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DEVELOPMENT OF NUCLEAR POWER AS AN ALTERNATIVE TO FOSSIL FUELS

Abstract

Research into environmental pollution and global warming has induced the energy industry and various levels of government to reduce their dependence on fossil fuels, especially coal and oil. One of the options being considered is increasing nuclear power generation, which has the advantage of high production capacity that can be fully utilized, low fuel consumption and low cost relative to the amount of electricity being generated. However, despite technological progress, the share of nuclear energy in the world's energy mix is decreasing, especially in countries with highly developed economies. The reasons for this are high capital expenditures and their uncontrolled increase, fear of contamination of the natural environment in the event of a failure or terrorist attack as well as difficulties in long-term disposal of radioactive waste. This article analyzes the development of nuclear power as an alternative to fossil fuels in the pursuit of sustainable development, in particular with regard to investment outlays, the cost of generating electricity, environmental protection and security.

Key words

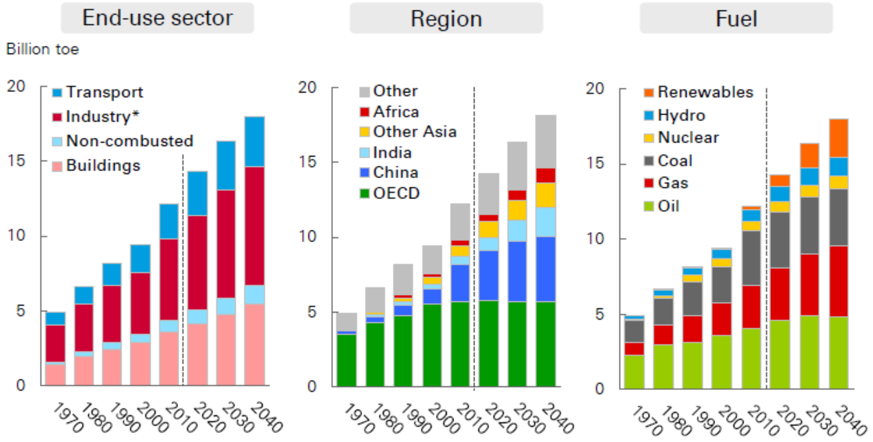
Energy, electricity, power, nuclear, innovation, management.

Introduction

Following the industrial revolution that relied mainly on steam power, in the 19th century, the second industrial revolution (also referred to as the technological revolution) laid the foundation for widespread use of electricity. The need for electricity was fueled primarily by three inventions:

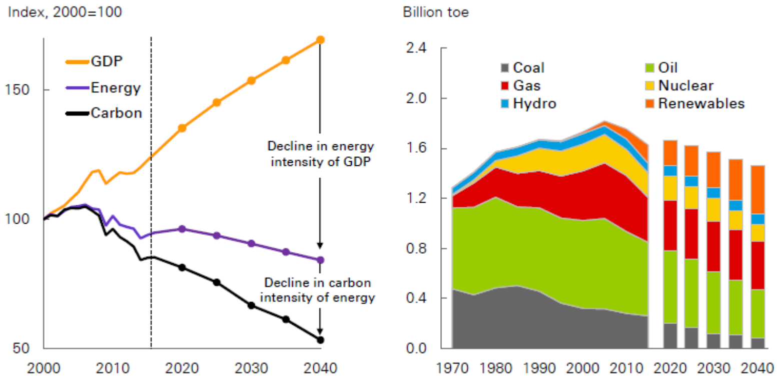
- The incandescent lightbulb allowed longer working hours and the prospect of increasing the quality of life throughout the world.
- The electric motor was an ideal alternative to steam power offering countless applications ranging from mechanical tools, to powering elevators and ships.
- The advent of electrochemistry, especially electrolysis and electroplating, allowed mass production of many relatively inexpensive chemicals, metals and products of unprecedented quality at significantly reduced cost. This opened entirely new frontiers and started a new era in manufacturing.

As world gross domestic product (GDP) continues to rise in the 21st century, increasingly more people in developing countries are rapidly expanding the range of modern products and services that they use. This leads to a forecasted growth in the use of primary fuel sources for the foreseeable future. However, as shown in Figure 1, the fuel mix is expected to change somewhat with the quickly expanding use of renewable energy sources and natural gas, while oil, coal and nuclear production are expected to stagnate.



Note: *Industry does not include uses other than combustion
Fig. 1. World primary energy demand 1970-2040
Source: [1].

The case of highly developed economies, such as the European Union (EU), is different in that coal consumption began decreasing in the 1980s and overall demand followed the same trend in the 2000s (Figure 2).



*Note: *toe = ton of oil equivalent; 1 toe = 41.868 gigajoules (GJ)*

Fig. 2. EU's GDP, energy, CO_2 emissions and primary energy demand 2000-2040

Source: [1].

In the 21st century, EU's GDP continues to increase but energy use started to decline due to decreasing energy intensity, i.e. the amount of energy used per unit of GDP – a measure of an economy's energy efficiency. Declining energy intensity and increasing use of renewables, mainly wind, hydro and solar power, results in a decline of carbon intensity too. This trend is expected to continue in the foreseeable future [2].

Nuclear power development

Despite significant gains in energy efficiency in highly developed countries, as mentioned previously, growing world GDP is correlated with increasing energy consumption. Furthermore, world electricity consumption is growing almost twice as fast as primary energy demand due to the ease in which it may be converted to other forms of energy such as mechanical energy to drive machinery and vehicles or heat. World electricity production has quadrupled from 6,131 TWh (terawatt hours) in 1973 to 24,973 TWh in 2016. The share of nuclear power has risen from 3.3% to 10.4% during this time. The only sources of power that grew faster than this were non-hydro renewables and waste (Figure 3).

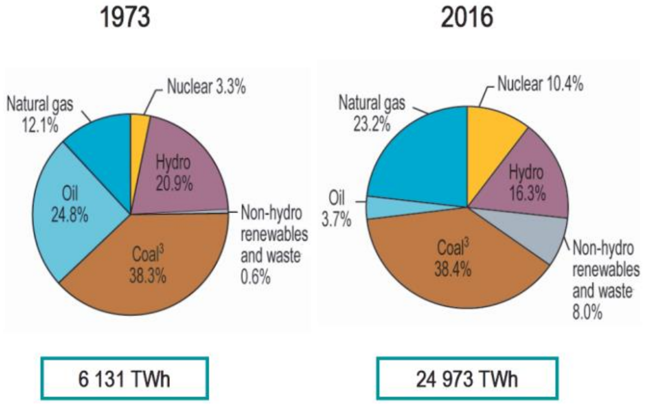


Fig. 3. Electrical energy consumption in 1973 and 2016

Source: [3].

The first nuclear power plants began operation in the 1950s, beginning in the Soviet Union in 1954, followed by the United Kingdom in 1956, the United States in 1957 and then Belgium, Canada, France, Germany, Italy, Japan and Sweden in the 1960s[4]. However, as shown in Figure 4, nuclear power development has stagnated in recent years.

Presently, the United States is the largest producer of nuclear energy with a production of 840 TWh, that is almost one third of the world's total and close to 20% of the country's electricity production. At 73%, France has the biggest share of nuclear power in the world. Ukraine is second with a share of 50%[3].

In 2018, the construction of nine plants providing 10.4 GW (gigawatts) of nuclear power were connected to the grid – seven in China, two in Russia. This was the largest addition since 1990. By comparison Poland's average energy demand is about 20 GW and installed production capacity is over 40 GW. Currently, 55 additional nuclear power plants in 18 countries with a total capacity of 56,6 GW (including 11 reactors in China alone) are under construction – all of them are due to start operating by the mid-2020s. In Japan, the operation of 12 nuclear reactors was resumed after they were taken offline following the Fukushima Daiichi nuclear disaster in 2011 [5-8].

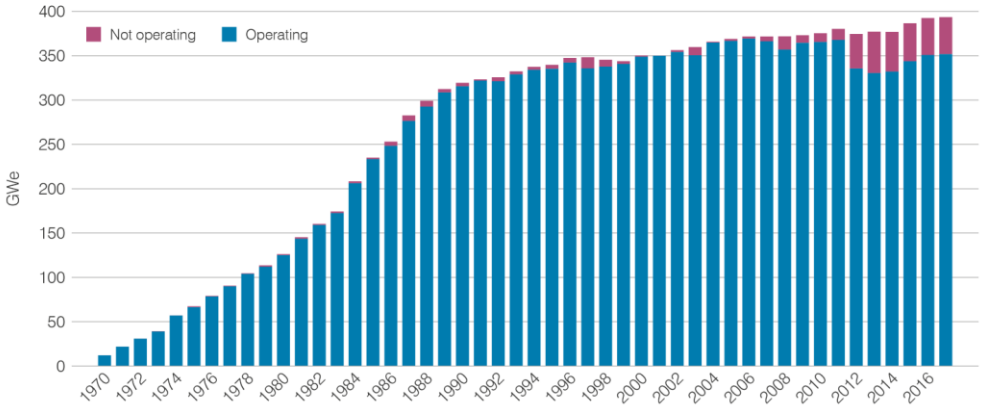


Fig. 4. World nuclear generating capacity

Source: [9].

According to forecasts by the International Energy Agency (IEA), worldwide production of electricity from nuclear power plants will gradually increase over the next 20 years but the growth will be much slower than the overall rate of growth for electricity demand [5]. Therefore, the share of nuclear energy in supply will decrease.

However, nuclear power plants have a high capacity factor (average ratio of actual production to maximum production) relative to most other types of fuel. This is due to the relatively low cost of nuclear fuel and the possibility of almost continuous operation at full power. This is in contract to relatively expensive fuels such as oil and natural gas or production from renewables which is dependent on the amount of water flowing, wind speed or insolation.

At the end 2018, Europe has the largest installed nuclear power capacity in the world: 164 GW. Of this, almost 40% (63 GW) is installed in France, 9.5 GW in Germany, 8.9 GW in the United Kingdom and 8.6 GW in Sweden. The United States is in second place with a production capacity of 99 GW, followed by China, Japan and Russia. However, this is expected to change with the largest increase forecasted in China with capacity almost tripling by 2030, India (up to 63 GW in 2032) and to a lesser extent Russia (up to 30 GW in 2040). However, according to governmental plans to phase out nuclear power, the installed capacity in the EU, Japan and Korea is to be reduced [5, 7]. Planned retirements and additions are shown in Figure 5. According to forecasts by the IEA, the production of electricity from nuclear power plants will gradually increase over the next 20 years but the growth will be much slower than the overall rate of growth for electricity demand. Therefore, the share of nuclear energy in supply will decrease.

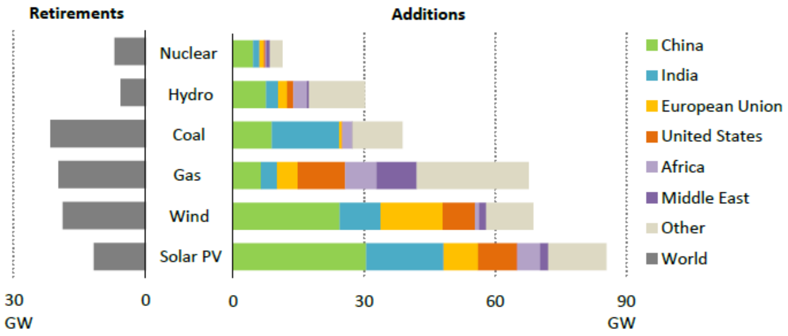


Fig. 5. Closing of existing and building new nuclear power plants forecast for 2017-2040

Source: [7].

It is estimated that the construction of new nuclear power plants will consume USD 1.1 trillion by 2040, of which 63% will take place in developing countries [5].

Nuclear fuel cycle and supply

The nuclear fuel cycle (Figure 6) starts with uranium mining and milling providing natural uranium that may be combined with recycled uranium. This is then converted and enriched to produce uranium hexafluoride (and depleted uranium that has mainly military but also some civilian applications).

Enriched uranium hexafluoride is used to make fuel for nuclear power plants. The fuel can be supplemented by plutonium taken from reprocessing of nuclear waste or military grade plutonium that has been transferred for civilian use. Spent fuel from nuclear power stations is highly radioactive and hot. It is usually placed into interim storage in water pools to help dissipate the heat. After this, it is sent for reprocessing into recycled uranium (the process also generates radioactive waste) or waste disposal. The recommended strategy for waste disposal is to place it in deep geological repository (DGR) chosen for their remoteness from inhabited zones as well as their geological as well as hydrogeological characteristics and stability to minimize the risk of ground, water and air contamination. DGRs are under development but they are not yet operational. Finland, France and Sweden are at various stages of constructing and licensing DGRs, with the first DGR to be operational in Finland in the early 2020s.

Uranium deposits are usually located in rocks. Most reserves have concentrations of about 1/1000 (i.e. 0.1%). Deposits can may be mined using both surface (open pit) and underground mining. Uranium reserves, i.e. resources that may be economically mined using proven technology, are usually defined as reasonably assured resources (RAR) that may be extracted at a cost of no more than 80 USD/kg of uranium [7]. The estimates of reserves change as a result of technological progress in uranium deposit mapping and mining technology.

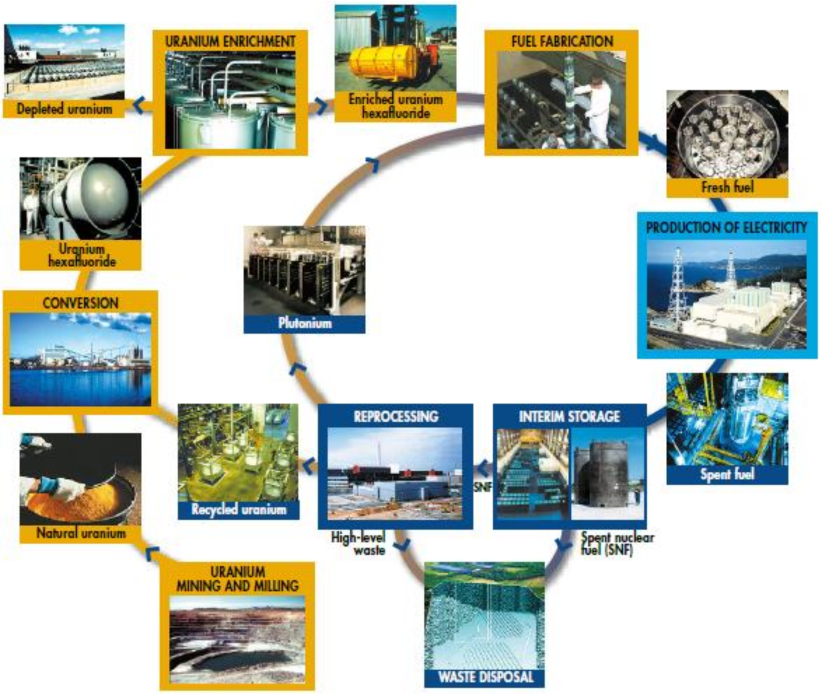


Fig. 6. Nuclear fuel cycle
Source: [9].

World uranium resources and reserves are more dispersed than hydrocarbon resources (Figure 7). Existing uranium reserves (in the <USD 80/kgU category) are estimated at 1.28 Mt (million tons), will last for 20 years at current production rates of 0.05934 Mt/year, whereas total identified resources in the <USD 260/kgU category amounting to 7.99 Mt are expected to last for 130 years at the current consumption level [10]. Some studies add an estimate of undiscovered resources, resulting in larger values, such as about 200 years for total resources in the <USD 260 kgU category [7]. The incentive for exploration is currently low given the relatively low prices tied to small production volumes and stagnating nuclear power development around the world.

Nevertheless existing resources are more than adequate to meet demand through 2035, even in the Nuclear Energy Agency's (NEA's) high demand scenario.

Kazakhstan provides almost 40% of the world's uranium supply, Canada 22.5%, Australia 10.1% and the remaining producers less than 6% each [7]. The market is driven by demand considering the low production volumes and relatively abundant supply. Production may be hindered by environmental issues [11].

Explosives are sometimes used to aid in the mining of the ore but most of it is extracted mechanically. After extraction, the ore is milled into a powder, which is then treated with chemicals, such as sulfuric acid, and dried into a powder called "yellowcake" due to its specific color. The procedure using acid creates liquid waste that is usually stored in large tanks. The yield is about one kilogram of yellowcake per two tons of uranium ore [12, 13].

In underground mining of uranium, a chemical process called in situ leaching (ISL) is used below earth's surface. A hole is drilled in the rock and a chemical solution is pumped into it to dissolve and absorb the uranium. The solution is then brought to the surface via another hole and the uranium is extracted from it. In general, this procedure should have less impact on the environment than other procedures. However, there is potential risk for pollution since not all contaminated liquid can be pumped out. Therefore, there is a risk of groundwater contamination, especially since groundwater flow models for mines may be inaccurate [12,13]. ISL accounts for about half of the world uranium production.

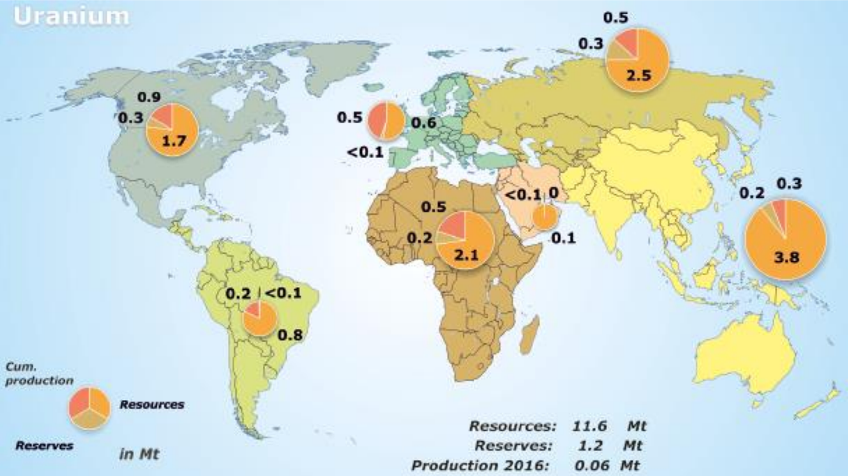


Fig 7. World uranium resources and reserves

Source: [7].

Most of the world's nuclear reactors require enriched fuel. Enrichment is the process of raising the proportion of the uranium 235 isotope from the naturally occurring less than 1% to about 3.5% to 5%. To accomplish this, uranium oxide (yellowcake) must be converted into uranium hexafluoride (UF6) in gaseous form. This process requires sophisticated technical equipment and highly specialized expertise since separating uranium-235 from uranium-238 is difficult due to their small difference in mass. Thousands of high speed vertical centrifuges must be used to create commercial quantities. This procedure is one of the main barriers to nuclear proliferation. Some reactors, notably Canadian CANada Deuterium Uranium reactors (CANDUs), use technology that does not require enriched uranium [13]. The thermal efficiency of this design is lower than of competing ones but this is mitigated by lower fuel cost.

Enriched uranium hexafluoride is converted to uranium dioxide which is then heated and placed into fuel assemblies that are a few meters long. A nuclear power plant uses about a hundred thousand times less fuel than a coal plant, e.g. 27 tons of uranium versus 2.5 million tons of coal per year for a typical 1000 MW plant [13].

Why nuclear power

Currently, three basic forces are used to produce electricity. Gravitational forces causing water flow were first used to drive various machinery such as mills and later hydroelectric power stations. Chemical energy from burning of traditional biomass or other fuels, such as coal, oil and natural gas, offered an increase of roughly a million times as much energy as flowing water. Now nuclear fission offers roughly a million times more energy per unit of fuel than can be obtained from burning fossil fuels [14]. The reason for this is found in Einstein's famous $E=mc^2$ equation which states that energy obtained in a nuclear reaction equals the mass converted to energy times the speed of light (c = 299,792,458 m/s) squared or 89,875,517,873,681,764 (roughly 90 million billion) times the mass that was consumed in the process. The difference in mass is very small but the amount of energy produced is great. Fusion offers still more energy potential due to a greater difference in mass, however, extensive research into harnessing it to produce energy has thus far not produced commercially viable results. Comparison of electricity generation technologies is made in Table 1.

Table 1. Electricity generation technologies

Force	**Gravitational**	**Chemical**	**Nuclear fission**	**Nuclear fusion**	**Wind, solar, geothermal**
Existing technology	Weights, flowing water	Burning and other chemical reactions	Fission or fusion	Hydrogen bomb	Turbines, Photovoltaic (PV), Concentrating solar power (CSP), heating
Fuel use	None (no fuel is consumed – it only changes location)	Wood (and other biomass, biogas or biofuels), waste, hydrocarbons (coal, oil, natural gas)	Mainly uranium but also plutonium and other	Hydrogen	None
Environmental concerns	Flooding and other land and waterway degradation	Pollution, including nitrogen oxides (NO_X), sulfur oxides (SO_X) and fine dust particulates (PM10 and PM2.5); plus large CO_2 emissions.	Radioactive waste from fuel mining, processing and burning; long term storage required.	None	Wind: noise from wind turbines, birds killed by blades; geothermal: risk of ground water contamination; solar: none
Amount of energy (relative to water)	1 (reference)	million x gravitational	million x burning	10 x fission	Between gravity and chemical.
Sustainability	Indefinite	Tens to hundreds of years	Thousands of years	Indefinite	Indefinite

Source: Author's

Concerns about nuclear power and technological development

One of the main advantages of nuclear power is the elimination of CO_2 emissions that are one of the main concerns with coal burning and also to a lesser extent natural gas, although natural gas CO_2 production is about half of that for coal. The main disadvantages of nuclear power plants are the high construction costs, the generation of radioactive waste and the risk of contamination of the natural environment in the event of a major accident or terrorist attack. In the case of construction of this type of facilities, there are often long delays, with investments going significantly, even several times, over budget due to underestimation of the actual cost. The reason for the increase in construction costs are often technological changes introduced during construction to meet legal regulations in the area of security. There were three main nuclear disasters that deeply influenced the nuclear industry (Table 2).

The first generation of nuclear reactors (I), developed until about 1965, were prototypes to test various technologies. Generation II reactors produced from about 1965 until 1995 are the most common type of reactors in operation today. They were the first commercial light water reactors (LWRs), pressurized water reactors (PWRs) or boiling water reactors (BWRs) and similar Soviet designs (VVERs and RBMKs).

Table 2. Most influential nuclear disasters

Name	**Three Mile Island**	**Chernobyl**	**Fukushima Daiichi**
Country	USA	Soviet Union (now Ukraine)	Japan
Year	1979	1986	2011
Technology	Gen2 1970s (PWR)	Gen2 1960s-1970s (RBMK-1000)	Gen2 1970s (GE Mark-I BWR)
Main cause	Stuck valve	Failed steam turbine test	Flooding from tsunami
Loss of life (estimate)	Direct: none; indirect: disputed	Official: 31; unofficial: 4,000 (WHO estimate); many more sick	Direct: 1; indirect: hundreds (disputed; compounded by earthquake and tsunami that killed 18,500 people)
Evacuation (estimate)	140 thousand	350 thousand	150-300 thousand
Cost (estimate)	1 billion USD	700 billion USD (USC Institute for Global Health estimate)	187 billion USD (2016 Japanese government estimate)
Significant impacts	- drop in support for nuclear power	- 100,000 km^2 of land contaminated	- 20 km evacuation zone
Notes		- reactor had no containment vessel to keep the radioactive materials from escaping in case of accident	- soon after, Germany accelerated plans to close all nuclear power plants by 2022

Note: both the direct and indirect impacts are estimated and strongly disputed.
Source: Author's based on [2, 4, 5, 12-15].

CANDU reactors should be viewed separately due to significantly different design using heavy water (D_2O – water with an extra neutron) for cooling (instead of the normal "light" water used by other reactors). Their efficiency is lower than that of other designs but they have the advantage of being able to use unenriched uranium and other fuels such as plutonium. Nevertheless, they as well as all other generation II reactors require active measures to keep them from melting down in the event of a malfunction. In other words, in the event of a malfunction operators must do something that usually requires a power source, to avoid an accident. This is a significant safety risk since power may be out or access to the reactor or its controls may be difficult.

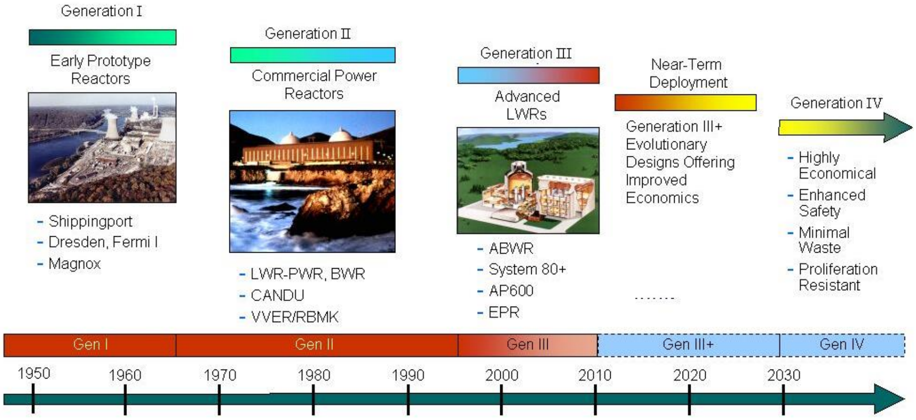


Fig. 8. Nuclear power reactor generations I-IV
Source: [16].

Generation III reactors (Figure 8 shows a comparison) were designed using lessons learned from malfunctions and accidents in generation II reactors, especially at Three Miles Island and Chernobyl. They started being introduced around 1995. Their main advantages are as follows (based on [13, 17]):

- Safety and economy:
  - More standardized design for each type of reactor to reduce regulatory approval time as well as reduce capital cost and construction time.
- Safety:
  - Combination of active and passive safety systems. In the event of a malfunction, passive systems rely on natural forces, such as gravity, convection or materials resistant to high temperatures, to avoid accidents. Thus no active intervention is required for a substantial

    period of time such as 3 days. This gives emergency personnel much more time to fix malfunctions and take other safety precautions.
  - Safer core design so that the probability of a core melt accident is reduced by 90%.
  - Stronger construction to resist terror attacks, even impact by aircraft.
- Economy:
  - Longer operating life: typically 60 years with the possibility of an extension.
  - Higher availability; reduced fuel consumption and thus also less radioactive waste.
- Other:
  - In some markets such as the EU and US Electric Power Research Institute (EPRI), new reactor designs must be able to follow load over a wide range of demand, such as from 50% to 100% of capacity.
  - Some new designs are modular to simplify and speed up construction.

Reactors introduced since the mid-1990s are built to withstand even the impact of a large aircraft to significantly reduce the risk of environmental contamination in the event of a terrorist attack. Generation IV reactors are currently in development. They are being designed to offer significant safety, reliability and economic advantages. The Generation IV International Forum (GIF) reviewed 130 reactor concepts and selected six for further research and development, including the Gas-cooled Fast Reactor (GFR), Lead-cooled Fast Reactor (LFR), Molten Salt Reactor (MSR), Supercritical Water-cooled Reactor (SCWR), Sodium-cooled Fast Reactor (SFR) and Very High Temperature Reactor (VHTR). Design testing is expected to take place in the 2020s and commercial deployment in the 2030s. Research is also ongoing to optimize the fuel cycle to minimize fuel use and waste [16-23] and use nuclear fuel for district heating in China with the newly developed Yanlong DHR-400 reactor [24]. Small modular reactors are being constructed to make nuclear power production more flexible [25]. Another area of innovation are floating nuclear power stations.

Conclusion

The article assessed nuclear power development, concerns, advantages and innovations leading to the following conclusions:

- World electricity consumption is growing almost twice as fast as primary energy demand due to lack of substitutes for many applications and the ease in which electricity may be converted to other forms of energy such as mechanical energy to drive machinery and vehicles or heat.
- Despite continuous technological progress, the share of nuclear in the world energy mix is decreasing, especially in countries with highly developed economies.
- World electricity production has almost quadrupled from 1973 to 2016. The share of nuclear power has risen from 3.3% to about 14% before the Fukushima Daiichi nuclear disaster in 2011 but has since dropped to 10.4% in 2016. 55 additional nuclear power plants in 18 countries with a total capacity of 56.6 GW (including 11 reactors in China alone) are under construction – all of them are due to start operating by the mid-2020s. It is estimated that the construction of new nuclear power plants will consume USD 1.1 trillion by 2040, of which 63% will take place in developing countries.
- Nuclear fission offers roughly one million times more energy per unit of fuel than can be obtained from burning.
- Some reactors, notably Canadian CANDUs, have the advantage of being able to use unenriched uranium and other fuels such as plutonium.
- Generation III reactors were designed using lessons learned from malfunctions and accidents in generation II reactors, especially at Three Miles Island and Chernobyl. They started being introduced around 1995. They offer a more standardized design that features active and passive safety systems, safer reactor design, stronger construction, longer life and reduced fuel consumption.
- Generation IV reactors that are currently being developed feature further safety, reliability and economic advantages. Research is also ongoing in using nuclear reactors for district heating and developing smaller, more flexible modular reactors. A Russian floating reactor became operational in 2018.

Despite significant technological progress, it is still unknown whether future innovations will be sufficient to outweigh the problems with: high capital expenditures and their uncontrolled growth, fears of contaminating the natural environment in the event of a failure or terrorist attack as well as difficulties in fuel and waste processing, especially long-term disposal of radioactive waste. However, progress in the construction of Deep Geological Repositories (DGRs) in countries such as Finland, France and Sweden should be noted.

Conflict of interest

There are no conflicts to declare.

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Units

GJ	gigajoules = 10^9 joules (units of energy)
GW	gigawatts = 10^9 watts (units of generating capacity)
Mt	million tons
MW	megawatts = 10^6 watts
toe	ton of oil equivalent; 1 toe = 41.868 GJ
TWh	terawatt hours = 10^{12} Wh (units of electrical energy)

Acronyms and abbreviations

BWR	Boiling Water Reactor
CANDU	CANada Deuterium Uranium (nuclear reactor)
CSP	Concentrating solar power
DGR	Deep geological repository
EPRI	Electric Power Research Institute
EU	European Union
GDP	Gross Domestic Product
GFR	Gas-cooled Fast Reactor
GIF	Generation IV International Forum
IEA	International Energy Agency
IAEA	International Atomic Energy Agency
ISL	In situ leaching
LFR	Lead-cooled Fast Reactor
LWR	light water reactor
MSR	Molten Salt Reactor
NEA	Nuclear Energy Agency
PV	Photovoltaic
PWR	Pressurized water reactor
RAR	Reasonably assured resources
SCWR	Supercritical Water-cooled Reactor
SFR	Sodium-cooled Fast Reactor
UF6	Uranium hexafluoride
VHTR	Very High Temperature Reactor