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STATE-OF-THE-ART PAPER

Implementing nuclear power plants (NPPs): state of the art, challenges, and opportunities

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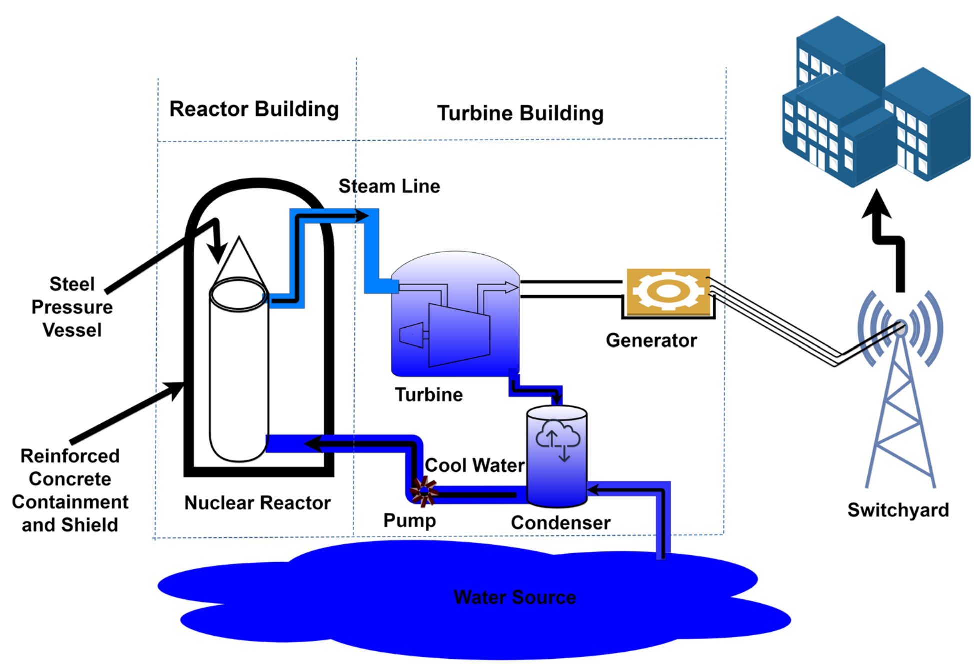
Abstract
Energy savings are a key issue in modern society. Nuclear energy may be a solution to provide clean power. Nuclear power plants (NPPs) use nuclear fission to generate electricity. There are numerous challenges to overcome for successful implementation of NPPs. This study presents an up-to-date overview of the principal research topics and trends within the NPP research domain, with the purpose of identifying opportunities and obstacles in NPP projects. Some of the challenges, including technological challenges, economic challenges, institutional/governance challenges, and social challenges, are examined, and the future of NPPs is discussed, including (i) the history of NPPs; (ii) the benefits of NPPs; (iii) major challenges in NPP construction; (iv) a review of the current state of the art for implementing NPPs; (v) the most important opportunity for implementing NPPs; (vi) the economics (life cycle costing) of nuclear energy; (vii) a comparison of NPP and renewable energy operations; (viii) different operational constraints for NPPs compared to other power plants; and (ix) nuclear energy for sustainable development. Issues in NPP construction and possible solutions are also addressed.

Graphical abstract



Keywords Energy sustainability · Renewable energy · Nuclear power plants · Nuclear industry · Nuclear energy

Extended author information available on the last page of the article

Introduction

Nuclear power plants (NPPs) use nuclear reactors and the Rankine cycle to produce electricity; the heat produced by the reactor turns water into steam, which spins a turbine and generator [1]. For a variety of factors, industry is continuing to lag behind in implementing NPPs. The nuclear industry is continuously striving to improve life cycle costing for (including design, construction and operation) of NPPs using technological development toward sustainability, as shown in Fig. 1. The nuclear power is a vital economical source when generating electricity integrating the benefits of the security, reliability, virtually zero greenhouse gas emissions, and cost-competitiveness. NPPs provide electricity as required [2]. A nuclear reactor in an external combustion engine produces steam, which can spin turbines and run a generator; the heat created by fission produces steam, which can spin turbines and run a generator. Despite the fact that there are several different types of reactors and nuclear reactions, all NPPs produce steam [3]. Solar, wind, geothermal, natural gas, coal, biomass, and petroleum power plants are all subject to different operating constraints than NPPs. The primary goal

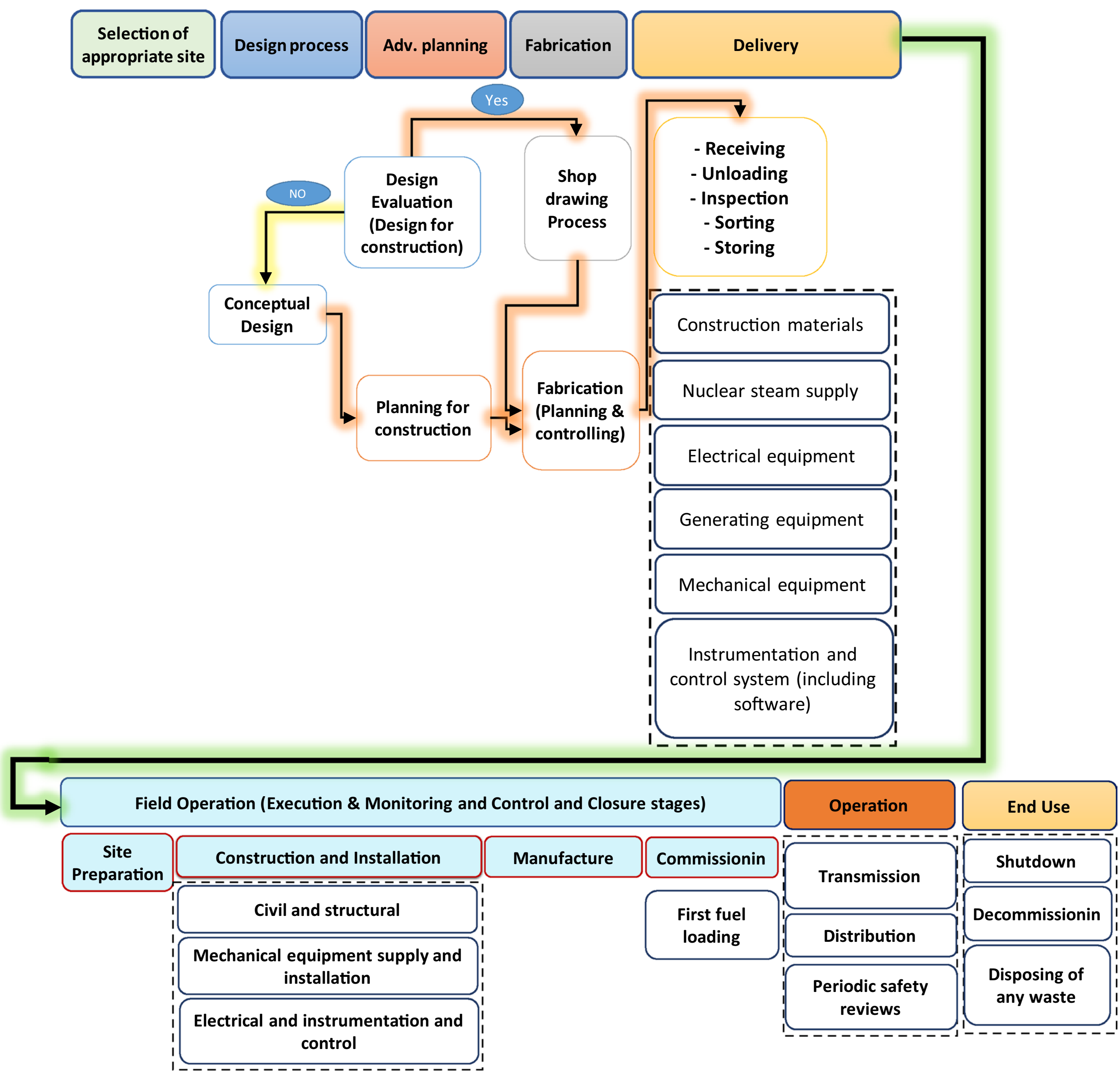


Fig. 1 Life cycle of a NPPs programme (Process for Construction of NPPs)

of this research is to recognize opportunities in addition to obstacles in an NPP project (technological challenges, economic challenges, institutional/governance challenges, and social challenges).

As shown in Fig. 2, the main components of an NPP are:

- Containment structure—Reactor building (nuclear reactor)
  - Reinforced concrete containment and shield
  - Steel pressure vessel
- Turbine building
  - Turbine
  - Condenser
  - Pump
  - Generator

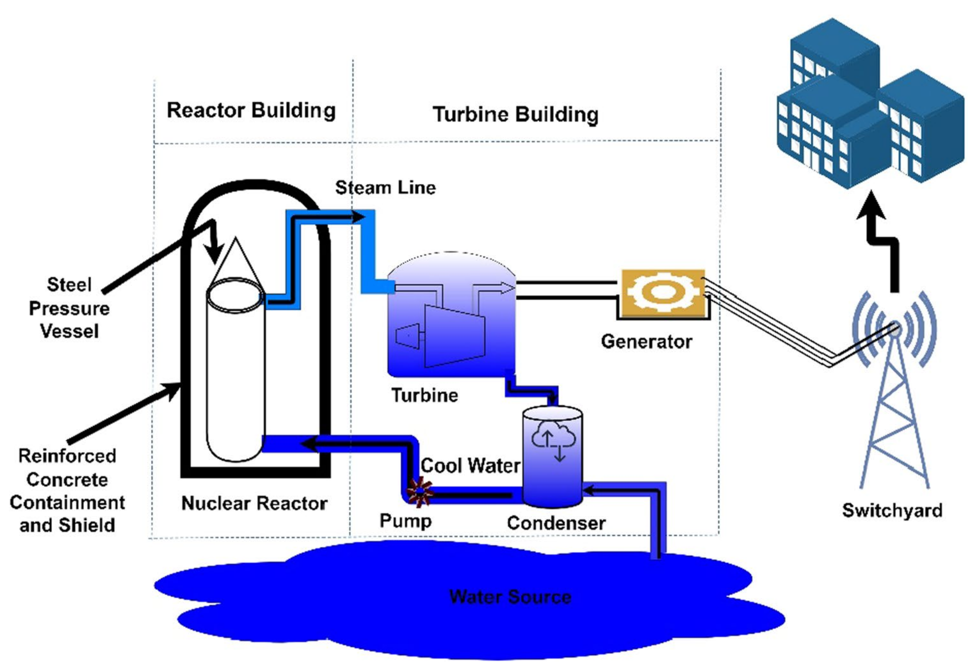
Data collection and methodology

The primary data for this study were assembled from engineering databases, international journals, and conference proceedings. This review is based on articles retrieved from respected academic journals within the NPP domain through the end of February 2021. Firstly, articles were searched using a diverse combination of key phrases, including NPP, renewable energy, energy sustainability, nuclear energy, civil engineering, and environmental engineering. Based on the findings of the first round, a second round was conducted to remove irrelevant papers by manually filtering papers related to NPPs in the energy field. To ensure that the papers were within the domain of energy sustainability and nuclear energy, the authors read the abstract of each paper. After two rounds of filtering, journal papers were classified into nine categories: (1) the history of NPPs; (2) the benefits of NPPs; (3) major challenges in NPP construction; (4) a review of current state of the art for implementing NPPs; (5) the most important opportunity for implementing NPPs; (6) the economics (life cycle costing) of nuclear energy; (7) a comparison of nuclear power plant operations with renewable energy; (8) different operational constraints for NPPs; and (9) nuclear energy: toward sustainable development. Many journals are included in this review, covering a broad range of research fields, mostly related to NPPs, renewable energy, and energy sustainability.

A History of nuclear power plants

On September 3, 1948, electricity was produced for the first time by a nuclear reactor at the X-10 Graphite Reactor in Oak Ridge, Tennessee, United States; this was the first nuclear power station to generate electricity for a light bulb [4, 5]. On December 20, 1951, at the EBR-I experimental station near Arco, Idaho, a second, larger experiment was performed. The Obninsk NPP, which was the first nuclear power plant to produce electricity for such a power grid, came to life on June 27, 1954 in Obninsk, Soviet Union [6]. Calder Hall, the first full-scale power station in the United Kingdom, started up on October 17, 1956 [7]. Nuclear power systems of four generations are currently in operation

Fig. 2 Shows the basis of a Nuclear Power Plant



around the world, originating from designs first produced to serve naval use in the late 1940s. Table 1 shows a schedule of plants under construction that until November 2010 [8].

Benefits of nuclear power plants (NPPs)

The renewal license for the current fleet of US nuclear power plants, as well as the implementation of cost-competitive advanced light-water reactors, was considered. The least-cost estimates for the electricity energy sector for fossil fuel plants, renewable energy sources, and nuclear power plants were evaluated [10]. The study took into account the effects of greenhouse gas emission restrictions. It was determined that installing up to 300 additional nuclear power plants in the United States by 2025 would be cost-effective in achieving the target of reducing emissions to 1990 levels by 2010 and after it [11]. Nuclear power produces almost 11% of total global electric power, with both the United States (33%) and France (17%) being the highest and leading producers [1].Germany, Russia, South Korea, Canada, as well as China are among the other famous producers of nuclear power [12]. East Asia is home to the majority of the world's largest nuclear power plants (in terms of net capacity). Following the Fukushima nuclear disaster in 2011, regular inspections and safety measures at large-capacity nuclear power plants were increased [13], as shown in Table 2. Nuclear power faces a number of challenges, including economics, catastrophic accidents, and the disposal of nuclear waste [14]. There are approximately 100 additional power reactors on order or scheduled, with a gross profit capacity of approximately 110,000 MWe, and more than 300 have been proposed. Nuclear power is expected to contribute about 8.5% of global power production in 2040 [15]. Table 3 shows the data visualization for worldwide nuclear power statistics. The charts in Fig. 3 show variations in nuclear production by country and year. According to Ref. [16], the

Table 1 Global NPP construction [9]

Reactor designs	China	France	Japan	Korea	Russia	Other Countries	Total GW
Generation 2							
CPR (1000) (Gen 2)	18						19.4
CNP series (Gen 2)	3						2
OPR (1000) (Gen 2)				4			4
V.V. ER series (Gen 2)					7	4	12.3
Generation 3							
A PR (1400) (Gen 3)				2			2.7
A BW R (Gen 3)			2			2	5.4
A PW R (Gen 3)			2				3.1
Generation 3+							
A P-1000 (Gen 3+)	4						4.8
EPR (Gen 3+)	2	1				1	6.6
Subtotal	27	1	4	6	7	7	
Total							60.3

Table 2 Top NPPs by capacity [13]

Sr. No	Name	Location	Nte Capacity
1	Kashiwazaki-Kariwa NPP	Japan	7965 MW
2	Bruce Nuclear Generating Station	Canada	6430 MW
3	Hanul NPP (Ulchin NPP)	South Korean	6189 MW
4	South Korea's Hanbit NPP (Yeonggwang NPP)	South Korea	5899 MW
5	Zaporizhzhia NPP	Ukraine	5700 MW
6	Gravelines NPP	France	5460 MW
7	Paluel NPP	France	5200 MW
8	Cattenom NPP	France	5200 MW
9	Yangjiang NPP	China	5000 MW
10	Shin Kori NPP	South Korea	4748 MW
11	Fukushima Daini (Fukushima II) NPP	Japan	4268 MW
12	Hongyanhe NPP	China	4244 MW

Table 3 Shows the data visualization for statistics on nuclear power in the world [16]

State or region	The percentage of electricity produced by nuclear power. (%)		Electricity produced by nuclear power (billion kWh)	
	2018	2019	2018	2019
Argentina	4.7	5.9	**6.5**	**7.9**
Armenia	25.6	27.8	**1.9**	**2**
Belgium	39	47.6	**27.3**	**41.4**
Brazil	2.7	2.7	**14.8**	**15.2**
Bulgaria	34.7	37.5	**15.4**	**15.9**
Canada	14.9	14.9	**94.5**	**94.9**
China				
– Mainland	4.2	4.9	**277.1**	**330.1**
– Taiwan	11.4	13.4	**26.7**	**31.1**
Czech Rep	34.5	35.2	**28.3**	**28.6**
Finland	32.4	34.7	**21.9**	**22.9**
France	71.7	70.6	**395.9**	**382.4**
Germany	11.7	12.4	**71.9**	**71.1**
Hungary	50.6	49.2	**14.9**	**15.4**
India	3.1	3.2	**35.4**	**40.7**
Iran	2.1	1.8	**6.3**	**5.9**
Japan	6.2	7.5	**49.3**	**65.7**
Korea, S	23.7	26.2	**127.1**	**138.8**
Lithuania	0	0	**0**	**0**
Mexico	5.3	4.5	**13.2**	**10.9**
Netherlands	3	3.2	**3.3**	**3.7**
Pakistan	6.8	6.6	**9.3**	**9.1**
Romania	17.2	18.5	**10.5**	**10.4**
Russia	17.9	19.7	**191.3**	**195.5**
Slovakia	55	53.9	**13.8**	**14.3**
Slovenia	35.9	37	**5.5**	**5.5**
South Africa	4.7	6.7	**10.6**	**13.6**
Spain	20.4	21.4	**53.4**	**55.9**
Sweden	40.3	34	**65.9**	**64.4**
Switzerland	37.7	23.9	**24.5**	**25.4**
UK	17.7	15.6	**59.1**	**51**
Ukraine	53	53.9	**79.5**	**78.1**
USA	19.3	19.7	**808**	**809.4**
Total	**707.4**	**714.1**	**2563.1**	**2657.2**

greatest nuclear production occurs in the US (809.4 billion KWh), followed by France (392.4 billion KWh), and mainland China (330.1 billion KWh).

Major challenges in NPP construction

All countries face problems in NPP construction according to the life cycle of an NPP program. The major challenges in NPP construction, such as construction cost, construction technology, and safety, are analyzed and discussed in this section.

Construction costs

Table 4 shows the costs associated with nuclear power. The most important assumption with the greatest impact concerns the construction cost. Construction costs vary greatly between regions because conditions differ, as do preferences concerning the quality, model, and design of NPPs [17, 18]. The charts in Figs. 4 and 5 show variations in nuclear production by country and year.

Cost overruns in nuclear economics [20]:

- Almost all nuclear reactors incur cost overruns.
- Nuclear cost overruns are universal.
- Cost overruns are much greater for nuclear power than for other energy sources.
- Nuclear cost overruns are heavily influenced by interest costs and time overruns.

Nuclear construction technologies

Advanced nuclear construction technology must be researched, to assist US agencies in designing successful nuclear construction policies, an initial understanding of the existing strengths and deficiencies of US nuclear construction technologies was given [21]. Distinct characteristics of NPP construction were explored to build a technique for selecting appropriate places for linear scheduling in NPP construction through a case study [22]. A 4-D CAD-based evaluation system was developed that automatically calculated utilization rate transitions for planning crane deployment in NPP construction [23]. A method for defining delay causes in operable NPP projects was presented [24]. An innovative prevention method for hydrogen–air deflagrations in nuclear power plants was suggested and built by a series of field trials involving different-sized explosion vessels to avoid huge radioactive dispersion into the environment [25]. By proposing and validating an unhealthy action model to forecast mistakes and failures at NPPs, researchers looked into worker attitudes and perceptions. Policymakers should concentrate on strategies to enhance the perceived utility, ease of use of job laws, and encourage a healthy behavior toward safety and security in order to reduce mistakes and risks [26–30].

Safety concerns

For all nuclear power plants, operation and maintenance protection is a top concern. The nuclear industry is constantly working for better safety in the design, production, and maintenance of nuclear reactors by technical advancements. After

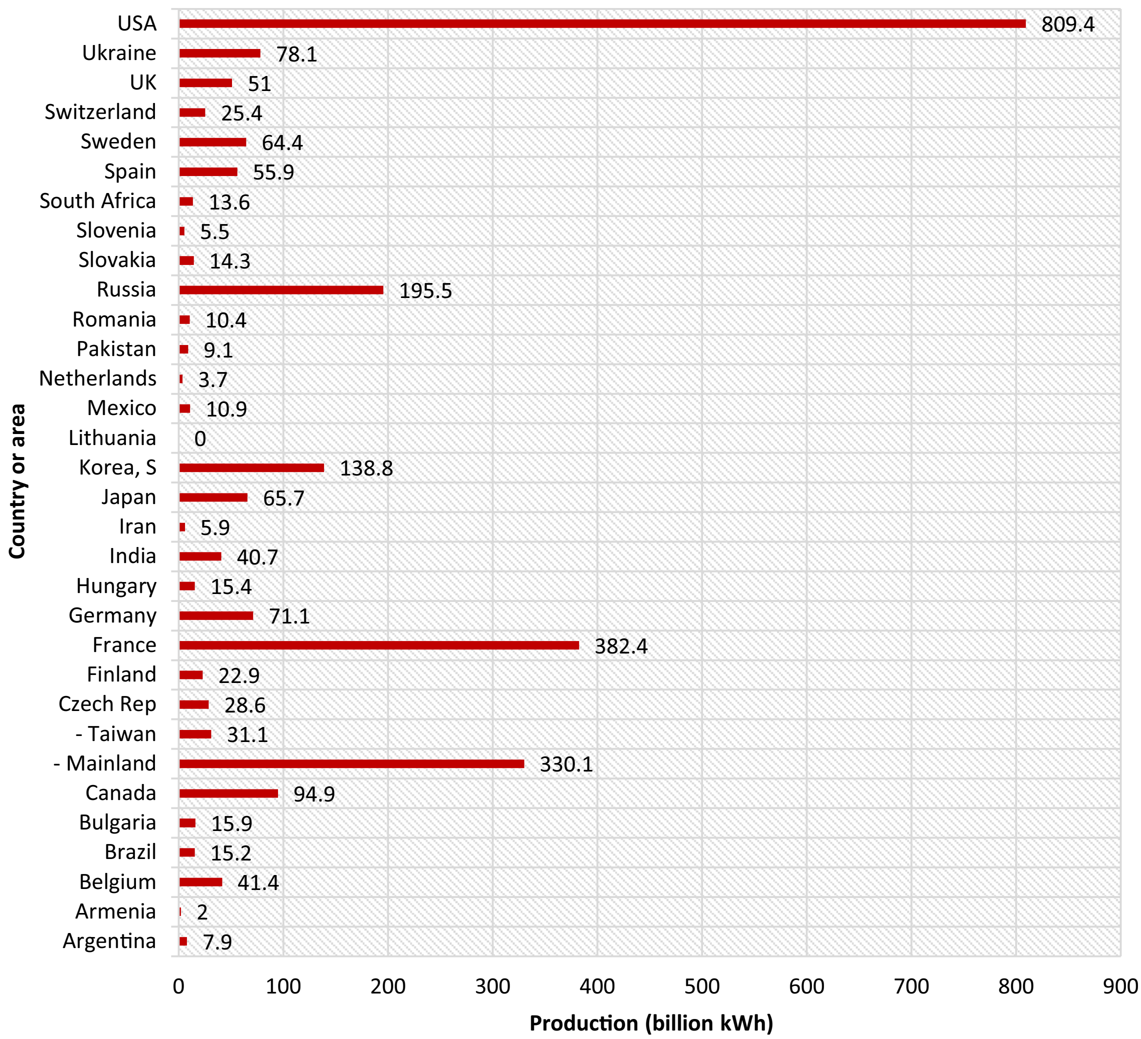


Fig. 3 Nuclear generation production (billion kWh) by Country 2019 [16]

Table 4 Assessing the costs of nuclear power

Capital costs ($ per kW)	• Cost of site preparation
	• Cost of construction
	• Cost of manufacturing
	• Cost of commissioning
	• Cost of financing
Plant operating costs	• Cost of operations and maintenance ($ per MWh)
	• Fuel cost ($ per MWh)
External costs	• Health and the environment
Other costs	• System costs and nuclear-specific taxes

the Chernobyl crisis, there have been 57 nuclear-related accidents, with 56 (out of 99) occurring in the United States [31]. The Fukushima Daiichi nuclear tragedy (2011), the Chernobyl disaster (1986), and the Three Mile Island explosion are all major nuclear power plant disasters (1979). The aim of all advanced reactor concepts is to improve safety; the concepts can vary, but the goal remains the same. The overall evaluation of the reactor is much more necessary than the evaluation of particular units, parts, or steps [32–34]. The safety of NPPs was evaluated using a Global Safety Index that included three indicators: the possibility of an accident, the efficiency of the safety mechanism during an

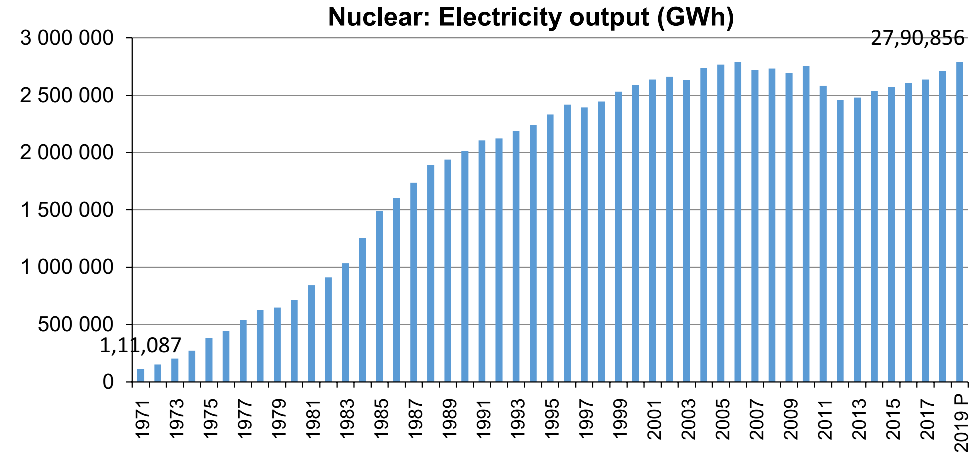


Fig. 4 Nuclear generation [Production (billion kWh)] by Year in the World [19]

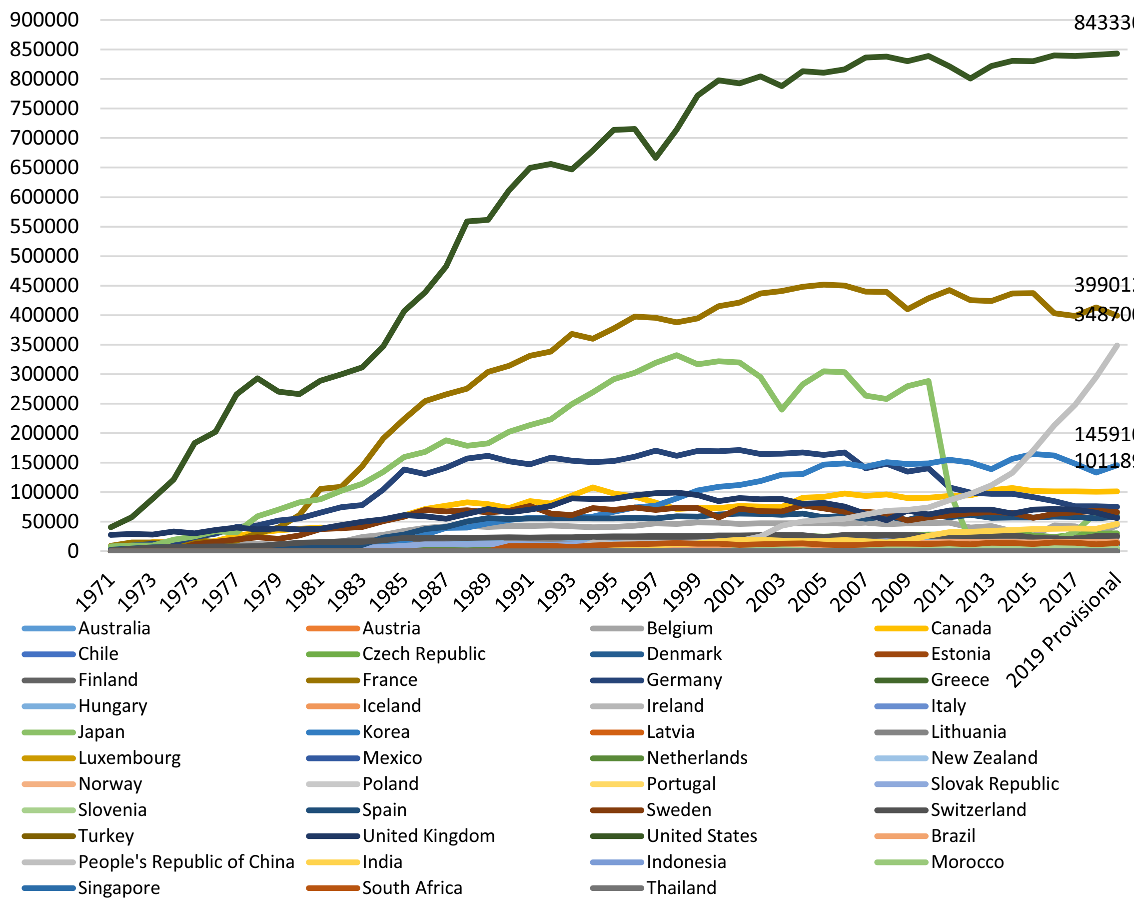


Fig. 5 Nuclear Generation [Production (billion kWh)] by Country in the World [19]

accident, and the effects of an accident. The Global Safety Index was created by monitoring the safety system's performance during a design-based accident, such as a coolant failure accident [35, 36]. The method of fire safety based on efficiency was implemented. The system of fire probabilistic safety evaluation and the fire protection model in a nuclear power plant (NPP) were mentioned [37]. Both potential leakage paths were investigated, as well as studies of the protective measures used in the design and construction of nuclear desalination plants. Innovative solutions were proposed, such as the use of heat pipes. For 250 demonstrated reactor-years, experience with commissioned programmers and procedures relating to commodity water safety revealed no cases of pollution. A list of practical measures and concepts used in nuclear desalination plants to ensure that the product water remained free of radiation contaminants [38]. The global energy transformation model was used to conduct scenario research. Alternative fissile material manufacturing approaches and global nuclear technology diffusion are the only ways to make a long-term approach to climate change mitigation by nuclear power. A long transition period is expected due to the accumulation of breeder reactor systems and large-scale use of enrichment technologies, as well as the associated proliferation risks [39, 40]. The safety appraisal method used in Lithuania during the construction of the Ignalina NPP's first decommissioning and decontamination project was presented [41]. The results of a statistical study of 216 nuclear-related accidents and incidents (happenings) are collected. Despite major changes in the aftermath of previous disasters, it is assumed that with 388 reactors in service, a Fukushima-level (or maybe more costly) occurrence happens every 60–150 years. Furthermore, it was discovered that the total cost of activities per year was nearly equivalent to the cost of building a new factory [42]. A statistical analysis of the risk of nuclear power systems was carried out. A list of nuclear disasters and accidents double the size of the previous best dataset was given and evaluated [43]. Domain conditions, obstacles, and possible solutions for implementing a human-centered automation system that efficiently supports resilient NPP outage management have been established [44]. The Severa decision support system is still being developed, with the goal of assisting the decision-making team during an accident or training exercise [45]. The new approach to fusion safety and methods of accident detection is explored as well as the core safety problems relating to fusion power [46].

Design lifetime

The stability and work of the equipment and components for extended life is verified at Paks NPP in order to prolong the operating time beyond the designed lifespan. Paks NPP continues to be a stable source of energy [47–49]. Power measurements for Paks NPP WWER-440/213 units were used to define, assess, and verify the basic aspects of reconstituting time-limited ageing [50]. In a stable NPP service, the refuelling time is crucial. In the safeguard procedure, the operator will evaluate the relative values. A higher value indicates protected power service, while a lower value may mean danger [51, 52]. A new design for offshore nuclear power plants was proposed, with upgraded safety features. It was planned to install a nuclear power plant on gravity-based systems, which are commonly used offshore structures. A large-scale land-based model APR1400 NPP, the newest NPP model in the Republic of Korea, was mounted on a gravity-based platform with minor changes to the initial APR1400 [53, 54] to show the concept's viability. It's crucial to boost nuclear power equipment's reliability, prolong its life, and refine its frameworks. Many researchers have explored fretting wear, fretting fatigue, and fretting corrosion activity in nuclear power equipment in past few decades [55]. Aging management and technical obsolescence management are becoming increasingly important in the operation of PWR reactors for more than 60 years, but particularly exceeding sixty years [56].

Review of current state of the art in implementing NPPs

The economics of nuclear power involve capital costs, plant operating costs, external costs, system costs, and nuclear-specific taxes [57].

- Capital costs.
- Plant operating costs.
- External costs.
- Other costs.

Wireless devices were used in a research and development project funded by the US Department of Energy's Small Business Innovation Research program to track equipment conditions and other applications in nuclear power plants [58]. The European Clearinghouse on Operational Experience for Nuclear Power Plants conducted a report on topics relating to the design, commissioning, and manufacturing of nuclear power plants. Civil engineering, electrical components, instrumentation, and control are subdivided into the key categories of design, production, and commissioning [59]. A method for estimating the formation of compressive strength in young concrete used in NPP construction was suggested in another study. Three representative mixes were selected and tested under different curing conditions. The mixes were cured at temperatures ranging from 10–40 °C and a relative humidity of 40–100% [60]. Another research suggested a stepwise approach for choosing suitable metrics to measure and compare the impact of various nuclear energy alternatives on sustainable development and energy security. A sodium-cooled fast reactor, known as a Generation IV reactor, was compared to nuclear power produced by standard pressurized water reactors and coal power [61]. Another research looked at a possible NPP site in the El-Dabaa region of Egypt's northwestern coast. The dynamic properties of shallow soil for NPP construction were described using seismic refraction profiles of 91 shallow P- and S-waves spread across the study region, as well as data from 76 boreholes [62]. The site evaluation processes in the United States, France, and India were also summarized and evaluated. The final guidelines took into account the lessons learnt from previous NPP damages and accidents [63]. A new statistical model for determining the suitability of possible land sites for the development of modular NPPs was suggested in another report. The proposed model used a mixed-integer nonlinear programming formulation to decide the best locations for small modular reactors in a distributed power grid, taking into account price, water availability for cooling, and earthquake risk [64]. A framework for determining the most undesirable ground motions for realistic, complex analyses of NPP systems was suggested in another research. The method's accuracy was validated by comparing the findings to the "true most undesirable ground movements," which were described as those that resulted in the highest destruction values in dynamic simulations [65]. In terms of cost, nuclear power can compete with other forms of electricity generation, except in regions where there is direct access to low-cost fossil fuels. Fuel costs for nuclear plants are a small proportion of total generating costs, although the capital costs of NPPs are greater than those of coal-fired plants, and much greater than those of gas-fired plants. Decommissioning and waste disposal costs are thoroughly considered in nuclear power economic studies [57, 66].

Most important opportunities in implementing NPPs

Today, nuclear energies have the ability to assist in the prevention of climate change and the advancement of sustainable growth. Nuclear power and CCUS will produce 3900 TWh globally by 2030, according to the IEA Sustainable Development plan, while wind and solar will generate 8100 TWh. The scenario's aim is to reach net-zero CO2 emissions by 2070. To meet this goal, an additional 15 GWe of nuclear capacity must be implemented over an annual basis. As of 2019, over 60 GW of new nuclear power plants is under construction, mainly in China, Russia, Korea, India, and the United Arab Emirates. Tiny modular reactors are being discussed by several countries; one such reactor in Russia will be linked to the grid in 2020 [67]. From 2000 to 2040, given the current traction in the market and the lack of widespread opposition to the technology, government policy should and will certainly solve these problems [68].

Economics (life cycle costing) of nuclear energy

Owing to the consequences of climate change, many countries are facing major difficulties in their economic growth. Energy is a significant economic engine. The complexity of the NPP supply chain was studied from a life cycle perspective, and an NPP program supply chain model was established to ensure the current nuclear program's construction timeline and stable operation [69, 70]. The global nuclear energy industry was exposed to a nonlinear dynamical analysis. Environmental and safety concerns were a big part of the study for nuclear power plants. Fundamentally, the economics of commercial trade between the two countries were important, and they were focused on oil demand and uranium price. The dynamics simulations revealed that many factors influenced the trade pattern. Using single and double arrow lines, event quantification for event flows, stocks, and feedback was conducted using the system dynamics technique [71]. Chemical/petroleum, paper, metal, and bioenergy industries with modest capacities (50–250 MWth) have the most promise. A cost overview (capital, operations and servicing, power, and decommissioning) for an analogous nuclear CHP that could compete against coal-CHP and natural gas-CHP was generated using parametric analysis. Sensitivity analysis showed that reactor capital costs and the cost of capital had the largest influence on competitiveness [72]. The IAEA continues to work on global water conservation issues of nuclear power plants. The use of waste heat to provide desalinated water for the plant and environment, as well as the use of waste heat for district or process heating to increase performance and overall economics, is a significant factor [73]. The original construction expense, the cost of the isolator, and the estimated damage cost over the life span of the device were all examined. With the use of isolators, the estimated damage cost was greatly decreased, resulting in a lower life cycle cost [74]. The main project management areas and nuclear project life cycle activities that are synonymous with active nuclear construction projects were depicted. According to statistics, the relative priorities of the six phases of a changed engineering procurement construction project life cycle for nuclear construction projects were established [75].

To define the driving factors that constitute the real-world execution of advanced cost and schedule controls, researchers looked into the specific characteristics of NPP construction. To model a case study, a scenario was developed [76].

Comparison of nuclear power and renewable energy

Renewable and nuclear technology have long been regarded as viable low-carbon energy sources, each with its own set of advantages and disadvantages. However, there are possible and mainly untapped synergies between nuclear and renewable energy that could help them achieve greater success. Integrating nuclear power with green energy systems may result in more opportunities for meeting energy needs and achieving energy policy objectives [77]. Nuclear power's future changes widely depending on political policies in various countries. Some countries have proposed plans to phase out nuclear power plants, while others in Asia have vowed to quickly increase nuclear power. Nuclear electricity, along with alternative energy sources, is expected as part of the energy mix in other countries to replace fossil fuel combustion with a renewable global nuclear energy grid, the following requirements must be met [78]:

- A radical reduction in greenhouse gas emissions for the entire life cycle by better technologies and productivity to reduce energy cannibalism during rapid growth
- Nuclear instability must be eliminated in order to reduce the threats associated with nuclear power.
- At the conclusion of the life cycle, nuclear waste is removed, and environmental damage is reduced across mining and operations.
- The nuclear power industry must restore public confidence or risk being outdated when a slew of clean energy technology advance in both technological and economic performance.

Coal and coal products account for 39.3% of electricity generation, followed by natural gas (22.9%), hydro (16%), nuclear power (10.6%), and other outlets (11.2%). Five promising clean energy technologies were analyzed and a clear point-to-point comparison was provided [79]. Data from similar studies are used to investigate technology characteristics, sustainability considerations, and future implementation drivers and barriers. According to the research, both clean energies and nuclear technology will help to combat climate change by reducing greenhouse gas emissions, which are virtually nil for nuclear technologies [79]. Flexible nuclear operations decrease power plant operating costs, raise owner profits, and significantly minimize renewables curtailment [80]. In the literature, a wide variety of costs was identified, primarily dependent on the price and availability of versatile system operations. At low levels of variable renewable energy adoption, costs are marginal, if not negative. Variable renewable energy sources may be an essential component of a low-cost decarburization plan [81]. Nuclear and clean energy plants have different operating limits.

Different operating limitations extend to nuclear power plants than to other power sources [80]. Sodium-cooled fast reactors are a safer societal, technological, and environmental solution to conventional nuclear power and coal-fired electricity production [61]. Lawrence Livermore National Laboratory published an energy flow map in 2019 that details the sources of energy production, how Americans consume energy, and how much waste there is [82]. Alternatives include solar and water-based energy generation, as well as microbe engineering for biofuel output. Several scientific, engineering, and policy issues and opportunities are outlined. Renewable electricity is quickly reaching cost parity with other energy sources. The shift to inexpensive, available, and renewable energy can be accelerated with increased participation from the science, financial, and public policy sectors, as well as the general public, to fuel economic development, improve energy security, and mitigate climate change risks [83]. To compare the distinct risk characteristics of fossil, coal, and NPPs, a structured risk assessment technique for NPP construction was proposed. In general, nuclear power plants represented much greater challenges than fossil-fuel plants. To create sustainable NPPs, the risk factors of NPP construction must be constantly tracked and evaluated [84].

Nuclear energy: toward sustainable development

This section examines and analyses the problems that nuclear power must address in order to be considered sustainable. The current state of nuclear power and its potential growth, as well as developments in reactor technologies and their effects on related risks and efficiency, are discussed. Advanced nuclear plants are meant to be simpler, cleaner, and less costly than existing reactors. Nuclear electricity has the potential to dramatically reduce greenhouse gas emissions. Significant concerns, however, exist, raising reservations for many decision-makers and the general public. Nuclear protection, hazardous waste disposal, and nuclear proliferation must all be discussed successfully in order to win public trust [14, 85, 86]. Nuclear fusion is a long-term alternative to the environmental issues that come with using fossil fuels to generate electricity. The consequences of increasing nuclear technology in India's power sector are investigated. MARKAL energy simulation software was used to create four scenarios, including a base case scenario. The energy mix's lowest-cost option was identified [87]. Several fast reactor design options operating in B&B mode have been compared to suggest a phased commercialization strategy that could provide a significant measure of energy sustainability much sooner than otherwise possible [88]. It is clear that creative technological solutions for nuclear technology's inherent environmental pitfalls must be created, and the nuclear industry must fix equity challenges for current and future generations [78]. Ninety criteria were used to decide whether nuclear power could lead to long-term growth and be a part of sustainable development. Earth, stability, threats, citizens, and politics are divided into five categories [89].

Thermodynamic cycle selection, plant performance, preliminary plans for the combined cycle power conversion system, component design factors and their technology bases, and main development criteria were all discussed [90, 91]. The advantages and limitations of NPPs are seen in Table 5.

Conclusions

- There is no way to build a nuclear power plant immediately. Implementing NPPs necessitates people with the requisite knowledge, expertise, attitude, and inspiration, which is a significant flaw in the current literature on the subject. Nuclear technologies, on the other hand, would also face a host of big challenges, including missile proliferation, security, waste management, high prices, and public acceptance, which has been harmed by recent incidents. This means that implementing creative NPP application, management, and technologies for architecture, development, manufacturing, and service is a major opportunity. The current state of NPPs, as well as current prospects and threats, has been addressed in this article.
- The key challenges that unique energy sources raise to a nuclear revival have been highlighted in this paper. Nuclear power, like other innovations, is rooted in social and political-economic matrices that form its evolution.
- New nuclear technologies could be less costly than older, more expensive reactors, but this would necessitate technical and manufacturing advancements, as well as large-scale construction of such plants. Nuclear power is expected to see technical advances, but the sluggish speed of siting and building continues to hold this industry chasing after rivals that are more competitive.
- The costs and implementation problems of NPP building, including those of other major infrastructure developments, are often overlooked. Except in regions with direct access to low-cost fossil energy, the cost of nuclear power is equivalent to that of other sources of electricity generating.
- Nuclear power is now commonly regarded as a costly source of electricity, and the expense of implementing NPPs is growing. This is due to more rigorous safety requirements and the numerous problems that can occur through implementation.
- Depending on the type of plant and the overnight prices, nuclear power can be a cheap source of energy. The initial resources determine the cost of NPPs, capacity, and other factors listed on this slide. The global demand for electricity is expected to rise, and the International Energy Agency (IEA) predicts that nuclear power generation will grow until 2040, owing to the need to minimize greenhouse gas emissions from electricity generation.
- The global demand for electricity is expected to rise, and the International Energy Agency (IEA) predicts that nuclear power generation will grow until 2040, owing to the need to minimize greenhouse gas emissions from electricity generation. Any countries are unable to deploy NPPs due to the high demand for water.
- Last but not least, the global nuclear building industry needs current awareness of nuclear power plant construction and innovative construction technology. With the global revival of nuclear power plants, it is important for any nation that wants to increase its focus on nuclear power to adopt policies that encourage and promote the production and use of innovative construction techniques in nuclear construction projects.

This study's results will provide decision-makers an analysis of NPP adoption, including benefits, limitations, opportunities, and risks.

Recommendations for Future Work

- Over the lifespan of an NPP, the cost of depreciation increases as the cost of safety features increases. Therefore, the cost of ongoing and regularly updated safety measures should be included in the total cost estimation, although these expenses may not appear during early operations. Periodic safety reviews will extend the lifespan of existing NPPs, which is economical in the long term.
- In order to preserve a sustainable future, we strongly recommend the widespread development and implementation of nuclear energy technology and related projects.

Table 5 Pros & Cons for NPPs [92]

Pros (Advantages)	Cons (Dis-advantages)
• The cost of generating nuclear electricity is smaller than the cost of producing energy from fossil sources including gas, oil, and coal. • Nuclear power plants emit less emissions than fossil fuel power plants. • Nuclear power stations consume less electricity to provide the same amount of energy as fossil fuels. • Nuclear power plants emit very little waste into the atmosphere	• The cost of building a nuclear power plant is very high • Nuclear power plants contain nuclear waste, which needs complex landfill sites in order to be properly disposed of • Crashes can occur, resulting in negative consequences for the environment and communities

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Data availability All data, models, and code generated or used during the study appear in the submitted article.

Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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