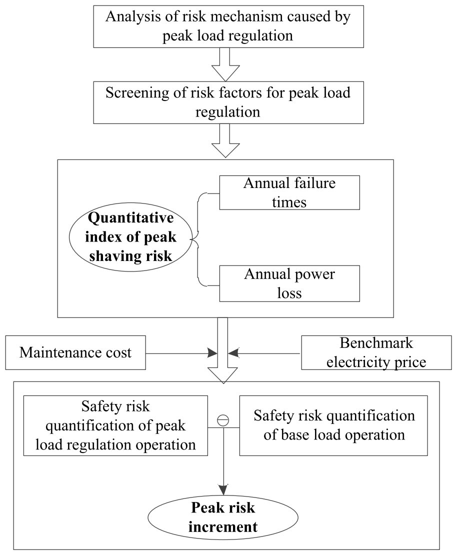


FIGURE 3. Nuclear power peak shaving comprehensive risk quantification process.

The main steps include 1) Analyzing the risk mechanism caused by peak shaving; 2) Screening out the factors that affect the risk of peak shaving; 3) Establishing the risk quantitative indicators respectively according to the risk factors, including the annual failure frequency and annual loss of electricity caused by the risk factors, so as to form a comprehensive quantitative indicator of nuclear power peak shaving risk; 4) According to the established quantitative indicators, combined with the unit failure shutdown time, unit maintenance cost, nuclear power grid benchmark price and other data, the corresponding safety risks of nuclear power units in peak shaving mode and with baseload mode are calculated. Finally the safety risk increment of nuclear power peak shaving operation is calculated.

III. MULTI-SOURCE OPTIMAL SCHEDULING MODEL CONSIDERING NUCLEAR POWER RISK AND WIND POWER CONSUMPTION

A. NUCLEAR POWER OUTPUT MODELING

Establish the model of nuclear power. The peak shaving depth k of nuclear power is made continuous [17]and improved a lot. The value of k should be within the range of safe peak shaving depth of nuclear power, generally $k \in [0.3, 1]$, as shown in Figure 4. Its full power state can be represented by 0-1 variable h, while its low power state can be represented by 0-1 variable l^k. For the 3-hour power-up and down phase, D_m^k represents the operation state of power down phase, U_m^k represents the operation state of power-up phase, m = 1, 2. Similarly, when m = 3, D_m^k and U_m^k respectively represent the power state of the unit during the 2h power transition period.

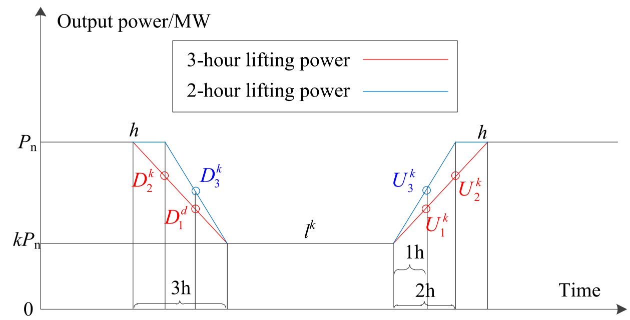


FIGURE 4. Output diagram of continuous nuclear power peak shaving depth.

Linear constraints are added to represent the nuclear power output model

$$P_{i,t} = P_i^{\max} g\left\{h_{i,t} + \frac{1}{2}\left(D_{3,i,t}^k + U_{3,i,t}^k\right) + \frac{1}{3}\left(D_{1,i,t}^k + U_{1,i,t}^k\right) + \frac{2}{3}\left(D_{2,i,t}^k + U_{2,i,t}^k\right)\right\} + P_i^{\max} g\left\{x_{i,t}^l + \frac{1}{2}\left(x_{i,t}^{D_3^k} + x_{i,t}^{U_3^k}\right) + \frac{2}{3}\left(x_{i,t}^{D_1^k} + x_{i,t}^{U_1^k}\right) + \frac{1}{3}\left(x_{i,t}^{D_2^k} + x_{i,t}^{U_2^k}\right)\right\} \tag{7}$$

where, $h_{i,t}$ refers to the variable of 0-1, if the value of $h_{i,t}$ is 1, it means that the nuclear motor unit i is in the full power operation state at time t; $x_{i,t}^y, y \in \left\{D_m^k, U_m^k, l^k\right\}, m = 1, 2, 3$ refers to the intermediate variable of equivalent linearization after multiplying the variable of 0-1 of each operation state and peak depth k.

The constraints of nuclear power output are as follows:

1) RUNNING STATE CONSTRAINTS

$$h_{i,t} + l_{i,t}^k + \sum_{m=1}^{3}\left(D_{m,i,t}^k + U_{m,i,t}^k\right) = 1 \tag{8}$$

where, $l_{i,t}^d$ is 0-1 variable. If its value is 1, it means that the nuclear power unit i is in low power operation state at time t.

2) HIGH AND LOW POWER MINIMUM OPERATION TIME CONSTRAINTS

$$\begin{cases} \sum_{\tau=t}^{t+T_h-1} h_{i,\tau} \geq T_h(h_{i,\tau} - h_{i,\tau-1}) \\ \sum_{\tau=t}^{t+T_l-1} l_{i,\tau}^k \geq T_l(l_{i,\tau}^k - l_{i,\tau-1}^k) \end{cases} \tag{9}$$

3) LIFTING POWER SYMMETRY CONSTRAINTS

$$\begin{cases} \sum_{\tau=t}^{T} U_{2,i,\tau}^k = \sum_{\tau=t}^{T} D_{2,i,\tau}^k \\ \sum_{\tau=t}^{T} U_{3,i,\tau}^k = \sum_{\tau=t}^{T} D_{3,i,\tau}^k \end{cases} \tag{10}$$

where T is the scheduling period, in general, $T = 24$h.

4) POWER-UP / DOWN PATH CONSTRAINTS

$$\begin{cases} h_{i,t+1} \geq U_{2,i,t}^{k} + U_{1,i,t-1}^{k} - 1 \\ l_{i,t+1}^{k} \geq D_{1,i,t}^{k} + D_{2,i,t-1}^{k} - 1 \\ D_{1,i,t+1}^{k} \geq D_{2,i,t}^{k} + h_{i,t-1} - 1 \\ U_{2,i,t+1}^{k} \geq U_{1,i,t}^{k} + l_{i,t-1}^{k} - 1 \\ h_{i,t+1} \geq U_{3,i,t}^{k} + l_{i,t-1}^{k} - 1 \\ l_{i,t+1}^{k} \geq D_{3,i,t}^{k} + h_{i,t-1}^{k} - 1 \\ h_{i,t-1} \geq D_{2,i,t}^{k} \\ l_{i,t-1}^{k} \geq U_{1,i,t}^{k} \\ l_{i,t-1}^{k} \geq U_{3,i,t}^{k} \\ h_{i,t-1} \geq D_{3,i,t}^{k} \\ D_{2,t}^{k} = D_{1,i,t+1}^{k} \\ U_{1,t}^{k} = U_{2,i,t+1}^{k} \end{cases} \tag{11}$$

5) LINEARIZATION CONSTRAINTS

$$\begin{cases} k - (1 - D_{1,i,t}^{k})\bar{k} \leq x_{i,t}^{D_1^k} \leq k \\ 0 \leq x_{i,t}^{D_1^k} \leq \bar{k} D_{1,i,t}^{k} \\ k - (1 - D_{2,i,t}^{k})\bar{k} \leq x_{i,t}^{D_2^k} \leq k \\ 0 \leq x_{i,t}^{D_2^k} \leq \bar{k} D_{2,i,t}^{k} \\ k - (1 - D_{3,i,t}^{k})\bar{k} \leq x_{i,t}^{D_3^k} \leq k \\ 0 \leq x_{i,t}^{D_3^k} \leq \bar{k} D_{3,i,t}^{k} \end{cases} \tag{12}$$

$$\begin{cases} k - (1 - U_{1,i,t}^{k})\bar{k} \leq x_{i,t}^{U_1^k} \leq k \\ 0 \leq x_{i,t}^{U_1^k} \leq \bar{k} U_{1,i,t}^{k} \\ k - (1 - U_{2,i,t}^{k})\bar{k} \leq x_{i,t}^{U_2^k} \leq k \\ 0 \leq x_{i,t}^{U_2^k} \leq \bar{k} U_{2,i,t}^{k} \\ k - (1 - U_{3,i,t}^{k})\bar{k} \leq x_{i,t}^{U_3^k} \leq k \\ 0 \leq x_{i,t}^{U_3^k} \leq \bar{k} U_{3,i,t}^{k} \end{cases} \tag{13}$$

$$\begin{cases} k - (1 - l^{k})\bar{k} \leq x_{i,t}^{l^k} \leq k \\ 0 \leq x_{i,t}^{l^k} \leq \bar{k} l^{k} \end{cases} \tag{14}$$

B. OBJECTIVE FUNCTION

The types of power sources studied include thermal power, nuclear power, pumped storage unit, gas-steam combined cycle unit, and wind power unit. At the same time, in order to establish a complete economic and safety dispatching scheme, the environmental economic dispatch is included in the objective function. The objective function includes the operation cost of various units, the risk cost of peak load regulation of nuclear power unit, the risk cost of wind abandonment and the environmental cost, which can be expressed as:

$$\min F = \underbrace{C^{\mathrm{N}} + C^{\mathrm{T}} + C^{\mathrm{PS}} + C^{\mathrm{CC}}}_{(1)} + \underbrace{C_{\mathrm{R}}^{\mathrm{N}} + C_{\mathrm{R}}^{\mathrm{W}}}_{(2)} + \underbrace{C_{\mathrm{Env}}}_{(3)} \tag{15}$$

1) OPERATING COSTS

a: THERMAL POWER OPERATION COST

The operation cost of thermal power unit takes into account its generation cost and unit start-up and shutdown cost, which is expressed as follows:

$$C^{\mathrm{T}} = \sum_{t=1}^{\mathrm{T}} \sum_{i=1}^{n_{\mathrm{T}}} \left[\delta_{i,t}^{\mathrm{T}} a_i^{\mathrm{T}} + b_i^{\mathrm{T}} P_{i,t}^{\mathrm{T}} + c_i^{\mathrm{T}} (P_{i,t}^{\mathrm{T}})^2 + S_{i,t}^{\mathrm{T}} \right] \tag{16}$$

$S_{i,t}^{\mathrm{T}}$ in equation (16) represents the start-up/shut-down cost of the thermal power unit, which can be expressed as follows:

$$S_{i,t}^{\mathrm{T}} = \alpha_{i,t}^{\mathrm{T}} C_{i,\mathrm{start}}^{\mathrm{T}} + \beta_{i,t}^{\mathrm{T}} C_{i,\mathrm{stop}}^{\mathrm{T}} \tag{17}$$

2) THE OPERATION COST OF PUMPED STORAGE UNIT

The pumped storage unit is a good peak load regulating power supply with flexible and rapid start-up and shutdown. Its operation cost mainly considers the start-up cost of the unit, which can be expressed as follows:

$$C^{\mathrm{PS}} = \sum_{t=1}^{T} \sum_{i=1}^{n_{\mathrm{PS}}} (\alpha_{i,t}^{\mathrm{G}} C_{i,\mathrm{start}}^{\mathrm{G}} + \alpha_{i,t}^{\mathrm{P}} C_{i,\mathrm{start}}^{\mathrm{P}}) \tag{18}$$

3) THE OPERATING COST OF NUCLEAR POWER UNIT

Combined with the actual situation in China, nuclear power units generally operate with baseload. In the modeling of daily scheduling optimization for nuclear power units, all nuclear power units participating in daily peak shaving operation are equivalent to one nuclear power unit. If the optimization result requires nuclear power to participate in peak shaving, the corresponding nuclear power units will be involved in daily load tracking according to the operation states and safety times of all nuclear power units. And the equivalent nuclear power unit operation cost C^{N} can be written as follows:

$$\begin{cases} C^{\mathrm{N}} = \sum_{t=1}^{T} \left[a_{\mathrm{eq}}^{\mathrm{N}} + b_{\mathrm{eq}}^{\mathrm{N}} P_{\mathrm{eq},t}^{\mathrm{N}} + C_{\mathrm{PS}}^{\mathrm{N}} (P_{\mathrm{eq,max}}^{\mathrm{N}} - P_{\mathrm{eq},t}^{\mathrm{N}}) \right] \\ a_{\mathrm{eq}}^{\mathrm{N}} = \sum_{i=1}^{n_{\mathrm{N}}} a_i^{\mathrm{N}} \\ P_{\mathrm{eq,max}}^{\mathrm{N}} = \sum_{i=1}^{n_{\mathrm{N}}} P_{i,\mathrm{max}}^{\mathrm{N}} \end{cases} \tag{19}$$

4) OPERATION COST OF COMBINED CYCLE UNIT

Its operation cost includes i) fuel power generation cost, ii) mode conversion cost [18]–[20], namely, (20), as shown at the bottom of the next page.

5) RISK COST

a: SAFETY RISK COST OF NUCLEAR POWER PEAKING

According to the analysis and calculation of the safety risk cost of nuclear power peaking, on the basis of formula (6), the safety risk cost of nuclear power daily peak shaving can be expressed as:

$$\begin{cases} C_{\mathrm{R}}^{\mathrm{N}} = \sum_{t=1}^{T} \sum_{i=1}^{n_{\mathrm{N}}} \varepsilon R_{i,t}^{\mathrm{N}} \\ R_{i,t}^{\mathrm{N}} = R_{\mathrm{day}}^{\mathrm{N}} (P_{i,\max}^{\mathrm{N}} - P_{i,t}^{\mathrm{N}}) \\ R_{\mathrm{day}}^{\mathrm{N}} = \dfrac{\Delta R_{\mathrm{PL}}}{\frac{1}{m_{\mathrm{PL}}} \sum_{i=1}^{m_{\mathrm{PL}}} f_{\mathrm{PL},i}^{\mathrm{day}} E_i^N} \end{cases} \tag{21}$$

b: Risk COST OF WIND POWER ABANDONMENT

The predicted output data of wind power is taken as the upper limit of the actual output of the wind farm, and the risk cost of wind power abandonment can be expressed as follows:

$$C_{\mathrm{R}}^{\mathrm{W}} = p^{\mathrm{W}} k^{\mathrm{W}} \sum_{t=1}^{T} \sum_{i=1}^{n_{\mathrm{W}}} \left(P_{i,t}^{\mathrm{W,pre}} - P_{i,t}^{\mathrm{W}} \right) \tag{22}$$

c: ENVIRONMENTAL COST

The environmental cost takes into account the coal-fired carbon emission cost of the thermal power unit and the carbon emission cost of the gas unit in the combined cycle unit [21]–[23], which can be expressed as follows:

$$C_{\mathrm{Env}} = \xi_{\mathrm{CE}} \left[\begin{array}{l} \sum_{t=1}^{T} \sum_{i=1}^{n_{\mathrm{T}}} C_{\mathrm{CE}}^{\mathrm{T}} P_{i,t}^{\mathrm{T}} + \\ \sum_{t=1}^{T} \sum_{i=1}^{n_{\mathrm{CC}}} \sum_{x' \in M_k} C_{\mathrm{CE}}^{\mathrm{CT}} \mu^{\mathrm{CC},x'} (P_{i,\min}^{\mathrm{CC},x'} u_{i,t}^{\mathrm{CC},x'} + \Delta P_{i,t}^{\mathrm{CC},x'}) \end{array} \right] \tag{23}$$

C. CONSTRAINTS

The basic constraints and unit operation constraints are as follows:

1) POWER BALANCE CONSTRAINTS OF THE SYSTEM

$$\sum_{i=1}^{n_{\mathrm{T}}} P_{i,t}^{\mathrm{T}} + \sum_{i=1}^{n_{\mathrm{N}}} P_{i,t}^{\mathrm{N}} + \sum_{i=1}^{n_{\mathrm{PS}}} P_{i,t}^{\mathrm{PS}} + \sum_{i=1}^{n_{\mathrm{CC}}} P_{i,t}^{\mathrm{CC}} + \sum_{i=1}^{n_{\mathrm{W}}} P_{i,t}^{\mathrm{W}} = P_t^{\mathrm{L}} \tag{24}$$

(2) The randomness and volatility of wind power and load make it difficult to accurately predict. Considering other stochastic factors of the system, it is required to reserve sufficient reserve capacity.

System reserve capacity constraints in (25), as shown at the bottom of the next page.

2) POWER OPERATION CONSTRAINTS

a: OPERATION CONSTRAINTS OF THERMAL POWER UNIT

The thermal power unit shall meet the maximum or minimum output restriction, start-up and shut-down time restriction and climbing rate restriction during operation, which can be expressed as follows:

$$\begin{cases} \delta_{i,t}^{\mathrm{T}} P_{i,\min}^{\mathrm{T}} \le P_{i,t}^{\mathrm{T}} \le \delta_{i,t}^{\mathrm{T}} P_{i,\max}^{\mathrm{T}} \\ \begin{cases} \delta_{i,x}^{\mathrm{T}} \ge \delta_{i,t}^{\mathrm{T}} - \delta_{i,t-1}^{\mathrm{T}}, x \in [t, \ \min(T, t + T_{i,\min}^{\mathrm{on}} - 1)] \\ \delta_{i,x}^{\mathrm{T}} \le 1 - (\delta_{i,t-1}^{\mathrm{T}} - \delta_{i,t}^{\mathrm{T}}), x \in [t, \min(T, t + T_{i,\min}^{\mathrm{off}} - 1)] \end{cases} \\ -r_{\mathrm{d},i}^{\mathrm{T}} \le P_{i,t}^{\mathrm{T}} - P_{i,t-1}^{\mathrm{T}} \le r_{\mathrm{u},i}^{\mathrm{T}} \end{cases} \tag{26}$$

b: OPERATION CONSTRAINTS OF PUMPED STORAGE UNIT

During the operation of the pumped storage unit, a series of constraints should be met, including the upper and lower limits of the output of the unit, the storage capacity of the reservoir, the balance of the daily pumping and generating capacity, the conversion of generating conditions and the conversion of pumping conditions, which can be expressed as follows:

$$\begin{cases} \delta_{i,t}^{\mathrm{G}} P_{i,\min}^{\mathrm{G}} \le P_{i,t}^{\mathrm{G}} \le \delta_{i,t}^{\mathrm{G}} P_{i,\max}^{\mathrm{G}} \\ \begin{cases} V_{\mathrm{u,min}} \le V_{\mathrm{u},t} \le V_{\mathrm{u,max}} \\ V_{\mathrm{d,min}} \le V_{\mathrm{d},t} \le V_{\mathrm{d,max}} \end{cases} \\ \sum_{t=1}^{T} \sum_{i=1}^{n_{\mathrm{PS}}} \delta_{i,t}^{\mathrm{G}} P_{i,t}^{\mathrm{G}} = - \sum_{t=1}^{T} \sum_{i=1}^{n_{\mathrm{PS}}} \eta_i \delta_{i,t}^{\mathrm{P}} P_{i,\max}^{\mathrm{P}} \\ \begin{cases} \alpha_{i,t}^{\mathrm{G}} - \beta_{i,t}^{\mathrm{G}} = \delta_{i,t}^{\mathrm{G}} - \delta_{i,t-1}^{\mathrm{G}} \\ \alpha_{i,t}^{\mathrm{G}} + \beta_{i,t}^{\mathrm{G}} \le 1 \end{cases} \\ \begin{cases} \alpha_{i,t}^{\mathrm{P}} - \beta_{i,t}^{\mathrm{P}} = \delta_{i,t}^{\mathrm{P}} - \delta_{i,t-1}^{\mathrm{P}} \\ \alpha_{i,t}^{\mathrm{P}} + \beta_{i,t}^{\mathrm{P}} \le 1 \end{cases} \end{cases} \tag{27}$$

IV. MODEL SOLVING METHOD

The process of solving the dispatching model of nuclear power system is mainly divided into two parts: model linearization and solution, and scheduling planning. Among them, the role of model linearization is to standardize the scheduling model, so as to realize the efficient solution of the scheduling model based on commercial optimization software CPLEX. The scheduling plan is to consider the limitation of daily peak shaving times of nuclear power plant, arrange the peak load regulation units in turn, and realize the balance of peak shaving and nuclear abandonment among nuclear power units belonging to different interest groups. As shown in Figure 5.

$$C^{\mathrm{CC}} = \sum_{t=1}^{T} \sum_{i=1}^{n_{\mathrm{CC}}} \sum_{x' \in M_k} \left[\begin{array}{l} \underbrace{a_i^{\mathrm{CC},x'} u_{i,t}^{\mathrm{CC},x'} + b_i^{\mathrm{CC},x'} \left(P_{i,\min}^{\mathrm{CC},x'} u_{i,t}^{\mathrm{CC},x'} + \Delta P_{i,t}^{\mathrm{CC},x'} \right)}_{1)} \\ + \sum_{y \in M_k^{\mathrm{F},x'}} \underbrace{c_i^{\mathrm{CC},x'y} v_{i,t}^{\mathrm{CC},x'y}}_{2)} \end{array} \right] \tag{20}$$

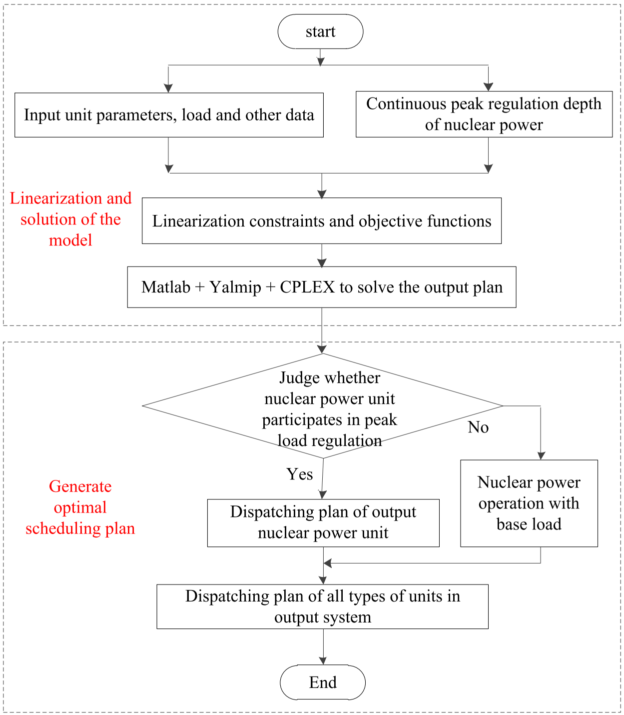


FIGURE 5. Optimal scheduling model considering nuclear power peak shaving.

Aiming at the fact that there are many 0-1 variables and various constraints in the objective function and constraints, this paper uses MATLAB + Yalmip + CPLEX to solve the multi-source optimal scheduling problem. The solution flow is shown in Figure 5, and the main steps are as follows:

(1) Input parameters of all types of units, daily load data, standby capacity factor and other parameters;

(2) The constraints in the model of continuous peak shaving depth of NPP are linearized, and the quadratic term in the objective function of thermal power units is expressed by piecewise linearization;

(3) Matlab + yalmip + CPLEX are used to solve the scheduling optimization model;

(4) Judge whether the nuclear power unit needs to participate in peak shaving according to the optimized results. If there is no need,the power unit will operate with baseload;

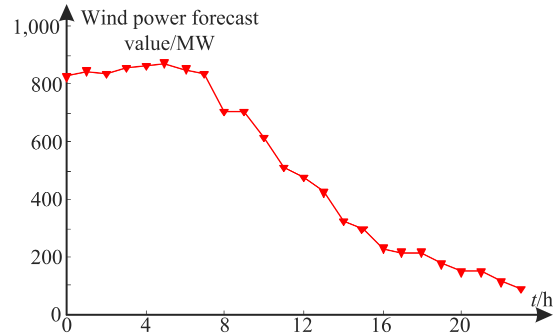


FIGURE 6. Predicted daily output of wind power.

(5) Output optimal dispatching plan for various types of generating units.

V. EXAMPLE ANALYSIS

A. EXAMPLE DESCRIPTION

Based on the improvement of references [24] and [25], an example of a coastal power grid in China is analyzed. The basic information of the system is as follows: two cnp600 nuclear power units in Qinshan, one AP1000 nuclear power unit in Sanmen, one onshore wind farm in Zhoushan, one offshore wind farm in Ningbo, two CCGT units in Wenzhou, three pumping and storage units in Xianju, 28 coal-fired units in Lanxi, Yueqing, Jiaxing, Zhoushan, Xiaoshan and Yuhuan. The total installed capacity of the system is 13965mw, of which the installed capacity of the wind farm is 1000MW. The parameters of the pumped storage unit, thermal power unit, CCGT unit, and nuclear power unit are shown in table b1-b5. The predicted daily output of wind power is shown in Figure 6 (assuming that the sea wind output is 1.1 times of the land wind output). The load curve of a typical day in summer is shown in Figure 7.

Referring to the data of International Renewable Energy Agency, carbon emission cost coefficients C_{CE}^{T} and $C_{\text{CE}}^{\text{CT}}$ are 0.976 ton/MW·h and 0.549ton/MW·h respectively, carbon emission cost ξ_{CE} is 22.81 \$/ton, and the $\mu^{\text{CC},x'}$ of CCGT in Mode3 and Mode4 is 0.6 and 0.8 respectively [26]. The cost

$$\begin{cases} \sum_{i=1}^{n_{\text{T}}} \min\left\{\delta_{i,t}^{\text{T}} P_{i,\max}^{\text{T}} - P_{i,t}^{\text{T}}\ , r_{\text{u},i}^{\text{T}} T_{\text{b}}\right\} + \sum_{i=1}^{n_{\text{PS}}} (P_{i,\max}^{\text{G}} - P_{i,t}^{\text{PS}}) + \sum_{i=1}^{n_{\text{W}}} (P_{i,t}^{\text{W,pre}} - P_{i,t}^{\text{W}}) \\ + \sum_{i=1}^{n_{\text{CC}}} \sum_{x' \in M_k} \min\left\{[u_{i,t}^{\text{CC},x'} (P_{i,\max}^{\text{CC},x'} - P_{i,\min}^{\text{CC},x'}) - \Delta P_{i,t}^{\text{CC},x'}],\, u_{i,t}^{\text{CC},x'} r_{\text{u},i}^{\text{CC},x'} T_{\text{b}}\right\} \\ \geq R_{\text{u}}\% \times P_t^{\text{L}} + W_{\text{u}}\% \times \sum_{i=1}^{n_{\text{W}}} P_{i,t}^{\text{W,pre}} \\ \sum_{i=1}^{n_{\text{T}}} \min\left\{P_{i,t}^{\text{T}} - \delta_{i,t}^{\text{T}} P_{i,\min}^{\text{T}}\ , r_{\text{d},i}^{\text{T}} T_{\text{b}}\right\} + \sum_{i=1}^{n_{\text{PS}}} (P_{i,t}^{\text{PS}} + P_{i,\max}^{\text{P}}) + \\ \sum_{i=1}^{n_{\text{CC}}} \sum_{x' \in M_k} \min\left\{\Delta P_{i,t}^{\text{CC},x'}, u_{i,t}^{\text{CC},x'} r_{\text{d},i}^{\text{CC},x'} T_{\text{b}}\right\} \geq R_{\text{d}}\% \times P_t^{\text{L}} + W_{\text{d}}\% \times \sum_{i=1}^{n_{\text{W}}} (P_i^{\text{W,max}} - P_{i,t}^{\text{W,pre}}) \end{cases} \tag{25}$$

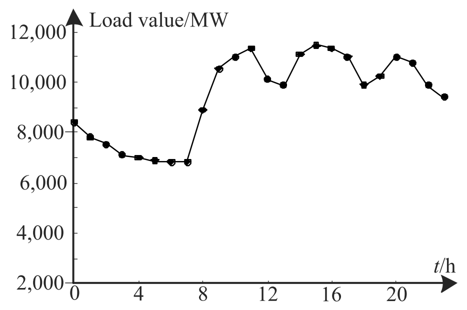


FIGURE 7. System daily load.

of wind power abandonment is 50 \$/MW·H (onshore wind power) and 71.97 \$/MW·H (offshore wind power) respectively for the two wind farms, and the risk coefficient k^W of wind power abandonment is 1. Load reserve $R_u\%$ and $R_d\%$ are 5%, wind power reserve $W_u\%$ and $W_d\%$ are 15%. Nuclear safety risk factor ε is 1. The maximum peak shaving depth of nuclear power is 70% P_n.

Modeling and solving platform: Intel Core i7-5650u 2.2GHz CPU; 8G memory, software: MATLAB R2016a; Yalmip R20180209; IBM ILOG Cplex 12.6.3, the solution precision of Cplex is 10^{-4}.

B. RISK CALCULATION AND ANALYSIS OF NUCLEAR POWER PEAK SHAVING

Based on the historical operation data of 5 nuclear power units with baseload operation and 15 nuclear power units participating in daily peak shaving operation[27], the peak shaving risk of nuclear power units is quantified by the quantitative index established in Chapter II, Section B

Figure 8 (a) shows the annual outage time of nuclear power under different operation modes. According to formula (1) ~ (2), the annual failure times and the annual power loss are calculated, as shown in Figure 8 (b). The influence of various risk factors on the annual outage time, number of failures and power loss is shown in Figure 8 (c).

It is analyzed by Figure 8:

(1) Annual failure outage time: peak shaving operation will increase the outage time, of which the steam supply system failure has the greatest impact, and the increase of failure caused by various risk factors is 61%, 37%, 86% and 14%, respectively. This shows that the peak shaving operation will have a little impact on the safety and stability of the nuclear power unit, mainly in the steam supply system fault, and has a significant impact on the safety and stability of the coolant circulation system and the reactor core.

(2) Annual failure times: with the unit participating in peak shaving operation, the number of failures increases and the risk of failure increases, among which the proportion of artificial misoperation is obvious, accounting for 71% and 65% respectively under base load mode and peak load mode. After peak shaving operation, the influence of various factors on the

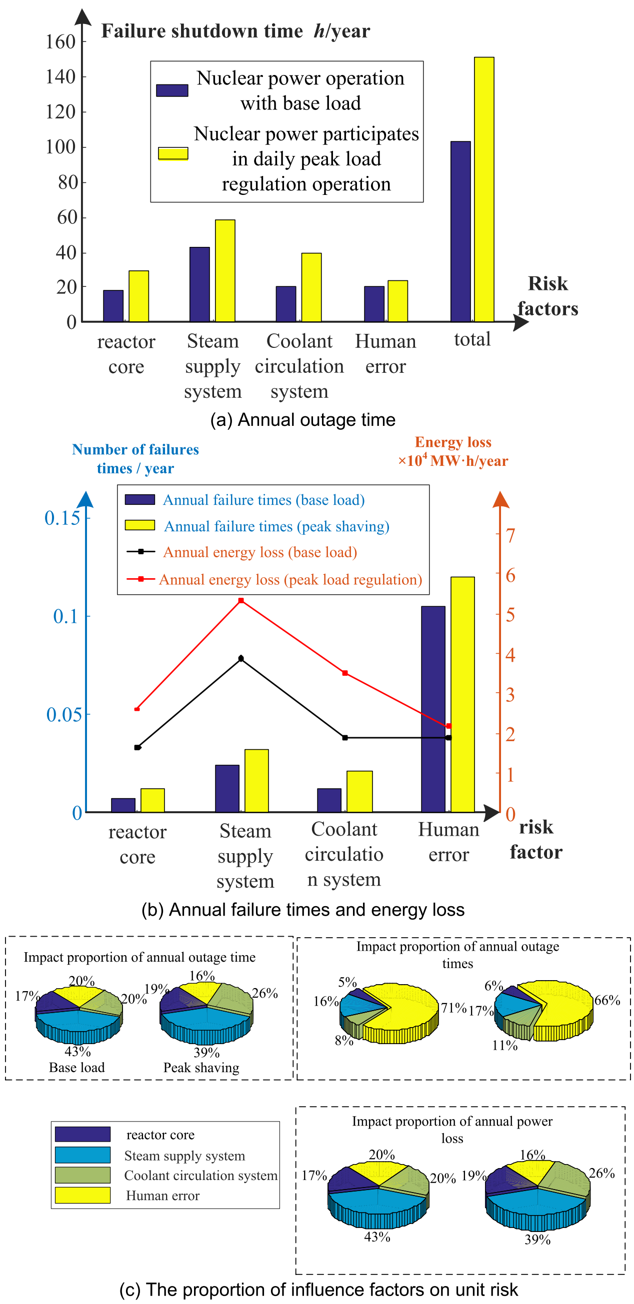


FIGURE 8. Influence of risk factors on nuclear power units under different operation modes.

number of failures increased by 60%, 33%, 75% and 14%, respectively, which indicated that human misoperation did not increase significantly due to nuclear power participating in peak shaving operation. And the risk source of peak load operation of the unit was still the coolant circulation system and reactor core.

(3) Annual loss of electricity: after the peak load operation of nuclear power units, there is a certain degree of improvement. And the main source of power loss risk is the steam supply system of the unit.

The pool purchase price of nuclear power is 0.057$/ kW·h, and the safety risk cost of nuclear power is calculated, as shown in Figure 9.

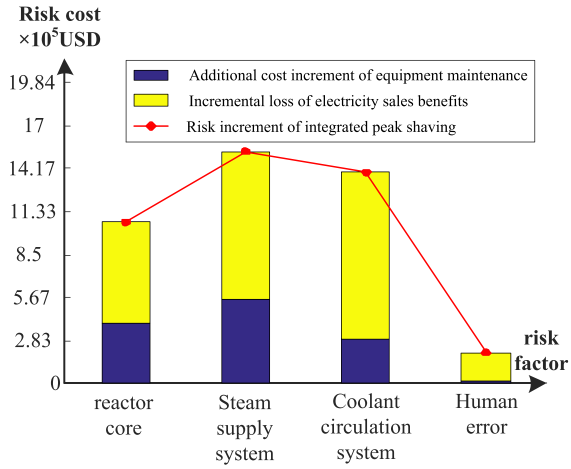


FIGURE 9. Nuclear power safety risk cost under the influence of various risk factors.

From Figure 9:

(1) The proportion of safety risk cost: human error operation cost is relatively low, accounting for about 5%. The reactor core, steam supply, and coolant circulation system account for 25%, 37%, and 33% respectively, which shows that the risk cost of nuclear power peak shaving operation to steam supply system is high.

(2) Source of safety risk cost: the main source is the loss of benefit from the sale of electricity, accounting for about 70% ~ 80% of all risk factors, which shows that under the current policy environment, the cost of nuclear power participating in peak shaving and nuclear abandonment is high, and the safety of the unit will be slightly affected, resulting in additional maintenance costs.

To sum up, (1) nuclear power will have some impact on the safety and stability of the core after participating in peak shaving operation. Frequent power changes will cause metal fatigue of components, and affect the coolant circulation system, etc., resulting in certain operation and maintenance risk costs. (2) Human error operation will not increase obviously with the unit participating in peak load regulation. (3) The comprehensive risk of peak shaving operation of the unit mainly comes from the loss of benefits from the sale of electricity.

Therefore, under the operation mode with high peak shaving pressure, nuclear power can be considered to participate in peak shaving operation properly on the premise of ensuring the safety and stability of nuclear power.

C. ECONOMIC ANALYSIS OF SCHEDULING STRATEGY

In the modeling of the day-ahead scheduling, the risk of nuclear power is equivalent to the daily incremental cost of the safety risk, that is, that is, the calculated value is $2.73 /MW H. Four models are set for comparative analysis,

TABLE 1. Four different models.

	Operation mode of nuclear power	Whether wind power is allowed to abandon wind	Whether the environmental cost is considered
Model 1	Baseload	Yes	No
Model 2	Baseload	Yes	Yes
Model 3	Peak shaving	No	Yes
Model 4	Peak shaving	Yes	Yes

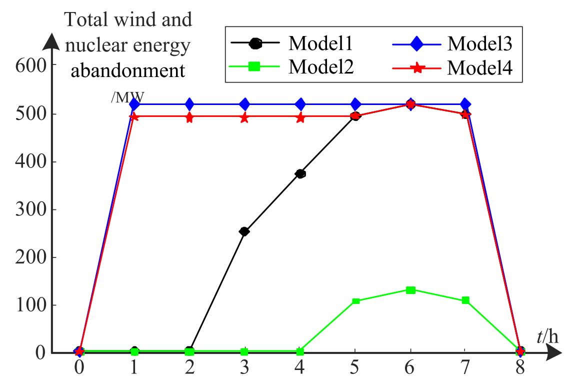


FIGURE 10. Total abandoned power under different scheduling models.

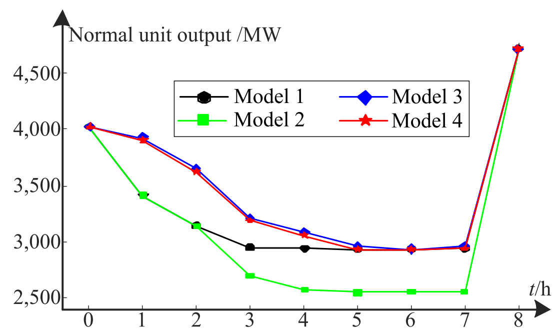


FIGURE 11. Total output curve of conventional units under different dispatching models.

as shown in table 1. Model 4 is the proposed scheduling strategy in this paper, which allows nuclear power to participate in peak shaving operation, and wind abandonment is also allowed. At the same time, the objective function considers the environmental cost of the system. The optimized scheduling results of each model are shown in table 2. Figure 10-11 shows the total wind and nuclear power consumption under different models, as well as the total output of conventional units. Since there is no wind abandonment phenomenon from 9:00to 23:00 and the NPP are operating with base load, only the comparison of dispatching results between 0:00 and 8:00 is given

Analysis by table 2 and Figures 10-11:

(1)Whether to consider the environmental cost: compared with model 1, model 2 reduces by 1814.85MW·h of abandoned wind, and the environmental cost reduces by

TABLE 2. Optimal scheduling results under four different models.

	Wind Abandonment /(MW • h)	Nuclear Abandonment /(MW • h)	Peak shaving depth of nuclear power	Start-up or shutdown /time		
				Thermal power	Combined cycle	Pumped storage
Model 1	2162.39	0	-	2	7	3
Model 2	347.54	0	-	6	5	3
Model 3	0	3674.94	52.50%	2	2	3
Model 4	33.77	3488.38	49.83%	1	0	3

	Various economic costs / $				Total cost / $
	Unit operation cost	Risk cost of wind abandonment	Nuclear safety risk cost	Environmental costs	
Model 1	3916080	104787	0	2979111	6999979
Model 2	4026275	16841	0	2931301	6974418
Model 3	3938264	0	10049	3000092	6948403
Model 4	3936704	1636	9539	2998459	6946339

$47804.8 This is due to the zero-emission characteristics of wind power, and its consumption is significantly increased after considering the environmental cost. At the same time, compared with model 1, the running cost of model 2 is increased by $110184. This is because the nuclear power unit of model 2 has baseload, and the peak shaving pressure brought by the inverse peak shaving characteristics of wind power intensifies the start-up and shutdown of conventional units, which makes the system operation cost rise.

(2) Whether the peak shaving has been carried out in NPP.: Compared with model 2, the total wind power and nuclear power of model 4 are increased. This is because the nuclear power unit is allowed to regulate the peak load. In the low load, it bears the peak shaving load of 3488.38MW·h; And the abandoned wind power is further reduced by 90.28% compared with model 2, only 33.77 MW·h. This shows that under the scheduling strategy in this paper, the power grid has a higher priority in wind power consumption due to its clean and pollution-free characteristics; The total output of model 4 conventional unit is small. Compared with model 2, the total operation cost of model 4 is reduced by $89562.4, and the total cost is reduced by $28076.3. This shows that the power reduction peak shaving of nuclear power is more economical than the start-stop peak shaving of conventional units, which greatly reduces the times of start-stops of conventional units.

(3) Whether to allow wind abandonment: Compared with model 4, the operation cost and environmental cost of model 3 are increased by $1559.6 and $1633.1 respectively, and the total cost is increased by $2063.3. The total abandoned peak shaving power is also the highest among the four models. This is because its scheduling strategy does not allow wind power to be abandoned. Although the wind power has been fully absorbed, the peak shaving power of the nuclear power unit is further increased by 186.56 MW·h due to the peak shaving pressure of the system, and the number of startup and shutdown of conventional units is increased.

To sum up, the model 4 proposed in this paper allows nuclear power to participate in the peak shaving operation of the system, and allows a small amount of wind abandonment.

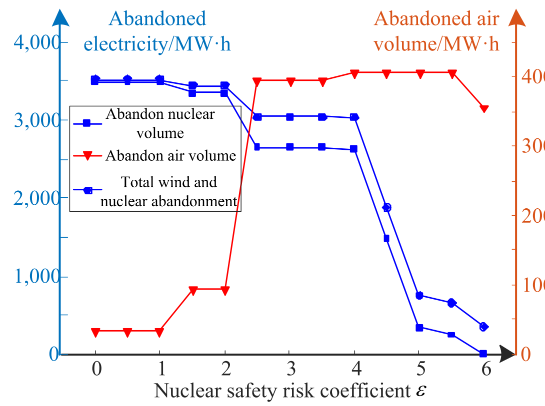


FIGURE 12. Change curve of abandoned nuclear and wind under different nuclear safety risk factors.

The optimization results show that the total cost of the system in model 4 is the lowest, which can effectively coordinate the benefits between wind abandonment, nuclear abandonment, and the start-up and shutdown of conventional units. The model can promote the consumption of wind power, and at the same time, with the economic advantage of peak shaving, the nuclear power unit can relieve the start-up and shutdown pressure of conventional units, and realize the safe, low-carbon and economic operation of the system.

D. ANALYSIS OF THE INFLUENCE OF NUCLEAR SAFETY RISK COEFFICIENT ON DISPATCHING RESULTS

Based on the above model 4, take different nuclear safety risk factors and calculate the optimal scheduling results under different risk factors, as shown in table 3. Figure 12 and Figure 13 show the change curve of the system's abandoned wind volume, abandoned nuclear volume, and total abandoned power peak shaving under different nuclear safety risk factors, as well as the change curve of nuclear safety risk cost and peak shaving cost.

Analysis from table 3 and Figures 13-14:

TABLE 3. Optimal scheduling results under different nuclear safety risk factors.

Nuclear safety risk coefficient	The quantity of load peak shaving /(MW·h)				Various economic costs/ $		
	Thermal power	CCGT	Pumped storage	Total peak shaving quantity of conventional unit	running cost	environmental costs	total cost
0	56609.45	19516	5940	82065.45	3936490.259	2998387.389	6936514.063
0.5	56609.45	19516	5940	82065.45	3936488.558	2998387.389	6941282.04
1	56603.59	19521.86	5940	82065.45	3936704.64	2998459.228	6946339.78
1.5	56649.45	19556	5940	82145.45	3935273.68	2997096.139	6950648.672
2	56642.06	19563.39	5940	82145.45	3935338.859	2997186.539	6955382.784
2.5	56749.45	19856	5940	82545.45	3929883.103	2991863.833	6958934.609
3	56749.45	19856	5940	82545.45	3929879.277	2991863.833	6962551.895
3.5	56749.45	19856	5940	82545.45	3929879.702	2991863.833	6966173.574
4	56758.67	19856	5940	82554.67	3929699.327	2991658.519	6969769.607
4.5	57908.42	19856	5940	83704.42	3969222.813	2966059.228	6973136.663
5	59042.42	19856	5940	84838.42	4008317.393	2940814.736	6973494.58
5.5	59136.92	19856	5940	84932.92	4012113.071	2938706.482	6974236.203
6	59476.79	19816.52	5940	85233.31	4025591.498	2931534.821	6974294.58

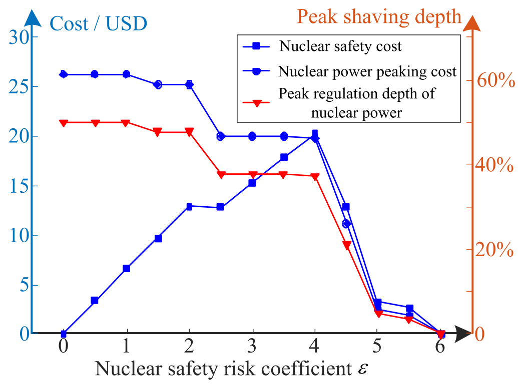
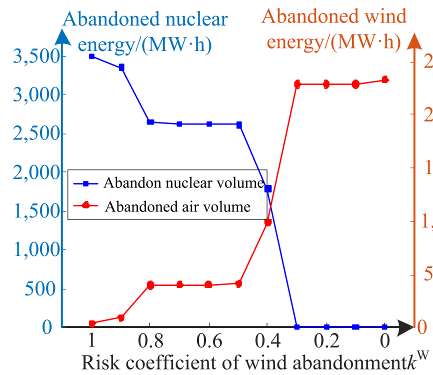
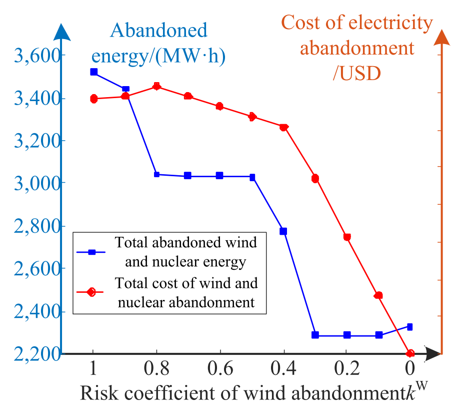


FIGURE 13. Nuclear safety cost and peak shaving cost under different nuclear safety risk factors.

(1) Trend analysis of peak shaving data: when ε is increased to 1.5, 2.5 and 4 respectively, the amount of abandoned nuclear energy is reduced by 140 MW·h, 700 MW·h and 21.51 MW·h respectively, the amount of conventional units increases by 80 MW·h, 400 MW·h and 9.22 MW·h respectively, the amount of abandoned wind is increased by 60 MW·h, 300 MW·h and 12.29 MW·h respectively, and the operation cost and environmental cost of the system are reduced. This is because, after the reduction of nuclear power abandonment, the peak regulating pressure is transferred to the conventional unit and wind power. Because the unit does not increase startup and shutdown, the reduction of power generation leads to the reduction of operation cost and environmental cost, respectively. Whenεincreases to 4.5, 5 and 5.5 respectively, the amount of nuclear power abandonment is further reduced by 1149.75 MW·h, 1133.997 MW·h and 94.503 MW·h respectively. the peak shaving of conventional



(a) Abandonment of nuclear energy and wind energy



(b) Total electricity abandonment and electricity abandonment cost

FIGURE 14. Optimal scheduling results under different risk factors of wind abandonment.

units has increased by corresponding values respectively, and the abandoned wind volume has no incremental change. The total operation cost increased by 39500 US dollars, 39100 US dollars and 3800 US dollars,respectively, and the environmental cost decreased by 25600 US dollars, 25200 US dollars and 21000 US dollars, respectively. This is because restricted by the environmental cost, the scheduling optimization result arranges that the wind power does not increase the abandoned wind volume, and the peak pressure of this part of nuclear power abandonment is borne by the power reduction and start-up/shut-down peak shaving of conventional units. The cost of start-up and shutdown is high, so the total operation cost is increased. At the same time, the environmental cost of the system is reduced due to the reduction of conventional generating capacity. When ε is increased to 6, the amount of abandoned nuclear energy is reduced by 248.62 MW·h, the amount of abandoned wind is reduced by 51.77 MW·h, and the peak shaving of conventional units is increased by 300.39 MW·h. This is because there is no environmental cost for wind power, and the system further encourages its absorption. The peak shaving pressure of wind power abandonment and nuclear power abandonment is borne by conventional units. At the same time, it can be seen that due to the relatively small carbon emission cost of CCGT units, the peak shaving of thermal power increases by 339.87 MW·h, so the operation cost further increases by 13500 US dollars, and the environmental cost decreases by 7200 US dollars. To sum up, when the safety risk of nuclear power peaking is large, the optimization goal of the system is more inclined to the economic scheduling dominated by environmental cost.

(2) Trend analysis of cost change: with the increase of ε, the peak shaving cost of nuclear power is decreasing, because its peak shaving power is decreasing. When ε is in the range of $0 \sim 4$, the reduction rate of the amount of abandoned nuclear is slow, and the nuclear safety cost increases with the increase of ε. This is because the safety risk cost of nuclear power peaking is rising at this time, but it is relatively not high, and it also has a certain peaking economy. When ε is in the range of 4.5-6, the risk cost of nuclear safety changes from rising to declining. This is because the risk of nuclear abandonment is high, and the amount of nuclear abandonment is obviously decreasing. At the same time, with the increase of ε, the total cost of the system is increasing, which indicates that the requirement of improving the safety of nuclear power will increase the total economic cost of the system.

(3) Analysis of the change characteristics of peak shaving: with the increase of ε, the total peak shaving of conventional units increases, and the nuclear power is decreasing, and the total wind and nuclear power are decreasing. This is because nuclear power tends to operate in a more conservative way due to the continuous improvement of safety requirements. When ε increases to 6, nuclear power will always operate with baseload. The decreasing and rising trend of peak shaving is not linear, this is because the start-up and shutdown state of conventional units contains 0-1 variables, and the peak shaving model of nuclear power must follow certain constraints, such as stable operation for a period of time in the low power stage, etc., Therefore, when the safety risk coefficient is greater than a certain value and the peak shaving economy of NPP decreases to a certain extent, the start-up and shutdown of conventional units can reflect a stronger economic advantage.

In the actual dispatching, when the requirements for nuclear power safety risk are high, the nuclear safety risk coefficient can be taken as about 4.5. At this time, the peak shaving power of nuclear power is not high, the risk cost of nuclear power peak shaving is low, and a small amount of wind is allowed to be abandoned, and the total peak shaving is small. In the future, with the continuous development of nuclear power technology, the risk of nuclear power peaking will continue to reduce, and the nuclear safety risk coefficient can be about 2-3. On the premise of ensuring the safety and stability of nuclear power, it can give full play to the peaking capacity of the unit, relieve the peak pressure of the system, and save the total economic cost of the system.

To sum up, it can be seen that the nuclear safety risk coefficient determines the depth of nuclear power participating in peak shaving operation of the system, and affects the selection strategy of wind abandonment, nuclear abandonment and deep peak shaving of conventional units. In the process of scheduling optimization, the balance between security and peak shaving should be considered.

E. IMPACT ANALYSIS OF WIND POWER ABANDONMENT RISK AND RESERVE CAPACITY ON DISPATCHING RESULTS

Based on model 4, the nuclear safety risk coefficient is taken as 1, and different wind power risk coefficients are taken respectively, i.e., k^W is taken from 1 to 0, and the corresponding wind and nuclear power consumption, total wind risk and nuclear cost are calculated, as shown in Figure 15. Figure 16 shows the total cost curve of the system under different risk factors of wind abandonment. The analysis is carried out according to Figure 14-15:

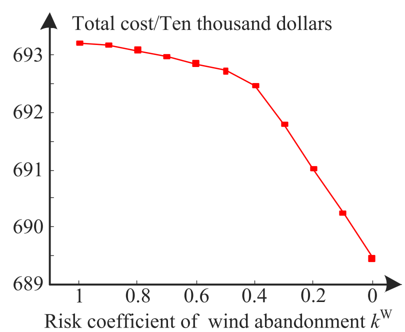


FIGURE 15. Change curve of total system cost under different risk factors of wind abandonment.

(1) Trend analysis of abandoned wind and nuclear power: with the decrease of k^W, the abandoned wind will gradually rise, and the abandoned nuclear power will continue to decline. This is because the economy of the abandoned wind will be more advantageous with the decrease of the cost in the abandoned wind. The total abandoned wind and nuclear power of the system will decline. When k^W is reduced to 0, the peak load of the total abandoned power will slightly

increase. This is due to the increase of abandoned wind volume, but the amount of abandoned nuclear is 0 and there is no further increase. Therefore, the total amount of abandoned electricity has increased slightly.

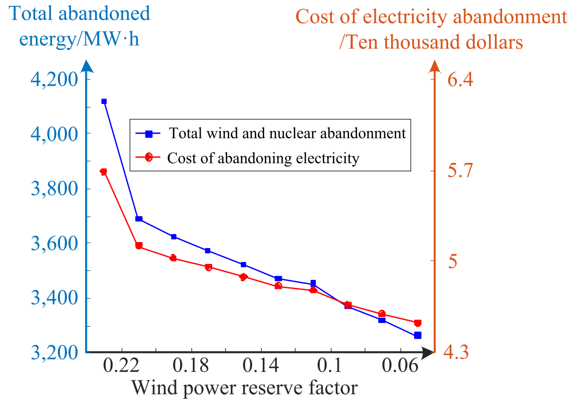
(2) Trend analysis on the change of power abandonment cost: it shows a downward trend with the reduction of wind abandonment risk; But in the process of kW decreasing from 1 to 0.8, there is a slight increase, which is due to the fact that nuclear power cannot be adjusted at will, and there are fixed climbing time and fixed low power operation time. At this time, nuclear power peak shaving has certain economic advantages, the reduction of nuclear power abandonment is not obvious, and the risk cost of wind power abandonment is relatively high, so the total cost of electricity abandonment has increased.

(3) Trend analysis of the total cost of the system: it decreases with the decrease of the risk of wind abandonment. When the risk cost of wind abandonment is high, the total economic cost of the system slows down. This is because when the risk of wind abandonment is high, the peak shaving pressure is mainly completed by nuclear abandonment. Therefore, with the decrease in wind abandonment cost, there is still a considerable amount of nuclear abandonment. When the risk coefficient of wind abandonment is as low as 0.4, the economic advantages and flexibility of wind abandonment are highlighted, and the total economic cost is rapidly reduced.

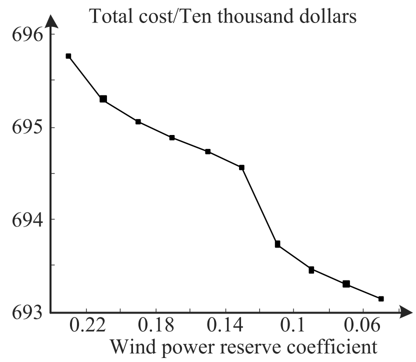
In addition, the research on the optimal allocation of wind power reserve capacity is more extensive. Therefore, take different wind power reserve coefficients $W_u\%$ and $W_d\%$, set$W_u\% = W_d\%$, and the corresponding optimal scheduling results are shown in Figure 16.

It can be seen from Figure 16 that with the reduction of the wind power reserve coefficient, the total power abandonment, power abandonment cost, and the total system cost are gradually reduced. Most of the decrease in the total abandoned electricity is the decrease of the abandoned nuclear energy and the decrease of the abandoned wind energy is very little. This is because the wind power in this dispatching example has strong inverse peak shaving characteristics. In the low load, the output of the conventional unit is mainly increased by discarding the nuclear, so that it has enough spinning reserve. Therefore, combined with the random fluctuation of the wind power, the prediction accuracy is improved, and the reserve capacity of the wind power is optimally configured at different times, which can further reduce the discarding of the nuclear and improve the operation economy of the system.

To sum up, with the technical development of wind power industry and the further promotion of related scientific research, the risk cost of wind power abandonment is reducing, which can further promote the economic dispatch of wind power systems with nuclear power peak shaving operation. At the same time, with the continuous improvement of wind power prediction technology, the reserve capacity required by the system can be further reduced, which is conducive



(a) Total energy abandonment and energy abandonment cost



(b) Total system cost

FIGURE 16. Optimal dispatching results under different wind power reserve coefficients.

to better coordination between the two, and provides a more powerful reference and guarantee for scheduling.

VI. CONCLUSION

This paper analyzes the factors and mechanisms that affect the safety risk of nuclear power, studies and calculates the comprehensive risk of nuclear power after peak shaving. A multi-source optimal dispatch model considering nuclear power risk and wind power consumption is established. The operation cost of each unit, incremental cost of nuclear power peak shaving risk, wind power abandonment cost and system environmental cost are considered in the model, and the corresponding constraints are given. Based on the example analysis of the regional power grid, this paper studies the strategic economy, nuclear safety risk and wind abandonment risk, and obtains the following main conclusions:

(1)After nuclear power participates in peaking operations, it has some safety impacts on the core and coolant circulation systems. The increment of human error operation probability is not obvious. The main source of risk cost increment is the loss of benefit from selling electricity, so the nuclear power unit can participate in the system peaking properly.

(2) The nuclear power unit can adjust the power linearly according to the technical requirements. The consideration of environmental cost is conducive to wind power consumption. In the peak load operation mode of nuclear

TABLE 4. Parameters of pumped storage unit.

Unit capacity /MW	Number of units / set	Upper reservoir (104m)		Launching reservoir (104m)		Upper (lower) limit of generating capacity (MW)	Crew efficiency	Pumping power (MW)	Start-up cost of power generation ($)	Pumping start cost ($)
		Capacity upper limit	Capacity lower limit	Capacity upper limit	Capacity lower limit					
300	2	420	140	453	151	300(100)	80%	300	298	298

TABLE 5. Thermal power parameters.

Unit capacity /MW	Number of units / set	Operation cost coefficient			Climbing rate / (MW/h)	Upper (lower) limit of output / MW	Minimum startup (shutdow) time /h	Start-up cost /$	Downtime cost /USA
		a /($ /h)	b /($ /(MW • h)	c /($ /(MW • h))					
60	3	93	3.64	0.0050	18	60(27)	4(3)	7935	1984
120	5	96	2.32	0.0003	36	120(54)	4(3)	15869	3967
125	3	98	2.33	0.00028	38	125(56)	4(3)	16530	4133
390	17	141	2.28	0.00007	117	390(176)	6(4)	51576	12894

TABLE 6. Operation parameters of CCGT in various modes.

Unit capacity /MW	Number of units /set	Pattern	Operation cost coefficient		Upper (lower) limit of output /MW	Minimum startup (shutdow) time /h	Climbing rate /(MW/h)
			a/($ /h)	b/($ /(MW • h))			
180	1	M0	0	0	0(0)	3(3)	0
		M1	126.95	13.00	63(14)	3(3)	16.2
		M2	251.84	13.00	126(29)	3(3)	32.4
		M3	202.31	10.75	90(22)	3(3)	22.8
		M4	340.33	9.23	180(45)	3(3)	45
300	1	M0	0.00	0.00	0(0)	3(3)	0
		M1	211.35	13.00	105(24)	3(3)	27
		M2	419.73	13.00	210(48)	3(3)	54
		M3	337.18	10.75	150(36)	3(3)	38
		M4	567.22	9.23	300(75)	3(3)	75

TABLE 7. CCGT mode to mode conversion parameters.

Unit capacity /MW	Pattern	Mode conversion climbing rate /(MW/h)					Mode conversion cost /$				
		M0	M1	M2	M3	M4	M0	M1	M2	M3	M4
180	M0	0	18	18	0	0	0	411	1472	0	0
	M1	18	0	18	18	0	490	0	1427	572	0
	M2	18	18	0	0	18	1584	1267	0	0	912
	M3	0	18	0	0	18	0	557	0	0	934
	M4	0	0	18	18	0	0	0	992	812	0
300	M0	0	30	30	0	0	0	686	2454	0	0
	M1	30	0	30	30	0	817	0	2378	953	0
	M2	30	30	0	0	30	2639	2111	0	0	1520
	M3	0	30	0	0	30	0	929	0	0	1556
	M4	0	0	30	30	0	0	0	1653	1354	0

power, the scheduling strategy of allowing a small amount of abandoned wind is helpful to relieve the start-up and shutdown pressure of conventional units. And realize the overall safe, low-carbon, and economic operation of the system.

(3) Under different risk factors, the depth of nuclear power participating in peak load operation is different, so the balance between safety and peak shaving should be considered comprehensively in the process of system scheduling optimization. With the increase of the nuclear safety risk coefficient, the optimization objective of the system is more inclined to the economic scheduling dominated by environmental cost, and the peak load of the system tends to decrease conservatively. When the risk is low, the economic advantage

TABLE 8. Nuclear power unit parameters.

Unit capacity /MW	Number of units /set	Upper (lower) limit of output /MW	Minimum full (low) power duration /h	Operation cost coefficient		Peak shaving cost /($ /(MW • h))	Safety risk cost /($ /(MW • h))
				a/($ /h)	b/($ /(MW • h))		
900	2	900(270)	6(6)	6534	9.25	10.68	2.73
1000	1	1000(300)	6(6)	7260	9.25	10.68	2.73

of nuclear power peaking is still greater than that of conventional unit start-up and shut-down.

(4) The economy of wind power wind abandonment is more advantageous with the decrease in wind abandonment cost. When the risk of wind abandonment is high, nuclear power peak shaving has a stronger economic advantage. Therefore, the reduction of the risk cost of wind abandonment can further promote the economic dispatch of the power system, which contains wind power and considers the peak shaving of nuclear power. At the same time, with the continuous improvement of wind power prediction technology, the reserve capacity required by the system can be further reduced, which is conducive to make a better coordination between them. The dynamic optimal allocation of the reserve capacity of wind power can further reduce the discarding of nuclear power and improve the operation economy of the system.

In the follow-up work, the peak shaving compensation mechanism and emergency dispatching control of nuclear power and wind power systems will be further studied.

APPENDIX

See Table 4 to 8.

ACKNOWLEDGMENT

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REFERENCES

[1] C. Cany, C. Mansilla, G. Mathonnière, and P. da Costa, "Nuclear power supply: Going against the misconceptions. Evidence of nuclear flexibility from the French experience," *Energy*, vol. 151, pp. 289–296, May 2018.

[2] J.-F. Petetrot and P. Coppolani, "La chaudiére des réacteurs à eau sous pression," EDP Sci., Paris, France, Tech. Rep., 2004, pp. 212–213.

[3] L. Xueyang P. Hassenboehler, and N. Joseph, "Applicability research of human reliability analysis method under background of peak-shaving operation in NPP," *At. Energy Sci. Technol.*, vol. 53, no. 8, pp. 1481–1487, 2019.

[4] China Nuclear Energy Industry Association. (Feb. 12, 2020). *National Nuclear Power Operation From January to December 2019 [EB/OL]*. [Online]. Available: http://www.china-nea.cn/site/content/36862.html

[5] N. Watanabe, "Trends and characteristics observed in nuclear events based on international nuclear event scale Reports.," *J. At. Energy Soc. Jpn./At. Energy Soc. Jpn.*, vol. 43, no. 10, pp. 1017–1026, 2001.

[6] P. H. Kvam, "A parametric mixture-model for common-cause failure data [of NPP]," *IEEE Trans. Rel.*, vol. 47, no. 1, pp. 30–34, 1998, doi: 10.1109/24.690894.

[7] H. George-Williams, M. Lee, and E. Patelli, "Probabilistic risk assessment of station blackouts in nuclear power plants," *IEEE Trans. Rel.*, vol. 67, no. 2, pp. 494–512, Jun. 2018, doi: 10.1109/TR.2018.2824620.

[8] S. Yunting, G. Yongji, and L. Zongxiang, "Probabilistic risk assessment for loss of offsite power of Tianwan nuclear power plant," *Nucl. Power Eng.*, vol. 24, no. 5, pp. 478–481, 2003.

[9] Z. Jie, D. Liu, Q. Lei, Z. Du, J. Wang, L. Zhou, and Y. Huang, "Operation mode and benefit analysis of nuclear power unit participating in peak load regulation," *Power Grid Technol.*, vol. 36, no. 12, pp. 250–255, 2012.

[10] G. Morales-España, J. M. Latorre, and A. Ramos, "Tight and compact MILP formulation for the thermal unit commitment problem," *IEEE Trans. Power Syst.*, vol. 28, no. 4, pp. 4897–4908, Nov. 2013.

[11] Z. Xuanrui, "Research on joint optimal dispatch of multiple power sources based on wind core coordination," North China Electr. Power Univ., Beijing, China, Tech. Rep., 2019.

[12] G. Wenkai, "Research on operation mode of nuclear power unit under large scale wind power integration," Shandong Univ., Jinan, China, Tech. Rep., 2018.

[13] H. Chen, P. Xuan, Y. Wang, K. Tan, and X. Jin, "Key technologies for integration of multitype renewable energy sources—Research on multi-timeframe robust scheduling/dispatch," *IEEE Trans. Smart Grid*, vol. 7, no. 1, pp. 471–480, Jan. 2016, doi: 10.1109/TSG.2015.2388756.

[14] S. Chouikhi, L. Merghem-Boulahia, M. Esseghir, and H. Snoussi, "A game-theoretic multi-level energy demand management for smart buildings," *IEEE Trans. Smart Grid*, vol. 10, no. 6, pp. 6768–6781, Nov. 2019, doi: 10.1109/TSG.2019.2911129.

[15] N. Zhang, C. Kang, Q. Xia, Y. Ding, Y. Huang, R. Sun, J. Huang, and J. Bai, "A convex model of risk-based unit commitment for day-ahead market clearing considering wind power uncertainty," *IEEE Trans. Power Syst.*, vol. 30, no. 3, pp. 1582–1592, May 2015.

[16] S. Youguo, Z. Jie, and L. Dichen, "Coordinated optimal dispatch of wind-nuclear power considering peak load shaving of NPP," *Proc. CSEE*, 39, no. 4, pp. 1018–1029, 2019.

[17] L. Zhaoyu, W. Hua, and H. Hong, "Safety output model with tight constraints and flexible regulation for NPP participating in peak shaving," *Automat. Electr. Power Syst.*, vol. 44, no. 4, pp. 63–83, 2020.

[18] Z. Yanglinzi, "Gas and steam combined cycle unit modeling and research on performance of off-design condition," North China Electr. Power Univ., Beijing, China, Tech. Rep., 2017.

[19] A. Perdichizzi, G. Barigozzi, G. Franchini, and S. Ravelli, "Peak shaving strategy through a solar combined cooling and power system in remote hot climate areas," *Appl. Energy*, vol. 143, pp. 154–163, Apr. 2015.

[20] G. Morales-Espana, C. M. Correa-Posada, and A. Ramos, "Tight and compact MIP formulation of configuration-based combined-cycle units," *IEEE Trans. Power Syst.*, vol. 31, no. 2, pp. 1350–1359, Mar. 2016.

[21] N. Yang, Y. Huang, D. Hou, S. Liu, D. Ye, B. Dong, and Y. Fan, "Adaptive nonparametric kernel density estimation approach for joint probability density function modeling of multiple wind farms," *Energies*, vol. 12, no. 7, p. 1356, Apr. 2019.

[22] Y. Nan, H. Yu, and D. Bangtian, "Research on the joint planning method of electricity-gas integrated energy system based on multi-agent game," *Proc. CSEE*, vol. 39, no. 22, pp. 6521–6533 2019.

[23] Y. Liu, N. Yang, B. Dong, L. Wu, J. Yan, X. Shen, C. Xing, S. Liu, and Y. Huang, "Multi-lateral participants decision-making: A distribution system planning approach with incomplete information game," *IEEE Access*, vol. 8, pp. 88933–88950, 2020, doi: 10.1109/ACCESS.2020.2991181.

[24] J. Wang, J. Zhao, X. Ye, D. Liu, Y. Weng, L. Wang, and H. Wang, "Safety constraints and optimal operation of large-scale nuclear power plant participating in peak load regulation of power system," *IET Gener., Transmiss. Distrib.*, vol. 11, no. 13, pp. 3332–3340, Sep. 2017.

[25] Q. Liu, J. Zhao, Y. Shao, L. Wen, J. Wu, D. Liu, and Y. Ma, "Multi-power joint peak-shaving optimization for power system considering coordinated dispatching of nuclear power and wind power," *Sustainability*, vol. 11, no. 17, p. 4801, Sep. 2019.

[26] W. Jun, "Study on optimal scheduling model of power system considering peak shaving of NPP," Wuhan Univ., Wuhan, China, Tech. Rep., 2018.

[27] *IRENA Renewable Power Generation Costs in 2017*, Abu Dhabi Int. Renew. Energy Agency, Abu Dhabi, United Arab Emirates, 2018.

JIE ZHAO was born in 1986. He received the Ph.D. degree in power system and automation.

From 2003 to 2012, he studied with the School of Electrical Engineering, Wuhan University. He was an Associate Professor. In 2018, he was a Visiting Scholar with The University of Tennessee at Knoxville, State Scholarship Council. He has presided over or participated with more than 20 scientific research projects of NSFC, the 863 Program, the Postdoctoral Fund, and the Power Grid Company. He has published more than 40 articles as the first or corresponding author, including more than 20 articles with SCI and EI. He holds authorized and accepted more than 20 national invention patents. He has participated in the compilation of one textbook and jointly guiding more than 20 Ph.D. and master's graduates. His main research interests include nuclear power, power grid coordination control, power system safety analysis and control, artificial intelligence application, and so on.

YUHUI MA (Graduate Student Member, IEEE) received the bachelor's degree from the Changsha University of Technology, in 2019. He is currently pursuing the master's degree with the School of Electrical and Automation, Wuhan University. His research interests include power system modeling and simulation and power system analysis and control.

QI LIU (Member, IEEE) received the B.E. degree in electrical engineering from the China University of Mining and Technology, Xuzhou, China, in 2017, and the M.E. degree in electrical engineering from Wuhan University, Wuhan, China, in 2020. He is currently with State Grid Xuzhou Power Supply Company. His research interests include power system operation and control and nuclear power dispatch.

LIBIN WEN, photograph and biography not available at the time of publication.

CHENYIYANG JIA, photograph and biography not available at the time of publication.

YUDI FANG, photograph and biography not available at the time of publication.