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Research Article

Nuclear Power Sustainability Path for China from the Perspective of Operations

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Nuclear power, as a low-carbon, stable, and efficient energy, plays an important role in replacing fossil fuels in the development of a globally sustainable energy system. However, nuclear power has deviated from the path to achieve the Sustainable Development Goals of the United Nations. The path of sustainable nuclear power for China was proposed based on an analysis of the development of global nuclear power and the situation in China, using advanced operation concepts and intelligent collaboration technology to change the labor-centered operation mode. It serves as a model for other countries with a labor-centered nuclear power operation mode and an aging society seeking to achieve carbon neutrality through the use of nuclear power around the world.

1. Introduction

Fossil fuels have contributed to global warming and climate change while advancing the advancement of modern industrial civilization. It endangers the global environment and biodiversity, as well as the sustainable development of the economic society. To avoid serious consequences, the Paris agreement is proposed to control the global average temperature that increase below 2 degrees Celsius compared with the preindustrial level [1–3]. To achieve this goal, CO_2 must be limited to around 450 ppm and the average intensity of carbon dioxide from electricity must be reduced from 430 g CO_2/kWh today to around 50 gCO_2/kWh by 2050 [3]. Nuclear power, as a low-carbon and efficient energy, plays an important role in replacing traditional fossil fuels. However, according to the International Energy Agency's (IEA) new report on the progress of clean energy, nuclear power was not on the path to achieve the Sustainable Development Goals (SDGs) of the United Nations [4]. According to the report, 9.4 GW of nuclear capacity was permanently shut down in 2019, while approximately, 5.5 GW of new nuclear capacity was first connected to the grid and 5.2 GW of new projects were started, both of which were significantly less than the permanent shutdown. Although nuclear power remains the second largest low-carbon electricity source in the world, it is not on the path to a sustainable development scenario [5].

Solar, wind, and other renewable clean energy generation costs have been significantly reduced in recent years, particularly when the learning rate of the photovoltaic power cost was greater than 23% [1, 2, 6, 7]. The cost of construction of nuclear power plants was increasing due to increasingly stringent safety regulations. The high cost of nuclear power construction hampered its long-term development, particularly in light of ongoing cost reductions in other clean renewable energy such as wind and solar, and the high construction and operational costs rendered nuclear power in developed countries "unable to build or develop" [8, 9]. Although nuclear power is expensive to build, due to the unit operating time of 40–60 years, existing nuclear power, including a large number of old units, will continue to play a role in the low-carbon electricity supply.

Although the vast majority of nuclear power units in China have not faced problems such as retirement and extended life, in the future, with the development of renewable energy, aging population, and slowing growth of electricity demand, China will face a serious economic problem with a large number of old units operating.

Therefore, it is necessary to analyze the current situation and the nuclear power problem and to present a sustainable path for China from the perspective of operation. This not only helps China reduce the cost of nuclear power operations but also helps the world realize a global sustainable low-carbon energy system.

2. Global Situation of Nuclear Power

2.1. Global Nuclear Power. In 2021, the total worldwide operation nuclear power capacity was 415 GW, the new nuclear power capacity was 6 GW, and the permanent shutdown nuclear power capacity was 5.4 GW (6 units). Nuclear power generates about 10% of the world's electricity and up to 20% in developed economies. Over the past 50 years, nuclear power has reduced carbon dioxide emissions by more than 60 billion tons, equivalent to nearly two years of global energy emissions. As the growth of electricity demand outpaced the growth of low-carbon power, energy-related CO_2 emissions hit a record high in 2018. Without extending the useful life of nuclear power, the new project could result in an additional 4 billion tons of carbon dioxide emissions. It underscored the importance of nuclear power to the global transition to low-carbon energy. According to the annual research report of IEA 2021, to achieve the goal of net zero energy by 2050, nuclear power must increase to 812 GW [10].

However, just as the world needs more low-carbon electricity, nuclear power is declining in developed economies. Nuclear power units begin to close. There is little investment in the construction of new units. After the Fukushima accident, some countries are phasing out nuclear power. The history of nuclear power development in the world is shown in Figure 1. Most nuclear power units were built before the 1990s in developed economies, and non-OECD countries (mainly China and Russia) are the main current nuclear power construction drivers, while China is building 22% of the world's nuclear power units in construction [11].

2.2. Nuclear Safety Supervision. So far, three serious nuclear accidents have had a serious adverse impact on the development of nuclear power. These accidents have led people to continuously reflect on nuclear safety hazards and preventive measures and have gradually formed a strong nuclear safety culture and regulatory system [12]. After the Three Mile Island nuclear accident, the US Nuclear Regulatory Commission established an independent nuclear safety regulatory team to take the lead in forming an effective nuclear safety management system and establishing a relatively complete legal system for nuclear safety. Relevant practices also provided references for other countries [13]. The Chernobyl nuclear accident helped the world foster openness and transparency and nuclear safety culture, which brought the world together for the first time to establish the international cooperation framework that still exists today. Under the auspices of the International Atomic Energy Agency (IAEA), safety standards, specifications, and data became an important part of international cooperation to form coordination with all national laws, regulations, and standards to support the international nuclear security regulatory system [12] (as shown in Figure 2).

After the Fukushima nuclear accident, the international community has presented new and higher requirements. Construction of the second generation of improved pressurized water reactors has gradually halted. The existing safety systems for the unit have been upgraded to deal with serious accidents. The economics was being challenged by the most stringent regulations and regulatory regimes, the concept of defense in depth, and competition with renewable energy. At the same time, in the open electricity market, economic factors greatly restrict the development of nuclear power. Nuclear power units have been forced to shut down early in Japan, the United States, and parts of the European Union. The strengthening of nuclear safety supervision has undoubtedly increased the cost and worsened development. Therefore, under the sponsorship of the US Department of Energy (DOE), senior government representatives discussed international cooperation in nuclear power development, looking for new opportunities in the nuclear power market to reduce costs, improve economic efficiency, increase flexibility in nuclear power design and thermal efficiency, and reduce radioactive waste [14]. However, it is not easy to develop advanced nuclear power systems. Therefore, for a long time, the global energy system will face the regulatory and economic challenges of a large number of aging units.

2.3. Nuclear Power Generation Costs. Nuclear power generation costs must be taken into account for the high initial investment and operating costs. Usually, capital costs account for more than 70% of total new power production costs. The fuel cost represents 5.7%, and the remaining cost includes the cost of the front fuel cycle, operation, and the cost associated with the back fuel cycle [15]. After the unit is put into operation, the capital cost related to depreciation, finance, and other investments of fixed assets will show phased characteristics. Among them, the life of fixed assets with comprehensive depreciation is about 30 years, and the capital cost will generally drop significantly after the loan repayment period of about 15 years [9].

Most units were built in the 1990s in developed countries, and the capital cost has fallen sharply, with operation costs accounting for the most. About 80% of nuclear power generation in the United States comes from plants with multiple reactors. Economies of scale allow operators to spread the cost across more units and reduce the cost. In 2020, the average total cost of a multiunit plant in the United States was $27.03/MWh, while the average total cost of a single-unit plant was $39.64/MWh. According to EUGG cost data for 2002 to 2020, the average annual operating cost in the United States accounted for 60% of the total cost, while the average annual capital cost accounted for only 21% of the total cost [16].

Most of the units in developing countries are in operation for a short time, and the fixed asset cost of depreciation accounts for most of the generation cost. At present, most of

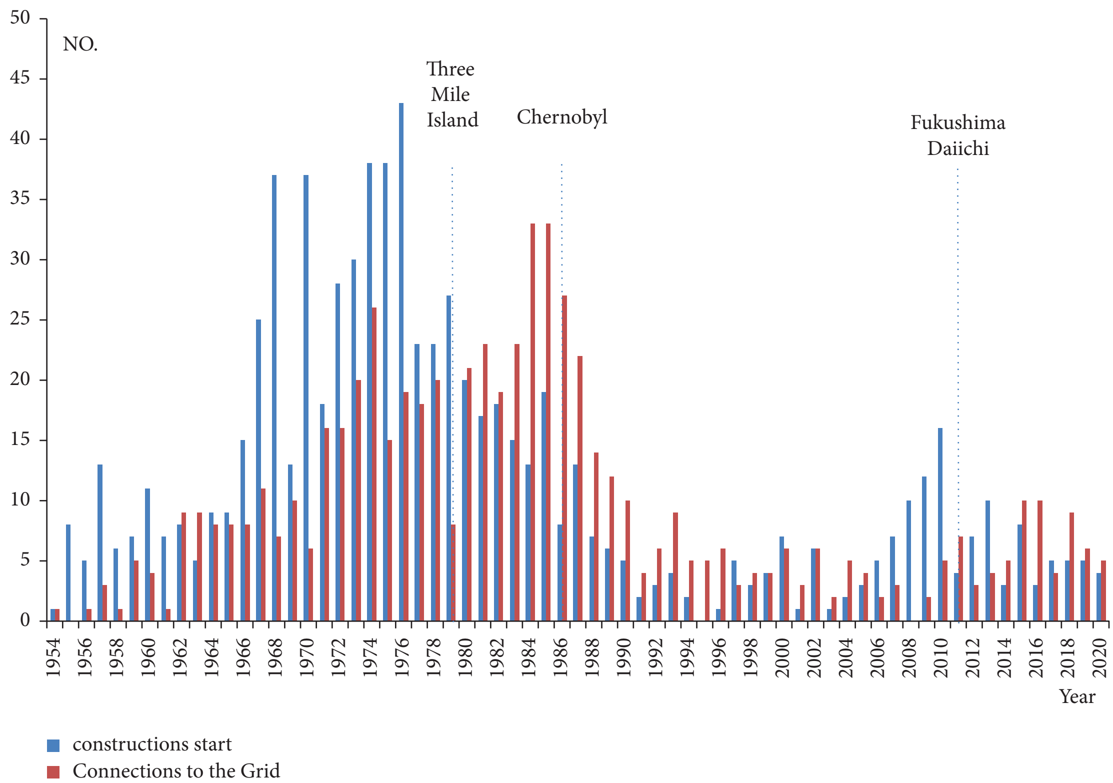

FIGURE 1: Annual number of nuclear power units in the world (1954–2020).

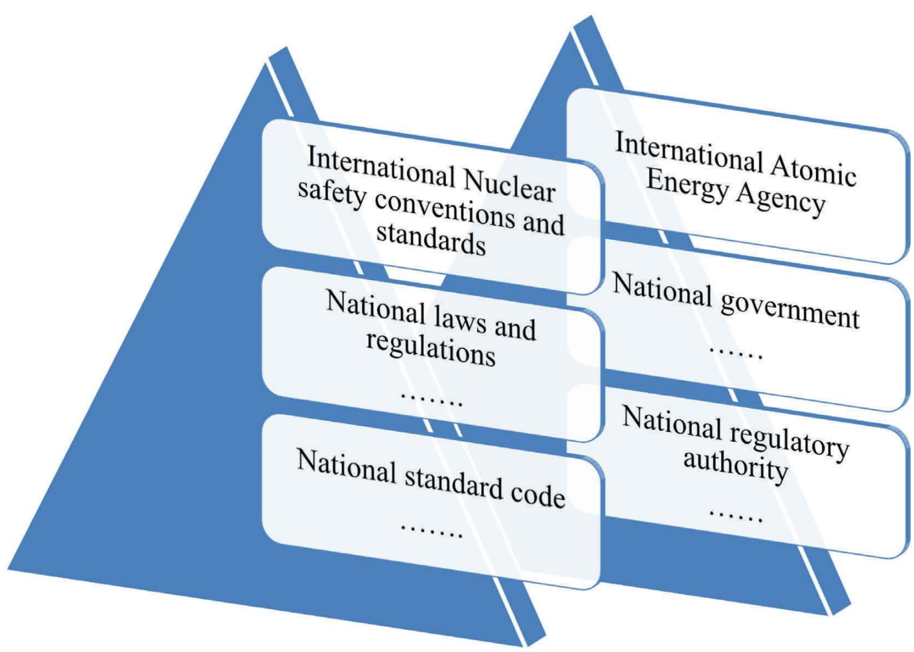

FIGURE 2: International nuclear safety regulatory system.

the units have been in operation for less than 15 years in China. They are still in the stage of depreciation and principal service of fixed assets and the capital cost accounts for a relatively high proportion. According to the 2017–2019 annual financial report of China Nuclear Power Co., LTD. (CNP), the first listed nuclear power company in China, the capital cost accounted for more than 44% of the total costs every year. That is more than double the capital cost ratio in the US.

Since the total cost of nuclear power has strong stage characteristics [9], the total cost of nuclear power is mainly affected by the principal and interest repayment in the early stage and the total cost will decrease year by year. In the middle stage, with the end of the influence of the principal and interest repayment, labor and maintenance costs will change under the influence of price factors, and in the last stage, the depreciation cost of fixed assets will decrease significantly. After the total cost is greatly reduced, fixed investment, labor operation, and maintenance costs may lead to a gradual increase in the cost due to the impact of life extension and decommissioning, but the capital cost overall trend is higher in the front and then lower. At present, due to the late construction time, nuclear power in developing countries is basically in the early stage of repaying capital and interest, with a relatively high capital cost, while most nuclear power in developed regions, especially the United States, is in the final stage, with a relatively low capital cost, and the power generation cost is mainly affected by the cost of labor, operation, and maintenance. With the increase in unit operation time, the impact of capital cost on nuclear power in developing countries will gradually decrease, while the impact of labor operation and maintenance cost may gradually increase for price factors.

2.4. Impacts of Renewable Energy. In the past, the cost of other clean energy such as renewable energy continued to fall dramatically, while the cost of nuclear power continued to rise for the safety inputs due to nuclear accidents; the cost of nuclear power is no longer competitive with some renewable power. This is the main reason for the decline of nuclear power in developed countries. According to IRENA research, from 2000 to 2020, global renewable capacity increased 3.7 times, from 754 GW to 2,799 GW. Driven by improving technology, economies of scale, competitive supply chains, and improved development experience, the average generating costs of renewable clean energy such as solar and wind have been significantly reduced. From 2010 to 2020, the average cost of photovoltaic generation was reduced by 85%, the average cost of solar thermal generation was reduced by 68%, the average cost of onshore wind generation was reduced by 56%, and the average cost of offshore wind generation was reduced by 48% [17].

The construction of third-generation nuclear power, such as EPR and AP1000, has been seriously delayed and cost overruns are large. It has reduced investor appetite for new nuclear power projects in developed countries. Currently, the cost of third-generation nuclear power construction is estimated at 7000–8000 USD/kWh, which is about 4 times the estimated cost in 2005 [11]. This has led to the decline of nuclear power investment in Europe and the United States. To reduce CO_2 emissions by 1%, the total cost of the new nuclear power system is approximately $1.7 billion, and the total cost of the new renewable energy system is approximately $3.97 billion, more than twice that of nuclear power [18]. Although the cost of nuclear power construction is much higher than that of renewable energy such as solar and wind power, it still has a cost advantage in the total cost of the system to reduce CO_2 emissions.

Nuclear power has an economic advantage in reducing global carbon emissions. This is an important reason why developing countries are still building new nuclear power. Although construction in developed economies has almost ground to a halt due to slowing electricity demand growth, they have been actively developing smaller modular nuclear power with lower investment costs and trying to reduce the operating cost and extend the useful life of nuclear power units. The IEA study also showed that although the average generation cost of new nuclear power is higher than that of new renewable clean energy in developed countries, considering the flexibility and reliability cost of solar and wind power, the cost of the system to prolong the unit life of nuclear power is much lower than that of solar, wind, and other renewable power [11]. Nuclear power remains an integral part of the global energy source of electricity for sustainable development.

3. China's Energy Policy and Nuclear Power Situation

3.1. Energy Policy. Currently, developed countries have reached a carbon peak, while China is a developing country, and its energy consumption will continue to increase for a certain time. To achieve the goals of the Paris Agreement, the Chinese government has proposed a development goal of achieving peak carbon emissions by 2030 and achieving carbon neutrality by 2060 [19]. To achieve the above goals, China will promote the construction of a new power system and vigorously develop clean and renewable energy [20]. It is expected that by 2030, installed photovoltaic and wind power will exceed 1.6 billion kW. By 2060, installed photovoltaic and wind power will exceed 5 billion kW [21].

As large-scale intermittent renewable new energy is connected to the power grid, the safe and stable operation of the power grid will be affected. With stable output and large rotational inertia, nuclear power can provide the necessary support for large-scale and high-proportion renewable energy access power systems. This is conducive to reduce the cost of large-scale renewable energy systems, and nuclear power plays an important role in building a low-carbon and efficient energy system in China [22, 23]. Currently, China has established a nuclear safety surveillance and emergency response system and has maintained a high level of safe operation performance. Compared with the region of OECD, the annual nuclear power generation ratio of China was only about 27% in 2020. There is still a large space for nuclear power to build a low-carbon sustainable energy system. In the 14th Five-Year Plan of People's Republic of China for National Economic and Social Development and the outline of the Long-Range Goals for 2035, the Chinese government has explicitly stated that by 2025, the nuclear power capacity will reach 70 million kW. By 2035, the nuclear power capacity in operation and under construction is expected to reach about 200 million kW, representing approximately 10% of the national power generation [24].

3.2. Nuclear Power Situation. With reform and development, rapid economic growth has introduced newer and higher requirements for energy, forcing China to begin to develop commercial nuclear power units in the 1990s [25]. According to data from the China Nuclear Energy Industry Association and literature research, Figure 3 shows the annual number of operating units in China (excluding the Taiwan region) in the past 30 years [26]. Nuclear power was developed rapidly in the early twentieth century and still showed relatively stable growth after the Fukushima nuclear accident. At the end of 2021, China (excluding the Taiwan region) had 53 units in operation with a capacity of 54.65 million kW. Nuclear power generation accounted for 5.02% of total annual power generation. With the 2030 carbon peak energy development strategy, the batch construction of third-generation nuclear power units will gradually be realized and there is still a large space for nuclear power growth in China.

Currently, most operation units have no more than 20 years in China, 75% have no more than 10 years, and 19% have 10 to 20 years. This also means that the capital cost is high and most units are still in the phase of principal and interest repayment of construction funds.

3.3. Sustainable Development Problems of Nuclear Power Cost. In operation, nuclear safety risks exist, and nuclear accidents not only directly produce serious consequences but also lead to social and public resistance, thus affecting the development of the economy and society. Furthermore, the operation has significant negative external risks, making it difficult to internalize external risks. The research showed that the input and regulatory measures of nuclear power companies are closely related to the probability of occurrence of nuclear accidents. Nuclear power enterprises' safety input will increase with increasing risks and losses. The loss due to hidden dangers discovered by regulatory inspection is the root cause of failures or negative effects of the safety control inspection [27]. Therefore, China has proposed to actively and orderly develop nuclear power and strengthen the safety control on safety premise. The safety input and supervision will undoubtedly increase the operational cost and thus reduce the competitiveness of nuclear power.

In 2002, China started the reform of market-oriented electric power and promoted electric power companies to improve production efficiency and reduce cost [28]. After 20 years of development, the reform of the China power market is still slow. The market is based mainly on planned consumption and government pricing. Market power transactions account for a relatively small. It is still in the transition from the planned economy to the market economy [29]. At present, although the feed-in price of some nuclear power in China is lower than the market-guided price due to market bidding, nuclear power enterprises can still enjoy the guided price and tax subsidy policies under the planned economic system. This enables nuclear power enterprises to have higher corporate profits to increase investment in upgrading nuclear power technology, which is obviously beneficial to the operation of nuclear power. However, with the reform of market-oriented electric power, especially with the reduction of the price of renewable energy, cheap and clean renewable energy will inevitably compete with nuclear power, leading to the reduction of the profits of nuclear power enterprises. When the profits of nuclear power enterprises cannot maintain the input of reproduction, it will inevitably affect the sustainable development of nuclear power operations.

Currently, China adopts the benchmarking feed-in price policy for newly built nuclear power units. In areas where the benchmark feed-in price of nuclear power is higher than that of coal-fired units, the benchmark feed-in price of local coal-fired units shall be implemented after the new units are in operation. By 2021, newly registered centralized photovoltaic power stations, industrial and commercial distributed photovoltaic projects, and newly approved onshore wind power projects will no longer enjoy government subsidies. The on-grid price of new projects is implemented according to the local benchmark price of coal-fired power generation and can be formed voluntarily through participation in market transactions. The lowest guide price for photovoltaic and wind power is only 0.24 yuan/kWh. In most areas, it is lower than the local benchmark price of coal-fired power generation. The guide price for the new nuclear power is 0.43 yuan/kWh, which is substantially higher than for wind and photovoltaics. This will undoubtedly lead to lower operating costs, especially for nuclear power participating in market transactions. In addition, China has entered an aging society, which will reduce the labor supply and increase labor costs [30]. As the population peak approaches, aging will also affect total social demand and thus affect economic growth [31]. This will also be bound to curb demand, making the nuclear power market more competitive in the future.

According to the 2014–2021 annual report released by China Guangdong Nuclear Power Co., LTD. (CGN), the largest nuclear power company in China, the number of CGN operation units increased year by year, the average unit revenue continued to grow, while the average capacity factor remained stable (approximately 90%), and the average number of crews and net profit margin decreased. Employee reduction did not enhance the net profit margin of nuclear power. The fundamental reason for this phenomenon is the high capital cost and operating costs, as shown in Figure 4. In the future, with increasing costs for social labor and competition for renewable energy, reducing the cost and increasing the efficiency of nuclear power will become a prominent focus. With the development of market reform, the cost of generation will determine the profitability and the ability to repay the principal and interest, and it will be a key factor restricting the sustainable development of nuclear power in China.

In summary, the main problems are as follows:

(1) Strict nuclear safety regulation not only discourages the upgrade of digital technology but also increases the cost of nuclear power operation
(2) If the cost of nuclear power cannot be reduced, with the reduction in the cost of renewable energy and the market-oriented reform of electricity in China, nuclear power will gradually lose competitiveness in the market

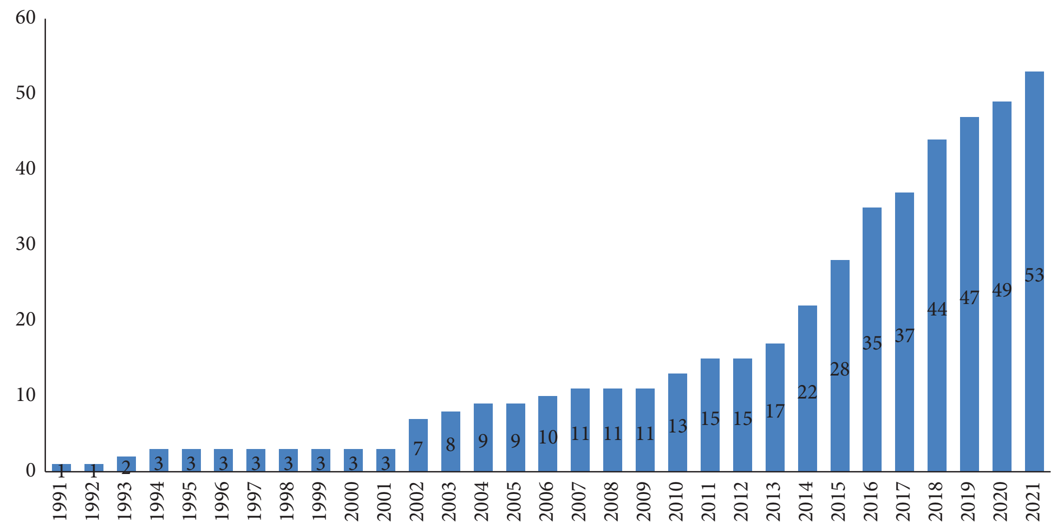

Figure 3: Number of units of nuclear power in operation in China (1991–2021).

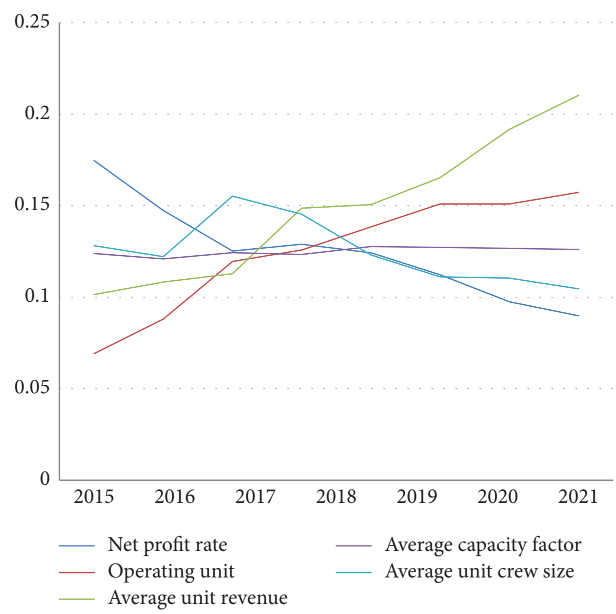

Figure 4: Normalized CGN nuclear power operation normalized data (2015–2021).

(3) It is difficult to reduce capital and fuel costs proactively. The only way to effectively reduce the cost of nuclear power is to reduce operating costs and ensure the economic input of nuclear safety. It will be difficult to reduce operating costs on a large scale by improving efficiency without changing the operating model.

4. Nuclear Power Sustainability Path for China

4.1. Operation Mode. Nuclear power operation involves manually performed inspections, calibration, testing, maintenance of plant assets at periodic frequency, and time-based replacement of assets, irrespective of equipment condition. This has resulted in a labor-centric business mode to achieve a high capacity factor. To improve operational performance and ensure safety, process and operation standardization made working procedures increasingly complicated and it was difficult to improve the level of operation by trying to improve the process. As the cost of renewable energy has fallen in the world, nuclear power is no longer one of the lowest-cost power sources [32].

The existing nuclear power business model is now a drag-on cost performance because it relies on a large number of highly skilled workers. In the United States, the operation represents 60% of the cost of nuclear power generation [16]. Digital technology and innovation are increasing the efficiency of energy production, leading to fierce competition in the market. In addition to shutdowns due to costly repair of components, nuclear power is now experiencing shutdowns for purely economic reasons in the United States [33, 34].

Although the labor cost in China is low and there is no nuclear decommissioning, the revenue of Chinese nuclear power companies in recent years shows that costs other than labor are still increasing and the low labor cost (not from the small number of employees but the low labor unit cost) does not keep the profit margin growth. With the aging of society in China and the development of renewable energy, the unit labor cost will continue to increase, making it difficult to achieve sustainable nuclear power development in China. Transformative digital technologies will fundamentally change the model of nuclear power operation. This required a strong focus on the elements of human-technology integration. Due to the lack of a clear vision, technical change and transformation have unfavorable risks. It made nuclear power operators reluctant to realize modernization in history, thus continuously missing the opportunity for nuclear power modernization [35].

4.2. Opportunities and Challenges. Today, most of the Chinese units are second-generation and advanced units. In terms of operation mode, there is not much difference from nuclear power in the United States, which is essentially labor-centered, and the difference in operation level between China and the United States is not obvious. Since the electricity market is based on planned electricity consumption and government pricing in China, nuclear power can enjoy certain preferential electricity price policies, and nuclear power construction has not stopped against the backdrop of increasing energy and electricity demand. It made the competition for nuclear power in China much smaller than in the United States. The degree of competition is closely related to the reform process of the electricity market and energy policy in China. At present, the price of new photovoltaic and wind power in China is generally lower than that of nuclear power, and the demand for nuclear power to participate in the regulation of the peak power grid is also increasing. As the reform of the electricity market, the implementation of the highest carbon neutral policy, and the cost of renewable clean energy power continue to reduce, nuclear power will face increasing competition in China. This will lower the cost of nuclear power generation. Table 1 shows data related to nuclear power operations in China and the United States separately.

As shown in Table 1, the operation unit time is generally short in China, while the majority of units in the United States have been operating for more than 20 years, and 40 units have been retired. In terms of the nuclear power capacity factor, the gap between China and the United States is relatively small. Although the cost of nuclear power generation in China is slightly lower than that in the United States, from a cost composition perspective, the ratio of capital cost and fuel-related cost in China is much higher than that in the United States. This is mainly because China units need to pay a large amount of capital for construction investment, and the Chinese government collects a fee for the disposal of spent fuel, which is close to 6% of the power generation cost, while the operation cost in China is only half that in the United States. Compared with the United States, the lower operating cost in China is directly related to the lower labor cost and shorter unit operating life. Labor cost in the United States nuclear power operation costs accounts for more than half, and the vast majority of operation units are more than 40 years old, and the maintenance cost is higher than that of China. Additionally, all plants adopt the multiunit operation and maintenance mode in China, which can also share the generation cost of each unit by sharing resources, further reducing the operation cost.

However, as society ages and people's views on employment change, the labor-centered model, which relies on experienced and highly skilled personnel, will not be sustainable for nuclear power in China. At present, the attraction to nuclear power is gradually decreasing for young Chinese workers, especially since nuclear power plants are far from the city center and the radiation working environment. People have been unwilling to work in nuclear power plants for a long time, leading to a shortage of experienced and highly skilled workers and increased human costs. According to the annual reports released by CGN, as the total number of construction and operation units increased year by year, the number of employees decreased year by year since 2017. As unit numbers and time increased, in recent years, the annual net profit margins of two major nuclear companies were presented with a downward trend in China; the decline in net profit showed that the operating cost was increasing, especially with the increase in unit operation time. In the future, combined with the increase in labor costs, nuclear power will face severe pressure from rising generation costs in China. From this perspective, although the degree of marketization in China is lower than in the United States, with the development of renewable energy and the strengthening of the electricity market, China will also face the problem of sustainable nuclear power development.

4.3. Nuclear Power Sustainability Path. Due to the growth of energy demand, the low degree of power marketization and labor costs, and the short operation time, Chinese nuclear power faces much less market competition than American nuclear power. However, this does not mean that Chinese nuclear power does not need to consider reducing generation costs and sustainable development. On the contrary, after the market-oriented reform and the 2030 carbon peak development strategy proposed by the Chinese government, clean and cheap renewable energy will have a profound impact on nuclear power operations. In particular, with the aging of units and the increase in labor cost caused by the aging society, the nuclear power operation in China will also face competition problems and the labor-centered operation model will not be sustainable. However, the cost of clean renewable energy, such as wind and solar, will still drop significantly under the promotion of large-scale promotion and technological progress. According to the current minimum guide price of 0.24 Yuan/kWh for new photovoltaic and wind power in China, the cost of nuclear power generation must be reduced by 46.51% to ensure the current profit level. As Chinese nuclear power units are still in the

Table 1: Nuclear power operation data between China and the United States.

	Parameter	China	The United States	The data source or description
	Generation ratio	4.9%	19.70%	PRIS (2022–04)
Unit	Operation unit.	54	93	
	Construction unit	16	2	
	Retired unit	0	40	
	The proportion of units operating for more than 20 years	5.56%	98.92%	
	The ratio of units operating for more than 40 years	0%	53.76%	
Performance	Capacity factor	90.81%	93.00%	NEI: NUCLEAR costs. IN CONTEXT 2021–11; annual financial report of CNP and CGN
Average generation cost	Total cost ($/MWh)	25.43	33.10	
	Fuel cost ratio	36.09%	19.61%	
	Capital cost ratio	34.85%	18.18%	
	Operation cost ratio	29.06%	62.61%	

repayment stage of principal and interest, the reduction of the cost of power generation can only be achieved by reducing the operating cost. According to the annual report CGN 2021, the gross profit margin of nuclear power is approximately 47%, the net profit margin is approximately 19%, and the operating cost represents 33% of the total cost of power generation. To make nuclear power competitive with photovoltaic and wind power, the operating cost of nuclear power must be reduced by 73% under the condition that current profitability is guaranteed and by 27% even under the condition that the company does not lose money. Clearly, under full competition in the power market, it will be difficult for China's nuclear power operations to achieve sustainable development.

In essence, under strong safety supervision, American nuclear power has missed the opportunity for technology-centered modernization. After all, the risks to safety and investment caused by technological upgrades can challenge the existing supervision mode. As a result, the United States has adopted advanced management practices to improve performance through process and operation standardization, with a large number of older plants still using outdated analog technology from the 1960s. Advanced process management and experience feedback make American nuclear power rely on a large number of experienced and skilled personnel. This labor-centered operation mode faces severe cost pressure in the context of aging nuclear power units and a sharp reduction in the cost of other clean and renewable power sources. It has become difficult to improve the operation process and methods to improve operational performance, and a large number of units have begun to retire for economic reasons, affecting the security and sustainable development of American energy and electricity, and the United States was forced to turn to the sustainable development path centered on nuclear power technology [36].

Currently, most of the nuclear units that operate in China are derived from the imported French M310 reactor, which is also essential from the United States [37–39]. Although China used advanced DCS technology, replacing most analog technology, the operation mode is the same as that of the United States, especially in nuclear safety-related design, operation, and regulation, still using some outdated analog technology and strict technical validation requirements. As a result, the application of advanced digital technology in nuclear power is extremely difficult, especially the application of wireless communication technology. Most nuclear power units do not have a communication environment for advanced digital technology applications. The on-site operation, inspection, equipment maintenance, remote monitoring, and other operations and maintenance activities are based on a large number of complex and standardized work procedures and processes through manual cooperation. Due to the existence of human error, a large number of workflows and management measures have been applied to prevent human error. Due to the limitations of the proven technical route and mode, the new technology is more to improve the existing process and mode. It makes it easy for operations and technical updates to deviate from the direction of nuclear power modernization. Several increased processes and management activities cannot substantially improve the safety level but can greatly increase human costs [40].

From the transformation of the mode of nuclear operation in the United States, it can be seen that China also needs to consider the sustainable development of nuclear power operations, especially the change of the mode of labor-centered operation. This operation model will undoubtedly bring challenges to the sustainable development of nuclear power operations in China. Therefore, according to the current situation in China and the conditions of economic, social, and technological development, the integrated operation principle and intelligent digital collaboration technology were proposed to improve the advanced level of operation monitoring, reduce the demand for highly skilled personnel, and improve performance, as shown in Figure 5. For the innovation of the national nuclear power operation digital emergency regulation system and sustainable development, the core content is to use intelligent collaboration and diagnosis of digital technology, to raise the modern monitoring level in nuclear power units and operations, overhaul, and equipment management efficiency, and to realize the automation of highly integrated ecologically people operating regulation mode. Cost savings can be

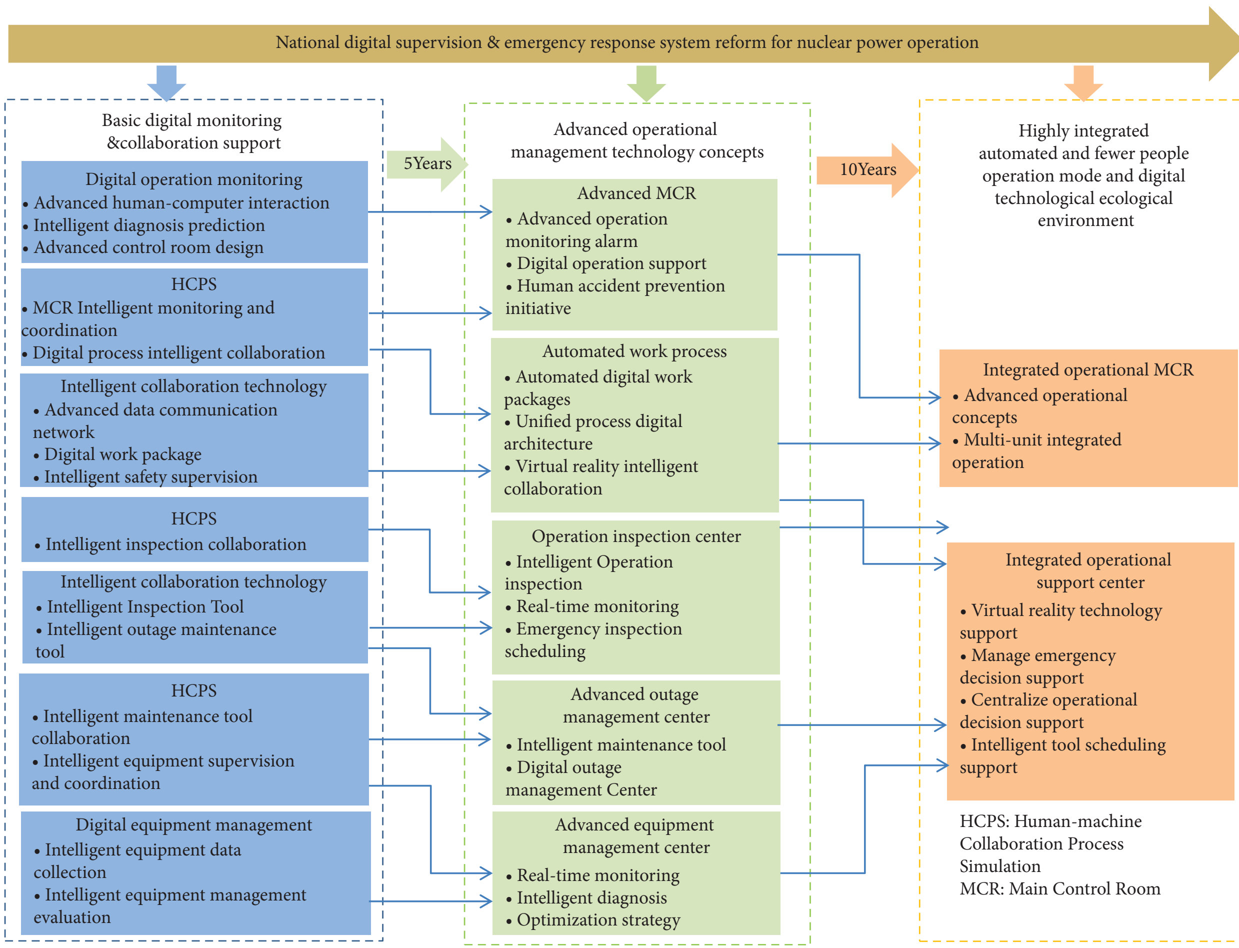

Figure 5: China nuclear power operation sustainable development path.

realized through the integrated operation mode of fewer people and intensification to deal with the problem of aging units and the increase of human costs that will lead to a sharp decline in the competitiveness of the nuclear power market in the future.

First, through advanced human-computer interaction and intelligent diagnostic development and prediction technology, advanced main control room design and intelligent DCS upgrade will be realized, the monitoring level of modern nuclear power units will be improved, and the operator error and workload risk will be reduced. For daily inspection, overhaul, equipment management, engineering transformation, and other operations, intelligent collaboration technology simulation will be carried out, and special intelligent collaboration tools and technology will be developed, while basic digital monitoring and collaboration support technology will also be built.

Second, for highly skilled personnel, such as master controller, field operator, and technical supporter, overhaul and equipment management personnel, using basic digital monitoring and collaboration support technology, integrated operation mode, and intelligent collaboration technology to develop advanced master control room, automated workflow, operation inspection center, overhaul, and equipment management center, and improve staff efficiency, personnel, load, and workflow requirements will be reduced; intelligent collaboration technology will be adopted to solidify the work experience and knowledge of highly skilled personnel, and advanced operations management technology concepts will be formed to ensure the safety level.

Third, by using advanced technology for the operational management concept to construct the integrated master control room and the operation support center, higher integration operations will be realized through intensive operations management, technology, and the manpower cost will be greatly reduced, and higher integrated automation of the operating model with fewer people and the ecological system technology will be formed, and the operational efficiency will be further increased, and the generation cost will be greatly reduced.

In essence, the path to sustainable nuclear power development in China is also the reform of the national nuclear power operation digital surveillance emergency response system. On the one hand, the transformation of labor-centered operation mode requires support from the national regulatory system and the verification of the application of digital and intelligent collaboration technology requires coordination and recognition from the national nuclear power regulatory system. The technological transformation of the nuclear power operation mode will also force the upgrading of the national nuclear power operation regulatory system. On the other hand, China has introduced the strategy of "accelerating digital development and building digital China," and the government's digital transformation is already underway [41]. In essence, national digital transformation is a process from a labor-centered mode to a technology-centered mode. In the process, nuclear power, as an important part of national energy security, will also develop its digitalization control and emergency response system and will further promote the technological transformation of digital nuclear power.

5. Conclusions

As a low-carbon, stable, and efficient energy, nuclear power plays an important role in replacing traditional fossil energy to build a globally sustainable energy system. However, nuclear power development deviated from the path to achieving the Sustainable Development Goals (SGD) of the United Nations. The main factor driving the decline in nuclear power in developed economies is the decreasing cost of clean renewable electricity, while the cost of nuclear power increases. The Fukushima disaster and the high construction cost have slowed nuclear power construction, although the growing electricity demand has not stopped developing countries from building nuclear power plants.

To achieve the goals of the Paris Agreement, the Chinese government has made great efforts to develop clean and renewable electricity and nuclear power in an orderly manner while ensuring safety. At present, the cost of photovoltaic and wind power in China is lower than that of new nuclear power. This will undoubtedly lead to a lower operating cost, especially if nuclear power participates in market transactions to form feed-in tariffs. The distance from urban centers and the radiation working environment make nuclear power less attractive to young Chinese workers, and the growing shortage of experienced and highly skilled operators will exacerbate the growth of the cost of nuclear power labor. As the population peaks, the growth of electricity demand will be curbed by aging. The reduction in electricity demand will intensify price competition in the electricity market. Compared with renewable energy, the nuclear power generation cost is higher. Under the downward trend of the feed-in price of nuclear power, nuclear power will face great competition pressure from the market in order to promote a continuous reduction in the nuclear power generation cost. As China reforms and develops, the cost of nuclear power generation will determine the level of profitability of nuclear power and the ability of construction capital to serve the principal and interest and will become a key factor restricting the sustainable development of nuclear power in China.

The operation time of nuclear power units in China is shorter than in the United States, the nuclear power operation cost is lower than that of the United States, and the market pressure is also lower than that of the United States, but the labor-centered nuclear power operation mode in China is not fundamentally different from that of the United States. Under the reform of the China electricity market, the competition for renewable clean energy power, and the aging society, it is difficult for this mode of operation to achieve the sustainable development of nuclear power in China. Therefore, regarding the change in the labor-centered mode to realize the sustainable development path, based on the operating status of nuclear power and the social development conditions in China, the sustainable development path of nuclear power in China was presented using the integrated operation principle and intelligent digital collaborative technology, thus improving the monitoring of nuclear power operation, reducing the demand for highly skilled personnel, and realizing the digital transformation of nuclear power and the technology-centered operation mode.

Data Availability

The number of nuclear power unit data supporting this systematic review are from PRIS datasets and are available at https://pris.iaea.org/pris/. The processed data and the normalized CGN nuclear power operation normalized data are available from the corresponding author upon request.

Disclosure

The scientific output expressed in this article may not under any circumstances be considered as stating an official position of China. Neither China nor any person acting on behalf of China is responsible for the use that might be made of this publication.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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