DEVELOPMENT DIRECTIONS OF NUCLEAR TECHNOLOGY TOWARDS THE MOST PROMISING SOURCE OF ENERGY[1]

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ABSTRACT

This paper explores the scope and limitations of nuclear energy in general, as well as trends in the development of nuclear technology. The big question is whether renewable energy sources can replace the growing global hunger for energy. Due to their polluting effects and relatively rapid drying up, fossil fuels will have to be replaced. What is the alternative? The author argues that renewable sources do not have the capacity to replace fossil fuels on the pedestal of world energy needs and that only nuclear energy is capable of this. The main hypothesis of the work is that nuclear energy is currently one of the cleanest form of energy production despite all its shortcomings, but in the not so distant future it will convincingly become the most ecological and cost-effective way of energy production. The main axes of development of nuclear technology with huge potential are: fusion reactors, thorium-based nuclear reactors and uranium extraction from seawater. All three fields of development have already been experimentally and operationally proven to work, and future progress is based on improving their commercial viability. Analyzing the consequences of the successful implementation of fusion and thorium reactors, with potentially unlimited sources of nuclear fuel, the author dares to predict when nuclear energy will take the number one position in the global energy arena.

Keywords: *nuclear energy, nuclear fusion, thorium-based reactor, energy security, uranium extraction, source of energy, ITER.*

Present and future of energy sources

The birth and advancement of humankind have been made possible by energy. In light of the fact that all matter and energy are interchangeable elements, it can be said to be identical with existence. When we discuss energy, we consider outside sources, such as mechanical power, steam engine power, internal combustion engine power, sun power, electricity, etc. Man has discovered a way to transform one form of energy into another and utilize it for his benefit. Here comes the key question, from which sources man can draw the energy? Because energy is required for lighting, heating, cooking, starting vehicles and aircraft, industrial output, and transportation in the contemporary world, there is an

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increasing need for it. The control of energy supplies has been the subject of numerous conflicts, and there is a complicated connection between energy and politics in general. The idea of energy security is being addressed more frequently because the creation, access, and distribution of energy sources are significant global problems. Coal, along with the steam engine, became the primary energy source that, starting in the middle of the 18th century, allowed for massive industrial output and the storing of extra goods. Coal, along with the steam engine, became the primary energy source that, starting in the middle of the 18th century, allowed for massive industrial output and the storing of extra goods. The 19th century can be considered the century of coal, the 20th century the century of oil, and the 21st century the opening of new fields of energy creation (nuclear fusion energy), even though the dominance of the triad of fossil energy sources continues. (coal, oil, and gas). Although the concept of nuclear fusion has the potential to provide humankind with almost limitless and inexpensive energy, we will need to wait a while before it becomes commercially viable (Vujić, Stojanović i Madžgalj, 2015).

The idea of an energy mix that uses both sustainable (biomass, solar, wind, and geothermal energy) and non-renewable energy sources is being discussed more and more. Less than 12% of the world's main energy comes from green sources, despite the strong propaganda and lobbying efforts of political-economic interest groups in favor of these sources (Ritchie and Roser, 2022a). Around 84% of the world's energy is produced using natural fuels, with nuclear energy making up 4.3% of that total (Ritchie and Roser, 2022a). Oil derivatives are the main source of energy for transportation, but for the generation of power, the scenario is somewhat different. Coal makes up 36.7% of the overall energy used in the creation of electricity, while gas makes up 23.5%, hydropower 15.8%, and nuclear power 10.4% (Ritchie and Roser, 2022b). Only 5.3% of the world's power is generated by wind energy, and even less, 2.7%, by solar cells (Ritchie and Roser, 2022b).

Possession of natural resources gives countries a comparative advantage in international relations, and technological inventiveness brings some to the foreground, while other types of resources fall into the background. Oil was not a resource of power in the 16th century, any more than uranium was in the 19th century. Despite the deceptiveness of the dominant resource, there is a constant human need for energy, sharply increasing with industrial production and motorized transport of goods and people. Oil was used in oil lamps and lighthouses in the 19th century and gained importance only in the 20th century with the commercial use of internal combustion engines. Energy sources strongly demonstrated their political potential during the Arab-Israeli conflicts in the seventies of the 20th century, when there was an oil crisis caused by a deliberate increase in the price of oil by Arab exporters.

The geopolitics of energy includes the uneven distribution of oil and gas, considering that over 90% of these fuels are stationed in just 20 countries in the world. In terms of energy, Russia is a superpower that directs the foreign policy courses of many countries in the world, especially member states of the European Union (EU). For instance, Russia ranks eighth in the list of countries with the largest oil reserves (Worldometer, 2022a), second in coal reserves (Worldometer, 2022b) and by far first in gas reserves, with almost a quarter of the world's deposits (Worldometer, 2022c). The quantity of fossil resources and the time frame during which their sources will run out are specific topics for analysis. According to the rate of global use, there will be 133 years' worth of coal, 52 years' worth of gas, and just 47 years' worth of oil left. (Worldometer, 2022b). Human inventiveness in technologies and the discovery of new deposits will probably extend the period of extraction of fossil resources. All experts do, however, concur that they will mainly vanish by the end of the 21st century. The need to abandon oil and gas before they leave us drives countries to alternative energy sources. The greenhouse effect, more or less caused by the consumption of fossil fuels, further accelerates the transition of the developed countries of the world to alternative energy sources. Regardless of the questionable dynamics of the global energy transition and the undoubted dominance of oil and gas in the next fifty years, nuclear energy occupies a special place in the energy mix.

The power of atoms: development of civilian nuclear technology

The origins of nuclear technology date back to the Second World War, which produced only one military nuclear force. The United States of America (US) opened a race for atomic weapons, and with the expansion of the nuclear club, the danger of nuclear war loomed over the planet (Петровић и Стојановић, 2012, с. 93-97). When humanity entered the nuclear age in 1945, the whole thing was a complete unknown, even to scientists who were unsure whether the first nuclear explosion in the Los Alamos desert would ignite the entire atmosphere or have a limited effect. Relevant analyses identify as many as 34 nuclear weapons development programs, of which only ten countries have developed nuclear weapons (Стојановић, 2021). Until the sixties of the 20th century, nuclear technology was reserved for the military domain, although the idea of nuclear energy for civilian purposes was initiated as early as December 8, 1953, by US President Dwight Eisenhower through the "Atoms for Peace" program (Eisenhower, 1953). The use value of nuclear energy, apart from the practice of deterrence, has been seen in the production of electricity, medicine, agriculture and the transport drive of large vessels, icebreakers and even missiles. The formal beginning of the commercial use of nuclear energy was in 1956 when the first commercial nuclear power plant was opened in Cumberland (BBC, 2019). In the 1960s, nuclear reactors were built on both sides of the "Iron Curtain", so today, there are as many as 448 nuclear reactors for the production of electricity in the world (Bhutada, 2022).

New nuclear power facilities are being built in large numbers of industrialized nations or those working toward that status. These nations, which continued to construct nuclear plants after Fukushima incident, are Japan, South Korea, South Africa, France, India, Poland and many others. There are currently nuclear reactors in at least 40 different nations. Considering how much mercury and other heavy metals are released into the atmosphere by thermal power plants, nations are moving toward "cleaner" energy sources. Nuclear power plants have a functional life that is only 20 years greater than thermal power plants. The statistics indicate that even in the most industrialized nations in the world, the so-called alternative energy sources, such as solar energy or energy from turbines that harness wind power, have a small percentage of the global energy market. Even in the richest nations, like Germany, where energy costs have skyrocketed since the decision to close down nuclear power facilities, solar panels and turbines are very costly. The main issue with alternative energy sources is that they are aspirational choices that cannot satiate the world's insatiable appetite for energy. When factoring in the initial investment, ongoing operating costs, and long-term investment, electricity produced by wind energy costs on average $90 per megawatt-hour, electricity produced by solar energy $88.7, electricity produced by coal-fired power plants $41, electricity produced by hydroelectric power plants $38 and electricity produced by gas plants 36 dollars, while the cost of electricity from nuclear source costs 33 dollars per megawatt-hour (Antonini, 2022). The Institute for Nuclear Energy estimates that more than 140,000 hectares of land are needed for a wind farm to produce energy comparable to one 1,000 megawatt nuclear plant (Antonini, 2022).

Nuclear technology is experiencing almost daily progress. Nuclear technology is improving, lengthening the durability of reactors and decreasing the original investment. The fourth and fifth versions of nuclear reactors will undoubtedly lower the risks of catastrophe to the lowest possible degree. These reactors will produce significantly less nuclear debris than earlier versions. Simply stated, nations that choose not to develop nuclear power facilities will soon find themselves in the unfavorable situation of having to depend on fossil fuels, and since their supply will be forever diminished, they will be forced to import energy.

Three revolutionary breakthroughs in the nuclear technology of the future

The world economy continues to grow at an annual rate of 3 to 4%, which means that it doubles every twenty years (Saks, 2014, s. 423). All this implies a multiplied increase in the needs of current generations for all resources and the big question of their survival for the generations yet to come. The use of nuclear energy is consistent and complementary to the goals of sustainable development. It is most important to mention three breakthroughs in the field of nuclear technology: nuclear fusion, thorium-based reactors and the extraction of uranium from seawater. Each of these three technological advances has been experimentally demonstrated to be feasible, and progress to commercial profitability is yet to come.

Nuclear fusion

The Sun, as a star on whose activity our lives depend, works and emits energy precisely on the principle of nuclear fusion. This means that the main source of all energy that exists on Earth is nuclear fusion. We actually owe all life on the planet to the nuclear fusion that occurs naturally in the Sun. The question that arises is whether man is capable of creating a mechanism for the production and control of energy obtained by fusion. From fiction to reality, fusion has the potential to provide cheap energy to humanity in unlimited quantities. Back at the summit in Geneva in 1985, the leader of the Soviet Union, Mikhail Gorbachev, proposed to US President Ronald Reagan that the two superpowers jointly launch a project to develop nuclear fusion for civilian purposes. French President Francois Mitterrand and British Prime Minister Margaret Thatcher also took part in the negotiations. That's when the idea was born that was embodied through the International Thermonuclear Experimental Reactor (ITER) project, which was formalized in 2006 at the Elysée Palace by the EU, the United States of America, China, India, Russia, Japan and South Korea.

ITER is already being built in the south of France. It will be the largest experimental tokamak nuclear fusion reactor and the largest magnetic confinement plasma physics experiment in the world when the main reactor and first plasma are finished, which is anticipated to happen in late 2025 (ITER 2022). ITER is intended to demonstrate that net fusion energy generation is possible, but due to the complexity of the reactor and the enormous superconducting magnets necessary to hold the hot gases in place, it comes at a significant cost, estimates for its construction roughly $25 billion (Clery, 2022).

In the not-so-distant year 2033, the first commercial nuclear power plant was designed to produce energy through the nuclear fusion of deuterium and tritium. The power plant is named "DEMO", short for "Demonstration Power Plant" and is a continuation of the ITER program that would successfully transition from the experimental to the commercial phase by constructing this nuclear power plant (ITER, 2022). The importance of ITER is also shown by the fact that it is the most expensive joint scientific project of several countries since the International Space Station.

The main problem that prolongs the commercialization of nuclear fusion lies in the fact that nuclear fusion takes place at extremely high temperatures, several times higher than on the surface of the Sun. This means that an enormous amount of energy is needed in order to heat the atoms to such an extent and encourage their fusion. Tiny hydrogen isotopes have a strong fusion resistance. National Ignition Facility at the Lawrence Livermore National Laboratory (LLNL) in

California made an important step towards nuclear fusion research. Experimental fusion reaction in laboratory produced more energy than it took to start the reaction (Chang, 2022). Fusion reactions in the past have required more energy inputs than they have generated. Nuclear fusion may not be commercially viable for another 30 years but future fusion power plants are clearly visible (Rapier, 2023).

Why are efforts and resources being invested to develop fusion in the energy sector? Deuterium and tritium, which are needed for nuclear fusion, and which in a few decades will be the fuel for fusion nuclear power plants, although they exist in nature in negligible quantities, are relatively easy to produce. In addition to natural limitations, resources such as oil, coal and natural gas carry with them the costs of the impact of external factors such as natural disasters that can cause environmental catastrophe. How much does it cost us to spill a tanker into the sea? Or treating people affected by the ill effects of coal mining? With deuterium and tritium fusion fuels, costs due to external action have a marginal value. An important technological fact of the future fusion reactors is that there is no risk of the reactor melting, thus avoiding disasters like the one from Chernobyl or recently from Fukushima. From the socio-political aspect, today we are familiar with wars for resources. Conflicts based on the possession of oil-rich territories such as Middle East are evident. By switching to fusion, we avoid economic and political tensions and pressures because fusion fuels do not depend on geographical distribution. Therefore, there is no monopoly of a certain region on a necessary resource, as is the case today with oil in the Middle East or natural gas in Russia. Therefore, in addition to the fact that energy from nuclear fusion is the most ecologically clean, potentially extremely cheap, it is also the most politically benign when viewed through the prism of geopolitical interests.

Thorium-based reactors

The use of thorium as a nuclear fuel might represent yet another technical advance in the realm of nuclear energy. Compared to uranium, thorium is less radioactive and generates less nuclear waste. In addition to being more prevalent in nature than uranium, its isotope thorium-232 may be turned into uranium-233, and it also offers safer handling and produces far less nuclear waste (Петровић, 2010). Because thorium originates from surface miners as opposed to deep mines, it is simpler to get. From the middle of the 1950s until the middle of the 1970s, when nuclear energy was still in its infancy, there was a lot of interest in developing thorium fuels and fuel cycles to replace uranium stocks. For nations with significant thorium resources but relatively little uranium stocks for their long-term nuclear power program, thorium fuels and fuel cycles are especially important.

Thorium is 3 to 4 times more common than uranium in nature, extensively dispersed, and is a resource that can be easily mined in many nations, although it has not yet been used for commercial purposes. As a result, thorium fuels support uranium fuels and assure the long-term viability of nuclear power (IAEA, 2005). The thorium fuel cycle is a desirable method for creating long-lasting nuclear energy with minimal radiotoxic waste (IAEA 2005). The problem with thorium is that due to its higher melting point, it requires the artificial creation of higher temperatures. Also, in 1980 International Atomic Energy Agency (IAEA) pointed out protactinium (element produced in thorium reactors) as a problem for generating uranium-233 which is material for nuclear weapons. Conclusion of IAEA report entitled „Advanced Fuel Cycle and Reactor Concepts“ was that thorium fuel cycle is equivalent to uranium/plutonium cycles in terms of weapon-grade material proliferation (Uribe, 2018). Practically, uranium-233 has better properties for nuclear weapons than uranium-235 but is always contaminated with small amounts of uranium-232 which is huge emitter of gamma radiation and tehrefore more dangerous to handle (Halem, 2014).

From the perspective of energy production, thorium has enormous potential. Thorium fuel cycles have appealing qualities include reduced levels of waste creation, a lower concentration of transuranic elements in that waste, and the ability to diversify the source of nuclear fuel. Despite these benefits, creating an economic rationale to carry out the required development work is one of the biggest obstacles to the commercialization of thorium fuels (WNA, 2020). As a by-product, thorium must be extracted using more expensive techniques than uranium. The quantity of thorium that can currently be extracted from the ground in an economical way is therefore less than the amount of uranium. However, if there was a greater need for thorium and its use in nuclear power plant development, this may alter (Vlasov, 2023).

China declared the completion of its first experimental thorium-based nuclear reactor in August 2021. The reactor will be tested over the following several years. It was built in the northern part of the nation, in the heart of the Gobi Desert. Beijing intends to build another reactor that might be capable of producing power for more than 100,000 houses if the experiment is successful (Vlasov, 2023). China is not the only country hoping to benefit from thorium's special qualities. India, Japan, the United Kingdom, the United States of America, and other nations have previously shown a keen interest in research into thorium's potential use in nuclear power. This metal has the potential to replace uranium, the most popular nuclear fuel, with one that is more plentiful and more eco-friendly.

Extraction of uranium from seawater

Although uranium is not a renewable energy source, its quantitative availability and extraction process help to preserve other finite resources, making it sustainable (Conca, 2016). A secure and predictable supply is provided by uranium's high energy density (1 ton of uranium has the same amount of energy as 14,000–23,000 tons of coal), ease of stockpile management, and vast geographic spread of its resources (NEA, 2023). The effects on humans and the environment are minimized by modern uranium mining and processing techniques. Although some believe there is a limited supply of uranium, two prior phases of vigorous investigation in the 1940s and 1970s, driven by rising demand, revealed amounts of resources significantly in excess of anticipated requirements. Natural uranium has been generated in excess of 2.3 million tons, and throughout the same time span, recognized uranium resources have mostly risen (NEA, 2023). The known uranium reserves as of right now would be sufficient for more than 100 years' worth of energy production (at current rates) (Conca, 2016).

The prospect of obtaining uranium from seawater as an alternate source of nuclear energy is being discussed by more and more experts. The difficulty in extracting uranium comes from the fact that saltwater has a relatively low concentration of uranium content. There are a lot of techniques for uranium extraction from seawater, including adsorption, pouring, electrochemistry, and more. According to the majority of analysis, method of adsorption, which involves a specific resin that can bind uranium, could be the most efficient. Another popular method involves the use of electrochemical cells that attract uranium, and then the uranium is extracted from the cells. Uranium can be found in seawater at a concentration of only about three micrograms per liter. However, due to the large amount of water contained in the oceans, the total amount of uranium in seawater is estimated at 4.5 billion tons, which is a thousand times more than the uranium currently found in the world's reserves (Abate, 2017).

One of the few countries with a strong commitment to extraction uranium from seawater is Japan, which has consistently made the most research efforts. Japan Tobacco and Salt Corporation conducted the initial studies on the extraction in the 1960s (Kanno, 1984). Since then, laboratory studies have been conducted at several colleges and institutions. The Japanese government began a program to investigate the extraction of uranium from seawater in 1974. In recent research, the Japanese Atomic Energy Agency (JAEA) produced a fibrous amidoxime-based preirradiation adsorbent for saltwater uranium extraction and carried out a marine experiment to assess the seawater uranium collection (Rao, 2010, pp. 4-5). About 7 kilometers off the coast of Aomori, Japan, a stack design with a floating frame and cage of adsorption beds was constructed. This location's sea depth was around 40 meters. The 0.5 M hydrochloric acid fractionally eluted the adsorbed uranium on the adsorbent fabric. For 30 days of soaking, the uranium absorption was 0.5 g-U/kg-ad on average (Rao, 2010, 5). This experiment accumulated enough uranium to equal around one kilogram of yellow cake during the course of 240 days submerged in the water (Rao, 2010, p. 5). Before the extracted uranium can be utilized for the manufacturing of yellow cake, it must first undergo a further purification by solvent extraction. Although it was experimentally proven to work, the cost of structure for collecting uranium accounted for about 80% of the value of the extracted uranium, which is still far from commercial viability.

Some scientists claim that, using existing technologies, it would be possible to extract enough uranium from seawater to fuel nuclear power plants for more than 10,000 years (Abate, 2016). However, this procedure is currently considered too expensive to be economically viable. There are still many concerns about the extraction of uranium from seawater, including questions about the environmental consequences of this process. With the increasing demand for nuclear energy, many scientists believe that this area is worth further research. Although the extraction of uranium from seawater can be challenging, the potential for obtaining nuclear energy from this source is great and can play an important role in the future of nuclear energy.

Conclusion

We are witnessing a constant increase in energy consumption, while at the same time the problems of lack of energy resources, environmental pollution and the global greenhouse effect are growing. Nuclear energy is a proven part of the energy mix and of all energy sources it has the most space for improvement. Nuclear fusion has the potential to provide mankind with unlimited and cheap energy without the effects of destroying the environment. Thorium reactors can be a kind of bridge between classical types of nuclear energy production and nuclear fusion. Extracting uranium from the ocean overcomes the problem of limited nuclear fuel resources, and when it first becomes commercially viable, it will significantly lower the cost of producing nuclear fuel. All three technological advances in the field of nuclear energy are developing in parallel, and the most significant of all is the fact that each of them has been experimentally proven to be achievable in practice. Although it is difficult to predict the time spans when these technologies will find widespread use, we can venture to conclude that it is only a few decades of additional research. The future definitely belongs to nuclear energy!

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