Comparison of nuclear power industry between China and the United States

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Abstract. Under of the global trend towards achieving net zero emissions, nuclear power emerges as a key clean energy source, playing an important role in the energy transition. As the world's two largest economic entities, China and the United States are leading the charge in global nuclear power development and implementation. Understanding their development through comparison is important for understanding the future of nuclear energy. The study begins with a detailed description of the evolution of the nuclear energy industry in both countries. It then discusses in depth the respective environmental impacts of the two countries, illustrating the current status and impact of technological advances in nuclear power generation, particularly Small Modular Reactors and Recycling Fuel. Subsequently, the study offers an in-depth comparative analysis of the policy support for nuclear power development, as well as the nuclear contamination regulatory laws in China and the United States. Moreover, from LCOE's viewpoint, the study analyzes and compares the economic efficiency and the differences between China and the U.S. inside different cost components. So overall, China is more competitive than the United States in all aspects of nuclear power development.

Keywords: Nuclear power industry; policy; Nuclear power technology; Development path; Economic Efficiency; Environmental impact, Small Modular Reactors; Recycling Fuel

1 Introduction

This study compares the nuclear energy industries in China and the United States. Nuclear energy is currently the most stable and efficient clean energy source for generating electricity. However, because of the risk of leaking radioactive material, nuclear energy has been controversial. Understanding the different paths taken by the two important countries in this industry can help predict the future of nuclear energy globally, as well as the energy industry as a whole.

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Overall, China has an advantage over the United States in terms of policy, government control, economic efficiency and technological advances in the development of the nuclear power industry. The thesis begins with background information on the historical development of nuclear power in both countries, highlighting the significant progress China has made in nuclear power generation since the turn of the century. On the environmental side, the study looks specifically at the environmental impacts of nuclear energy, including radioactive waste generation and contamination. On the technical side, the study further discusses the differences between the two countries in small modular reactors and fuel recycling technologies. China has made great strides in fuel recycling and is developing SMRs for a variety of uses. The study then compares the policies of the two countries. China's one-party political system and government control make planning and execution of nuclear power programs more straightforward. Chinese policies are more conducive to nuclear power development than those of the United States, which relies more on private companies for funding and subsidies and has a more diverse population. A comparison of environmental impact technologies shows that China and the United States use similar methods of nuclear waste disposal and both have mastered vitrification technology. However, China uses a more advanced closed nuclear fuel cycle system than the United States. The study also analyzes the economic efficiency of nuclear power in China and the U.S. from LCOE perspective. China's nuclear power production costs are cheaper than those of the United States by comparing the construction costs, labor, capital costs, financing costs, overnight costs, and raw material costs of nuclear power production in China and the United States.

2 Background

2.1 General Information

The nuclear power industries in the United States and China have both made great strides, despite at different times and on different ways. The United States built the world's first nuclear power plant in 1957, and the nuclear industry boomed in the following decade. Although challenges such as nuclear waste disposal, potential accidents, and environmental considerations slowed the industry's growth in the 1970s and 1980s, the United States continues to dominate global nuclear power production [1]. By 2021, there were 93 operating nuclear reactors at 55 U.S. power plants, accounting for 22% of total U.S. electricity generation. Two new nuclear reactors are currently under construction in Georgia, each with a planned generating capacity of approximately 1,100 MW [2].

On the other hand, since the turn of the century, China's nuclear energy generation has grown significantly faster than that of the United States. From 2000 to 2020, the growth rate of nuclear power generation in the U.S. was 1,713.6%, compared to China's 16,637.3%, suggesting that China's growth rate is much higher [3]. By 2023, China is expected to have 55 operating nuclear power plants with a total installed capacity of 57GW, 22 nuclear power plants under construction with a total installed capacity of 24GW, and more than 70 nuclear power plants under construction with a total installed capacity of 88GW [4].

2.2 Advanced Nuclear Technology

Some of the latest technology, such as thorium reactor, molten salt reactor and other reactor technology is still under continuous research and development. Those technologies are still immature, so this study focuses mostly on small modular reactors.

2.2.1 Recycling Fuel.

The recycling fuel plays a key role in the reuse of energy, environmental protection, and the development of national economies. Recycled fuels are made from the waste products of primary fuel combustion, such as carbon dioxide, into secondary fuels through artificial technologies, including nanotechnology, and such recycling technologies can significantly reduce the pollution caused to the environment while lowering the cost of fuel manufacturing.

2.2.2 Small Modular Reactors (SMR).

The SMR, is a type of nuclear fission reactor that is much smaller than conventional nuclear reactors. At the same time, it has significant advantages in terms of construction costs, cycle time, and land area - it can be built in a single plant and then transported, commissioned, and operated at a single designated location, and the technology is still advancing, with designs ranging from existing downsized versions to the current Generation IV design, which proposes thermal and fast neutron reactors, etc. The design of fourth-generation technology optimizes the efficiency of power generation via high-temperature steam and therefore adds significant additional economic advantages.

While such small reactors can greatly improve reaction times and save on construction time costs, they also simultaneously lose the advantage of scale, and the total amount of power output pales in comparison to conventional reactors. It must be said, however, that the economic gap created by the SMR brings immeasurable benefits to the mass production of subsequent propulsion units [5].

2.2.3 Environmental impact of SMR.

Small Modular Reactors (SMRs) are gaining traction in the global nuclear industry, with China leading in their development and deployment. The "LingLong One" in Hainan, scheduled for completion in 2022, will be the first land-based commercial compact modular reactor. In contrast, the United States has yet to operationalize any SMRs, largely due to the time-consuming approval procedure of the Nuclear Regulatory Commission (NRC) [6]. Despite this, the U.S. is preparing to build SMRs, indicating a growing interest in this technology.

SMRs can contribute to climate change mitigation and air quality improvement as a low-carbon energy source. They generate power without adding to carbon emissions or air pollution. However, the application of SMRs has sparked controversy, particularly concerning nuclear waste management. According to Lindsay Krall of Stanford University's Center for International Security and Cooperation (CISAC), most SMR designs could increase the volume of nuclear waste requiring management and disposal [7]. This is primarily due to neutron leakage, which increases radioactivity through the neutron activation process. The excess waste volume is often attributed to the use of neutron reflectors and chemical reaction fuels and coolants in SMR designs. The final composition of the waste depends on the initial fuel composition, physical fuel design, burnup, and type of reactor structural material. However, with proper design, these issues can be mitigated [8].

SMRs also bring environmental advantages, including reduced fuel consumption, decreased risk of nuclear reactor accidents, and lower water consumption. Compared to traditional plants that require refueling every one to two years, SMR-based power plants may only need refueling every three to seven years, with some SMRs running up to 30 years without refueling [9]. Furthermore, SMRs use advanced cooling technology to operate at lower water flow rates or with alternative cooling methods, thereby reducing overall water consumption. Some SMRs utilize air- or sodium-cooling technologies, which operate at high temperatures and have high thermal conductivity, allowing for quicker heat dissipation and reducing the potential risk of nuclear reactor accidents

3 Policy Comparison

3.1 General Policies and Future Plans

Due to the unique political and economic system, China's nuclear industry has developed rapidly. After World War II, China uses a single-party authoritarian political system in which the entire nation is ruled by the Communist Party, the only party that displays an observable impact on the society. Under the economic system of Capitalism with Chinese characteristics, many firms in some key industries are owned by the nation, including nuclear power. The Chinese government has absolute control over the entire nuclear industry, including all the technological investigation and infrastructure construction. The government makes direct plans regarding nuclear power.

The Chinese government makes Five Year plans that outlined the development of most of the important industries since 1953. The Fourteenth Five Year Plan outlined some principles of developing nuclear power such as safety and increasing and stabilizing uranium supply, as well as the development goal of eight specific provinces. For example, the local government of Guangdong Province will initiate the construction of Taipingling Nuclear Power Plant Phase I Project, Lufeng, Lianjiang and Taipingling Nuclear Power Plant phase II Project and establish medical base focusing on treatment of nuclear radioactivity near those nuclear power plants; the institute in Hainan Province will focus on the application of nuclear power in the environmental and medical field as well as development of maintenance services [10]. Based on the implementation of those Five-Year plans in the past, it's relatively promising that these plans would become reality in the near future.

The Chinese government supports the nuclear industry in multiple ways. First, nuclear power plants receive a lower price and a designated share of electricity consumption. Second, the government provides capital of lower cost through policy bank. In addition, the government helps to arrange land and resources for the power plant [11]. The government is either directly providing aid or pushing the development through other governmental organizations or companies, which has been shown to be generally functional.

The scenario looks a lot different in the US because the fundamental difference in the political and economic system. Two parties, the Democrats and the Republicans, impact the nation the most, while this factionalism often makes it difficult for certain policies to maintain or develop consistently as there would often be opposition from the opposing party through the pressure of other branches of the government. The economic system is the traditional capitalist system which the government would not often interrupt. As a result, the government has no direct control over the nuclear industry, meaning that the government can only encourage the development of nuclear power by providing funds or subsidies to the companies which actually carries out projects and constructions.

Unlike the role of government in the development of nuclear industry in China, the US Department of Energy (DOE) funded several “domestic advanced nuclear technology projects” with approximately $18 million and $26.9 million in 2018 and 2020. Those projects belong to one of the three categories: First-of-a-Kind (FOAK) Nuclear Demonstration Readiness Project-to address advanced technology to existing plant; Advanced Reactor Development Projects-to support advanced technology design; and Regulatory Assistance Grants-to resolve design regulatory issues [12]. In addition, DOE announced $540 million in funding 54 universities and 11 natural laboratories as well as $40 billion loan guarantees according to the Inflation Reduction Act passed in 2022 [13]. To deal with the problem of retirement of many nuclear power plants that were built much earlier, six states have “intervened to provide financial support for 16 nuclear reactors—representing 15,734 MW of electricity generation capacity (16.5% of total current U.S. nuclear capacity)” in forms such as power purchase agreement, zero emission credit and nuclear resource credit.

3.2 Environmental Policies

The Chinese government is now working to implement this mandate the Vitrification of radioactive nuclear waste. An operating unit of a nuclear installation shall, after treating the radioactive solid waste generated by it and the radioactive waste liquid that cannot be purified and discharged, transform it into stable and standardized solid waste, Timely delivery to radioactive waste disposal units for disposal.

As the safety and environmental friendliness of nuclear power in the United States has evolved, the relevant laws have been relaxed. The ADVANCE Act stated that the U.S. will support the creation of the next generation of nuclear reactors, including fusion reactors. [14]. The U.S. does not currently have significant use of nuclear energy because of some nuclear waste concerns. If technology can be developed to reduce waste, these concerns might diminish. Meanwhile, the U.S. Department of Energy's goal is to develop safe, clean, and affordable nuclear energy. So, the US is going to build advanced nuclear reactors in the foreseeable future.

4 Evaluation of Industrial Competitiveness

In undertaking a detailed assessment of industrial competitiveness, it is necessary to consider a number of perspectives. The study will delve into four main dimensions: policy, economic efficiency, technology and environmental impacts. Each dimension interacts with the others to influence and shape the landscape of industrial competitiveness.

4.1 Policies

The policies and government in China and the US share some similarities. Both governments are proactive in the development of nuclear energy with similar directions of constructing more power plants and advancing nuclear technology. There are regional restrictions in both countries, only eight provinces in China and 28 states in the US have nuclear power plants. The development goals, advancing technology and constructing more power plants, are the same based on scientific researches.

Both countries have its own advantage in nuclear development from the perspective of the government. The single-party political system and ideology of compliance allows the policies to be issued and implemented fairly easily that the government directed all the projects. By contrasts, the US government only provided funds or subsidies (in various forms) to support the institutions without limiting them too much. This system encourages innovation to some extent. Based on the fact that China is about two years ahead of the US in the development of small modular reactors, the Chinese system seems to be more effective as there isn’t much opposition.

Besides, the difference in electricity generation share of nuclear power in future plans may also contribute to difference in development. According to the US Energy Information Association, the share of nuclear power in electricity generation would gradually decrease comparing to the increase of combined shares of other renewables (solar, wind and hydro) whereas China plans to increase that from 5% currently to 13.5% in 2035 [15, 16]. The difference in determination and focus also explains the slow growth speed of nuclear power in the US as the government emphasizes it less comparing to other clean energy sources.

Another difference would be the public opinion. More people support the development of nuclear power (70.3% in China and 35.0% in the US) than those who oppose (6.0% in China and 26% in the US). Men were generally more supportive than women. The lower percentage of support in the US could be accounted by factionalism that Republicans and the Republican-leaning group are far more likely to support nuclear power and to recognize the urgency of solving climate change [17, 18]. Based on these data, it’s reasonable to conclude that Chinese are more supportive of the government than Americans in general, which could be a factor that slightly impacts the policies.

Consequently, the policies in China drives the nuclear energy industry better than those of the US, which contributes to the conclusion that the nuclear energy industry in China exhibits to be more competitive than the US.

4.2 Economic Efficiency

While assessing the cost and benefits equilibrium, the levelized cost of electricity (LCOE) have been implemented and referred as the most commonly used formula for investors to consider whether such construction is worth the cost. Typically, LCOE includes the cost of raw material, maintenance, operation cost and other construction cost. In addition, LCOE also considers the total power generated during the lifespan of such plant, divide the overall economic cost of the plant. Therefore, the cost per unit (megawatt/ hour) electricity could be calculated throughout the implementation of LOCE. The bright side of such policy is that it considers the capital component within the investment as cost instead of the simple comparison on power delivering efficiency or so called “overnight” cost. In this passage, the comparison of cost-benefits efficiency would be driven out from the perspective of LCOE.

By 2021.9 the price of 1kg uranium as the applicable material for nuclear reactor is around $1663. Relatively, the cost of uranium as a raw material is fixed, the significant different is going to be the processing technology to transfer them into the usable material. Until 2023, China is still not able to produce enough uranium, with solely 1900 tons U3O8 productivity while the requirement is 9500 tons. In 2021, Chinese uranium import cost was around $1.31 billion, and this number is still going to expand certainly [19].

In contrary, China managed to show advantages on its low “overnight cost” comparing to U.S and other nuclear countries. According to World Nuclear Association, Chinese CPR-1000’s overnight cost is $1748 and AP-1000’s overnight cost is $2302, which are the two most widely implemented reactors in China. Comparing to United States’ third plus generation reactors’ $3382/kW and $3860/kW for French EPR reactor. Such advantages indicate that Chinese nuclear reactors are durable to operate in a relatively high capacity for a certain long periods. In addition, the cost of repairing or maintenance would also be significantly lower in terms of the time it needs to cease operating.

Under the perspective of investment cost, the fee could be largely different from country to country. China for instance, during the construction of 3rd generation nuclear reactor, in this case CAP-1000 and Hualong One; the entire civil construction fee (without paying related interest and material fee) took around 14.8 (CAP-1000) and 15.3 (Hualong One). Surprisingly, with the government’s policy support, the value-added tax receives a good amount of deduction, which bring the entire cost down 588-1026 yuan ($84-$146.6) per kW [20]. In comparison, United States’ similar subsides policy such as production tax credits (PTC), which will be deployed after 202, offers a $3-$15 subsides per MWh (notice *Wh is different with *W). It is hard to tell which country offers a more generous subsides on nuclear energy industry, but the process of requesting such subsides are relatively easier for Chinese organization to get approved by the government.

United States on other side, which owns the richest nuclear power deliver with 772,221 GWh produced in 2022. Such producing power nearly doubles more than Chinese nuclear energy productivity. According to United States Department of Energy and other related policies and plans; the motivation for U.S to continuously investing enormous amount of funds into nuclear energy industry could be distributed into various of fields and generates certain level of social welfare. Unlike Chinese nuclear department's social recruitment requirement, United States offers a less complicated and friendly list in terms of academic degree, experience, and other standard. Under such policy. According to World Nuclear Association's data, in 2015, Entergy's Indian point 2&3 reactors in New York State creates annually $1.6 billion income for state and $2.5 billion to the country, offered around 11,000 job positions during its entire lifespan[21]. Compared to Chinese Ningde Nuclear Reactor, which starts commercial operation since 2016, expected to be creating 10,000 job opportunities and generates more than $1.5 billion tax income [22].

According to WNA's Nuclear Power Economics and Project Structuring in 2017; the cost of newly constructed nuclear power plants is impacted 60% from their capital cost in LCOE [23]. Since nuclear energy costs mostly on its capital, in this case, the cost of nuclear varies a lot comparing to other power sources such as CCGT (natural gas) and coal etc. From the data provided by WNA, when the discount rate is lower or equal to 3%, the nuclear energy takes the lowest energy cost from all. When the discount rate reaches 7%, it shares relatively the same cost with coal, and higher in 10%. The increase in costs would be around two to three times higher from 3%-10% discount rate due to the capital dense that nuclear energy has. In this case, despite the discount rate difference; United States has relative the same cost per megawatt hour (/mWh) with China ($43.9 and $49.9). However, when the discount rate reaches 10%, the overall cost after combing and considering other cost components from LCOE algorithm for United States to produce one mWh could be nearly 20% higher than Chinese ($98.6 over $82.1) [21]. This problem is probably due to the subsides and interest rate polices; since nuclear energy businesses are all operated by government in China.

As the information provided above, China is currently owning the better position with a leading production efficiency from various perspectives. Despite China is facing the reality of lacking in uranium exploit and reproduction, direct import from other countries could safe the mining cost from a certain degree. In addition, with different corresponding policies and unique operation model with which directly monitored and controlled by government, the cost in tax and funds could also be reduced. In conclusion, with the rapid development in Chinese nuclear industry, China indeed shares some of the advantages in terms of policies and construction costs over United States, which make the future of construction operable and clear.

4.3 Technology

The "Linglong-1" has a small footprint, short construction period and high efficiency that could be of great use to China's nuclear energy. Due to China's complex land types and dense population, building traditional large reactors in energy-rich coastal areas may not only have side effects on the environment, but small modular reactors (SMRs) are well adapted to China's complex environment. The International Atomic Energy Agency defines SMR as having a power of less than 300,000 kilowatts, condensing all the functions of a third-generation reactor and maximizing technological innovation.

The U.S. Nuclear Energy Administration recently announced plans for the construction of the first small modular reactor, which is expected to be completed in 2029.

4.4 Environmental Impact

China and the United States have similar approaches to nuclear waste by using dry drums or tanks, keep the nuclear waste underwater and choose to vitrify the nuclear waste. The US does not have a central repository for nuclear power plant waste, which is usually stored within the facility. This waste is kept underwater or in dry casks or canisters [24]. At the same time, both countries master the technology that melting nuclear waste into glass. Noticeably, China is currently adopting to the closed nuclear fuel cycle system [25]. In which the leftover uranium and plutonium isotopes in used fuel are removed to reuse it as fuel, as China's primary goal is to build an advanced nuclear industry. This technology will help China to better deal with nuclear waste. Even the US has Fuel Recycling, but China's closing Fuel Recycling Further develops on this concept. the difference is Fuel Recycling is to Recover fissile materials, whereas, Close Fuel Recycling: Reuse fissile materials multiple times in the same reactor, conserving resources. Therefore, from the fuel cycling perspective, China is more advanced.

5 Industry Outlook

5.1 Balancing Investment Trends

The nuclear energy landscape is shaped by the interplay of various factors, including cost-efficiency, uranium production, and international cooperation. China's nuclear energy development exhibits a slight advantage over the United States in cost-benefit efficiency, albeit with a deficiency in uranium production. Future prospects suggest an increased likelihood of Sino-American collaboration in technology and resource exchange, such as uranium import and export. For the United States, enhancing subsidies for nuclear energy and related labor market welfare could be beneficial. Since 2019, uranium production and exploitation have declined by over 50%. Reviving the production rate of raw materials is a pressing issue for the future.

China, on the other hand, faces a high demand for ingredient production technology. The country aims to phase out aging pressurized water tanks in favor of more efficient reactors. As China's economic growth decelerates, electricity demand follows suit. Balancing investment in nuclear plants is crucial to prevent a slowdown in nuclear energy development.

5.2 Pursuit of Safer, More Environmentally Friendly Nuclear Power

Existing nuclear energy technology is not safe and efficient enough for large-scale investment by the United States and China.

The latest Generation IV gas-cooled fast reactor technology lacks in investment efficiency and marginal benefits compared to Generation III nuclear reactors. Although

China's fourth-generation gas-cooled fast reactor technology, in combination with reactors under construction and in operation, most of them are third-generation AP1000 and CPR1000 nuclear reactors. New Generation IV nuclear reactors, and related developments may need to await new solutions for further implementation.

Fuel recycling is not effective enough. Priority continues to be given to the adoption and development of safety and security measures and technologies to increase the safety of power generation and reduce accidents and nuclear proliferation.

China has realized technological innovations in the SMR industry that could significantly alleviate China's energy problems. While the U.S. has also invested resources in the SMR industry, China has established a self-sufficient industry and has a technological advantage over the United States.

6 Conclusion & Discussion

In the study, it have summarized the development and differences between the nuclear energy industries in China and the United States, revealing some notable differences and similarities. In terms of policy, China's authoritarian one-party political system and centralized control of the nuclear industry have led to more efficient planning and implementation of nuclear programs. The government's five-year plans and direct involvement in decision-making have contributed to the rapid growth of China's nuclear industry. In contrast, the U.S. democracy and market-driven approach have led to a more diverse energy portfolio, with nuclear energy facing challenges in competing with other renewable energy sources, and nuclear energy facing challenges in obtaining sustained support and funding.

China has made significant progress in its focus on advanced nuclear technologies such as small modular reactors (SMRs) and nuclear fuel recycling. The deployment of the small modular reactor, Linglong-1, demonstrates China's commitment to innovation and its potential to become a global leader in nuclear technology. In contrast, the United States is still in the early stages of implementing small modular reactors, facing uncertainty and controversy over waste management and economic viability.

In summary, China's nuclear energy industry currently demonstrates a higher degree of competitiveness than that of the United States in terms of growth rate, technology development, and policy support, but both China and the United States have their own strengths and challenges. The continued development of nuclear energy in China and the United States is important to the global shift to a cleaner, more sustainable energy future.

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