Chapter 3
The Importance of Having Nuclear Power Technologies for Sustainable Energy Development

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3.1 Introduction

After the industrial revolution, the concept of energy has spread to all areas of life and has increased its importance day by day. With intensified production, consumption and urbanization, the need for energy has become a common problem in all people and countries (Kim & Barles, 2012). Because industrialization and urbanization have increased the human population and increased the energy demand considerably. Therefore, the energy issue will be the most important issue of the twenty first century and perhaps the next centuries. The fact that energy resources are limited, unevenly distributed and some of them have negative effects on the environment and human health show that intensive studies on energy should be done. Energy resources are divided into non-renewable and renewable resources. In this context, various fuels are used as an energy source. Fossil fuels can be listed simply as coal, natural gas and oil. Renewable energy sources are solar, wind, geothermal, hydrogen, wave, biomass and hydraulic. In addition to all these, nuclear energy sources are thorium and uranium (Ulutaş, 2005).

Fossil fuels meet most of the increasing energy demand in the world. Fuels formed by the decay of plants and animals over millions of years are carbon-based. Since the rate of formation of these carbon-based fuels is much lower than the rate of consumption, fossil fuels are included in the class of non-renewable energy sources. Although various energy crises and environmental reasons question

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the dominance of fossil fuels over energy production, fossil fuels remain important because they are cheap and easily accessible. However, the environmental damage caused by carbon-based fuels shows that carbon emissions should be reduced in the long run. In this context, it is necessary to reduce the use of fossil fuels (Sheng & Guo, 2016). One of the environmental damage caused by fossil fuels is air pollution. Air pollution not only reduces people's quality of life, but also brings health problems in the long run. Therefore, it creates fragility in the economy by increasing health expenditures (Yuksel et al., 2022a, 2022b). Besides, high carbon emission is one of the main causes of global warming and directly or indirectly causes climate change. Under these circumstances, renewable energy sources have become an important alternative to fossil fuels. Because renewable energy sources do not create carbon-based pollution to the environment during the energy production process, so they have a reducing effect on carbon emissions (Dinçer et al., 2021). Although they are quite environmentally friendly and have high potential energy types, renewable energies also have disadvantages (Dincer et al., 2023). The high cost of renewable energy investments and the fact that energy production cannot provide uninterrupted energy due to weather conditions are among the most obvious disadvantages. Considering all these disadvantages, it is clear that the importance of nuclear energy is quite high (Çağlayan et al., 2022).

Uranium, the element with the most protons and neutrons, is enriched and used as fuel in nuclear power plants. The method used to produce energy from uranium is the fission reaction. Neutrons formed as a result of the fission reaction react with uranium atoms and this reaction continues until the neutrons are removed from the environment. The energy produced during the fission reaction is quite high, so it needs to be controlled. The uncontrolled fission reaction creates huge explosions and causes serious losses. Therefore, neutron controllers are used to control the fission reaction. The high-temperature water that emerges from the uranium, which is decomposed in a controlled way, evaporates and turns the turbines connected to the generator and the necessary energy is produced. The biggest environmental advantage of this energy production process is that it does not contain any carbon emissions (Hassan et al., 2022). In addition to this feature, it is an important advantage that the thorium and uranium reserves that can be used as fuel in nuclear power plants are relatively high. In addition, the energy obtained through nuclear power plants is uninterrupted, unlike renewable energies. It is not affected by weather conditions. In this way, since nuclear energy provides efficient energy flow to investor countries, it reduces energy imports of countries, prevents foreign dependency in energy and reduces energy-based current account deficit. The existence of more than one nuclear power plant in many countries and the fact that the world has gained experience in the field of nuclear energy is the most important driving force in the development of nuclear energy (Carayannis et al., 2022; Li et al., 2022a, 2022b; Yükel et al., 2022a, 2022b; Mikhaylov et al., 2022). Despite this, nuclear energy still has not proven itself against society and people have some concerns. Among these concerns, safety, waste management and installation cost are the main factors (Yüksel et al., 2021). Scientific studies and researches instill hope that they will solve problems such as safety concerns about nuclear energy, environmental concerns related to waste management, in the short or long term. Therefore, nuclear energy will continue to be one of the most effective types of energy that can meet the energy needs of countries in the future.

3.2 Generations of Nuclear Reactors

After the nuclear power plant accidents in Chernobyl and Fukushima, the future of nuclear energy and the status of existing reactors were questioned (Kim et al., 2013). There is a need for the development of the nuclear energy field on various issues, especially security problems, for existing power plants and future nuclear power plant investments. Because knowing the pros and cons of nuclear energy will increase the acceptance of nuclear energy by the public and will positively affect the future of nuclear energy (Xie et al., 2020). One of the most important concepts in the development of nuclear energy is sustainability. Because, with the protection of natural resources and the environment, the ability of future generations to easily meet their needs will be preserved. Existing nuclear power plants and newly designed nuclear power plants seem to help sustainability with their carbon zero characteristics (Fiore, 2006). Reducing carbon emissions with electricity generation through nuclear energy will both slow down the rate of increase in global warming and reduce long-term health costs based on air pollution. In this sense, nuclear power plants are known as a very environmentally friendly energy source.

Although the carbon zero feature of nuclear power plants is an important advantage, the radioactive wastes generated by nuclear power plants are one of the biggest obstacles to sustainability by threatening the environment and future generations. Therefore, it is clear that waste management in line with sustainability goals is a weakness for nuclear power plants (Prăvălie & Bandoc, 2018). Despite this, studies are continuing intensively for the development of nuclear technology in terms of increasing the advantages and eliminating the weaknesses of the said power plants. As stated before, the issue of safety is one of the factors that necessitate the development of nuclear energy systems such as waste management. The process of generating electricity from the nuclear power plant, which dates back to the 1940s, has experienced very few nuclear power plant accidents until today. Therefore, the fact that nuclear power plants are operated with intense security measures and that there are very few accidents shows that nuclear energy gives a good test in terms of safety. However, when compared to other energy systems, the danger of nuclear energy causes greater losses. Therefore, although nuclear power plants have performed well in terms of safety, it is clear that there is still a long way to go. Thus, it can be said that the future of nuclear power plants depends on the developments to be followed in the field of safety as well as waste management.

Considering all this, it should be said that the establishment and development of existing and future nuclear power plants is influenced by more than one factor. Factors such as cost factor, security and compatibility with existing electricity grid are some of them. Based on cost effectiveness, the price per kilowatt hour of nuclear energy is expected to be competitive compared to other energy systems such as renewable energy and fossil fuels. Additionally, the safety factor can be said to be one of the most compelling determinants in this context. There are multiple risk factors in terms of safety, such as the explosion risk of the nuclear reactor, the risks posed by radioactive waste, and natural disasters (Basu, 2019). In this context, existing and planned nuclear power plants must meet the expectations in terms of safety. Other important considerations when it comes to the principle of security are non-proliferation and terrorism prevention. It is expected that existing and newly established power plants will be prepared against the risks of nuclear theft and terrorism and will minimize these risks. The suitability of nuclear power plants to the existing grid is another important factor. The capacities of the local or national electricity networks must be able to meet the power of the electricity to be produced by the reactor planned to be established. Therefore, nuclear power plant investments bring with it an additional investment requirement on existing grids. Various designs of nuclear reactors, which are prepared by considering various factors such as cost, safety and network compatibility, are divided into categories as "generations". Gen I, II, III, III+ and IV characterize the basic features of the power plants that have been or will be built and make the differences between the nuclear power plants in question clear.

Gen I

The first reactors established between the 1940s and 1960s, which can be assumed as prototypes, can be given as examples of Gen I nuclear reactors. One of the said power plants is the Magnox reactor. The reactor takes its name from the composition of the rods in which the fuel is located. This compound is known as magnesium non-oxidizing. The Magnox reactor is one of the first commercial nuclear reactor types used in the world. The cooling gas of the Magnox reactor, which belongs to the gas-cooled reactor class, is carbon dioxide. The fuel of the reactor, in which graphite is used as the moderator, is natural uranium coated with Magnox. It is known that the reactor was exported to other countries, although it was mostly built in Great Britain since 1950. Currently, there is no Magnox reactor known to be operating. The last reactor was shut down in 2015.26 Magnox Reactors in the UK have been shut down since 1989. Another example of a Gen I nuclear power plant is the Shippingport Atomic Energy Plant. Shippingport is known as the first commercial centralized power generation station in the United States to use nuclear power. It is stated by various sources that Shippingport is a pressurized water reactor (PWR) in which the reactor core is cooled with high pressure water (Cummins & Matzie, 2018). The activities of the mentioned nuclear power plant were stopped in 1982. Another important Gen I nuclear power plant is the Dresden-1 nuclear power plant. The power plant is the first privately financed nuclear power plant established in the USA. The Dresden-1 became operational in 1960 and was discontinued in 1978. Units 2 and 3 of Dresden have been operational since 1970.

Gen II

Gen II nuclear power plants are one of the design classifications for a nuclear reactor, such as Gen I nuclear power plants, and generally refer to reactors built until the late 1990s. Gen II nuclear power plant is a class of commercial reactor designed to be economical and reliable. Older models of reactor types such as pressurized water reactors (PWR), boiling water reactors (BWR), advanced gas-cooled reactors (AGR) are among Gen II reactors. In addition, the number four reactor that caused the accident in Chernobyl and the three damaged reactors of Fukushima are Gen II reactors. Known examples of Gen II reactors include CANDU. The CANDU reactor is a Canadian pressurized water-powered nuclear reactor. It was designed in the 1960s. CANDU is an acronym formed from the initials of the words CANada Deuterium Uranium. The first CANDU reactor started operation in 1962 as Canada's first nuclear power plant and operated until 1987. These types of reactors are used in Canada, China, Pakistan, India, South Korea and many more countries. In this context, another important reactor type is the water-water energetic reactor, abbreviated as WWER or VVER. This type of reactor is a kind of pressurized water reactor. Although VVER was developed before 1970, it is a type of reactor that has been continuously improved. Thus, it would not be wrong to associate VVERs with multiple types of reactor designs, from Gen I reactors to Gen III+ reactor designs. VVER power plants were used in the former Soviet Union and Russia. In addition, this type of reactor is seen in many countries such as Ukraine, Germany and India. Turkey, on the other hand, is one of the countries that is preparing to put the VVER reactor into operation.

Gen III

Gen III nuclear power plants refer to a class of reactors with improvements in their design to replace Gen II reactors. Therefore, the Gen III reactor is actually a Gen II reactor with state-of-the-art equipment. Advanced safety systems, including passive nuclear safety systems, designs aimed at thermal efficiency and cost reduction are the focus of Gen III reactors. As an example, the first Gen III nuclear power plants installed in 1996 and 1997, Kashiwazaki six and Kashiwazaki seven, were ABWRs with advanced boiling water reactors. Both reactors were shut down as a result of various safety concerns. ABWR turns the turbine connected to the generator and provides power by evaporating the water after the high temperature released as a result of the fission reactions. Although most ABWR construction projects have been cancelled, it is licensed to operate in the US and Japan. Lastly, the AP600 is a type of reactor designed by Westinghouse Electric Company, which is in the Gen III reactor class with its passive safety system features.

Gen III+

Gen III+ reactors can be called the advanced version of the Gen III reactors. In this context, various reactor designs can be mentioned. For example, the Advanced CANDU Reactor, ACR-1000, is an example of such designs. The design was developed by Atomic Energy of Canada Limited (AECL) to be a Gen III+ nuclear reactor. The system combined the features of existing CANDU pressurized heavy water reactors (PHWR) with those of light water-cooled pressurized water reactors (PWR). The ACR-1000 was introduced as a lower-priced option compared to the CANDU 9, a larger version of the base CANDU being designed. The ACR was slightly larger but cheaper to build and operate. Another design is the Economic Simplified Boiling Water Reactor (ESBWR). The system is a passively safe Gen III+ reactor design derived from the Simplified Boiling Water Reactor (SBWR) and the Advanced Boiling Water Reactor (ABWR). The biggest difference between the Gen III+ designs and the designs that can be evaluated under this generation from the Gen II designs is that they have passive safety system designs that do not require active controls or various interventions.

Gen IV

Gen IV nuclear reactors are one of the reactor designs aimed at improved safety, sustainability, efficiency and cost. One of the most advanced Gen IV nuclear reactors is the sodium-cooled fast reactor. The reactor represents a fast neutron reactor cooled by liquid sodium. Various sodium-cooled fast reactors have been built over time, and there are operating reactors in Russia. In addition to Russia, Japan, India, China, France and the USA are among the countries investing in technology. Another important IV. Another important Gen IV technology is the molten salt reactor (Buckthorpe, 2017). The molten salt reactor (MSR) uses molten salt for higher thermodynamic efficiency. The heat efficiency of the reactor, which can operate at high temperatures thanks to molten salt, is quite high compared to today's reactors. Because the molten salt is responsible for both the movement of the fuel in the nuclear reactor and the transfer of heat energy (Marsden et al., 2017). In the next few decades, fourth generation reactors can be expected to start commercial operations and become widespread (Locatelli et al., 2013; Horvath & Rachlew, 2016). The majority of operating reactors today are Gen II reactors, since nearly all Gen I systems have been decommissioned. In addition, several Gen III reactors are in operation today. Gen V reactors, on the other hand, are purely theoretical and not yet feasible.

3.3 An Evaluation for the Critical Issues in Nuclear Energy Technology Investments

Having nuclear energy technologies is vital for countries' energy policies to be sustainable. In this context, countries need to pay attention to some issues to have these technologies (Martínez et al., 2022; Sun et al., 2022; Kafka et al., 2022; Mukhtarov et al., 2022). In this context, the necessary budget should be allocated for research and development studies. Secondly, qualified personnel must also be employed. Thanks to these personnel, it will be possible to operate nuclear power plants with complex processes in a safer way (Dong et al., 2022; Dinçer et al., 2022b, 2022c, 2022a; Zhang et al., 2022; Yüksel & Dinçer, 2022). Third, government incentives are also important for the development of these technologies. Finally, the economic growth of countries is another important issue in this context. In other words, to have up-to-date technologies related to nuclear energy, countries must first be economically developed (Xu et al., 2022; Bhuiyan et al., 2022; Kou et al., 2022). Priority analysis of these four different factors will be made under this heading. In this process, the DEMATEL method will be considered. DEMATEL technique is used to find the most important ones among different criteria (Eti et al., 2023; Li et al., 2022a, 2022b; Haiyun et al., 2021; Yuan et al., 2021). On the other hand, it is possible to determine the causal relationship between the specified criteria with this method (Fang et al., 2021; Kayacık et al., 2022; Eti et al., 2022; Dinçer et al., 2023). The analysis results obtained are presented in Table 3.1.

It is determined that economic development is the key factor for the purpose of improving nuclear energy technologies. Research and development studies also have a significant role in this respect. Qualified personnel and government incentives are in the last ranks.

3.4 Conclusion

Nuclear energy is very important for the sustainability of energy policies of countries. In this context, countries focus on nuclear energy investments. On the other hand, some countries are worried about nuclear energy due to risks such as radioactive waste and explosion. In this context, it is possible to minimize these problems thanks to new generation nuclear energy technologies. In this study, it is aimed to determine the priority issues for the development of nuclear energy technologies. To

Table 3.1 Weighting Results

Criteria	Weights
Research and Development studies	0.2412
Qualified personnel	0.2117
Government incentives	0.2386
Economic development	0.3085

achieve this aim, an analysis was carried out with the DEMATEL method. It is determined that economic development is the key factor for the purpose of improving nuclear energy technologies. Research and development studies also have a significant role in this respect. Qualified personnel and government incentives are in the last ranks.

It is obvious that the establishment and development of existing and future nuclear power plants is influenced by more than one factor. Factors such as cost factor, security and compatibility with existing electricity grid are some of them. Based on cost effectiveness, the price per kilowatt hour of nuclear energy is expected to be competitive compared to other energy systems such as renewable energy and fossil fuels. Additionally, the safety factor can be said to be one of the most compelling determinants in this context. There are multiple risk factors in terms of safety, such as the explosion risk of the nuclear reactor, the risks posed by radioactive waste, and natural disasters.

The results obtained from this study show us that for the development of nuclear energy technologies, countries must first grow their economies. In other words, countries with underdeveloped economies will not be able to find the necessary budget for nuclear energy technologies. In this case, the necessary research and development studies for these current technologies will not be able to be carried out. This will create an important barrier to the development of nuclear energy technologies. On the other hand, there will be a problem of qualified personnel in countries whose economy is not developed enough. Therefore, stabilizing the economies of the countries is very necessary for the development of nuclear energy technologies. In this context, it is important for countries to implement policies that will develop their economies first.

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