Review on Optimization of Nuclear Power Development: A Cyber-Physical-Social System in Energy Perspective

Xinxin Yang, Bin Cai, and Yusheng Xue

Abstract—**Nuclear power development is a complex issue spanning cyber, physical, and social systems that is essential to achieving energy security and climate goals. With the ongoing worldwide trend towards carbon neutrality, the positioning of nuclear power in energy mix should be reconsidered. This paper aims to present a systematic review of current research on optimization of nuclear power development. The concept of cyber-physical-social system in energy (CPSSE) is adopted, which provides a suitable perspective and enables the review of relevant studies to achieve some novel insights. Based on the CPSSE, firstly, a research framework is established and the main research elements in optimization are identified, followed by a proposed conceptual risk-based optimization model. Secondly, current studies are analyzed and classified into four categories according to the research boundary. The status quo and limitations are discussed. It is found that the research results of nuclear-specific issues have not been well integrated into the optimization of nuclear power. As a relatively reliable power supply, nuclear power is capable of maintaining power and electricity adequacy of the whole system, especially in the case of power shortage caused by long-period low output of renewable energy or extreme external disasters. This superiority should not be ignored in the optimization. Other critical factors that should be further considered include disruptive technologies, nuclear safety, energy policies, and stakeholder behaviors. Finally, suggestions are given for future research.**

Index Terms—**Carbon emission, carbon neutrality, cyber-physical-social system in energy (CPSSE), comprehensive evaluation, dynamic interactive hybrid simulation, energy transition, multi-objective optimization.**

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I. Introduction

In response to the challenges of global climate change, many countries have formulated carbon neutrality goals. Driven by the new climate commitments, effective actions have been applied to accelerate the process of energy transition, for example, reducing fossil energy consumption and increasing the proportion of zero-carbon and low-carbon energy resources [1]. Nuclear power, featured by the characteristics of being low-carbon, clean, stable, and highly efficient, is perceived as one vital option to meet the power demand and ensure the energy security, while contributing to a potentially sustainable energy transition [2].

Nuclear power has played an important role in many countries and regions. By the end of 2019, the total installed capacity of nuclear power has reached 400 GW in over 30 countries and regions in the world. With a capacity factor of over 80%, nuclear power provides about 10% of the global electricity with only 4% of the global total installed capacity. This makes it the second-largest low-carbon electricity contributor after hydropower [3]. In comparison, wind power and photovoltaics, whose installed capacities are about 1.6 and 1.5 times of nuclear power, only provide less than 6% and 3% of the world's electricity, respectively [4].

As a technology with great development potential, the prospect of nuclear power, however, has been facing great controversies. The urgent need to achieve significant global carbon emission reduction at an affordable cost drives the development of nuclear power [1]. Compared with intermittent renewable energy such as wind and photovoltaic power, nuclear power can continuously provide controllable and reliable low-carbon electricity. Generally, nuclear power serves as the base load with consideration of operation efficiency and economic reasons. In fact, all modern nuclear power plants (NPPs) have been designed with the capacity of peak load regulation [5]. Hence, in countries where nuclear power takes up a high ratio in energy structure, such as France, nuclear power also plays a certain role in peak load regulation and frequency regulation (approximately 40% of the fleet is currently involved in load-following) [6]. With large-scale intermittent renewable energy resources integrated into the power grid, there is an increasing demand for flexible power resources, and nuclear power should be seriously considered as an important component of these resources [7], [8]. However, some practical factors including high initial investment costs, long lead time, and excessive construction delays, have weakened the economic competitiveness of nuclear power [9]. In addition, concerns about serious nuclear leakage accidents, nuclear proliferation, long-term disposal of radioactive nuclear waste have limited the expansion of nuclear power to some extent [10]. Therefore, the future development of nuclear power has great uncertainty. Predictions on nuclear power potential vary widely. For example, the International Atomic Energy Agency (IAEA) estimates that the global installed capacity of nuclear power will increase to 715 GW in a high-growth scenario, and decrease to 392 GW in a low-growth scenario by 2050, slightly lower than the 2020 level [11]. In contrast, the International Renewable Energy Agency (IREA) concludes that the renewable energy and electric energy substitution will play the key role in the process of energy transition, and the global installed capacity of nuclear power will drop to 300 GW by 2050 [12].

It is an important issue to position the role of nuclear power and optimize its share in energy mix, involving multi-dimensional factors of technology, economy, environment, politics, and society [13]. There have been many studies on nuclear power development, focusing on the characteristics and pros and cons of nuclear power [14], technology directions and roadmap [15], development opportunities and challenges [16]-[18], assessment of nuclear power development scenario [19], influence of public opinion on nuclear power deployment [20], etc. These studies spread across multiple dimensions, covering the entire nuclear industrial chain and whole lifecycle of nuclear power. The dissemination and popularization of relevant research paradigms and conclusions pose an influential effect on the perception and decision-making of nuclear power, as well as the follow-up research. Therefore, it is necessary to sort out and review the current research status in time. However, according to our investigation, there are few reviews on nuclear power development in existing literature. Reference [21] is one of the few reviews on research status of nuclear power, which has surveyed more than 20000 nuclear power-related literature from 1996 to 2015 using the bibliometric techniques. Its main research purpose is to analyze the country-specific distribution, research institutions, research topics, and academic influence statistically and macroscopically. However, [21] does not discuss the specific research contents and methods, and the assessment and optimization of nuclear power development are also left out. Besides, most previous review articles mainly focus on a certain aspect of nuclear power development, such as the driving forces and barriers for nuclear power development [22], lifecycle greenhouse gas (GHG) emissions and potential contribution in mitigating carbon emissions [23], [24], technical status of multi-unit risk assessment in NPPs [25], risk perception and psychological consequences [26], public acceptance [27], etc. Therefore, this paper aims to systematically analyze the research status of optimization of nuclear power development from a comprehensive perspective, which has not been fully reported.

For the optimization of nuclear power development, attention should be paid not only to the characteristics of nuclear power chain, but also to a wider range of external factors such as energy economy, policy mechanism, climate change response, and investment game behavior. Multi-dimensional objectives of technology − economy − environment − society should be coordinated [28]. In [29], a new concept of cyber−physical − social system in energy (CPSSE) has been proposed, which emphasizes that the energy transition problem should be comprehensively analyzed by integrating cyber, physical, and social systems with considerations of environmental, social, and human impacts. The concept of CPSSE and the corresponding research paradigm provide this paper with a new perspective to explore the research on optimization of nuclear power development to achieve some novel insights. Evaluation is the basis of optimization; thus, this paper also includes relevant evaluation research. In addition, as there still exist great uncertainties in the commercialization of controlled nuclear fusion technology, the following discussion will be limited to nuclear fission technology.

The main contributions of this paper lie in two aspects. Firstly, this paper provides some new thoughts for optimizing the long-term nuclear power development. Based on the CPSSE perspective, a framework model is constructed, including cyber, physical, and social spaces. The basic components, interactions, and key research elements are clarified. Following this, a conceptual optimization model based on the risk concept is proposed, in which multi-dimensional objectives are unified into the objective function in the form of economic value. Secondly, this paper systematically analyzes the current research status from a new perspective. The existing studies are summarized into four categories based on their research boundaries: research on nuclear power chain, research within energy chain considering non-nuclear energy system, research within generalized physical environment considering non-energy physical system, and research comprehensively considering generalized physical system and social system. Moreover, future research suggestions are put forward from the following aspects: ① research framework and methodology; ② simulation model and computational analysis technique; ③ knowledge extraction based on trajectory; ④ decision-making support. By demonstrating the possible future development direction and challenges, we hope that this paper can inspire more thinking on the positioning and optimization of nuclear power development.

The rest of this paper is organized as follows. Section II describes the research elements of each dimension (cyber, physical, and social), and the conceptual optimization model of nuclear power development. Section III summarizes the research status and analyzes the merits and limitations of common research methods. Future research suggestions and conclusions are arranged in Sections IV and V, respectively.

II. Research Elements and Conceptual Optimization Model of Nuclear Power Development

A. A Framework Model Established from CPSSE Perspective

The optimization of nuclear power development has the characteristics of long timescale (several decades), multi-period (past, present, and future), and multi-spatial scale (global, national, and regional). It involves behaviors of multiple stakeholders (policy makers, energy suppliers, and energy consumers) [28]. A framework model for optimization of nuclear power development from CPSSE perspective is schematically illustrated in Fig. 1, which consists of the cyber space, physical space, and social space. The basic compositions of each space and interactions between them are described.

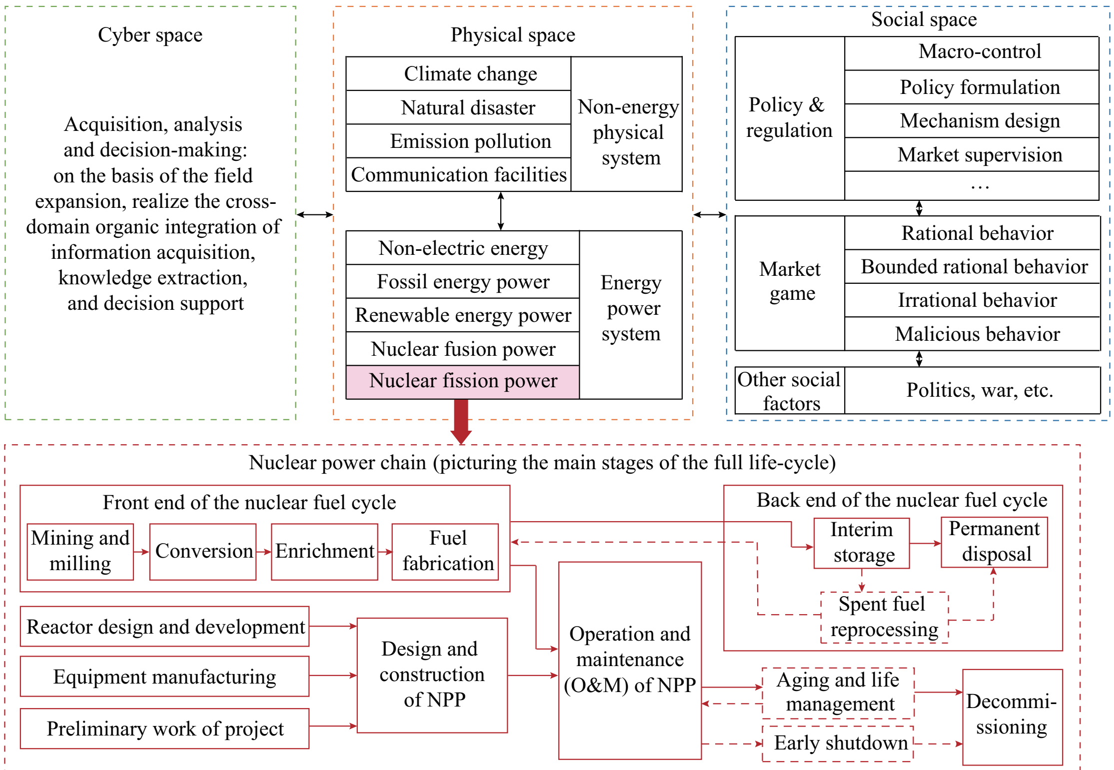

Fig. 1. Framework model for optimization of nuclear power development from CPSSE perspective.

The physical space consists of the nuclear power chain and its external physical systems. As nuclear power is the main research object, the entire lifecycle of nuclear power chain is depicted in detail. The main links include reactor design and development, equipment manufacturing, preliminary work of project (such as site selection, project development, and construction preparation before project kickoff), design and construction of NPP, O&M, aging and life management, early shutdown and decommissioning of nuclear facilities, nuclear fuel cycle (including mining, milling, conversion, enrichment, fuel fabrication, use at the reactor, spent fuel reprocessing, interim storage, and permanent disposal) [30]. In addition to the internal factors within nuclear power chain, the optimization of nuclear power development is closely related to the whole energy chain including renewable energy and fossil energy, as well as factors in non-energy physical systems such as climate change, natural disasters, emission pollution, and communication facilities [22].

Deploying nuclear power is not only a technical issue, but also a complex social-economic issue [10]. The social space is composed of policy & regulation, market game, and other social factors. Policy & regulation includes macro-control, policy formulation, mechanism design, market supervision and other modules, which are associated with government and regulatory agencies [31]. Market game involves behaviors of multi-type participants (e.g., investors and operators of NPPs, suppliers of other energy resources and energy consumers) in various types of markets (e.g., energy markets, electricity markets, and carbon markets). Human behavioral factors are complicated and diverse. It is necessary to consider not only rational and bounded rational behaviors, but also irrational and even malicious ones. In addition, the development of nuclear power can also be affected by politics, wars, terrorist attacks, and other social factors [2], which are difficult to be qualitatively or quantitatively included in strategic decision-making and are generally ignored in the optimization.

The cyber space not only refers to the enabling information technologies such as big data, cloud computing, artificial intelligence, simulation reduction, and network science, but also covers information abundance, information security, analysis, and control in a broad sense [32]. It emphasizes the cross-domain organic integration of information acquisition, knowledge extraction, and decision support based on the expansion of research vision [29]. Social system and physical system are integrated together by intelligent human-machine interaction in cyber-space, achieving management and control of the whole socio-technical systems [33], [34]. In recent decades, nuclear power business has been gradually developing towards digitization, informatization, and intellectualization, which will promote nuclear power development into a new pattern. Through deep integration of lifecycle business of NPPs and artificial intelligence technology, the safety, reliability, efficiency, and economy of nuclear power operation could be greatly improved [35]. For example, Électricité de France (EDF) has developed an industrial mode namely "integrated architect-engineer mode" to optimize design, construction, and operation of NPPs, which has greatly contributed to the success of the French nuclear program [36].

B. Research Elements in Three Dimensions

The optimization of nuclear power development involves many interrelated cyber, physical, and social factors. The main research elements that should be considered in optimization are clarified. The complex interactions between the elements of different dimensions in the concept of CPSSE have been described in detail in [33].

1) Physical Elements

Physical elements mainly include the technical-economic-environmental characteristics of nuclear power, as well as the safety features which are of particular concern. Among them, key elements related to technical characteristic include reactor type, installed capacity, design life, refueling cycle, capacity factor, equipment availability, technical dispatchability, and nuclear fuel supply. Elements related to economic characteristic correspond to the cost-benefit of each part in the whole lifecycle of NPPs. In addition to power generation costs such as construction, O&M, fuel, and decommissioning costs, social costs such as carbon emission cost are also included [37]. The elements related to environmental characteristic include CO_2 and other GHG emissions, accumulated radioactive waste, thermal discharge and other pollutant emissions, resource consumption such as uranium mines, water resources, land occupation, and the corresponding environmental impacts [38]. Finally, the elements related to safety characteristics mainly include operation accidents and safety risks [39].

As mentioned above in the framework model, in addition to the nuclear power chain, the optimization of nuclear power development also needs to take other relevant state variables under the generalized physical environment into account. Some examples of key factors include: ① technical-economic-environmental performance parameters of fossil and renewable energy (for example, construction cost of renewable energy, carbon emission per unit of coal power generation), which affect the competitive advantages of nuclear power, thereby affecting investment in nuclear power [1]; ② size and structure of power grid, and renewable energy accommodation capacity [31], [40]; ③ electric intensity and end-use energy efficiency [41]; ④ disruptive technologies emerging in hydrogen energy, energy storage, and nuclear fusion energy, which can greatly change the world energy supply and demand pattern [42]; ⑤ climate targets such as temperature rise limitation and carbon emission reduction [43]; ⑥ natural disasters that bring safety risks to nuclear power operation [44]; ⑦ communication network and other related public networks [35], etc.

2) Social Elements

Social elements are closely related to various types of gaming behaviors of participants [10]. Policy & regulation elements mainly involve energy development planning and nuclear power specific planning, market access examination and approval, new project investment and operation approval, taxation, electricity prices and subsidies, nuclear safety regulation and legislation, NPP accident emergency management, public acceptance and other public opinion regulation, and human resource reserve [31], [45]. In terms of market game, the elements that should be taken into account are development demand, macro-economy, market operation, and behavioral elements such as investment management, multi-player game, malicious competition, and research and development training [46]. Nuclear power is a technology-talent-intensive industry as well as a strategic resource. In addition to the aforementioned elements, other hidden benefits such as driving economic development, providing employment opportunities, promoting scientific and technological innovation, and social issues such as public health risks, nuclear proliferation risks, waste management, geopolitical situation [2], and international public opinion, should also be reasonably assessed [22], [47].

The objectives and behaviors of different participants jointly drive the dynamic process of nuclear power development, which, as a matter of fact, are not completely consistent. For example, government agencies often maximize the benefits of the entire society or the specific classes they represent. They may either guide or intervene in the installed capacity scale and evolution path of nuclear power development by formulating energy and climate policies, setting development goals and plans, adjusting taxes and subsidies, changing the financing environment and other means. On the other hand, energy investors are concerned about maximizing the economic efficiency of enterprises, considering a desirable trade-off between risks and benefits, and carrying out the investment and operation of actual nuclear power projects. From the view of the public, it is a general demand to have access to safe, reliable, and affordable power resources. Nonetheless, there is considerable disagreement over "willingness to live in areas adjacent to NPPs" [26]. Based on subjective risk perception, the public expresses their attitude towards nuclear power, which, to some extent, has affected the formulation of relevant policies, as well as the construction and timely delivery of new projects [48], [49]. For example, after the Fukushima nuclear accident, Germany decided to phase out nuclear power by 2022 due to the high anti-nuclear voice in the referendum [50].

The social elements are often difficult to be mathematically described. However, if the influence term is ignored in the decision-making process of optimization, the actual trajectory of nuclear power development could significantly deviate from the planning expectation, thus bringing unpredictable risks. Therefore, it is strongly suggested in further research to embed social elements into nuclear power development planning.

3) Cyber Elements

Cyber elements refer to the generalized information elements related to nuclear power development, and should be closely integrated with the research objective. Cyber elements include information acquisition, knowledge extraction, and decision support, which are necessary for the analysis, control, and intervention of physical and social systems.

Information acquisition refers to obtaining related data and knowledge such as information of working condition, topology, and fault. The effective approaches commonly used are investigation and consultation, specialized acquisition equipment, literature document, expert knowledge, model simulation, and economic experiment [51].

Knowledge extraction should comprehensively utilize energy, statistics, economics, psychology, and some other multidisciplinary knowledge. It should also integrate a large number of heterogeneous static data and dynamic data of causality, statistics, behavior, and simulation at different time scales. Knowledge extraction aims to quickly refine in-depth knowledge and apply it to explain the trajectory of simulation, analyze the formulation reasons of the phenomenon, define the hypothesis premise and credibility of the conclusion, and draw policy and strategic implications [52].

Finally, the shift to decision-making paradigm of risk quantification can be carried out through sand table deduction. The causality and correlation are excavated to support the relevant decision-making in planning, operation, and control management for the development of nuclear power and the entire socio-technical complex systems.

C. Conceptual Optimization Model Based on Risk Concept

Optimization of nuclear power development is a multi-year, multi-domain, and multi-objective, nonlinear, and dynamic programming problem, which should coordinate multi-dimensional objectives including but not limited to economic benefit, safety requirement, resource consumption, environmental impact, and social benefit. Taking the change of nuclear power installed capacity as the main decision variable, the optimization includes two levels of sub-problems: ① optimization of the gross installed capacity in the target year i.e., target optimization; ② optimization of the development trajectory to achieve the given targets, i.e., pathway optimization. Nuclear power and other energy technologies jointly meet the total energy and power demands of the system. Therefore, its development target and pathway are an integral part of the whole energy planning, and the optimization of nuclear power development is a sub-problem of the optimization of energy and power structure.

Conventional deterministic planning and probabilistic planning methods cannot coordinate both the security and economy [53]. Although special infrastructures such as NPPs and large water reservoirs have high safety design standards and the occurrence probability of a disaster that exceeds the design standards is negligible, the resulting consequences can be catastrophic once the disaster occurs. For example, the Fukushima nuclear accident in 2011 caused by successive natural disasters has fully demonstrated that the high-risk chain of extreme events, regardless of their low probability, should be considered in optimization decisions [53], [54].

Based on the risk concept, safety conditions and other inequality constraints can be converted into the risk cost, which is expressed in currency. Economy and security objectives can be unified in a monetized objective function. This method enables the collaborative optimization under multi-dimensional objectives. The optimization objective function is to maximize the total risk-return of the entire energy chain R^{BC} during the planning period. The mathematical model can be formulated as:

$$\max R^{BC} = \sum_{s=1}^{N_s}\sum_{t=1}^{N_t} P_{s,t}(R^B_{s,t}(\boldsymbol{x}_{s,t}, \boldsymbol{u}_{s,t}, \boldsymbol{d}_{s,t}) - R^C_{s,t}(\boldsymbol{x}_{s,t}, \boldsymbol{u}_{s,t}, \boldsymbol{d}_{s,t})) \quad (1)$$

s.t.

$$\boldsymbol{g}(\boldsymbol{x}_{s,t}, \boldsymbol{u}_{s,t}, \boldsymbol{d}_{s,t}) = \boldsymbol{0} \quad (2)$$

$$\boldsymbol{h}(\boldsymbol{x}_{s,t}, \boldsymbol{u}_{s,t}, \boldsymbol{d}_{s,t}) < \boldsymbol{0} \quad (3)$$

where N_t is the number of time sections included during the planning period; N_s is the number of scenarios for risk optimization; $P_{s,t}$ is the probability of scenario s occurring in time section t; $R^B_{s,t}$ is the support benefit of energy chain for economic and social development, such as contribution to carbon emission reduction, employment promotion, and science and technology competitiveness; $R^C_{s,t}$ is the total risk cost of the entire energy chain, including energy infrastructure construction cost, O&M cost, fuel consumption cost, energy storage and transmission cost, carbon emissions cost, decommissioning and waste management cost, scarcity value of non-renewable energy resources, public health impact, and other social cost, etc.; and $\boldsymbol{g}(\cdot)$ and $\boldsymbol{h}(\cdot)$ are the equality and inequality constraint functions of the optimization, respectively.

According to (1), the formulation of risk optimization scenario needs to consider not only the uncertainties of working condition (variables $\boldsymbol{x}_{s,t}$, such as energy production and consumption, energy prices, and carbon emission prices) but also the uncertainties of disturbance (variables $\boldsymbol{d}_{s,t}$, such as nuclear leakage, policy change, public opinion, disruptive energy technology, and extreme external disasters). The former is generally expressed in terms of multiple possible time trajectories and the corresponding probabilities. Differently, the latter can be calculated by multiplying the probability of disturbance and the control cost corresponding to active measures that aim to avoid serious consequences once the disturbance occurs (related to variables $\boldsymbol{u}_{s,t}$), to obtain risk value and select disturbances that should be considered based on the risk value sorting and engineering standards.

Equation (2) refers to equality constraints, including energy balance, power balance, energy storage power balance, etc. Equation (3) refers to various inequality constraints in the fields of physics, economy, and emissions, such as the upper and lower limits of yearly new installed capacity, reserve constraint, investment capital restriction, and cap on carbon emissions.

For different research objects and purposes, the objective function and constraint conditions may have some differences in terms of constituent items and mathematical expressions, and their formalization should be completed in conjunction with specific problems.

III. Status of Current Research

From the CPSSE perspective, the current research status with respect to the optimization of nuclear power development could be summarized from the aspects of research elements considered, research methods, and decision support effects and limitations. The logical framework to review the research status of nuclear power development from CPSSE perspective is shown in Fig. 2. Firstly, the relevant research on nuclear power chain is sorted out, which provides the basic information and input parameters of technical, economic, environmental, and safety characteristics for optimized decision-making. Then, the related literature within the energy chain considering the non-nuclear energy systems is reviewed. It is found that the existing studies have mainly focused on the comparative evaluation of nuclear power and other energy technologies, the assessment of long-term nuclear power development scenarios, and the optimization of energy and power structure considering nuclear power. Whereafter, the research on nuclear power development within the generalized physical system considering a series of non-energy physical systems is discussed. In this part, the focus is on nuclear power development and climate change mitigation analysis, and risks brought by extreme environmental events such as extreme weather and natural disasters. Finally, studies considering generalized physical system and social system comprehensively are analyzed. These studies have considered all-round factors, especially quantitative consideration of social factors, which are neglected in most previous studies. Major research topics include the multi-dimensional evaluation indicators for nuclear power development, comprehensive comparison and selection of multiple energy technologies including nuclear power, and evaluation and optimization of nuclear power development. We mainly analyze and summarize the three features of this kind of research: ① what research elements have been considered or ignored; ② how to consider various social factors; ③ how to coordinate the multi-dimensional objectives.

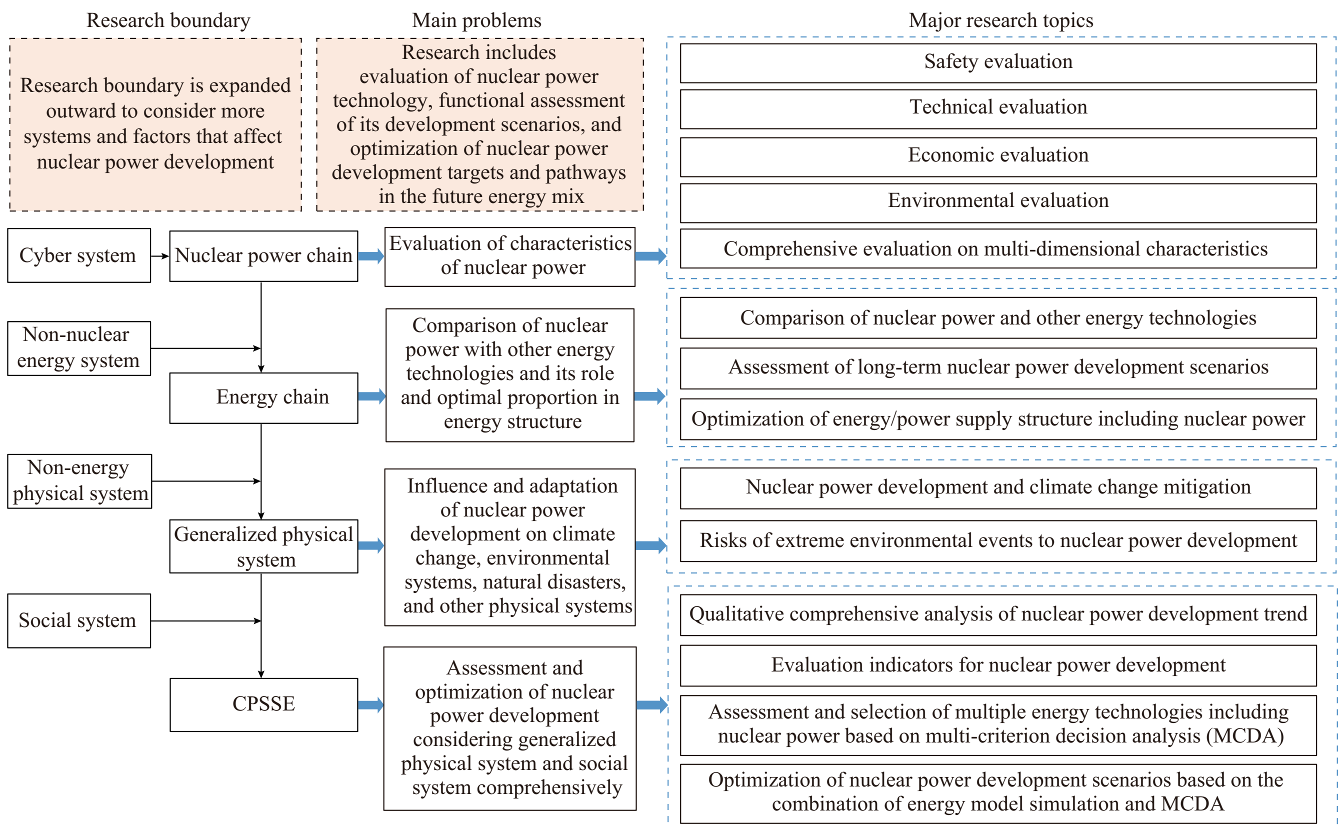

Fig. 2. Logical framework to review research status of nuclear power development from CPSSE perspective.

A. Research on Nuclear Power Chain

The research on the nuclear power chain involves different links of the entire lifecycle including construction, operation, nuclear fuel cycle, and decommissioning. Numerous studies have fully evaluated the safety, technical, economic, and environmental performances of nuclear power. Table I summarizes the evaluation contents frequently discussed in relevant studies of assessment of nuclear power characteristics. It is organized according to the links of the nuclear power lifecycle involved in the assessment.

1) Safety Evaluation

Due to the potentially high impact on the ecological environment and public health as well as the difficulty encountered to control the consequences once a nuclear leakage accident occurs, safety is the primary prerequisite for the sustainable development of nuclear power. Safety risk mainly stems from the superposition of various factors, for example, mechanical failure, site risk, external natural disaster, and mis-operation behavior [25]. It should be noted that, safety evaluation usually runs through the entire lifecycle of nuclear power, with a time span of hundreds of years. After the Fukushima nuclear accident, retrospective analysis on the causes and consequences of historic nuclear accidents, probabilistic safety assessment of nuclear power multi-unit accidents, as well as the site risk assessment, once again have sparked heated discussions at the time [55]. For example, based on the number, operating hours, and serious accident times of all civil nuclear reactors in the world, the Max Planck Institute of Chemistry in Germany has performed a probability estimation. It is found that accidents like Fukushima and Chernobyl levels may occur every 10-20 years, which are more than 200 times higher than the prediction of the US Nuclear Regulatory Commission in 1990 [56]. However, some scholars believe that "the danger of nuclear energy" has been exaggerated and insist that with more advanced technology and modern safety management capability, even for the case of malfunction, there will hardly be any serious leakage of radioactive substances to the external environment [2].

TABLE I
EVALUATION CONTENTS FREQUENTLY DISCUSSED IN RELEVANT STUDIES OF ASSESSMENT OF NUCLEAR POWER CHARACTERISTICS

Type	Nuclear fuel cycle	Construction	Operation	Decommissioning	Lifecycle
Safety	Nuclear fuel cycle safety management	Construction safety management of NPPs	Safe operation strategy of NPPs, operational risk management, safety performance indicators	Decommissioning safety hazard risk assessment	Nuclear accident probability safety evaluation
Technical	Nuclear fuel cycle strategy, evaluation of reprocessing technology, spent fuel classification	Site-selection evaluation, feasibility study for each stage of project construction	Nuclear power unit operating state simulation, peak regulation capability	Pre-research on decommissioning technology, national and regional macro-level nuclear power decommissioning preparations	Nuclear technology roadmap, power performance evaluation of different reactors, comprehensive utilization of nuclear energy
Economic	Cost-benefit analysis of the entire nuclear fuel cycle, fuel cost, spent fuel disposal cost	Economic evaluation of NPP construction, nuclear power investment options, investment estimation of nuclear power project	O&M cost analysis, power generation benefit calculation	Decommissioning cost analysis, decommissioning fund management	Overall economic evaluation, influencing factors analysis and economic improvement methods, lifecycle levelized power generation cost analysis, cost variation and uncertainty analysis
Environmental	Environmental impact assessment of nuclear waste disposal and storage	Environmental impact assessment of newly built NPPs	Operational environmental impact assessment including carbon emission, thermal discharge, etc.	Analysis of decommissioned radioactive source items, environmental impact assessment of nuclear facilities decommissioning	GHG emission and other environmental impact assessment of entire lifecycle of nuclear power

2) Technical Evaluation

In general, nuclear power technology is moving towards a higher level of security, higher fuel utilization efficiency, less waste, better flexibility, and multi-use development [57]. Relevant studies in these areas have mainly focused on the following aspects: development directions and technology roadmap [15], [58], performance comparison of reactors belonging to different generations [59], matching fuel cycle technology (including reprocessing, permanent treatment, and disposal technology) [60], operating state simulation of NPPs [61], etc. In addition, improving the flexibility of the power system has gradually become the key to the low-carbon transition, and nuclear power has attracted new attention to undertaking auxiliary services such as peak load regulation [6]. Moreover, to expand the application prospects of nuclear power in the energy system, there is a growing interest in small and medium sized modular reactors which are featured with good inherent safety, flexible usage, and low investment for one single reactor [62], [63]. Similar increasing popularity is also observed in the analysis of the comprehensive utilization potential, such as heating, hydrogen production, seawater desalination, and marine nuclear power [64].

3) Economic Evaluation

The economic cost of nuclear power is one of the key factors that constrain its sustainable development. Related studies have mainly focused on the total cost and cost composition of nuclear power generation and the changing trend and influencing factors of its economics. In general, traditional economic evaluations calculate the internal rate of return and net present value of NPPs based on engineering economics [65], [66]. With the construction cost accounting for about 60% of the total power generation cost, nuclear power is a capital-intensive technology. Therefore, the changing trend of construction cost is an important part in economic evaluation. Based on historical trend analysis, there is no decisive or fixed learning rate for nuclear power construction cost [67]. Related factors influencing the economics of nuclear power include nuclear safety standards, site condition, regulatory mechanism, technical progress, construction period, international cooperation [68], etc. Although the entire industry is committed to improving the economics of nuclear power, some scholars have expressed concerns about the increasing cost on nuclear power generation investment due to construction delay and other obstacles [69].

4) Environmental Evaluation

Environmental evaluation mostly adopts methods of lifecycle analysis (LCA) and process chain analysis. These studies can be broadly divided into two categories. The first category is the emission pollution assessment. It includes the assessment of CO_2 emissions, radioactive waste accumulation, thermal drainage, and other emissions [70], [71]. Potential environmental impact (e.g., global warming, thermal pollution) and health effect (e.g., human toxicity) caused by pollutants are also covered [72]. In the context of climate change, the assessment of the lifecycle carbon emissions has received particular attention. The other category is the evaluation of resource consumption, e. g., land occupation, water resources, and uranium consumption [73]. Environmental characteristics are closely related to reactor technology and nuclear fuel cycle options. For example, the closed fuel cycle in France can save more than 17% of natural uranium resources compared with the equivalent once-through cycle, with a lower effect on the environmental footprint [74].

5) Comprehensive Evaluation on Multi-dimensional Characteristics

In addition to the aforementioned specialized assessment of nuclear power in different aspects, correlation analysis and comprehensive evaluation of multi-dimensional characteristics are also quite common in current studies. In particular, the coordination of economy and safety has always been one of the biggest challenges that nuclear power development faces, especially in the market environment [75]. The pursuit of favorable economics must be paired with sufficient operation safety. Nonetheless, too high safety standards can in turn reduce the economics of nuclear power [75]. Moreover, the global average age of NPP fleet is relatively high. Therefore, the comprehensive analysis of long-term operation of NPPs has been a popular research topic, which aims at extending the operating lifetime of NPPs to produce more electricity in a safe, reliable, low-cost, and low-carbon manner in a longer period, based on comprehensive consideration of technical feasibility, safety, economics, and environmental impact [76].

B. Research Within Energy Chain Considering Non-nuclear Energy System

1) Comparisons Between Nuclear Power and Other Energy Technologies

The comparative assessments results of nuclear power and other energy technologies are valuable references for decision-makers to determine their respective roles in the energy system.

Some qualitative studies have coordinated the requirements of energy–economy–environment based on the concept of sustainable development to achieve a comprehensive evaluation of pros and cons of nuclear power compared with other energy technologies [77]. Literature research, Delphi method, comprehensive evaluation, and analytic hierarchy process (AHP) are common methods used in these studies.

A quantitative analysis can provide more reliable results for the selection of energy technology and decision-making. The existing quantitative comparative analysis between nuclear power and non-nuclear energy technologies is mainly centered on the environmental impact and economic competitiveness of unit power generation throughout the lifecycle.

The comparisons of environmental impact often use lifecycle CO_2 emissions or equivalent CO_2 emissions considering other GHG as evaluation criteria [78]. In recent decades, more studies have paid attention to the comparison of broader environmental impacts caused by energy utilization. Examples include exacerbating global warming, acid rain, photochemical pollution, and the potential impact on public health [79]. Radioactive waste is one of the main attributes of nuclear power that distinguishes it from other energy technologies and causes the most controversy. However, the discussions so far regarding this feature of nuclear power are mostly addressed qualitatively, and very few quantitative analyses have been conducted.

Cost competitiveness evaluation is the main subject of economic comparison studies. The levelized cost of electricity (LCOE), which is calculated according to the discounted cash flow method, is often used as the evaluation criteria [9]. LCOE enables the aggregation of all direct technical costs into one indicator, but it fails to include system costs such as power transmission and distribution cost, and ignores the differences between system and market [80]. Furthermore, it cannot reflect the systematic value of the energy technology in ensuring the adequacy, security, and quality of power supply. Thus, the LCOE indicator alone cannot fully describe the economic competitiveness of a given energy technology [81]. To overcome the deficiency of the original LCOE indicator, other modified indicators have been identified to measure the economic competitiveness of energy technologies more comprehensively, e. g., the system LCOE [80], the value-adjusted LCOE [81], and the levelized avoided cost of electricity [82], which consider the system cost and/or value. Some studies have further considered external costs such as the impacts on the environment and human health as a component of the total cost, thus coordinating the environmental and economic indicators to some extent [83].

Based on evaluation results achieved for different countries or regions in different years, it can be observed that by using the aforementioned evaluation criteria, the relative rankings of nuclear power and other energy technologies are not fully consistent. Therefore, it is difficult to draw a universal conclusion on "which energy technology is the best choice".

2) Nuclear Power Development in Energy Mix

The optimization of nuclear power development needs to consider a series of constraints such as total energy demand, various resource endowments, and characteristics of different energy technologies from the perspective of the entire energy chain [84]. Currently, the mainstream research is energy power planning considering nuclear power technology. In general, technology-economic energy models such as the Wien automatic system planning package (WASP), integrated MARKAL-EFOM system (TIMES), long-range energy alternatives planning (LEAP), model for energy supply strategy alternatives and their general environmental impact (MESSAGE), and integrated policy assessment model for China (IPAC) are adopted in these studies, the majority of which focus on the total nuclear power capacity of a given country, while the discussions on regional distribution optimization are rather limited [84], [85]. The objective function is to minimize total economic cost during the entire energy transition period. The (quasi-) optimal energy structure and power source development scheme are solved under given boundary assumptions and constraints. On this basis, this type of research could further analyze the impact of uncertainties

(e. g., power demand and policy) on the development scale of nuclear power [86]. Another derived research is to analyze the potential pros and cons of developing nuclear power by comparing the optimization results in different scenarios, in terms of economic indicators (e.g., the total energy transition cost), environmental indicators (e. g., carbon emissions), and other aspects [87]. However, in these studies, nuclear power is often regarded as one of the alternative options among a variety of energy and power technologies. Therefore, the quantity of uranium resources, spent fuel disposal capability, site resource reserve, nuclear safety, peaking capability, and other necessary factors are not described and modeled in detail. Some studies even consider the non-development of nuclear power as exogenous constraints in certain optimization scenarios [86].

Differently, some studies calculate the installed capacity scale of nuclear power in the target year and its evolution pathway according to some simple constraints of power demand and resource development limits [88]. On this basis, they analyze the equipment manufacturing capacity, site resource conditions, uranium supply/demand and external dependency, radioactive waste, disposal capacity for spent fuel, and total investment cost required to achieve the above targets and pathways [19]. Reference [88] estimates the total installed capacity of nuclear power expected in China by 2050 for achieving the 1.5 °C global temperature rise target, along with the analysis on feasibility of achieving the aforementioned target and main challenges. However, this type of research does not optimize the development pathways for nuclear power or other energy technologies from the perspective of entire energy chain.

C. Research Within Generalized Physical System Considering Non-energy Physical System

As mentioned above, nuclear power development is closely related to the generalized physical systems such as climate, ecology, and natural disasters. The development of nuclear power has changed the generalized physical system. For example, nuclear power generation involves no direct carbon emissions and could be rendered a sustainable energy option to reduce global warming [47]. However, the extreme weather and natural disasters can bring risks to the operation of nuclear power facilities and restrict the expansion of nuclear power. Consequently, the nuclear industry needs to adapt to the change of external system in time [89].

1) Nuclear Power Development and Climate Change Mitigation

Some studies have improved the optimization model to consider the impact of climate goals on nuclear power development [90]. Based on the method discussed in Section III-B, they have considered carbon emission cap in constraints, or emission-related cost directly added in the objective function. Sensitivity analysis and multi-scenario comparisons are conducted to quantitatively evaluate the role of nuclear power in long-term climate scenarios and the potential contribution of large-scale deployment of nuclear power in reducing GHG emissions, achieving emission reduction targets, and reducing the climate mitigation costs [43], [90]. The commonly used simulation models include global relationship assessment to protect environment (GRAPE), TIMES, MESSAGE, global energy transition (GET), etc. In addition to the research focusing on the national scale of nuclear power development, some scholars have managed to use the global energy model or the climate change economic model, e. g., the world induced technical change hybrid (WITCH) model, to quantitatively analyze the penetration level of global nuclear power development with different CO_2 concentration levels in long-term climate scenarios [91].

2) Risks of Extreme Environmental Events to Nuclear Power Development

Climate change leads to more frequent occurrence of extreme environmental events, which have affected the operating conditions for different types of energy systems, particularly the power plants. Among all power generation technologies, nuclear power has the highest safety standards. It is more superior to other intermittent renewable energies in maintaining the stable operation status under extreme weather conditions or natural disasters [31]. For example, during the extreme cold weather event in Texas, USA in early 2021, thermal power plants had to cease operating due to the freezing of natural gas pipelines; wind turbine blades were frozen and photovoltaic panels were covered with ice and snow. There was up to nearly half of the power generation capacity forced to shut down in the worst circumstances [92]. By contrast, one nuclear reactor, though also tripped due to interruption of the low-temperature feedwater pump, was able to resume its operation in a short time. The nuclear power has shown higher reliability than other generation technologies in this extreme cold weather event [93]. However, nuclear power has its own unique climate risks. For example, the sea level rise could impose potential safety risk to disposal of spent fuel in NPPs, thus hindering the development of nuclear power [94].

The lessons of the Fukushima nuclear accident have indicated that major nuclear power operational incidents or serious nuclear leakage accidents may still occur under serious natural disasters. Related studies, which analyze the impact of natural disasters on nuclear power development, mainly focus on the safety operational risk assessment of NPPs in response to natural disasters such as earthquakes and tsunami [44].

However, the aforementioned risks have not been fully considered in the current studies of multiple energy technology selections or power structure optimization including nuclear power. In the optimization objective function, the corresponding risk costs should be considered, which include the opportunity cost of avoiding accidents and the residual risk of accidents that may still occur.

D. Research Considering Generalized Physical System and Social System Comprehensively

At present, most comprehensive analyses of nuclear power development considering technical, economic, environmental, and social factors are qualitative descriptions, which is helpful to understand the nuclear power development problem and can provide forward-looking judgments on its development trend [16]-[18]. On the other hand, the relevant quantitative research is still at an early stage. Table II summarizes the three types of quantitative research considering generalized physical system and social system from two aspects: multi-dimensional assessment methods, and ways of considering social factors.

TABLE II
THREE TYPES OF QUANTITATIVE RESEARCH CONSIDERING GENERALIZED PHYSICAL SYSTEM AND SOCIAL SYSTEM

Research content	Main feature	
	Multi-dimensional assessment methods	Ways of considering social factors
Evaluation indicator system for nuclear power development	Analyze separately and do not aggregate	Provide evaluation indicators
Assessment and selection of multiple energy technologies including nuclear power based on MCDA	Combine into one indicator by weighted aggregation	Expert discussion (scoring, setting weights, etc.)
Optimization of nuclear power development scenarios based on combination of energy model simulation with MCDA	Combine into one indicator by simulation analysis and weighted aggregation	Expert discussion (scoring, setting weights, etc.)

1) Evaluation Indicators for Nuclear Power Development

Based on the LCA, an all-sided list of multi-objective decision-making-based evaluation indicators is proposed, serving as a tool to identify the issues that are critical to nuclear power development and to provide numerical information for possible investment in nuclear power or the assessment of the given nuclear power development scenarios [14], [46], [95]. In 2015, the IAEA released a report entitled "Indicators for Nuclear Power Development", which proposed a set of 42 indicators to assess the introduction or expansion of nuclear power in the following four main areas: the macro-socioeconomic, energy and electricity, techno-economic aspects of nuclear power, and the environmental dimension [46]. However, it is difficult for decision-makers to optimize the nuclear power development scenarios using these complex multi-dimensional evaluation indicators, compared with using one aggregated indicator.

2) Assessment and Selection of Multiple Energy Technologies Including Nuclear Power Based on MCDA

MCDA method has been widely used in the assessment and selection of energy technologies and power planning [96]. Table III summarizes typical studies of the comprehensive selection of multiple energy technologies including nuclear power based on the MCDA method.

TABLE III
TYPICAL STUDIES OF COMPREHENSIVE SELECTION OF MULTIPLE ENERGY TECHNOLOGIES INCLUDING NUCLEAR POWER BASED ON MCDA METHOD

Reference	Research content	MCDA techniques	Social elements involved	Multi-dimensional evaluation criteria (number of indicators)
[97]	Comprehensive ranking of 13 generation technologies including nuclear power based on their compatibility with the sustainable development of the industry	Weighted sum multi-attribute utility (WSMAU)	External costs (human health), job creation, social acceptability, external supply risk	Economic (1), technical (3), environmental (2), socio-political (4)
[98]	Choice of the most sustainable one from 33 generation technologies including advanced pressurized water reactor	Multi-objective optimization on the basis of a ratio analysis plus the full multiplicative form (MULTIMOORA) and technique for order preference by similarity to ideal solutions (TOPSIS)	Technology-specific job opportunities, food safety risk, fatal accidents from the past experience, severe accidents perceived in future	Economic (5), environmental (4), social (4)
[99]	Priority ranking of nuclear and other non-fossil energy development in Kazakhstan	AHP	Public acceptance, job creation	Technical (5), economic (3), social (2), environmental (3)
[100]	Selection of generation technologies for power sector and feasibility evaluation of developing nuclear power in Lithuania	AHP and additive ratio assessment method (ARAS)	Influence on social welfare, sustainable development of society, public acceptance, etc.	Institutional-political (5), economic (4), social ethics (3), technical (4), environmental (4)
[101]	Assessment of nuclear energy sustainability	Fuzzy logic	Proliferation risk, public opinion	Environmental, economic, socio-political
[102]	Optimal selection of an energy resource where taking Egypt as a case study, nuclear energy was found to be an appropriate choice	Fuzzy multi-attribute utility theory (MAUT)	Proliferation risk	Economic, environmental, social

The contributions of these quantitative studies for multi-comprehensive quantitative evaluation include two aspects. ① Based on expert system, some social dimension criteria that are usually evaluated only qualitatively are classified and converted into numerical information (e.g., [97] set three grades of "high-medium-low" to represent public acceptance of nuclear power corresponding to different scores according to expert opinions). ② Based on expert experience and preference, weights are set for different dimensions and evaluation indicators, and a single total evaluation indicator (e.g., sustainability index [98]) is aggregated and obtained using equivalent weighting, optimal weighting, ranking weighting, and other approaches, so as to realize the coordination of multi-dimensional objectives. Unfortunately, most of these studies have not considered dynamic changes of the system, and thus, they are unable to directly support the decision-making process aiming at the optimization of mid-and-long-term nuclear power development.

3) Optimization of Nuclear Power Development Scenarios Based on Combination of Energy Model Simulation and MCDA

This category of research combines the cost-minimized energy optimization model with the MCDA method to propose an effective two-stage energy and power planning analysis framework which not only simulates the dynamic process of system development, but also considers environmental and social factors in a quantitative manner for optimization [103]. Among them, the energy model can simulate the technical-economic characteristics of nuclear power and other energy options in detail, and provide the optimal solutions in different scenarios. It is important to note that the model ensures that only technically feasible and economically optimal solutions enter the later stage of multi-criteria decision analysis. The MCDA techniques can consider the evaluation indicators or criteria of non-economic dimensions such as environmental impact and social welfare benefit. At the same time, they can aggregate multi-domain and multi-dimensional evaluation criteria to provide the optimal results with consideration of multi-dimensional conflicting objectives [99]-[102].

Currently, this analysis framework is mainly used in national energy and power planning [103], [104]. Only a minority of studies are devoted to the nuclear power development problems [28]. These studies not only consider the generally involved evaluation criteria such as energy supply cost and carbon emissions, but also pay special attention to the evaluation criteria closely related to nuclear power development, which yet are often ignored, such as nuclear waste accumulation, nuclear proliferation risk, energy security, etc. Furthermore, they also analyze different viewpoints of various stakeholders on nuclear power, as well as the influence of decision-makers' preferences on the proportion of nuclear power in the energy system. Inevitably, the evaluation and optimization results of this category of research are significantly affected by subjective weights, which can even be misleading sometimes. There is still a long way to go to effectively support the relevant decision-making on nuclear power development through model simulation.

IV. Suggestions for Future Research

Currently, the research methodologies for safety and technical–economic–environmental characteristics evaluation of nuclear power are quite mature. However, the fruitful results have not been well applied to the optimization of nuclear power development. For example, significant efforts have been devoted to studying the operational flexibility and reliability of NPPs, yet in current research of energy transition and power planning, only the contribution of installed capacity of nuclear power to low-carbon electricity during the regular operation has been considered, while its potential contributions to participating in auxiliary services and improving the reliability of system under extreme weather conditions are ignored.

In the context of carbon neutrality, the future energy system will be integrated with a high proportion of intermittent renewable energy, which is dominated by wind and photovoltaic power. The subsequent problems such as peak load regulation and frequency regulation must be dealt with through low-carbon technologies including nuclear power, especially in the case of insufficient flexible reserve capacity of the system (e.g., in extreme conditions where the output of renewable energy sources is insufficient for a long period, while the energy storage systems cannot be charged and discharged normally). Therefore, the research results of nuclear-power-specific should be better integrated into the research on energy transition and power planning. In addition, the competition and complementarity between nuclear power and other energy technologies including renewables and energy storage should also be considered in different scenarios, so as to more effectively reflect the role of nuclear power in the transition of energy and power structure. Last but not least, current quantitative studies usually only consider technological, economic, and carbon emission issues. It still requires continuous innovations in research frameworks, simulation tools, and analysis methods on how to consider other environmental factors besides carbon emission and social factors.

The simulation model is one of the most important research methods for studying the optimization of nuclear power development and other energy transition problems. Although the numerical model cannot completely reflect all the elements of the object system, it can quantitatively describe the dynamic characteristics of the system, which is conductive to reveal the basic properties of the object system. However, current studies neither reflect the dynamic process of nuclear power development driven by the behaviors of government agencies, energy investors, the public and other participants, nor consider the dynamic response of the system after serious nuclear leakage accidents, disruptive energy technologies, or other disturbances.

Notably, it is not easy to integrate the aforementioned factors, especially considering the complex social factors. A feasible way is to study based on the CPSSE framework, including the development of multi-domain simulation platform, modeling, investigation of multi-source heterogeneous data, hybrid simulation, uncertainty analysis, and decision support [33]. To combine causal analysis, statistical analysis, and behavior analysis, [105] has proposed a hybrid interactive simulation paradigm of technology–economy–behavior model with human participation, which has already been applied to the research of power grid ancillary service behavior [106], energy transition analysis [107], and carbon emission market [108], [109]. In this dynamic interactive hybrid simulation method, the links that can be expressed by mathematical models are constructed into an objective experimental environment. Policy-making, public opinion, and other human behaviors are reflected by building multi-agent models or human participation in simulation.

After obtaining the sequential trajectories of nuclear power development and the entire energy system through simulation methods, it is also necessary to improve the trajectory-based knowledge extraction and decision-support capabilities. The MCDA method is commonly used to coordinate multi-dimensional conflicting objectives. However, the quantitative processing of environmental and social indicators is relatively simple with the given weights affected by subjective expert cognition. The common optimization objective is to minimize (maximize) the economic cost (benefit). Based on this, in the future, the performance indicators of environmental and social dimensions, as well as the risk of uncertain events such as nuclear leakage accidents, should be estimated by economic value and regarded as a component of the objective function. The main objective is to unify the cross-domain and multi-dimensional objectives into economic value, and achieve the optimal nuclear power development targets and pathways considering generalized physical and social elements comprehensively.

V. Conclusion

Under the background of carbon neutrality, it is extremely important to make reasonable decisions on the mid-and-long-term development of nuclear power, due to its particular role in power system. The optimization of nuclear power development in energy structure is complicated, brought by its characteristics of multiple domains, multiple objectives, multiple timescales, multiple spatial-scopes, and long timespans. It involves generalized physical elements such as nuclear power chain, non-nuclear energy systems, and climate system; social elements related to human behaviors such as policy and public acceptance; and cyber elements that realize the cross-domain integration of information acquisition, knowledge extraction, and decision support.

Current researches tend to have the following limitations: ① the cyber–physical–social elements for optimizing decision-making are roughly considered and are not discussed in different certain situations; ② the coordinated optimization of cross-domain and multi-dimensional objectives is not well achieved; ③ the special research on nuclear power chain is not integrated into the comprehensive research of energy and power system planning; ④ the potential contribution of nuclear power to continuously providing reliable and low-carbon power is underestimated or even ignored; ⑤ the influence of high-risk and low-probability events such as nuclear leakage and extreme weather events are not well considered.

Further attention should be paid to the following areas in future research: improvement in research framework, construction of multi-domain hybrid simulation models, specification of objective functions and constraints, evaluation of the role of nuclear power in ensuring the safe operation of power system in particular scenarios with high penetration of renewable energy, quantitative analysis of the impact of social factors such as policy and market game on nuclear power development, risk decision-making considering external disturbances such as nuclear leakage accidents, and joint optimization strategy of nuclear power development targets and pathways.

The global action of achieving carbon neutrality provides a new opportunity for a thorough and comprehensive reflection on the positioning of nuclear power. We believe that through the cross-disciplinary integration of nuclear science, energy, climate, economy, policy, human behavior, and other natural and social sciences, the cyber–physical–social elements and their interactions involved in the optimization of nuclear power development can be quantified more effectively.

References

[1] 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

[2] V. Nian and S. K. Chou, "The state of nuclear power two years after Fukushima – the ASEAN perspective," *Applied Energy*, vol. 136, pp. 838-848, May 2014.

[3] WNA. (2019, Dec.). World nuclear power reactors & uranium requirements. [Online]. Available: https://world-nuclear. org/information-library/facts-and-figures/world-nuclear-power-reactors-archive/reactor-ar -chive-december-2019.aspx

[4] REN21. (2020, Jun.). Renewables 2020 global status report. [Online]. Available: https://www. ren21. net/wp-content/uploads/2019/05/gsr_2020_full_report_en.pdf

[5] J. Zhao, D. Liu, N. Yang *et al.*, "Operation mode and benefits of nuclear power plant participating in peak load regulation of power system," *Power System Technology*, vol. 36, no. 12, pp. 250-255, Dec. 2012.

[6] C. Cany, C. Mansilla, G. Mathonnière *et al.*, "Nuclear power supply: going against the misconceptions. Evidence of nuclear flexibility from the French experience," *Energy*, vol. 151, pp. 289-296, May 2018.

[7] C. Mansilla, G Mathonnière, and P. D. Costa, "Nuclear contribution to the penetration of variable renewable energy sources in a French decarbonised power mix," *Energy*, vol. 150, pp. 544-555, May 2018.

[8] Y. Xue. (2021, May). Dual-carbon path 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

[9] H. Khatib and C. Difiglio, "Economics of nuclear and renewables," *Energy Policy*, vol. 96, pp. 740-750, Sept. 2016.

[10] C. İ. Aydın, "Nuclear energy debate in Turkey: stakeholders, policy alternatives, and governance issues," *Energy Policy*, vol. 136, Jan. 2020.

[11] IAEA. (2019, Sept.). Energy, electricity and nuclear power estimates for the period up to 2050. [Online]. Available: https://www. iaea. org/publications/13591/energy-electricity-and-nuclear-power-estimates-for-the-period-up-to-2050

[12] IRENA. (2020, Apr.). Global renewables outlook: energy transformation 2050. [Online]. Available: https://www.irena.org/publications/2020/Apr/Global-Renewables-Outlook-2020

[13] F. Gralla, D. J. Abson, A. P. Møller *et al.*, "Energy transitions and national development indicators: a global review of nuclear energy production," *Renewable and Sustainable Energy Reviews*, vol. 70, pp. 1251-1265, Apr. 2017.

[14] A. Verbruggen, E. Laes, and S. Lemmens, "Assessment of the actual sustainability of nuclear fission power," *Renewable and Sustainable Energy Reviews*, vol. 32, pp. 16-28, Apr. 2014.

[15] X. Du, Q. Ye, M. Xu *et al.*, "Research on technology directions and development roadmap of nuclear energy," *Strategic Study of CAE*, vol. 20, no. 3, pp. 17-24, May 2018.

[16] C. Karakosta, C. Pappas, V. Marinakis *et al.*, "Renewable energy and nuclear power towards sustainable development: characteristics and prospects," *Renewable and Sustainable Energy Reviews*, vol. 22, pp. 187-197, Jun. 2013.

[17] I. N. Kessides, "Powering Africa's sustainable development: the potential role of nuclear energy," *Energy Policy*, vol. 74, no. supplement 1, pp. S57-S70, Dec. 2014.

[18] S. Zhou and X. Zhang, "Nuclear energy development in China: a study of opportunities and challenges," *Energy*, vol. 35, no. 11, pp. 4282-4288, Nov. 2010.

[19] 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.

[20] A. Abdulla, P. Vaishnav, B. Sergi *et al.*, "Limits to deployment of nuclear power for decarbonization: insights from public opinion," *Energy Policy*, vol. 129, pp. 1339-1346, Jun. 2019.

[21] Q. Wang, R. Li, and G. He, "Research status of nuclear power: a review," *Renewable and Sustainable Energy Reviews*, vol. 90, pp. 90-96, Jun. 2018.

[22] C. Greenhalgh and A. Azapagic, "Review of drivers and barriers for nuclear power in the UK," *Environmental Science & Policy*, vol. 12, no. 7, pp. 1052-1067, Aug. 2009.

[23] M. Lenzen, "Life cycle energy and greenhouse gas emissions of nuclear energy: a review," *Energy Conversion and Management*, vol. 49, no. 8, pp. 2178-2199, Aug. 2008.

[24] B. van der Zwaan, "The role of nuclear power in mitigating emissions from electricity generation," *Energy Strategy Reviews*, vol. 1, no. 4, pp. 296-301, May 2013.

[25] C. Seong, G. Heo, S. Baek *et al.*, "Analysis of the technical status of multiunit risk assessment in nuclear power plants," *Nuclear Engineering and Technology*, vol. 50, no. 3, pp. 319-326, Apr. 2018.

[26] M. W. Edwards, R. D. Schweitzer, J. Shakespeare-Finch *et al.*, "Living with nuclear energy: a systematic review of the psychological consequences of nuclear power," *Energy Research & Social Science*, vol. 47, pp. 1-15, Jan. 2019.

[27] M. J. Goodfellow, H. R. Williams, and A. Azapagic, "Nuclear renaissance, public perception and design criteria: an exploratory review," *Energy Policy*, vol. 39, no. 10, pp. 6199-6210, Oct. 2011.

[28] M. Lehtveer, M. Makowski, F. Hedenus *et al.*, "Multi-criteria analysis of nuclear power in the global energy system: assessing trade-offs between simultaneously attainable economic, environmental and social goals," *Energy Strategy Reviews*, vol. 8, pp. 45-55, Jul. 2015.

[29] 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.

[30] A. Carnino, "The lifecycle of a nuclear power plant," in *Infrastructure and Methodologies for the Justification of Nuclear Power Programmes*, 1st ed., Cambridge: Woodhead Publishing, 2012, pp. 37-54.

[31] P. Liu, P. Chu, and J. Hou, "Accommodation issue of nuclear power in China: status quo, barriers and solutions," *Energy Strategy Reviews*, vol. 22, pp. 166-178, Nov. 2018.

[32] X. Yu and Y. Xue, "Smart grids: a cyber-physical systems perspective," *Proceedings of the IEEE*, vol. 104, no. 5, pp. 1058-1070, May 2016.

[33] Y. Xue. (2021, Aug.). The new-type power system actively supporting the dual carbon target of China via CPSSE. [Online]. Available: https://mp.weixin.qq.com/s/z_hH6HUI40jnaBNqpXjXaQ

[34] J. Zhang, F. Wang, X. Wang *et al.*, "Cyber-physical-social systems: the state of the art and perspectives," *IEEE Transactions on Computational Social Systems*, vol. 5, no. 3, pp. 829-840, Sept. 2018.

[35] Q. Ye, "The main direction and focus of China's nuclear energy technology development in the future," *China Nuclear Power*, vol. 11, no. 2, pp. 30-133, Jun. 2018.

[36] OECD-NEA. (2015, Nov.). Technology roadmap: nuclear energy 2015 – annex: nuclear energy case studies. [Online]. Available: https://www.oecd-nea.org/pub/techroadmap/techroadmap-2015-annex.pdf

[37] IAEA. (2006, Feb.). Economic performance indicators for nuclear power. [Online]. Available: https://www-pub. iaea. org/MTCD/Publications/PDF/TRS437_web.pdf

[38] C. McCombie and M. Jefferson, "Renewable and nuclear electricity: comparison of environmental impacts," *Energy Policy*, vol. 96, pp. 758-769, Sept. 2016.

[39] J. L. Rempe, "Safety, regulation, and decommissioning of commercial nuclear power reactors – introduction," *Encyclopedia of Nuclear Energy*, vol. 2, pp. 1-5, Jun. 2021.

[40] X. Chen, M. B. Mcelroy, Q. Wu *et al.*, "Transition towards higher penetration of renewables: an overview of interlinked technical, environmental and socio-economic challenges," *Journal of Modern Power Systems and Clean Energy*, vol. 7, no. 1, pp. 1-8, Jan. 2019.

[41] A. Verbruggen, "Renewable and nuclear power: a common future?" *Energy Policy*, vol. 36, no. 11, pp. 4036-4047, Nov. 2008.

[42] Z. Jin, Z. Bai, and L. Yang, "Thinking on general trends of energy development and directions of energy science and technology," *Strategy & Policy Decision Research*, vol. 35, no. 213, pp. 52-58, May 2020.

[43] K. Vaillancourt, M. Labriet, R. Loulou *et al.*, "The role of nuclear energy in long-term climate scenarios: an analysis with the World-TIMES model," *Energy Policy*, vol. 36, no. 7, pp. 2296-2307, Jul. 2008.

[44] S. Kwag and D. Hahm, "Development of an earthquake-induced landslide risk assessment approach for nuclear power plants," *Nuclear Engineering Technology*, vol. 50, no. 8, pp. 1372-1386, Dec. 2018.

[45] D. Adler, A. Jha, and E. Severnini, "Considering the nuclear option: Hidden benefits and social costs of nuclear power in the U.S. since 1970," *Resource and Energy Economics*, vol. 59, pp. 101-127, Feb. 2020.

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

[47] A. Adamantiades and I. Kessides, "Nuclear power for sustainable development: current status and future prospects," *Energy Policy*, vol. 37, no. 12, pp. 5149-5166, Dec. 2009.

[48] X. Yuan, J. Zuo, R. Ma *et al.*, "How would social acceptance affect nuclear power development? A study from China," *Journal of Cleaner Production*, vol. 163, pp. 179-186, Oct. 2017.

[49] M. W. Edwards, R. D. Schweitzer, J. Shakespeare-Finch *et al.*, "Living with nuclear energy: a systematic review of the psychological consequences of nuclear power," *Energy Research & Social Science*, vol. 47, pp. 1-15, Jan. 2019.

[50] A. Kerstine. (2015, Jul.). The history behind Germany's nuclear phase-out. [Online]. Available: https://www. cleanenergywire. org/factsheets/history-behind-germanys-nuclear-phase-out

[51] Y. Xue and Y. Lai, "Integration of macro energy thinking and big data thinking–part one: big data and power big data," *Automation of Electric Power Systems*, vol. 40, no. 1, pp. 1-8, Jan. 2016.

[52] Y. Xue and Y. Lai, "Integration of macro energy thinking and big data thinking–part two: applications and explorations," *Automation of Electric Power Systems*, vol. 40, no. 8, pp. 1-13, Apr. 2016.

[53] 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.

[54] Y. Shu, Y. Xue, B. Cai *et al.*, "A review of energy transition analysis part two uncertainties and approaches," *Automation of Electric Power Systems*, vol. 42, no. 10, pp. 1-12, May 2018.

[55] T. N. Srinivasan and T. S. G. Rethinaraj, "Fukushima and thereafter: reassessment of risks of nuclear power," *Energy Policy*, vol. 52, pp. 726-736, Jan. 2013.

[56] J. Lelieveld, D. Kunkel, and M. G. Lawrence, "Global risk of radioactive fallout after major nuclear reactor accidents," *Atmospheric Chemistry Physics*, vol. 12, no. 9, pp. 4245-4258, May 2012.

[57] G. I. Tshinsky, O. G. Komlev, and K. G. Mel'Nikov, "Nuclear power technologies at the stage of sustainable nuclear power development," *Progress in Nuclear Energy*, vol. 53, no. 7, pp. 782-787, Sept. 2011.

[58] V. Nian, "Progress in nuclear energy technology perspectives from 1950 to 2100 and policy implications for the global nuclear power industry," *Progress in Nuclear Energy*, vol. 105, pp. 83-98, May 2018.

[59] M. Joyce, "Advanced reactors and future concepts," in *Nuclear Engineering: A Conceptual Introduction to Nuclear Power and Methodologies for the Justification of Nuclear Power Programmes*, 1st ed., Oxford: Butterworth Heinemann, 2017, pp. 263-295.

[60] L. Rodríguez-Penalonga and B. Y. M. Soria, "A review of the nuclear fuel cycle strategies and the spent nuclear fuel management technologies," *Energies*, vol. 10, no. 8, p. 1235, Aug. 2017.

[61] M. El-Sefy, M. Ezzeldin, W. El-dakhakhni *et al.*, "System dynamics simulation of the thermal dynamic processes in nuclear power plants," *Nuclear Engineering and Technology*, vol. 51, no. 6, pp. 1540-1553, Sept. 2019.

[62] J. Vujić, R. M. Bergmann, R. Škoda *et al.*, "Small modular reactors: simpler, safer, cheaper?" *Energy*, vol. 45, no. 1, pp. 288-295, Sept. 2012.

[63] H. Hidayatullah, S. Susyadi, and M. H. Subki, "Design and technology development for small modular reactors – safety expectations, prospects and impediments of their deployment," *Progress Nuclear Energy*, vol. 79, pp. 127-135, Mar. 2015.

[64] J. H. Kim, M. M. Song, and S. A. Alameri, "Emerging areas of nuclear power applications," *Nuclear Engineering and Design journal*, vol. 354, p. 110183, Dec. 2019.

[65] G. D. Roo and J. E. Parsons, "A methodology for calculating the levelized cost of electricity in nuclear power systems with fuel recycling," *Energy Economics*, vol. 33, no. 5, pp. 826-839, Sept. 2011.

[66] G. Harris, P. Heptonstall, R. Gross *et al.*, "Cost estimates for nuclear power in the UK," *Energy Policy*, vol. 62, pp. 431-442, Nov. 2013.

[67] Y. Matsuo and H. Nei, "An analysis of the historical trends in nuclear power plant construction costs: the Japanese experience," *Energy Policy*, vol. 124, pp. 180-198, Jan. 2019.

[68] J. R. Lovering, A. Yip, and T. Nordhaus, "Historical construction costs of global nuclear power reactors," *Energy Policy*, vol. 91, pp. 371-382, Apr. 2016.
[69] J. Portugal-Pereira, P. Ferreira, J. Cunha *et al.*, "Better late than never, but never late is better: risk assessment of nuclear power construction projects," *Energy Policy*, vol. 120, pp. 158-166, Sept. 2018.
[70] V. Nian, S. K. Chou, B. Su *et al.*, "Life cycle analysis on carbon emissions from power generation – the nuclear energy example," *Applied Energy*, vol. 118, pp. 68-82, Apr. 2014.
[71] J. Beerten, E. Laes, G. Meskens *et al.*, "Greenhouse gas emissions in the nuclear life cycle: a balanced appraisal," *Energy Policy*, vol. 37, no. 12, pp. 5056-5068, Dec. 2009.
[72] S. M. Rashad and F. H. Hammad, "Nuclear power and the environment: comparative assessment of environmental and health impacts of electricity-generating systems," *Applied Energy*, vol. 65, no. 1-4, pp. 211-229, Apr. 2000.
[73] L. Wang, Y. Wang, H. Du *et al.*, "A comparative life-cycle assessment of hydro-, nuclear and wind power: a China study," *Applied Energy*, vol. 249, pp. 37-45, Sept. 2019.
[74] C. Poinssot, S. Bourg, N. Ouvrier *et al.*, "Assessment of the environmental footprint of nuclear energy systems: comparison between closed and open fuel cycles," *Energy*, vol. 69, pp. 199-211, May 2014.
[75] X. Kang, "Nuclear power prospect: the balance between safety and economy," *China Investment*, vol. 12, pp. 32-36, Dec. 2013.
[76] IAEA. (2018, Sept.). Economic assessment of the long term operation of nuclear power plants: approaches and experience. [Online]. Available: https://www. iaea. org/publications/11162/economic-assessment-of-the-long-term-operation-of-nuclear-power-plants-approaches-and-experi-ence
[77] J. Vujić, D. P. Antić, and Z. Vukmirović, "Environmental impact and cost analysis of coal versus nuclear power: the U. S. case," *Energy*, vol. 45, no. 1, pp. 31-42, Sept. 2012.
[78] Z. Jiang, "Nuclear power development for greenhouse gas emission reduction in China," *Advances Climate Chang Research*, vol. 2, no. 2, pp. 75-78, Jun. 2011.
[79] O. Siddiqui and I. Dincer, "Comparative assessment of the environmental impacts of nuclear, wind and hydro-electric power plants in Ontario: a life cycle assessment," *Journal of Cleaner Production*, vol. 164, pp. 848-860, Oct. 2017.
[80] F. Ueckerdt, L. Hirth, G. Luderer *et al.*, "System LCOE: what are the costs of variable renewables?" *Energy*, vol. 63, pp. 61-75, Dec. 2013.
[81] IEA. (2020, Dec.). Projected costs of generating electricity 2020. [Online]. Available: https://www. iea. org/reports/projected-costs-of-generating-electricity-2020
[82] EIA. (2020, Feb.). Levelized cost and levelized avoided cost of new generation resources in the annual energy outlook 2020. [Online]. Avaolable: https://www. eia. gov/outlooks/archive/aeo20/electricity_generation.pdf
[83] M. Ram, M. Child, A. Aghahosseini *et al.*, "A comparative analysis of electricity generation costs from renewable, fossil fuel and nuclear sources in G20 countries for the period 2015-2030," *Journal of Cleaner Production*, vol. 199, pp. 687-704, Oct. 2018.
[84] J. Feng, F. Zhang, J. Zhang *et al.*, "Multi-scenario comparison analysis on nuclear power development in China," *IOP Conference Series: Earth and Environmental Science*, vol. 227, no. 4, p. 042046, Feb. 2019.
[85] S. Yu, B. Yarlagadda, J. E. Siegel *et al.*, "The role of nuclear in China's energy future: insights from integrated assessment," *Energy Policy*, vol. 139, Apr. 2020.
[86] Y. E. Lee and Y. B. Jung, "Challenges of nuclear power for sustainable role in Korean energy policy," *Energy Conversion Management*, vol. 49, no. 7, pp. 1951-1959, Jul. 2008.
[87] N. Maïzi and E. Assoumou, "Future prospects for nuclear power in France," *Applied Energy*, vol. 136, pp. 849-859, Dec. 2014.
[88] X. Xiao and K. Jiang, "China's nuclear power under the global 1.5 °C target: preliminary feasibility study and prospects," *Advances in Climate Change Research*, vol. 9, no. 2, pp. 138-143, Jun. 2018.
[89] N. Kopytko and J. Perkins, "Climate change, nuclear power, and the adaptation-mitigation dilemma," *Energy Policy*, vol. 39, no. 1, pp. 318-333, Jan. 2011.
[90] A. Okagawa, T. Masui, O. Akashi *et al.*, "Assessment of GHG emission reduction pathways in a society without carbon capture and nuclear technologies," *Energy Economics*, vol. 34, no. supplement 3, pp. S391-S398, Dec. 2012.
[91] B. V. D. Zwaan and M. Tavoni, "Coal-based power generation with CCS versus nuclear energy: two competitive base-load climate control options," in *Proceedings of the 10th International Conference on Greenhouse Gas Control Technologies*, Amsterdam, Netherlands, Sept. 2010, pp. 5830-5837.
[92] ERCOT. (2021, Feb.). Review of February 2021 extreme cold weather event – ERCOT presentation. [Online]. Available: http://www. ercot. com/content/wcm/lists/226271/Texas_Legislature_Hearings_2-25-2021. pdf
[93] U.S. NRCOC. (2021, Feb.). Event notification report for February 16, 2021. [Online]. Available: https://www. nrc. gov/reading-rm/doc-collections/event-status/event/2021/20210216en.html
[94] L. M. Jenkins, R. Alvarez, and S. M. Jordaan, "Unmanaged climate risks to spent fuel from U.S. nuclear power plants: the case of sea-level rise," *Energy Policy*, vol. 137, Feb. 2020.
[95] L. Stamford and A. Azapagic, "Sustainability indicators for the assessment of nuclear power," *Energy*, vol. 36, no. 10, pp. 6037-6057, Oct. 2011.
[96] E. W. Stein, "A comprehensive multi-criteria model to rank electric energy production technologies," *Renewable and Sustainable Energy Reviews*, vol. 22, pp. 640-654, Jun. 2013.
[97] A. Maxim, "Sustainability assessment of electricity generation technologies using weighted multi-criteria decision analysis," *Energy Policy*, vol. 65, pp. 284-297, Feb. 2014.
[98] 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.
[99] S. Ahmad, A. Nadeem, G. Akhanova *et al.*, "Multi-criteria evaluation of renewable and nuclear resources for electricity generation in Kazakhstan," *Energy*, vol. 141, pp. 1880-1891, Dec. 2017.
[100] 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.
[101] 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.
[102] A. E. Abouelnaga, A. Metwally, M. E. Nagy *et al*., "Optimum selection of an energy resource using fuzzy logic," *Nuclear Engineering and Design*, vol. 239, no. 12, pp. 3062-3068, Dec. 2009.
[103] B. Brand and R. Missaoui, "Multi-criteria analysis of electricity generation mix scenarios in Tunisia," *Renewable and Sustainable Energy Reviews*, vol. 39. pp. 251-261, Nov. 2014.
[104] V. Aryanpur, M. S. Atabaki, M. Marzband *et al.*, "An overview of energy planning in Iran and transition pathways towards sustainable electricity supply sector," *Renewable and Sustainable Energy Reviews*, vol. 112, pp. 58-74, Sept. 2019.
[105] 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.
[106] J. Wu, Y. Xue, D. Xie *et al.*, "Multi-agent modeling and analysis of EV users' travel willingness based on an integrated causal/statistical/behavioral model," *Journal of Modern Power Systems and Clean Energy*, vol. 6, pp. 1255-1263, Nov. 2018.
[107] 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.
[108] J. Huang, Y. Xue, C. Jiang *et al.*, "An experimental study on emission trading behaviors of generation companies," *IEEE Transactions on Power Systems*, vol. 30, no. 2, pp. 1076-1093, Mar. 2015.
[109] C. Jiang, Y. Xue, J. Huang *et al.*, "Aggregated impact of allowance allocation and power dispatching on emission reduction," *Journal of Modern Power Systems and Clean Energy*, vol. 5, no. 6 pp. 936-946, Nov. 2017.

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