Pathway Planning of Nuclear Power Development Incorporating Assessment of Nuclear Event Risk

Xinxin Yang, Yusheng Xue, and Bin Cai

***Abstract*—The nuclear event risk (NER) is an important and disputed factor that should be reasonably considered when planning the pathway of nuclear power development (NPD) to assess the benefits and risks of developing nuclear power more objectively. This paper aims to explore the impact of nuclear events on NPD pathway planning. The influence of nuclear events is quantified as a monetary risk component, and an optimization model that incorporates the NER in the objective function is proposed. To optimize the pathway of NPD in the low-carbon transition course of power supply structure evolution, a simulation model is built to deduce alternative NPD pathways and corresponding power supply evolution scenarios under the constraint of an exogenously assigned carbon emission pathway (CEP); moreover, a method is proposed to describe the CEP by superimposing the maximum carbon emission space and each carbon emission reduction (CER) component, and various CER components are clustered considering the emission reduction characteristics and resource endowments of different power generation technologies. A case study is conducted to explore the impact of NER and its risk valuation uncertainty on NPD pathway planning. The method presented in this paper allows the impact of nuclear events on NPD pathway planning to be quantified and improves the level of coordinated optimization of benefits and risks.**

***Index Terms*—Low-carbon transition, power supply structure evolution, nuclear power development (NPD), quantitative analysis, nuclear event, risk evaluation.**

NOMENCLATURE

A. Indices

i	Numbering of generating units
j	Numbering of carbon emission reduction (CER) components
J	Number of categories of CER curves according to characteristics
m	Severity of a nuclear event
n	Type of generation technology
t	Time period

B. Parameters

α	Coefficient describing trend of CER component curve of non-hydro renewable energy generation
σ_t^{CG}	Average coal consumption rate of power supply in period t
$\sigma_c^{CO_2}$	Carbon dioxide emission factor of standard coal
$\sigma_{n,t,i}^{CO_2}$	Amount of carbon dioxide emitted per unit of electricity of generator i of generation technology n in period t
$c_t^{CO_2}$	Carbon emission cost in period t
$c_{n,t,i}^{om}$	Operation and maintenance cost per unit of electricity of generator i of generation technology n in period t
$c_{n,t,i}^{fu}$	Fuel cost per unit of electricity of generator i of generation technology n in period t
$c_{n,t,i}^{dec}$	Decommissioning cost per unit of electricity of generator i of generation technology n in period t
CER_{nhRen,t_0}^{nf}	CER amount of non-hydro renewable energy generation in the starting year t_0
CE_t^{ul}	Carbon emission cap of system power generation in period t
$H_{nucl,t}$	Annual utilization hours of nuclear power in period t
$LLS_{n,t}^{NG}$	Lower limit of annual newly installed capacity of generation technology n in period t
$p_{n,t}^{sys}$	Grid-level system cost of generation technology n per unit of electricity in period t
PD_t	Electricity demand forecast in period t
r	Discount rate
t_0	Starting year of assessment period
t_f	Target year of assessment period

Manuscript received: April 27, 2023; revised: September 29, 2023; accepted: December 12, 2023. Date of CrossCheck: December 12, 2023. Date of online publication: January 11, 2024.

This work was supported in part by the NARI Group Corporation Science and Technology project "Research on Coordinated Development of Carbon Emission Reduction and Carbon Sink Enhancement".

X. Yang and Y. Xue (corresponding author) are with the School of Electrical Engineering, Southeast University, Nanjing, China, and they are also with State Grid Electric Power Research Institute (NARI Group Corporation), Nanjing, China, and Y. Xue is also with State Key Laboratory of Smart Grid Protection and Operation Control, Nanjing, China (e-mail: yangxinxin9281@163. com; xueyusheng@sgepri.sgcc.com.cn).

B. Cai is with State Grid Electric Power Research Institute (NARI Group Corporation), Nanjing, China, and he is also with State Key Laboratory of Smart Grid Protection and Operation Control, Nanjing, China (e-mail: caibin@sgepri.sgcc.com.cn).

DOI: 10.35833/MPCE.2023.000265

$ULS_{n,t}^{NG}$	Upper limit of annual newly installed capacity of generation technology n in period t
ULS_{n}^{G}	The maximum operational installed capacity of generation technology n by the target year

C. Variables

$c_{n,t,i}^{depr}$	Depreciation cost of generator i of generation technology n in period t
$c_{n,t,i}^{fin}$	Financial expense of generator i of generation technology n in period t
$C_{n,t}^{Inv}$	Investment cost of generation technology n in period t
$C_{n,t}^{OM}$	Operation and maintenance cost of generation technology n in period t
$C_{n,t}^{Fuel}$	Fuel cost of generation technology n in period t
$C_{n,t}^{CE}$	Carbon emission cost of generation technology n in period t
$C_{n,t}^{Dec}$	Decommissioning cost of generation technology n in period t
$C_{t}^{GridSys}$	Grid-level system cost in period t
$C_{t,m}^{NE}$	Socioeconomic loss per reactor year of m-level nuclear events in period t
$C_{nucl,t}^{Gen}$	Generation-side cost of nuclear power in period t
$C_{ren,t}^{Gen}$	Generation-side cost of renewable energy generation in period t
$C_{fos,t}^{Gen}$	Generation-side cost of fossil power generation in period t
CE_{t}	Carbon emission from system power generation in period t
$CER_{nuel,t}^{nf}$	CER amount of nuclear power generation in period t
$CER_{nhRen,t}^{nf}$	CER amount of non-hydro renewable energy generation in period t
CER_{nhRen,t_f}^{nf}	CER amount of non-hydro renewable energy generation in target year t_f
$E_{n,t,i}$	Annual power generation of generator i of generation technology n in period t
$E_{nucl,t}$	Nuclear power generation in period t
$E_{ren,t}$	Renewable energy generation in period t
$E_{fos,t}$	Fossil power generation in period t
$P_{t,m}^{NE}$	Probability of occurrence per reactor year of m-level nuclear events in period t
RC_{t}^{NEs}	Risk cost of nuclear events in period t
S_{n,t_f}^{G}	Installed capacity of generation technology n in the target year t_f
$S_{nucl,t}^{G}$	Installed capacity of nuclear power in period t
$S_{n,t}^{NG}$	Annual newly installed capacity of generation technology n in period t
w_{t}	Number of operating nuclear reactors in period t

D. Sets

$CE(t)$	Exogenously given carbon emission curve
$CE^{caps}(t)$	The maximum carbon emission space
$CER^{nf}(t)$	Set of CER component curves
$CER_{j}^{nf}(t)$	CER component curve numbered j
$CER_{nucl}^{nf}(t)$	CER component curve of nuclear power
$CER_{nhRen}^{nf}(t)$	CER component curve of non-hydro renewable energy generation
$CER_{hyd}^{nf}(t)$	CER component curve of hydropower
I_{n}	Set of generating units of generation technology n
M	Set of severities of nuclear events
N	Set of generation technologies n
N_{fos}	Set of fossil power generation technologies
N_{ren}	Set of renewable energy generation technologies
T	Set of all time periods during assessment

I. INTRODUCTION

IN the last two years, the frequent occurrence of extreme weather and changes in the international situation have overlapped and intensified the global energy crisis. The comprehensive utilization of nuclear power and renewable energy has gradually become the key to achieving climate commitments and ensuring energy security [1]. China has ranked first in the number of nuclear power units under construction worldwide for many years. The "carbon peaking and carbon neutrality" goals have further accelerated the approval of new nuclear power projects, and ten nuclear power units were approved for construction in 2022, reaching a new high since 2008. Nuclear power, a controllable low-carbon technology that can potentially replace fossil power generation on a large scale, can effectively fill the incremental baseload deficit in constructing a new electric power system based on new energy sources. Therefore, nuclear power is a significant component of the low-carbon transition of power systems, and studying the pathway planning of nuclear power development (NPD) is of great practical significance.

The future NPD is a balanced choice between potential benefits and hidden risks. There are many reasons for decision-makers to consider introducing or expanding nuclear power into the energy supply mix, including its benefits in providing employment opportunities, supporting socioeconomic development, enhancing energy security by expanding dependable and autonomous sources of supply, mitigating climate change, and enhancing national competitiveness in science and technology [1]-[4]. However, hidden risks must also be seriously considered in the planning horizon, including accidents and safety issues, the challenge of nuclear waste disposal, the potential for nuclear proliferation, and the economic feasibility associated with construction delays and cost overruns [2], [3], [5]. In particular, nuclear events (including incidents and accidents) have always caused controversies over the NPD [6]. A severe nuclear accident is likely to overturn the global NPD strategy, as the Fukushima Dai-ichi nuclear disaster did in 2011.

The uncertainty of NPD is driven not only by technological, environmental, and climate factors, but also by social factors such as energy economics, policy, and public acceptance. It is a typical problem that needs to be considered under the framework of the cyber–physical–social system in energy (CPSSE) [7], [8]. Reference [8] systematically reviews the research status of NPD optimization from the CPSSE perspective. It points out that complex factors such as nuclear events, the contribution of nuclear power to long-term power adequacy, policy, and investment behavior have yet to be well considered in existing studies, and it suggests that the results of the specialized studies on nuclear power can be incorporated into the research on planning decisions and optimization of NPD. On this basis, this paper mainly discusses how to consider NER and incorporate it into the medium- to long-term planning of NPD. Target planning and pathway planning are both parts of full energy transition planning [9]. This paper is mainly about pathway planning for NPD, which means figuring out the installed capacity evolution path year by year to reach the goal.

Most current studies on NPD are limited to qualitative discussions of nuclear events. Categorized by research methods, some studies estimate the future development space of nuclear power according to the development priority order and supply capacity of different power generation technologies. Overall, these studies are somewhat confined to static evaluation. For instance, [5] estimates the total expansion of nuclear power in China and the layout of installed capacity in specific provinces under the 1.5 ℃ global temperature target and analyzes site resources, equipment manufacturing, and fuel supply and demand. Another category of existing research is the low-carbon transition of power systems and power structure optimization, which usually uses a technological-economic energy model to obtain the (quasi-) optimal energy development and power supply plan. NPD is included to minimize cumulative economic costs during the assessment period. For example, [10] adopts an iterative combination of the model for energy supply strategy alternatives and their general environmental impact and the dynamic of the energy system–atomic energy model to simulate energy supply and NPD scenarios and optimize nuclear power growth according to available nuclear fuel resources. Reference [11] examines the potential of NPD in France with various nuclear policy options and emission targets. This analysis is based on a specialized integrated MARKAL-EFOM system model called TIMES-FR, which accurately represents the French energy system. Nevertheless, the aforementioned studies have not considered the impact of nuclear event risk (NER) on NPD.

In assessments of nuclear power's sustainability and comparative studies with other power generation technologies, certain researchers have considered indicators related to NER based on methods such as multi-criterion decision-making techniques, fuzzy logic, and fuzzy multi-attribute utility theory. For example, [12] considers reactor safety and nuclear proliferation risk using linguistic values (strong, weak, and medium); [13] uses marking to describe technical reliability and accident risk; and [14] considers indicators such as radionuclide external costs, past fatal accidents, and severe accidents expected in the future. The initial values and weight coefficients of evaluation indicators depend highly on experts' experience and subjective judgment. Furthermore, coordinating the NER with other power supply costs is challenging.

Currently, there are numerous studies on nuclear power safety risk assessment. Among them, the probabilistic safety analysis (PSA) is the most fundamental risk quantification method in the nuclear industry. It analyzes the accident sequence caused by the initial event through logical reasoning about its structure; it is commonly used for numerical estimation of the safe operation and vulnerability risk of a nuclear power plant (NPP) [15]. The reliability of PSA largely depends on the inclusiveness of scenarios and the accuracy of modeling potential cascading effects. Some studies have noted that PSA underestimates the risk of nuclear events [16]. Another method is probabilistic and statistical analysis based on risk theory, which mainly constructs stochastic models of the frequency and severity of historical nuclear events and predicts their return periods. For the severity of nuclear events, [17] uses the International Nuclear Event Scale (INES) to rank it discretely from 1 to 7; [18] proposes a new quantitative nuclear accident magnitude scale (NAMS) using only off-site atmospheric release of radioactivity; [19] and other related references suggest applying the monetary value of damage to make it comparable. For the occurrence probability of nuclear events, the prediction results of different studies vary widely. For example, [18] predicts that a nuclear disaster of (or exceeding) the Fukushima scale will occur every 12-15 years, whereas [6] claims a 50% probability of at least one occurrence every 60-150 years. Although people may question the accuracy of using historical data to assess current and future NER, the above studies do provide valuable insights into calibrating PSA and understanding the loss and insurability of nuclear events. Undoubtedly, if the impact of NER can be factored into the overall optimization of the NPD pathway, new insights will be gained.

In summary, although nuclear events have long received attention at a qualitative level, they are yet to be well considered in the mid-to-long-term pathway planning of NPD. Hence, this paper explores the risk evaluation of nuclear events and examines the optimization of the NPD pathway considering the NER. The impact of NER on NPD pathway planning and decision support is also analyzed through dynamic simulation. The contributions of this paper are briefly summarized as follows.

1) This paper builds a bridge between the coordinative optimization of the low-carbon energy transition and dual-carbon transformation. A simulation model is developed to deduce the installed capacity evolution pathway of nuclear power and renewable energy generation under the constraint of an exogenously assigned carbon emission pathway (CEP). The CEP is defined by the maximum amount of emission space and multiple carbon emission reduction (CER) components, which are clustered and described according to the emission reduction characteristics of different power genera-

tion technologies.

2) NER is defined as the product of the probability and loss of nuclear events. Quantitative assessment of the NER for a given NPD pathway is achieved by statistical analysis of global historical nuclear events and applying findings from existing nuclear event evaluation studies to NPD pathway planning. An NPD pathway optimization model that includes the NER in the objective function is constructed, which realizes the coordination between the NER and other power supply costs.

3) Through dynamic simulation and multi-scenario comparison, the impact of NER and its valuation uncertainty on the planning outcomes of NPD are quantitatively analyzed, and a decision-making methodology that combines stakeholders' subjective risk perceptions with objective technology−economy−environment simulation is discussed to support the actual planning of NPD pathways better.

The remainder of this paper is organized as follows. Section II introduces the methodology and model, including a simulation model for deducing NPD pathways and corresponding power supply evolution scenarios, quantitative evaluations of NER, and an optimization model accounting for NER. Section III presents a case study that compares the simulation results with and without consideration of NER and analyzes the impact of NER and its uncertainty on the NPD pathway planning. Conclusions are summarized in Section IV.

II. Methodology and Model

A. A Simulation Model for Dynamic Deduction of NPD Pathways and Corresponding Power Supply Structure Evolution Scenarios

The energy transition and dual-carbon transformation are complex giant system problems of cross-domain multi-objective optimization, which need to be solved by decoupling and iterating from domain, time, space, and other dimensions [20]. NPD pathway planning is one of the sub-problems. In 2018, the authors' research team proposed a research paradigm based on technology−economy−behavior−real human hybrid interactive simulation and coordinated optimization of transition goals and pathways [21]. Based on this paradigm, [9] describes the energy transition pathways by clustering them in the form of a power function on a phase plane composed of the time axis and the non-fossil energy proportion, and constructs several typical scenarios satisfying a given non-fossil energy proportion to quantitatively assess China's energy revolution strategy (2016-2030). After the "carbon peaking and carbon neutrality" goals are put forward, [20] and [22] propose a fresh idea of coordinative optimization of energy transition and dual-carbon transformation based on whole-reductionism thinking (WRT). Based on the above research, this paper focuses on the long-term pathway planning of NPD. Considering the CEP constraint and NPD characteristics of being strictly constrained by site resources, the policy environment, and other factors, a method to deduce NPD pathways and corresponding power supply evolution scenarios under a given CEP constraint is constructed. Carbon sinks are not considered in this paper. The following will describe how to give the CEP constraint in terms of exogenous policy-related variables. In future studies, the CEP is derived from the results of carbon balance optimization.

It is challenging to set the CEP directly, which needs to be matched with the status quo of installed capacity, development goals, resource endowment, and the rest. Therefore, we provide a way to set a reasonable CEP for the power system to be evaluated by considering the CER characteristics of low-carbon power generation technologies for feature clustering: ① decoupling the to-be-planned CEP into the maximum carbon emission space and several CER components (i. e., the carbon emission reduced by the equivalent replacement of fossil power generation); ② estimating the maximum carbon emission space based on the current status of installed capacity, load growth rate, and other factors; ③ analyzing the carbon reduction characteristics of each low-carbon power generation technology, clustering them by features, and selecting appropriate expressions to describe each CER component, respectively; ④ superimposing curves of the maximum carbon emission space and various CER components to obtain the planned CEP.

$$CE(t) = CE^{caps}(t) + CER^{nf}(t) \tag{1}$$

$$CER^{nf}(t) = CER_1^{nf}(t) + \ldots + CER_j^{nf}(t) + \ldots + CER_J^{nf}(t) \tag{2}$$

Equation (1) indicates that the CEP is set by superimposing the maximum carbon emission space and CER components. Equation (2) represents CER component curves classified according to their emission reduction characteristics.

The clustering and mathematical descriptions of CER components are closely related to the research system. Take the regional power system in the case study in Section III of this paper as an example to explain the process of generating CEP in detail. Hydropower has limited and prioritized development potential, which allows its CER component to be a given input value. Nuclear power has a large single-unit capacity, high annual utilization hours, and a long construction time; newly installed capacity of nuclear power will bring a partial and significant emission reduction increment to the system in the year of grid connection. Therefore, the CER curve of the nuclear power has discrete characteristics related to the construction and grid connection time sequence. New energy (this paper primarily considers wind power and photovoltaic (PV)) needs to generally meet the requirements of high-quality industry development and the steady growth of grid consumption; thus, its CER component grows smoothly overall, as expressed by a power function. Equation (3) represents the decomposition of the system CER into nuclear power, non-hydro renewable energy generation, and hydropower based on their characteristics. Equations (4) and (5) represent the calculation of the CER of nuclear power and non-hydro renewable energy generation in year t, respectively.

$$CER^{nf}(t) = CER_{nucl}^{nf}(t) + CER_{nhRen}^{nf}(t) + CER_{hyd}^{nf}(t) \tag{3}$$

$$CER_{nucl,t}^{nf} = S_{nucl,t}^{G} H_{nucl,t} \sigma_t^{CG} \sigma_c^{CO_2} \tag{4}$$

$$CER_{nhRen,t}^{nf} = CER_{nhRen,t_0}^{nf} + (CER_{nhRen,t_f}^{nf} - CER_{nhRen,t_0}^{nf}) \left(\frac{t-t_0}{t_f-t_0} \right)^{\alpha} \tag{5}$$

This paper constructs a simulation flow for deducing NPD pathways and corresponding power supply structure evolution scenarios under a given CEP constraint and electricity demand, as shown in Fig. 1. Also, a relevant functional module is built and embedded in the energy transition dynamic evaluation model and simulation application, which is developed based on the simulation platform for the cyber-physical-social system (Sim-CPSS) of the State Grid Electric Power Research Institute [23] (also known as the dynamic simulation platform for the power market and power system (DSPMPS) [24]-[26]). Due to space limitations, the generator-level technical-economic-emission model, as well as the modeling of external environments such as the power market, the capital market, and the carbon emission system, are not presented in this paper, but can be seen in [9] and [27] for details. The simulation time depends on the size of the evaluated power system, the length of the evaluation period, the simulation time step, the computing power used, and other considerations. For instance, our case study in Section III, with an assessment period between 2019 and 2035, a yearly simulation time step, and an Intel Core i7-13700H CPU @ 2.40 GHz computer processor, will take approximately 10-12 min to simulate.

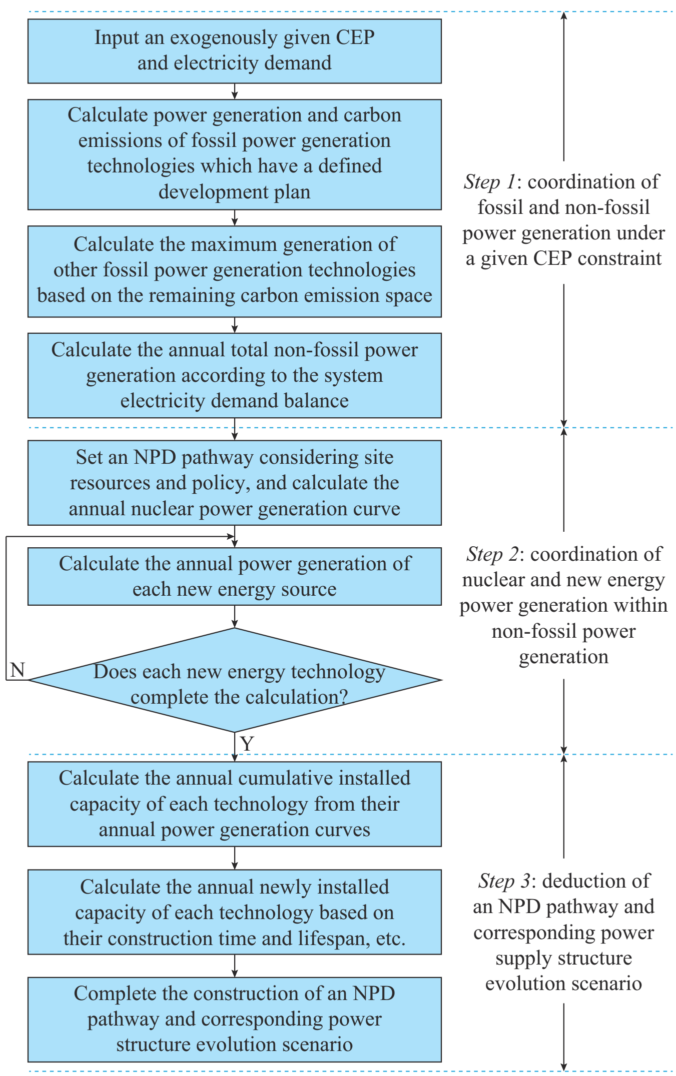

Fig. 1. Flowchart of deduction process of NPD pathways and corresponding power supply structure evolution scenarios under a given CEP constraint and electricity demand.

Firstly, the annual generation from fossil and non-fossil energy sources is calculated separately under a given CEP constraint and electricity demand balance. Secondly, alternative NPD pathways are set considering plant site resources, policy orientation, and construction duration. Taking the NPD pathway as the principal decision variable, generation from nuclear and new energy is calculated to meet the total amount of electricity from non-fossil energy sources. Then, based on some heuristic allocation principles (e.g., installed capacity ratio of wind power and PV in the target year), the upper and lower limits of development resources, annual growth limits and other constraints, and power generation curves of wind power, PV, and other new energy sources are deduced. Finally, according to the exogenous simulation input parameters given, such as annual utilization hours, construction time, and design lifespan, the yearly cumulative installed capacity and newly installed capacity are inversely calculated from power generation curves of each technology to realize the construction of an NPD pathway and the corresponding power supply evolution scenario under a given CEP constraint.

B. *Optimization Model Considering NER*

1) *Objective Function*

Reference [28] proposes that some inequality constraints such as power supply security constraints can be converted into default costs and considered in an objective function. Based on this idea, the impact of nuclear events is quantitatively characterized as a monetary value of NER, which is included in the objective function to coordinate with the power generation cost. In addition, the widely varying costs of supplying electricity to the grid from different generating options must play a role in future energy decisions. Grid-level system costs are therefore also taken into account, comprising the costs for additional investments to extend and reinforce transport and distribution grids, as well as to connect new capacity, and the costs for the short-term balancing and the maintenance of long-term secure electricity supplies [29]. The optimization objective function (6) minimizes the cumulative power supply risk cost during the assessment period.

$$\min TRC=\sum_{t\in T}\left(C^{Gen}_{nucl,t}+C^{Gen}_{ren,t}+C^{Gen}_{fos,t}+C^{GridSys}_{t}+RC^{NEs}_{t}\right)\cdot (1+r)^{-(t-t_0)} \tag{6}$$

$$C^{Gen}_{nucl,t}=C^{Inv}_{n,t}+C^{OM}_{n,t}+C^{Fuel}_{n,t}+C^{Dec}_{n,t} \tag{7}$$

$$C^{Gen}_{ren,t}=\sum_{n\in N_{ren}}\left(C^{Inv}_{n,t}+C^{OM}_{n,t}\right) \tag{8}$$

$$C^{Gen}_{fos,t}=\sum_{n\in N_{fos}}\left(C^{Inv}_{n,t}+C^{OM}_{n,t}+C^{Fuel}_{n,t}+C^{CE}_{n,t}\right) \tag{9}$$

$$C^{Inv}_{n,t}=\sum_{i\in I_n}\left(c^{depr}_{n,t,i}+c^{fin}_{n,t,i}\right) \tag{10}$$

$$C^{OM}_{n,t}=\sum_{i\in I_n}E_{n,t,i}c^{om}_{n,t,i} \tag{11}$$

$$C^{Fuel}_{n,t}=\sum_{i\in I_n}E_{n,t,i}c^{fu}_{n,t,i} \tag{12}$$

$$C^{CE}_{n,t}=\sum_{i\in I_n}E_{n,t,i}\sigma^{CO_2}_{n,t,i}c^{CO_2}_{t} \tag{13}$$

$$C_{n,t}^{Dec} = \sum_{i \in I_n} E_{n,t,i} c_{n,t,i}^{dec} \tag{14}$$

$$C_t^{GridSys} = \sum_{n \in N} \sum_{i \in I_n} E_{n,i,t} p_{n,t}^{sys} \tag{15}$$

Equations (7)-(9) represent the generation-side costs in period t of nuclear power (i,e., $n = nucl$), renewable energy generation, and fossil power generation, respectively. Equation (10) represents the investment cost of generation technology n in period t. Note that the annual investment cost consists of two parts: the costs associated with unit depreciation and financial expenses, which are apportioned to each year on a full life-cycle basis and related to installed capacity, construction cost, interest rate, depreciation life, construction period, operating lifespan, etc. Equations (11)-(13) represent the operation and maintenance (O&M) cost, fuel cost, and carbon emission cost of generation technology n in period t, respectively. Equation (14) represents the decommissioning cost in period t. Note that only nuclear power currently includes decommissioning cost in generation-side costs through the nuclear facility decommissioning reserve fund. Equation (15) represents the grid-level system costs in period t. It should be noted that the calculation of actual grid-level system costs is very complex and requires detailed grid planning and operation optimization. This paper only makes assumptions and estimates based on the NEA research report [29]. In addition, the quantitative assessment of NER is introduced in detail in Section II-C.

2) Constraints in Dynamic Simulation

$$PD_t = E_{nucl,t} + E_{ren,t} + E_{fos,t} \quad \forall t \in T \tag{16}$$

$$CE_t \leq CE_t^{ul} \quad \forall t \in T \tag{17}$$

$$LLS_{n,t}^{NG} \leq S_{n,t}^{NG} \leq ULS_{n,t}^{NG} \quad \forall t \in T, n \in N \tag{18}$$

$$S_{n,t_f}^{G} \leq ULS_n^G \quad \forall n \in N \tag{19}$$

This paper focuses on the long-timescale expansion planning of power generation. Therefore, the supply-and-demand balance of electricity is the primary equality constraint, as shown in (16). Note that the electricity demand is assumed to be met by installed capacity within the system without considering net import electricity. Inequality constraints (17)-(19) represent carbon emission caps, generation resource limits, and installed capacity expansion planning constraints, respectively, limited by cost reduction, resource endowment, engineering construction capacity, policy, development conditions, and other factors. These inequality constraints are not converted into costs or considered in the objective function.

C. Quantitative Evaluation of NER

Based on the concept of risk, the probability of occurrence and loss consequence of nuclear events are uniformly monetized as NER, as shown in (20). The variable w_t is related to the NPD planning pathway.

$$RC_t^{NEs} = \sum_{m \in M} w_t P_{t,m}^{NE} C_{t,m}^{NE} \tag{20}$$

The occurrence probability and loss valuation per reactor year are essential to evaluate NER quantitatively. Many studies have been conducted to analyze historical nuclear events statistically, yet the findings have not reached a broad agreement. The main objective of this paper is to monetize NER and add it to the objective function of NPD pathway optimization. For this purpose, existing typical studies that statistically analyze historical nuclear events, such as those in [6], [18], [30], [31], are applied to estimate the NER per reactor year, which are incorporated into the NPD pathway planning research. The specific estimation process and results are as follows. Without special notation, economic losses are discounted to the purchasing power in 2019 (the starting year of the case study in this paper).

1) Estimate Based on Statistical Averages of Historical Frequency and Loss Valuation of Each INES-level Nuclear Event

Referring to [17] and [32], INES is used to describe the severity of nuclear events, and a statistical analysis of historical nuclear events is performed. The probability of a nuclear event per reactor year is considered by counting the number of historical nuclear events at each INES level, using a standardized ratio of the number of operating reactors per year. Economic losses are conservatively estimated and assumed according to the loss valuations of historical nuclear events in each INES level, i. e., economic losses of equally severe future nuclear events are assumed to be the statistical averages of empirical losses for the corresponding INES level. The probability and cost are multiplied to obtain the estimated NER per reactor year.

Using the nuclear event database provided in [31] and obtaining the annual number of nuclear reactors in operation from [33], as shown in Fig. 2, this paper performs a preliminary analysis of 216 historical nuclear events from 1954 to 2015, of which 102 have INES scores, and 68 have currency valuations (including direct economic loss and statistical life values of casualties [31]). The estimated NER per reactor year is about 31.94 M$, identified as "ENER-1" hereafter.

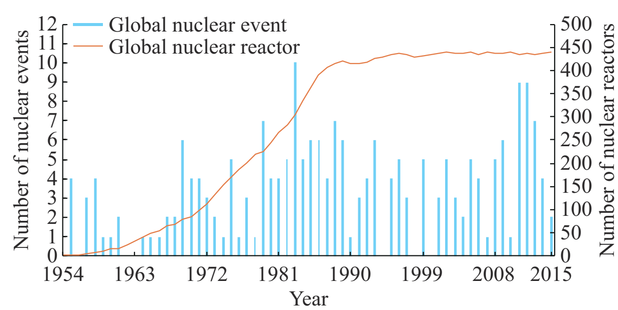

Fig. 2. Number of global nuclear events and nuclear reactors in operation.

2) Estimate by Applying Stochastic Model of Frequency and Severity of Historical Nuclear Events Established in [30]

Since the Fukushima nuclear accident, there has been a significant increase in research on nuclear power safety and assessments of historical nuclear events. Reference [30] is one of the earlier studies that uses classical probability models from risk theory to analyze 102 historical nuclear events from 1957 to 2011, which guides many subsequent studies. We apply the annual loss-count and loss-severity distribution model of nuclear events constructed in [30] to estimate the NER per reactor year, and the corresponding steps are as follows.

1) Select a typical range of possible economic losses, and based on the loss-severity distribution model, the estimated excess probability curve of the annual nuclear event loss distribution for an average single NPP is determined, with the horizontal coordinate being the economic loss and the vertical coordinate being the probability of nuclear events exceeding the corresponding economic loss.

2) Divide the entire typical economic loss range into several closely spaced loss intervals, use the median of each loss interval to represent the loss valuation of a nuclear event falling within that loss interval, and estimate the probability of a nuclear event at that loss level based on the excess probability of two adjacent loss intervals.

3) Estimate the risk of each loss interval and add it up to obtain the overall estimated NER per reactor year.

The typical possible economic loss range is set to be 20 to 242800 M$ (as of 2010), of which the minimum possible loss is the fixed threshold used in loss modeling in [30], and the maximum potential loss is the highest economic loss valuation of the historical nuclear disasters that can be investigated as far as the author knows (from [31]). The estimated excess probability curve of the annual nuclear event loss distribution for an average single NPP is obtained as shown in Fig. 3. According to the segmentation bound of 150 M$ (as of 2010) for the loss-severity distribution model in [30], the loss interval is spaced at 10 M$ and 100 M$ (as of 2010), respectively. The estimated NER per reactor year is approximately 2.65 M$, denoted as "ENER-2".

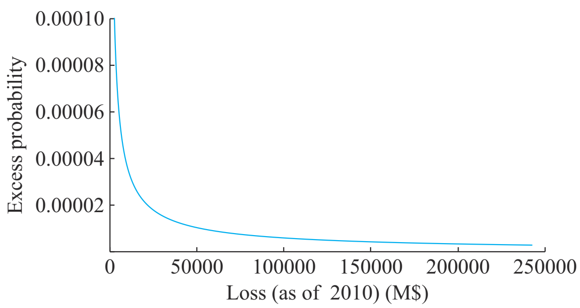

Fig. 3. Estimated excess probability of annual nuclear event loss distribution for an average single NPP.

3) Estimate by Applying Frequency-loss Relationship of Historical Nuclear Events in [6], [18], and [31]

By quantitatively examining the frequency-loss relationship of historical nuclear events, several studies have predicted the return periods of future nuclear events at various severity levels. The findings of [6], [18], and [31] are applied to estimate the NER per reactor year in this paper. The probability of nuclear events per reactor year can be roughly estimated based on the predictions for the return periods. On this basis, a conservative estimate is made to evaluate the NER per reactor year, assuming that the highest losses of historical nuclear events at various severity levels represent the maximum possible losses of future nuclear events at the same severity levels.

We utilize the above valuation approach to estimate the NER per reactor year, and the results are presented below and detailed in Appendix A Table AI. Based on [18], the estimated NER per reactor year ranges from approximately 28.00 M$ to 35.00 M$, with the high and low values denoted as "ENER-3" and "ENER-4", respectively. The valuation of the NER per reactor year based on [6] is about 6.22 M$, identified as "ENER-5". Based on the findings in [31], the estimated NER per reactor year falls within the range of 2.40 M$ to 5.53 M$, with the high and low values designated as "ENER-6" and "ENER-7", respectively. It should be noted that the aforementioned studies have focused mainly on "major events" resulting in significant losses. Nevertheless, the ten most costly historical nuclear events constitute over 90% of the total losses in the dataset and, consequently, can reflect the overall risk level associated with nuclear events to a certain extent.

In summary, based on the existing statistical analysis of historical nuclear events and safety evaluation studies, this paper estimates the overall range of NER per reactor year to be about 2.40 M$ to 35.00 M$, with the maximum and minimum estimates differing by one order of magnitude. By substituting the estimated NER per reactor year and the number of nuclear reactors in operation in the system year by year into (20), the NER of a planned NPD pathway in each level year and for the entire assessment period can be obtained.

It should be noted that the assessment of NER in this paper is based on several assumptions, including but not limited to estimating the NER of a specific power system based on global historical nuclear events and the current nuclear fleet, not considering factors such as regional differences and reactor types, assuming that the economic losses of nuclear events of the same severity level are the same, using the maximum empirical loss of historical nuclear events to estimate, and assuming that the NER per reactor year is constant during the entire assessment period. The quantitative analysis of NER is a very complex research challenge. This paper mainly explores how to incorporate NER into optimizing the NPD pathway and quantify its impact. Therefore, although there are limitations such as the small sample size of historical nuclear events, the difficulty in collecting economic loss data, and the considerable uncertainty in risk valuation, they do not affect the overall analysis method of considering NER in NPD pathway planning proposed in this paper. Moreover, in future research, more accurate NER quantification techniques and prediction results can be incorporated into the NPD pathway deduction, simulation, and evaluation model constructed in this paper to better support analysis.

III. Case Study

A. Scenarios and Parameters

We take the NPD pathway planning of a provincial power system in China as an example to carry out the case study. The existing total power capacity is about 136 GW in 2019, with the installed capacity of nuclear, renewable, and fossil power generation accounting for 3.47%, 20.08%, and 76.45%, respectively. The region is a typical high-electricity-consumption province dominated by fossil power generation, with a current annual demand of 5.06×10^{11} kWh, and the proportion of nuclear, renewable, and fossil power generation is 6.50%, 6.70%, and 86.80%, respectively.

Electricity demand varies at an assumed annual load growth rate and is assumed to be met entirely by in-province generation, with no external power; besides, grid planning has not been considered. According to the overall CER target, annual carbon emissions from electricity generation are set to decrease by 30% by 2035, and the entire CEP is formed through the method presented in Section II-A.

Based on resource endowment and policy orientation, up to two new NPP sites can be developed during the assessment period, each capable of accommodating two to four new million-kilowatt-class nuclear power units. Based on the simulation reduction model built in Section II-A, three NPD pathways and corresponding power supply structure evolution scenarios are constructed and identified as low-NPD, medium-NPD, and high-NPD, respectively, as shown in Table I. Due to the space limitation, the assumptions and settings related to the installed capacity expansions of other power generation technologies are described in Appendix B. Key background parameters and physical – economic – emission parameters for various types of newly-built generators are described in Appendix B Table BI and Table BII, respectively. The NER per reactor year and related parameters are set as detailed in Section II-C, and the median of the above NER valuations is taken as the benchmark value (i.e., ENER-5, about 6.22 M$ per reactor year). The grid-level system costs are set according to [29].

TABLE I
THREE NPD PATHWAYS AND CORRESPONDING SCENARIOS BASED ON NPP SITE RESOURCES AND POLICY ORIENTATION

Scenario name	Description of scenario	Newly installed capacity target (MW)	Construction timing
Low-NPD	No newly built nuclear power unit		
Medium-NPD	Developing one site with four newly built nuclear power units	1200×4	2021-2024
High-NPD	Developing two sites with eight newly built nuclear power units	1200×8	2021-2024, 2026-2029

B. Result Analysis

1) Comparison of Physical Quantities in Different NPD Pathways and Corresponding Scenarios

In different NPD scenarios, the annual carbon emission curves obtained from dynamic simulation are consistent with the expected CEP (the average yearly deviation is only about 0.59%). Considering the limited remaining development space of hydropower in the evaluated region, the low-carbon power increment of the system mainly comes from nuclear power, onshore wind power, offshore wind power, and PV; thus, there is room for coordinated optimization of the installed capacity growth of nuclear power and new energy. The sequential evolution trajectories of the system power structure and the proportion of installed capacity of nuclear power during 2020-2035 in different NPD scenarios are shown in Fig. 4.

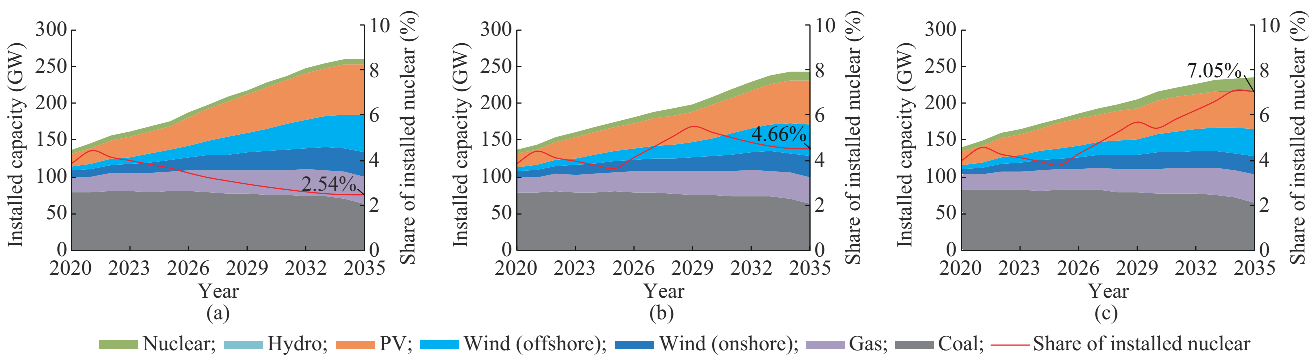

Fig. 4. Evolution trajectories of system power structure and proportion of installed capacity of nuclear power in different NPD scenarios. (a) Low-NPD scenario. (b) Medium-NPD scenario. (c) High-NPD scenario.

Each scenario has the same power installation scale and structure until 2025, following the regional "14th Five-year Plan". After 2025, no new nuclear power unit will be built in the low-NPD scenario, new low-carbon electricity demand will be mainly met by wind power and PV, and the proportion of installed capacity (generation) of nuclear power will decrease year by year from 3.76% (8.37%) to 2.54% (7.44%) by 2035. A new NPP site will be developed in the medium-NPD scenario, and 4.80 GW of nuclear power will be installed cumulatively from 2026 to 2029, with a corresponding reduction of about 15% in cumulative installed capacity of new energy compared with the low-NPD scenario. During this period, the proportion of installed capacity (generation) of nuclear power will grow year by year at an average annual rate of 0.48% (1.34%). Then, it will slowly decline, with a proportion of installed capacity (generation) of about 4.66% (12.84%) by 2035. Two new NPP sites will be developed in the high-NPD scenario, with 9.60 GW of newly installed capacity of nuclear power and cumulative installed capacity of new energy reduced by 39.59 GW compared with the low-NPD scenario. The proportion of installed capacity (generation) of nuclear power will grow steadily year by year. By 2035, the proportion of installed capacity of nuclear power will reach 7.05%, which is about twice that of the initial year and can meet about 18% of the system electricity demand, comparable to the current average level of the Organization for Economic Co-operation and Development (OECD) countries. The cumulative newly installed capacity and the annual proportion of nuclear power generation during the assessment period are shown in Fig. 5(a) and (b), respectively.

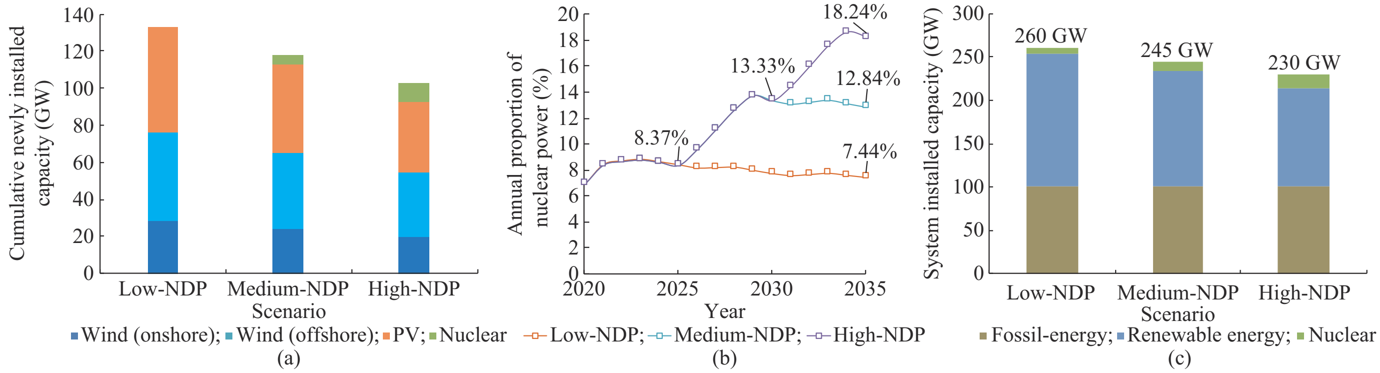

Fig. 5. Cumulative newly installed capacity, annual proportion of nuclear power generation, and total installed capacity and power supply structure in 2035. (a) Cumulative newly installed capacity. (b) Annual proportion of nuclear power generation. (c) Total installed capacity and power supply structure in 2035.

The total installed capacity and power supply structure of the system in 2035 in each scenario are shown in Fig. 5(c). Nuclear power has a high load factor, and the installed capacity of wind power and PV is about 3-6 times that of nuclear power for the same power supply capability. The total installed capacity of the system by 2035 in the high-NPD scenario is the smallest, at 230 GW, approximately 13.04% less than that in the low-NPD scenario. During the assessment period, nuclear power cumulatively provides about 4.333×10^{12} kWh of controllable low-carbon electricity (equivalent to the system electricity demand in 2019), which is 1.1 and 1.5 times more than that in the medium- and low-NPD scenarios, respectively.

2) Changes in Economic Costs and Optimization Results Before and After Considering NER

The differences in installed capacity and power generation in different NPD scenarios bring about changes in economic costs. With specific parameter settings in this case study (discount rate of 0%), cumulative generation-side costs are very close in different NPD scenarios, with a maximum difference of only 1409 M$ (only 0.25% change). Figure 6 illustrates the cost share of each non-fossil power generation technology in cumulative generation-side costs during the assessment period, with nuclear power and new energy accounting for about 5.32%-8.23% and 18.31%-21.38%, respectively, in different scenarios.

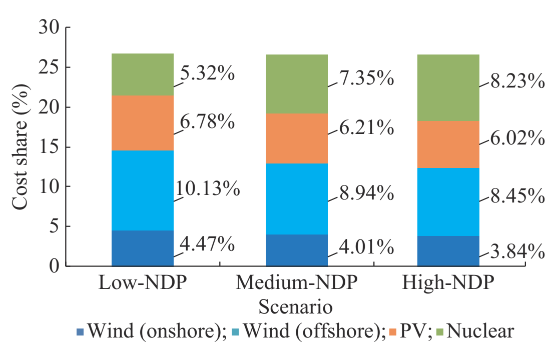

Fig. 6. Cost share of each non-fossil power generation technology in cumulative generation-side costs.

Nuclear power has the advantage of low operating costs, but its construction cost will likely increase with technology upgrades and safety-standard enhancements, whereas the construction cost of wind power and PV shows a downward trend. Therefore, the planned nuclear power projects during the assessment period are more economically competitive when built early. Simulation results show that the impact of the same nuclear power installation increment on generation-side costs differs in the low-, medium-, and high-NPD scenarios with the addition of four new nuclear power units in sequence. The generation-side costs necessary for the first four new nuclear power units are lower than those required for new energy to provide the same amount of electricity, with an average cost of electricity of 0.0444 $/kWh. The four additional nuclear power units are less economical than new energy sources, with an average cost of electricity of 0.0477 $/kWh. Thus, cumulative generation-side costs are the lowest in the medium-NPD scenario.

As shown in Fig. 7, the fuel and depreciation costs differ in different NPD scenarios. The high-NPD scenario has a 1.38% higher fuel cost and a 0.54% lower depreciation cost than the low-NPD scenario. According to the analysis of physical quantities, the power supply capacity of one unit of installed nuclear power is approximately equal to 3-6 units of installed new energy sources. Therefore, although the construction cost of nuclear power is higher than that of new energy, the low-NPD scenario has the largest cumulative newly-installed capacity, and the cumulative power construction costs (corresponding to unit depreciation and financial cost) are about 1.96% and 0.69% higher than those of medium-NPD and high-NPD, respectively. The above analysis indicates that optimizing the NPD pathway is a complex nonlinear problem, which should be quantitatively analyzed based on dynamic simulation.

The cumulative power supply risk costs of each cost item throughout the assessment period in different NPD scenarios (NER takes the benchmark value) are shown in Fig. 8. When we only consider generation-side costs in the objective function, the medium-NPD pathway is optimal, and the high-NPD pathway is suboptimal. Moderate development of nuclear power is likely to help reduce generation-side costs. When considering generation-side costs and NER in the objective function, NER accounts for about 0.11%-0.16% of the total cost. Under such circumstances, the medium-NPD pathway remains the optimal choice. However, in the high-NPD pathway, the increased investment in nuclear power poses a greater risk of nuclear events. The economic cost gap between the high- and low-NPD scenarios narrows from 1253 M$ to 955 M$ (a 23.78% decrease). We can reasonably speculate that the ranking of the high- and low-NPD pathways may reverse if the NER cost is estimated to be much higher than the benchmark value.

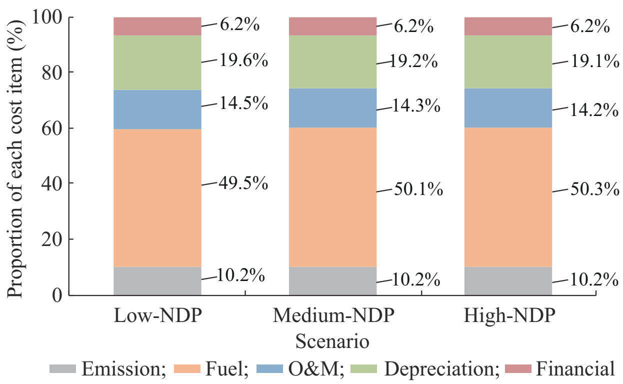

Fig. 7. Proportion of different cost items in cumulative generation-side costs.

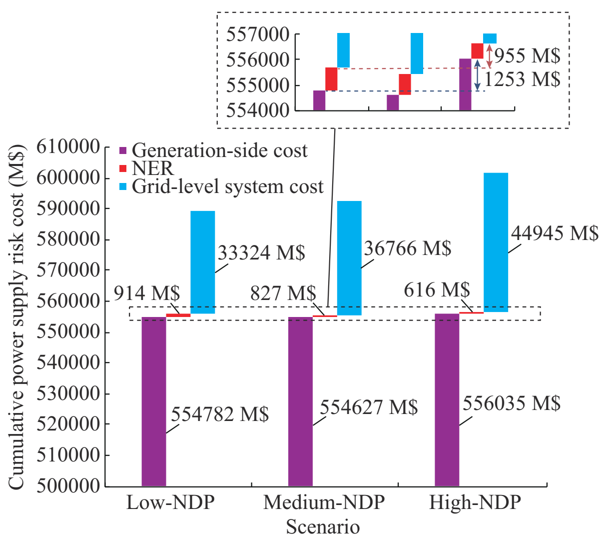

Fig. 8. Cumulative power supply risk costs of each cost item in each NPD scenario.

When considering generation-side costs, NER, and grid-level system costs together in the objective function (i.e., the cumulative power supply risk cost), the NER and non-generation-side costs account for about 0.10%-0.16% and about 5.81%-7.57% of the total cost, respectively. Less development of nuclear power can reduce NER. However, a corresponding increase in volatile renewable energy generation requires more energy storage, demand-side flexibility, and extensive transmission grid expansion to support consumption, which raises grid-level system costs. The combined result shows that the high-NPD pathway is optimal, and the medium-NPD pathway is suboptimal. Under the parameter settings of this case study, the grid-side system cost is much higher than NER in terms of absolute quantity and has a more significant impact on NPD pathway optimization. In other words, the increased NER caused by more NPD is far less than the reduced grid-level system costs. Taking the pathway from low-NPD to high-NPD as an example, more investment in nuclear power leads to a 48.48% increase in NER (about 0.05% of the cumulative power supply risk cost) and a 25.86% reduction in grid-side system cost (about 2.09% of the cumulative power supply risk cost). It is also in line with [34], which emphasizes that the contribution of nuclear power in the continued provision of stable and controllable low-carbon electricity in the context of deep decarbonization of the power system should be given reasonable weight.

Figure 9 shows the impact of the discount rate on the generation-side cost and the complete objective function value (i.e., the cumulative power supply risk cost). Under different discount rates, the ranking of each NPD scenario does not change with and without considering the NER (NER takes the benchmark value), and the impacts of the discount rate on different NPD pathways are almost the same. The reason is that, with scenarios and parameters set in this case, cumulative power supply risk costs of different NPD scenarios are initially relatively close.

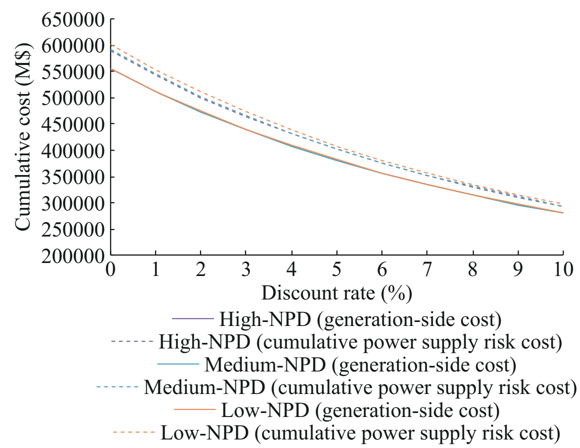

Fig. 9. Impact of discount rate on generation-side cost and complete objective function value.

3) Impact of Uncertainty in NER Estimation on Pathway Optimization

As discussed in Section II-C, there is considerable uncertainty in the quantitative assessment of NER. Figure 10 is the box plot of different NER valuations in this paper. Taking the high-NPD scenario as an example, NER ranges from 353 M$ to 5145 M$, with a median of 914 M$. The median value is about 1.88% of the total nuclear power generation cost and only 0.16% of the cumulative power supply risk cost.

For different NER valuations, the proportion of NER in the cumulative power supply risk cost does not exceed 1%, with a maximum of about 0.87% observed in the high-NPD scenario with ENER-7 and a minimum of only 0.04% observed in the low-NPD scenario with ENER-1. Additionally, the proportion of NER in the total nuclear power generation cost ranges from about 10.10%, observed in the low-NPD scenario with ENER-7, to about 0.73%, observed in the high-NPD scenario with ENER-1. After considering NER, the average generation cost of nuclear power increases by 0.29-4.29 \$/MWh, which is close to the range of the potential nuclear accident cost in Europe estimated by [35] of 0.3-3.0 €/MWh (about 0.35-3.55 \$/MWh).

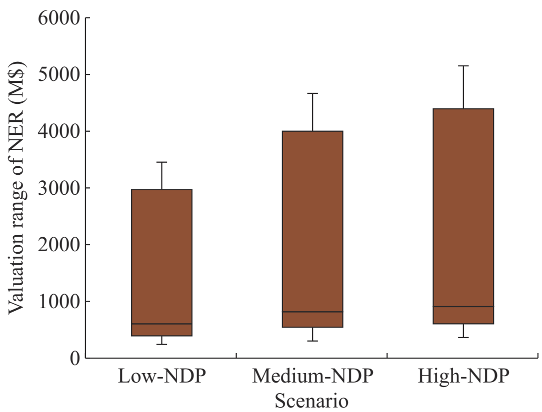

Fig. 10. Box plot of different NER valuations in this paper.

The cumulative power supply risk costs of each NPD scenario with different NER valuations are shown in Fig. 11. The high-NPD pathway is always the optimal planning decision under the relevant risk parameter settings used in this paper; thus, two new NPP sites are suggested to be developed, with eight new nuclear power units to be built in this region during the assessment period. However, as the NER valuation increases, the difference between the optimal and suboptimal NPD pathways in the cumulative power supply risk cost gradually shrinks.

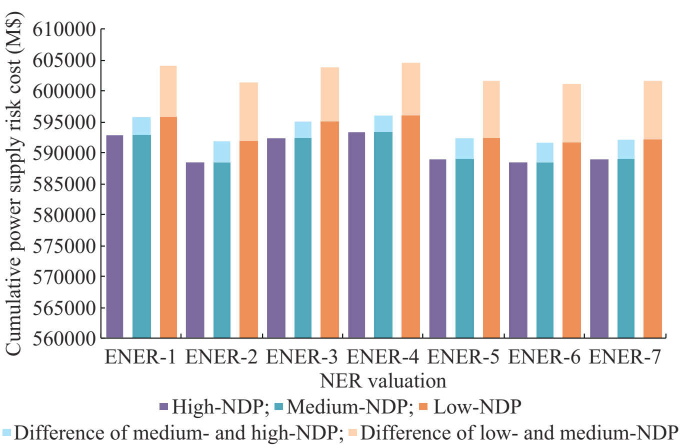

Fig. 11. Cumulative power supply risk costs of each NPD scenario with different NER valuations.

Therefore, Fig. 12 further explores the relationship between the numerical range of NER and the optimal NPD pathway and discusses the risk boundary that affects the ranking of various NPD scenarios. If the NER valuation per reactor year is increased to 37.8-43.1 times the benchmark value, the optimal choice changes from the high-NPD pathway to the medium-NPD pathway, and the cumulative power supply risk cost of the low-NPD scenario is the highest, so nuclear power should be appropriately developed. In this case, the total NER during the assessment period ranges from 31274 M\$ to 35741 M\$, accounting for about 5.02% to 5.70% of the cumulative power supply risk cost in the optimal scenario. When it is 43.2-45.3 times the benchmark value, the medium-NPD is still the optimal choice, but the cumulative power supply risk cost of the high-NPD scenario becomes the highest. The risk caused by increasing the installed capacity of nuclear power will outweigh its benefit when it is greater than 45.4 times the benchmark value. In this case, the low-NPD pathway is optimal, i.e., it is not advised to plan any new nuclear power units, and the total NER is about 27959 M\$, accounting for about 4.45% of the cumulative power supply risk cost in the optimal scenario.

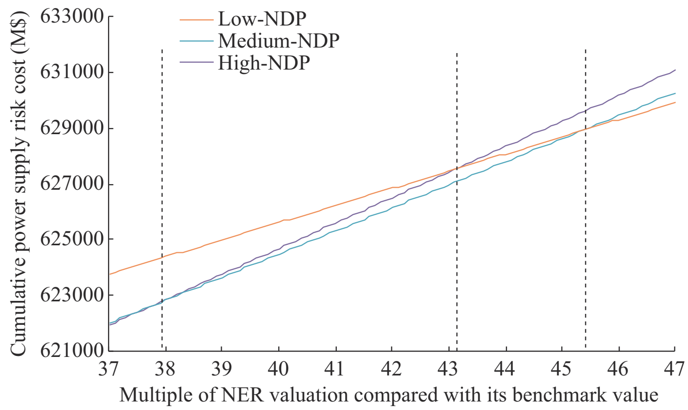

Fig. 12. Impact of uncertainty in NER valuation on NPD pathway planning.

4) *Discussion: from Simulation Results to Decision-support*

The risk perceptions and attitudes of decision-makers vary significantly for different forms of energy use [36]. Therefore, to use the simulation results to assist in practical decision-making, the decision-makers' subjective judgment needs to be considered besides the uncertainties of models and parameters. In this regard, we propose a research idea that combines objective dynamic simulation-based technical–economic–environmental indicators with subjective experience-based risk perception. Specifically, interval assessment can be used instead of accurate value assessment for risk cost terms such as NER, which are highly controversial and challenging to quantify accurately. By evaluating the numerical range of other costs in the optimization of the objective function, decision-makers make subjective judgments on the difficult-to-quantify parts, determine the optimal pathway, and take corresponding decision risks.

Based on this idea, a relatively reliable value interval (denoted as $\varDelta \in [\varDelta^{\min}, \varDelta^{\max}]$) can be obtained for the other components of the objective function except for the NER in this research case, i.e., cumulative generation-side costs and grid-level system costs. From the perspective of decision-making, a high-NPD optimal planning decision can be given if the decision-maker is relatively sure that the difference in NER of different pathways is less than $\varDelta^{\min}$; a low-NPD optimal planning decision can be given if the decision-maker is relatively sure that the difference in NER of different pathways is larger than Δ^{max}; and a decision-making mistake is more likely to occur if the difference is between Δ^{min} and Δ^{max}. Although the decision-making challenges caused by insufficient information cannot be eliminated, applying this analytical idea can improve the evaluations and better apply the simulation deduction results to support decision-making.

IV. Conclusion

This paper presents an exploratory study of NPD pathway planning in the context of the "carbon peaking and carbon neutrality" goals, incorporating the assessment of NER. A deductive simulation model is developed to construct the NPD pathway and the corresponding power supply structure evolution scenario under a given CEP constraint. NER is defined as the product of the occurrence probability and loss of nuclear events. We quantitatively estimate the NER of a given NPD pathway through statistical analysis of a historical nuclear event data set and applying the findings from existing nuclear safety evaluations. An NPD pathway planning optimization model is proposed, incorporating NER into the objective function. The impact of the NER and its uncertainty on NPD pathway planning are analyzed through dynamic simulation and multi-scenario comparison.

Taking a specific regional power system as an example for quantitative analysis, the simulation results show the following conclusions.

1) With the scenarios and parameters set in this paper, the increased NER brought by the expansion of nuclear power is far less than the corresponding reduced grid-level system costs, and the high-NPD pathway is the optimal scheme regardless of whether or not NER is considered. The NER accounts for about 0.73%-10.10% of the total nuclear power generation cost and only 0.04%-0.87% of the cumulative power supply risk cost.

2) Considering NER, the average generation cost of nuclear power increases by about 0.29-4.29 \$/MWh, similar to potential nuclear accident costs in Europe estimated from a Nuclear Energy Agency report [35].

3) The assessment of NER faces significant uncertainty. If we further extrapolate the risk margin affecting the optimal NPD pathway, when the NER valuation is 37.8 times the benchmark value or greater, the medium-NPD scenario is optimal and nuclear power should be developed appropriately. When the NER valuation is greater than 45.4 times the benchmark value, it is not recommended to plan new nuclear power.

The above conclusions are closely related to the installed capacity, power structure, resource endowment of the evaluated power system, etc. The model and parameter uncertainties can also exert an influence on the results.

This paper intends to provide a pathway planning method that considers the risk of nuclear events for NPD pathway planning. Unfortunately, NER estimation is restricted by the quantity and quality of historical data and model assumptions. In addition, it should be noted that this study is based on the premise that renewable energy generation can be built and put into operation on schedule following the planned ratio. This paper does not examine in detail the impact of grid accommodation capacity on actual CER pathways, the influence of social factors such as politics and public acceptance on pathway planning, and the interaction between CEP and low-carbon transition planning of the power system. In addition, the accident risks of other power generation technologies are also neglected, which should be similarly assessed based on experience and compared with nuclear power in future research. Since nuclear power has the dual advantages of low emissions and stable power supply capacity compared with coal-fired power and intermittent renewables, based on the study of the impact of NER on NPD pathway planning, subsequent research will further quantify the potential contribution of nuclear power in resisting extreme external disturbances and securing the power supply to achieve a comprehensive and objective evaluation of the risks and benefits of developing nuclear power.

Appendix A

TABLE AI
Estimated NER Per Reactor Year by Applying Frequency-loss Relationships for Historical Nuclear Events in [6], [18], and [31]

Reference	Year span and quantity of historical nuclear events used in analysis	Nuclear events of different severities	Occurrence probability per reactor year	Loss valuation of one nuclear event (M\$)
[6]	1946-2014, 174 nuclear events	Fukushima-scale (or larger)	2.58×10^{-5}	182698
		Chernobyl-scale (or larger)	4.77×10^{-5}	35286
		Three Mile Island-scale (or larger)	1.29×10^{-4}	3051
		Smaller but still expensive (≥20 M\$ of 2013)	2.58×10^{-3}	22
[18]	1950-2011, 102 nuclear events	INES 7-scale (or larger)	1.53×10^{-4}-1.92×10^{-4}	182698[a]
[31]	1952-2014, 216 nuclear events	Fukushima-scale (or larger)	8.59×10^{-6}-2.15×10^{-5}	182698
		Three Mile Island-scale (or larger)	6.44×10^{-5}-1.29×10^{-4}	12001
		Smaller but still expensive (≥20 M\$ of 2013)	2.58×10^{-3}	22

Note: unless otherwise noted, the loss valuations are discounted to the purchasing power of the U.S. dollar in 2019; the loss scales of historical nuclear events are assumed to represent the typical possible losses that would result from nuclear events of the same severity in the future and are conservatively estimated based on the historical maximum loss valuations for nuclear events of different severity levels, respectively, with data obtained from the corresponding references (except for the superscript a, due to the lack of data in the original reference, the loss valuation of the Fukushima-scale event is assumed and set with [6]).

APPENDIX B

The main assumptions and settings for the development of the installed capacity of other power generation technologies are as follows: ① coal-fired power will be developed according to the "14th Five-year Plan" before 2025, and there will be no new growth after 2025; ② gas power will be developed according to the "14th Five-year Plan" before 2025, and 1200 MW installed capacity will be invested annually after 2025; ③ hydropower has almost reached the upper limit of development, thus there will be no new growth; ④ the power generation ratio among onshore wind power, offshore wind power, and PV is assumed to reach 2: 5: 3 from the initial ratio by 2035, and it is assumed to change linearly year by year.

TABLE BI
KEY BACKGROUND PARAMETERS

Year	Electricity demand (kWh)	Carbon emission (t)	Coal price ($/t)	Gas price ($/m^3)	Nuclear price ($/MWh)	Carbon price ($/t)	Carbon emission factor	
							Coal (tCO_2/t)	Gas (tCO_2/m^3)
2020	5.07×10^{11}	2.8×10^{8}	103	0.30	8.79	7.97	2.4933	0.00216
2025	5.94×10^{11}	2.9×10^{8}	118	0.30	8.79	11.60		
2030	6.45×10^{11}	2.6×10^{8}	118	0.30	8.79	15.22		
2035	6.69×10^{11}	2.1×10^{8}	118	0.30	8.79	18.85		

TABLE BII
PARAMETERS OF NEWLY CONSTRUCTED GENERATORS

Type	Year	Construction time (year)	Life span (year)	Construction cost ($/kW)	O&M cost ($/MWh)	Utilization time (hour)	Type	Year	Construction time (year)	Life span (year)	Construction cost ($/kW)	O&M cost ($/MWh)	Utilization time (hour)
Nuclear power	2020	6	60	2936	8.7	7523	Onshore wind power	2020	1	25	909	9.42	1695
	2025			3117	8.7	7523		2025			763	9.42	1730
	2030			3299	8.7	7523		2030			763	9.42	1765
	2035			3480	8.7	7523		2035			763	9.42	1800
Coal-fired power	2020	3	30	490	6.96	5000	Offshore wind power	2020	1	25	2175	15.95	1933
	2025			483	6.96	5000		2025			1450	15.95	2189
	2030			476	6.96	5000		2030			1044	15.95	2429
	2035			468	6.96	5000		2035			1044	15.95	2700
Gas power	2020	2	30	357	8.84	2796	PV	2020	1	25	732	10.15	1047
	2025			351	8.84	2796		2025			468	10.15	1098
	2030			347	8.84	2796		2030			468	10.15	1149
	2035			341	8.84	2796		2035			468	10.15	1200

REFERENCES

[1] IEA. (2022, Jun.). Nuclear power and secure energy transitions. [Online]. Available: https://www. iea. org/reports/nuclear-power-and-secure-energy-transitions

[2] WNA. (2022, Aug.). Economics of nuclear power. [Online]. Available: https://world-nuclear. org/information-library/economic-aspects/economics-of-nuclear-power.aspx

[3] S. Yu, B. Yarlagadda, J. Siegel *et al.*, "The role of nuclear in China's energy future: insights from integrated assessment," *Energy Policy*, vol. 139, p. 111344, Feb. 2020.

[4] IAEA. (2015, Nov.). Indicators for nuclear power development. [Online]. Available: https://www.iaea.org/publications/10910/indicators-for-nuclear-power-development

[5] X. Xiao and K. Jiang, "China's nuclear power under the global 1.5 °C target: preliminary feasibility study and prospects," *Advances Climate Change Research*, vol. 9, no. 2, pp. 138-143, Jun. 2018.

[6] S. Wheatley, B. Sovacool, and D. Sornette, "Of disasters and dragon kings: a statistical analysis of nuclear power incidents and accidents," *Risk Analysis*, vol. 37, no. 1, pp. 99-115, Apr. 2015.

[7] Y. Xue and X. Yu, "Beyond smart grid – a cyber−physical−social system in energy future," *Proceeding of the IEEE*, vol. 105, no. 12, pp. 2290-2292, Dec. 2017.

[8] X. Yang, B. Cai, and Y. Xue, "Review on optimization of nuclear power development: a cyber − physical − social system in energy perspective," *Journal of Modern Power Systems and Clean Energy*, vol. 10, no. 3, pp. 547-561, May 2022.

[9] Y. Wen, B. Cai, X. Yang *et al.*, "Quantitative analysis of China's low-carbon energy transition," *International Journal of Electrical Power & Energy Systems*, vol. 119, p. 105854, Jul. 2020.

[10] D. K. Mohapatra and P. Mohanakrishnan, "A methodology for the assessment of nuclear power development scenario," *Energy Policy*, vol. 38, no. 8, pp. 4330-4338, Aug. 2010.

[11] N. Maïzi and E. Assoumou, "Future prospects for nuclear power in France," *Applied Energy*, vol. 136, pp. 849-859, Dec. 2014.

[12] A. E. Abouelnaga, A. Metwally, N. Aly *et al.*, "Assessment of nuclear energy sustainability index using fuzzy logic," *Nuclear Engineering and Design*, vol. 240, no. 7, pp. 1928-1933, Jul. 2010.

[13] D. Štreimikiene, J. Šliogeriene, and Z. Turskis, "Multi-criteria analysis of electricity generation technologies in Lithuania," *Renewable Energy*, vol. 85, pp. 148-156, Jan. 2016.

[14] D. Streimikiene, T. Balezentis, I. Krisciukaitienė *et al.*, "Prioritizing sustainable electricity production technologies: MCDM approach," *Renewable and Sustainable Energy Reviews*, vol. 16, no. 5, pp. 3302-3311, Jun. 2012.

[15] IAEA. (2001, Feb.). Applications of probabilistic safety assessment (PSA) for nuclear power plants. [Online]. Available: https://www.iaea. org/publications/6116/applications-of-probabilistic-safety-assessment-psa-for-nuclear-power-plants

[16] W. Kroger and D. Sornette, "Reflections on limitations of current PSA – methodology," in *Proceedings of International Topical Meeting on Probabilistic Safety Assessment and Analysis*, Columbia, USA, Sept. 2013, pp. 1204-1214.

[17] H. Duong and V. Journé, "Calculating nuclear accident probabilities

from empirical frequencies," *Environment Systems and Decisions*, vol. 34, no. 2, pp. 249-258, May 2014.

[18] D. Smythe. (2011, Dec.). An objective nuclear accident magnitude scale for quantification of severe and catastrophic events. [Online]. Available: https://pubs. aip. org/physicstoday/Online/1851/An-objective-nuclear-accident-magnitude-scale-for

[19] K. Hsü, "Nuclear risk evaluation," *Nature*, vol. 328, no. 6125, p. 22, Jul. 1987.

[20] Y. Xue. (2023, Aug.). A research framework for mechanisms of emergence phenomena – whole reductionism thinking (WRT) based on integrating models with trajectories. [Online]. Available: https://mp.weixin.qq.com/s/ymcWLN456eF2plYpNNIyywM

[21] Y. Shu, Y. Xue, B. Cai *et al.*, "A review of energy transition analysis part one elements and paradigms," *Automation of Electric Power Systems*, vol. 42, no. 9, pp. 1-15, May 2018.

[22] Y. Xue. (2021, May). Dual-carbon pathway from the CPSSE perspective: Collaborative optimization of energy flow−emission flow−capital flow−behavior flow−information flow. [Online]. Available: https://mp.weixin.qq.com/s/28RH19hNm-s-R3NWJsEB0A

[23] Y. Xue, D. Xie, F. Xue *et al*., "A cross-field interactive simulation platform for supporting research on cyber−physical−social systems," *Automation of Electric Power Systems*, vol. 46, no. 10, pp. 138-148, May 2022.

[24] J. Huang, Y. Xue, J. Xu *et al*., "Dynamic simulation platform for power market and power system: part one function design," *Automation of Electric Power Systems*, vol. 35, no. 10, pp. 16-23, May 2011.

[25] D. Xie, Y. Xue, F. Xue *et al.*, "Dynamic simulation platform for power market and power system: part two support layer design," *Automation of Electric Power Systems*, vol. 35, no. 11, pp. 1-7, Jun. 2011.

[26] D. Xie, Y. Xue, F. Xue *et al.*, "Dynamic simulation platform for power market and power system: part three application layer design," *Automation of Electric Power Systems*, vol. 35, no. 12, pp. 7-14, Jun. 2011.

[27] B. Cai, Y. Xue, X. Yang *et al.*, "Quantitative analysis of clean transition strategy of traditional coal-dominated GenCos," *Energy Procedia*, no. 152, pp. 1021-1026, Sept. 2018.

[28] Y. Xue and S. Xiao, "Comprehensively defending high risks events with low probability," *Automation of Electric Power Systems*, vol. 35, no. 8, pp. 1-11, Apr. 2011.

[29] OECD-NEA. (2012, Nov.) Nuclear energy and renewables: system effects in low-carbon electricity systems. [Online]. Available: https://www. oecd-ilibrary. org/nuclear-energy/nuclear-energy-and-renewables_9789264188617-en

[30] M. Hofert and M. V. Wuthrich, "Statistical review of nuclear power accidents," *Asia-Pacific Journal of Risk and Insurance*, vol. 7, no. 1, pp. 1-18, Dec. 2012.

[31] S. Wheatley, B. K. Sovacool, and D. Sornette, "Reassessing the safety of nuclear power," *Energy Research & Social Science*, vol. 15, pp. 96-100, May 2016.

[32] L. E. Rangel and F. Lévêque, "How Fukushima Dai-ichi core meltdown changed the probability of nuclear accidents?" *Safety Science*, vol. 64, pp. 90-98, Apr. 2014.

[33] IAEA. (2020, Jul.). Nuclear power reactors in the world 2020 edition. [Online]. Available: https://www. iaea. org/publications/14756/nuclear-power-reactors-in-the-world

[34] NEA. (2019, Jan.). The costs of decarbonization: system costs with high shares of nuclear and renewables. [Online]. Available: https://www.oecd.org/publications/the-costs-of-decarbonisation-9789264312180-en.html

[35] W. D'Haeseleer. (2016, Jan.). Synthesis on the plant-level cost of nuclear. [Online]. Available: https://www. oecd-nea. org/ndd/workshops/cost-electricity/presentations/docs/2b-dhaeseleer

[36] S. Hirschberg, P. Burgherr, G. Spiekerman *et al.*, "Severe accidents in the energy sector: comparative perspective," *Journal of Hazardous Materials*, vol. 111, no. 1-3, pp. 57-65, Jul. 2004.

Xinxin Yang received the B.E. degree in electrical engineering and automation from Southwest Jiaotong University, Chengdu, China, in 2016. She is currently pursuing the Ph. D. degree in electrical engineering in Southeast University, Nanjing, China. She has been working in State Grid Electric Power Research Institute (NARI Group Corporation), Nanjing, China, as an Industrial Trainee since 2016. Her research interests include low-carbon energy transition modeling and simulation, power planning, nuclear power development, and cyber−physical−social system in energy (CPSSE).

Yusheng Xue received the B. E. degree from Shandong University, Jinan, China, in 1963, the M. S. degree from State Grid Electric Power Research Institute, Nanjing, China, in 1981, and the Ph. D. degree in electrical engineering from the University of Liège, Liège, Belgium, in 1987. He is the Member of Chinese Academy of Engineering, Honorary President of State Grid Electric Power Research Institute (NARI Group Corporation), Nanjing, China, and Professor in the School of Electrical Engineering, Southeast University, Nanjing, China. His research interests include power system stability control, security, and economic operation, and CPSSE.

Bin Cai received the B. S. degree in automation and the Ph. D. degree in control science and engineering from Nanjing University of Science and Technology, China, in 2007 and 2014, respectively. He is currently a Senior Engineer in State Grid Electric Power Research Institute (NARI Group Corporation), Nanjing, China. His current research interests include low-carbon energy transition simulation and optimization, energy policy, and CPSSE.