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The Advantages Of Nuclear Energy Over Other Energy Sources

D.I. Abdusamadova, R.M. Eshburiyev*, M. Fayzullaeva, D. Sharipov
Samarkand State University
*Corresponding author: eshburiyev0082@gmail.com (R.Eshburiyev)

Abstract
This article provides information on the advantages of nuclear energy over other energy sources and its economic efficiency. It discusses the energy released during the fission of uranium and thorium isotopes in nuclear reactors, the formation of these isotopes, the operating principles of nuclear reactors, the use of uranium and plutonium as fuel, the processes of producing these isotopes, and the difference and superiority of the energy released from the fission of uranium-235 nuclei compared to energy obtained via chemical means. Furthermore, the equivalence of energy released in nuclear reactions and in thermonuclear fusion reactions is also addressed. Some research on the safety issues of nuclear energy is included. In addition, the prospects for nuclear energy in Uzbekistan are discussed, along with relevant safety issues.
Keywords: nuclear energy, nuclear reactor, chain reaction, uranium, plutonium, radiation safety, nuclear waste, environmental impact, thermonuclear fusion, alternative energy sources, isotope, generator, turbine, active zone, thermonuclear synthesis, carbon.

Introduction

In the modern energy system, nuclear energy occupies an important position. One of its main advantages is its ability to produce extremely high-power electricity without releasing various gases into the atmosphere, making it environmentally clean. However, the development of nuclear energy also brings about a number of issues, including radiation safety, disposal of nuclear waste, and constant monitoring of technological processes at nuclear power plants.

In recent years, energy shortages have become increasingly apparent worldwide. To address this problem, several countries have initiated the development of nuclear energy. Countries such as the United Arab Emirates, Belarus, Bangladesh, Kazakhstan, India, Turkey, Egypt, Nigeria, and Uzbekistan [1] are currently building nuclear power plants, while European countries are developing long-term programs to address energy shortages through nuclear energy.

Today, countries such as the USA, France, Korea, Russia, Ukraine, Japan, and China make extensive use of nuclear energy. According to 2023 data, 193 nuclear power plants comprising 443 reactor blocks were operational in 32 countries [2]. These NPPs produced 5,966.6 TWh of electricity in 2022, with a total capacity of 705 GW. This accounts for 21.1% of the total global electricity production [3].

Currently, the total amount of energy produced worldwide meets only 75–80% of overall demand. In total, nuclear, thermal, hydro, and alternative energy sources together generated 29,165.1 TWh of electricity in 2022. In 2019, all nuclear power plants produced 2,586.2 TWh, meaning that by 2022, nuclear power generation had increased by more than 1.5 times.

Assuming a global annual energy production growth of 10–15%, it is predicted that by the 2030s, the current production level (29,165.1 TWh) could rise to approximately 50,000 TWh or even higher. Considering the depletion of fossil fuel reserves such as coal, natural gas, and oil, it is not difficult to foresee the future role of atomic energy in meeting humanity’s energy demands.

Nuclear energy is fundamentally an environmentally clean form of energy. It does not produce carbon dioxide, nitrogen oxides, or sulfur oxides. In contrast, a 1000 MW thermal power plant burns 3.9 million tons of coal and 5.5 billion cubic meters of oxygen per year, releasing 10 million tons of CO_2, 124,500 tons of SO_2, 35,000 tons of NOx, 7,500 tons of aerosols, and other carcinogenic substances into the atmosphere [4].

Today, many countries are working to solve energy shortage problems by modernizing nuclear reactors and developing safer technologies. This article analyzes the advantages of nuclear energy production, its environmental cleanliness, and its efficiency compared to the energy generated from burning chemical fuels. It also discusses the future prospects of nuclear energy, including the importance of new technologies such as thermonuclear fusion.

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Although the efficiency of nuclear energy has made it a strategic energy source for many countries, safety-related issues remain a globally pressing concern. Past nuclear disasters—specifically, the Chernobyl disaster of 1986 and the Fukushima incident of 2011—demand the utmost caution in the operation of nuclear reactors. Such events have compelled humanity to continually improve nuclear technologies and to ensure strict safety measures are in place throughout the development and use of nuclear energy systems.

At the same time, the issue of disposing of and storing nuclear waste over the long term remains unresolved. These wastes can create a radiation background in the Earth's environment for thousands of years, negatively impacting the entire ecosystem.

This article examines the issues related to nuclear energy production, the generation of uranium-$^{233}_{92}U$ and plutonium-$^{239}_{94}Pu$ sotopes, and the advantages of nuclear energy compared to other sources. It also discusses the future prospects of nuclear energy, including the significance of technologies such as thermonuclear fusion.

The process of generating nuclear energy takes place in nuclear reactors, where the heat released from the fission of uranium and plutonium isotopes in the reactor core is converted into electrical energy. The isotopes uranium-$^{238}_{92}U$, uranium-$^{235}_{92}U$, uranium-$^{234}_{92}U$ and thorium-$^{232}_{90}Th$ are natural, while uranium-$^{233}_{92}U$, plutonium-$^{239}_{94}Pu$, and plutonium-$^{240}_{94}Pu$, are considered artificial isotopes. The reactions for producing plutonium from uranium-$^{238}_{92}U$ and uranium from thorium -$^{232}_{90}Th$ are shown below [5].

$$^{238}_{92}U(\mathrm{n},\gamma) \rightarrow {}^{239}_{92}U\left(\beta^-, \mathrm{T}_{\frac{1}{2}} = 23.5'\right) \rightarrow {}^{239}_{93}Np\ (\beta^-, \mathrm{T}_{\frac{1}{2}} = 2.3\ \mathrm{d}ays) \rightarrow {}^{239}_{94}Pu \qquad (1)$$

$$^{232}_{90}Th(\mathrm{n},\gamma) \rightarrow {}^{2335}_{90}Th\ (\beta^-, \mathrm{T}_{\frac{1}{2}} = 23.3') \xrightarrow{\beta^-} {}^{233}_{91}Pa\left(\beta^-, \mathrm{T}_{1/2} = 27.4\ \mathrm{d}ays\right) \xrightarrow{\beta^-} {}^{233}_{92}U \qquad (2)$$

The uranium -$^{233}_{92}U$ and plutonium-$^{239}_{94}Pu$ isotopes produced from reactions (1) and (2) can be used as nuclear fuel in reactors.

The main sources of nuclear energy are radioactive isotopes such as uranium-$^{235}_{92}U$ and plutonium -$^{239}_{94}Pu$ To initiate nuclear energy production, it is sufficient for the uranium-$^{235}_{92}U$ nucleus to undergo fission under the influence of thermal neutrons. This fission reaction releases a large amount of energy. A single fission event of a uranium -$^{235}_{92}U$ nucleus produces about 200 MeV of energy [6-8]

$$^{1}_{0}\mathrm{n} + {}^{235}\mathrm{U} \rightarrow {}^{236}_{92}\mathrm{U} \rightarrow ({}^{139}_{54}\mathrm{Xe} + {}^{95}_{38}\mathrm{Sr}) + 2\,^{1}_{0}\mathrm{n} + 200\ MeV \qquad (3)$$

In this reaction, the uranium-$^{235}_{92}U$ nucleus splits into at least two fragments and emits 2–3 prompt neutrons. These neutrons then induce the fission of other nuclei, thereby maintaining a chain reaction. In a nuclear reactor, generating 1 MW of power requires approximately 10^{16} fission events per second.

The uranium-$^{235}_{92}U$ sotope primarily undergoes fission by thermal neutrons (~0.025 eV), as it has a high fission cross-section at this energy, about 540 barns (1 barn = 10^{-28} m^2 Most reactors operate using uranium-$^{235}_{92}U$ isotopes, which are typically enriched to no more than 4–5%. The thermal efficiency of these reactors is around 31–33%. The temperature at the output of the radioactive loop is 321°C, with a pressure of 160 atmospheres. The high-temperature steam is directed under high pressure to a steam generator, which then drives a turbine at high speed. This, in turn, activates a generator that produces electricity in the circuit.

Due to its high efficiency and low carbon emissions, nuclear energy production technology may play a crucial role in global energy generation in the future. However, its safety and environmental issues require serious attention. For the development of nuclear energy, it is essential to research and develop technologies for its safe and efficient management.

Energy release in nuclear reactors

It is well known that the combustion (oxidation with oxygen) of a single carbon atom releases approximately 4 eV of energy:

$$\mathrm{S+O_2 \rightarrow SO_2 + 4\ eV.} \qquad (4)$$

In contrast, the fission of a uranium-$^{235}_{92}U$ nucleus by thermal neutrons releases 200 MeV of energy:

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$$^{235}_{92}U + n \rightarrow BM_1 + BM_2 + (2\text{-}3)\, n + 2\cdot 10^8 \text{ eV} \quad (5)$$

Considering the mass ratio of uranium to carbon atoms (235:12), the energy released per unit mass in uranium fission is approximately 2.5 million times greater than that from the chemical combustion of carbon.

When comparing the energy released in the fission of heavy nuclei per unit mass with that from fusion of light nuclei:

For 1 gram of uranium $^{235}_{92}U$, the energy yield is:

$$\frac{6{,}02\cdot 10^{23}}{235}\cdot 200 \approx 5.1\cdot 10^{23}\text{MeV} \approx 0.95 \text{ MeV}\cdot\text{day}. \left(N_{\text{A}} = 6.02\cdot 10^{23}\frac{1}{\text{mol}}\right).$$

In thermonuclear fusion, an enormous amount of energy is also released. For example:

$$^{2}_{1}N + ^{3}_{1}\text{N} \rightarrow ^{4}_{2}\text{Ne} + ^{1}_{0}n + 17.6 \text{ MeV} \quad (6)$$

Calculating the energy per 1 gram of fuel:

$$\frac{6.02\cdot 10^{23}}{5}\cdot 17.6 \approx 21\cdot 10^{23} \text{ MeV} \approx 3.9 \text{ MW}\cdot \text{d}ay$$

In chemical reactions, the energy released per 1 gram of a combustible substance is:

$$\sim 29.4\cdot 10^{3}\text{J} \approx 3.4\cdot 10^{-7}\text{MW}\cdot\text{days}:$$

Thus, comparing the energy released in nuclear, thermonuclear, and chemical reactions:

1. Nuclear fission yields ~ 0.95 MW·day
2. Thermonuclear fusion yields ~ 3.9 MW·day
3. Chemical reaction yields ~ 3.7×10^{-7} MW·day

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As mentioned above, the combustion of a single carbon atom releases ≈ 4 eV of energy, while a single fission event of a uranium ^{235}U nucleus releases ≈ 200 MeV. The energy difference between these two processes is about 2.5 million times. That is:

$$\text{N} = \frac{200 \text{ MeV}}{4 \text{ eV}}\cdot\frac{12}{235} = 2.5\cdot 10^{6}.$$

From these calculations, it is evident that the energy released from a thermonuclear fusion reaction is 4 times greater than that of uranium $^{235}_{92}U$ fission, while the energy from a chemical reaction is 2.5 million times less than the energy released in a single fission event of the uranium $^{235}_{92}U$ isotope [6].

A ton of uranium (specifically, isotope $^{235}_{92}U$) contains approximately $N = 2.55\cdot 10^{27}$ nuclei.

If each nucleus undergoes fission releasing 200 MeV, then, assuming the entire ton is fully converted into fission products, the total energy yield would be:

$$\text{E}_{\text{B}} = 2.55\cdot 10^{27}\cdot 200 \text{ MeV} = 5.1\cdot 10^{29}\text{MeV}$$

Knowing that:

$$1 \text{ eV} = 1.6\cdot 10^{-19}\text{J} = 1.6\cdot 10^{-19}\text{W}\cdot s$$

this energy can be converted to more practical units:

$$\text{E} = 8.2\cdot 10^{16}\text{W}\cdot\text{s} = 8.2\cdot 10^{10}\text{MW}\cdot\text{s} = 0.95\cdot 10^{6}\text{MW}\cdot\text{day} = 10^{3}\text{GW}\cdot\text{day}.$$

Thus, when uranium is 100% burned, approximately 10^3 GW·days per ton of specific energy is released. If only 1% of the uranium is burned, the energy released would proportionally be around 10^1 GW·day/ton.

Let's compare the amount of fuel required to produce 1 GW of energy in thermal power plants (TPPs) and nuclear power plants (NPPs). It's known that the combustion of a single carbon atom releases ~4 eV of energy:

Since $(1 \text{ eV} = 1.6\cdot 10^{-19}\text{W}\cdot\text{s}, \text{then } 1\text{W}\cdot\text{s} = 6.25\cdot 10^{18}\text{eV})$

Now, for a nuclear plant with an efficiency (η) of 25%, the energy produced in one day is:

$$4 \text{ GW } (25\%) = 4\cdot 10^{9}\text{W}\cdot\text{h}r = 4\cdot 10^{9}\text{W}\cdot 24\cdot 3600 = 3.5\cdot 10^{14}\text{W}\cdot\text{s} = 2.2\cdot 10^{33}\text{eV}:$$

To generate this much energy by burning carbon (4 eV per atom), it would require:

$2.2\cdot\frac{10^{33}\text{eV}}{4\text{eV}} = 5.5\cdot 10^{32}$ carbon atoms.

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Using Avogadro's number:

$$M=\left(5.5\cdot\frac{10^{32}}{6\cdot10^{23}}\right)\cdot 0.012\approx 10^{7}\text{kg}=10^{4}\text{ tons of carbon}$$

This mass equals approximately the weight of three full freight trains, each composed of 60 railcars with a mass of 60 tons

The required oxygen mass would be:

$$m=(5.5\cdot 10^{32}/6\cdot 10^{23})\cdot 0.032=2.5\cdot 10^{4}\text{ tons}$$

That is, 2 kg of oxygen is required to burn 1 kg of carbon fuel.

To obtain the same 2.2×10^{33} eV of energy using uranium fission (200 MeV per nucleus):

$$2.2\cdot\frac{10^{33}\text{eV}}{200\text{MeV}}\approx 10^{25}\text{uranium } {}^{235}_{92}U \text{ nuclie}$$

And the corresponding mass is:

$$(10^{25}/6\cdot 10^{23})\cdot 0.235\approx 4\text{ kg of uranium } {}^{235}_{92}U.$$

So, to generate 2.2×10^{33} eV of energy:

- 4 kg of uranium ${}^{235}_{92}U$ is needed
- 10^4 tons of carbon and 2.0×10^4 tons of oxygen would be required for equivalent fossil combustion [5];

The isotope ${}^{234}_{92}U$ can also be formed via the following nuclear reaction, though its natural abundance is only ~0.0054%. Its formation requires one alpha and two beta-minus decays from ${}^{238}_{92}U$:

$$ {}^{238}_{92}U \xrightarrow{\alpha} {}^{234}_{90}\text{Th} \xrightarrow{\beta^-} {}^{234}_{91}\text{Pa} \xrightarrow{\beta^-} {}^{234}_{92}\text{U} \qquad (7)$$

${}^{235}_{92}U$-isotope undergoes fission with thermal neutrons, because it has a large fission cross-section for low-energy neutrons. However, ${}^{238}_{92}U$only undergoes fission with fast neutrons, as its threshold energy is about 1 MeV, and its fission cross-section is only ~1 barn. So,${}^{238}_{92}U$ and ${}^{232}_{90}$Th both require fast neutrons in the energy range of 10–14 MeV to undergo fission.

The cross-section ratio is

$$\sigma_{\text{thermal}}=(540)\sigma_{\text{fast}} \qquad (8)$$

Thus, thermal neutrons are 540 times more effective than fast neutrons in inducing fission in ${}^{235}_{92}U$.

The future of nuclear energy in Uzbekistan

Speaking of the future of nuclear energy in Uzbekistan, the *Presidential Decree* of July 19, 2018, titled "On the Development of Nuclear Energy in the Republic of Uzbekistan", serves as the legal basis for utilizing nuclear energy in the country. The decree aims to:

- Meet the growing electricity demands of the population and economy
- Expand the nation's power generation capacity
- Diversify the energy sector
- Promote the peaceful use of nuclear energy
- Introduce advanced and innovative technologies in this field [9].

Looking at Uzbekistan's annual electricity production:

- In 2016, electricity consumption was 50.1 billion kWh
- By 2023, it exceeded 80 billion kWh
- Demand has grown by 25–27% over this period [10].

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Meanwhile, the capacity of thermal and hydroelectric plants is declining, and these plants require massive quantities of oil, gas, and coal, leading to significant emissions of CO_2, CO, nitrogen oxides, and sulfur oxides, which disrupt the global environmental balance.

Given the low cost and environmental cleanliness of nuclear energy, along with rising energy demands, the prospects for building a nuclear power plant in Uzbekistan are clear and favorable.

Conclusion

The production and use of nuclear energy offers tremendous economic benefits. While chemical reactions emit various harmful gases and require twice the mass of oxygen relative to the combustible fuel, nuclear reactions release no such pollutants. The accumulation of gases from chemical combustion reduces the oxygen content in the atmosphere and contributes to global environmental degradation.

Experts believe that if humanity were to rely solely on thermal power plants for electricity, millions of tons of toxic gases would accumulate in Earth's atmosphere, leading to severe ecological consequences.

From this perspective, utilizing clean and affordable nuclear energy not only yields major economic benefits but also greatly reduces production costs, especially since nuclear reactors can operate continuously for 50–60 years.

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