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Overview of nuclear energetics development in Europe and Serbia's perspectives

Pregled razvoja nuklearne energetike u Evropi i perspektive Srbije

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Abstract: Despite all expectations of a decline in interest in energy in the 21st century, the issue of energy seems more relevant than ever. The problem of energy supply has become universal and all-encompassing. The entire global economy has been impacted by the energy crisis due to fuel shortages, rising costs, and increasing consumption. Serbia, like the rest of the world, is facing tremendous challenges in the energy sector: the use of fossil fuels, slow development of technologies, and the adoption of renewable energy sources or nuclear power development. The energy system of Serbia is the backbone of the economy, but also a source of progress in sustainable and green development. The energy potential of alternative and renewable sources is underutilized due to the dominance of outdated technologies, especially in the energy sector of Serbia, while plans for nuclear energy are still in development. European countries, in contrast, use nuclear energy, thereby obtaining large amounts of energy while avoiding dirty technologies. Currently, a special focus is on the development of small modular reactors (SMR), which could be a sustainable option for Serbia, which has yet to use nuclear energy.

Keywords: Electricity system, Nuclear power, Climate change, Decarbonization, SMR.

Sažetak: Uprkos svim očekivanjima o padu interesovanja za energetiku u 21. veku, pitanje energetike se čini aktuelnijim nego ikad. Problem snabdevanja energijom postao je univerzalan i sveobuhvatan. Cela svetska ekonomija je pogođena energetskom krizom zbog nestašice goriva, rastućih troškova i sve veće potrošnje. Srbija se, kao i ostatak sveta, suočava s ogromnim izazovima u energetskom sektoru: korišćenje fosilnih goriva, spor razvoj tehnologija, usvajanje obnovljivih izvora energije ili razvoj nuklearne energije. Energetski sistem Srbije je okosnica privrede, ali i izvor napretka u održivom i zelenom razvoju.
Energetski potencijal alternativnih i obnovljivih izvora je nedovoljno iskorišćen zbog dominacije zastarelih tehnologija, posebno u energetskom sektoru Srbije, dok su planovi za nuklearnu energetiku još u izradi. Evropske zemlje, nasuprot tome, koriste nuklearnu energetiku, čime dobijaju velike količine energije, a izbegavaju prljave tehnologije. Trenutno je poseban fokus na razvoju malih modularnih reaktora (SMR), koji bi mogli da budu održiva opcija za Srbiju koja još uvek ne koristi nuklearnu energiju.

Ključne reči: Elektroenergetski sistem, Nuklearna energija, Klimatske promene, Dekarbonizacija, SMR.

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INTRODUCTION

The introduction of modern energy technologies into the existing energy system is generally aimed at improving the energy transition process, which is defined through the matrix of decarbonization, decentralization, digitalization, and democratization of the energy sector (Parović, 2023). Energy needs vary across different parts of the world, but the growth of the global population and the increasing energy demands of industries undoubtedly lead to a rising demand. On the other hand, questions are being raised about security, access, and sustainability. The energy trilemma addresses three often conflicting challenges: energy security, equitable access to energy, and environmental sustainability (Liu et al., 2022).

Primary energy can be obtained from non-renewable energy sources, such as fossil fuels and nuclear fuels, as well as from renewable energy sources. Nuclear energy is increasingly being discussed as an alternative energy source. Although it is a non-renewable source, nuclear energy, due to its low fuel consumption (high energy density) and high productivity in energy generation, can also be viewed in this way (Čučulović et al.,2024).

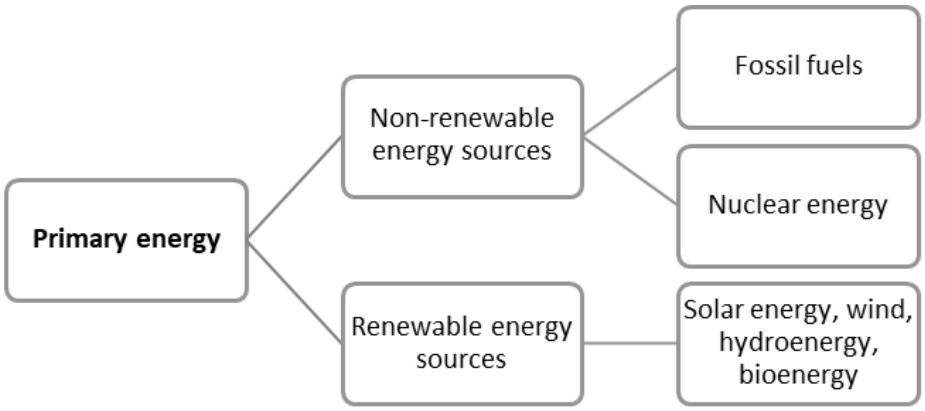

Figure 1 – Systematization of primary energy
Source: Author's figure

A higher presence of air pollutants promotes the generation of nuclear energy as an alternative to fossil fuel energy sources. While nuclear energy generation produces no air pollution, it does impose significant land use requirements, potentially leading to ecosystem degradation. Factors such as uranium extraction, nuclear waste management, disposal, and accidents contribute to this impact (Soto & Martinez-Cobas, 2024).

Nuclear energy and the promise of cost-effective small modular reactors (SMRs) is high on the EU's policy agenda, against the backdrop of a difficult global geopolitical context and the Union's energy security and climate ambitions. The EU is building a comprehensive strategy for the development and deployment of SMRs, acknowledging their potential benefits and challenges. Innovative nuclear technologies are of significant strategic value, with big steps being taken to increase the supply of advanced nuclear fuels and research and innovation capacities in this area.

Conventional reactors typically require low-enriched uranium (LEU), defined as being enriched to less than 5 % U-235. HALEU is a type of nuclear fuel that is distinguished from LEU by continuing the enrichment process to the range of 5 % to 20 % U-235. This increase, although seemingly modest, paves the way for innovative reactor designs, enhancing efficiency and safety (EP, 2024).

This the development of SMRs is still promising, in the energy mixes of countries, there are operational conventional nuclear reactors, historically marked by accidents such as the one in Chernobyl in 1986. These reactors may not offer the same level of safety that SMRs with HALEU fuel could achieve, but they continue to generate energy that remains in use.

1. METHODOLOGY

This paper relies on a descriptive and analytical method, as well as a comparative analysis of European countries regarding nuclear energy based on World Nuclear Association database (WNA, 2025). Through a prediction method: SWOT analysis of potential nuclear energy utilization in Serbia, the foundation for the future development of nuclear energy in Serbia is presented. The research is divided into two sections. The first part presents an overview and comparative analysis of all European countries that utilize nuclear energy. The second part of the research focuses on the potential for nuclear energy development in Serbia.

2. RESULTS AND DISCUSSIONS

Uranium has characteristics that can enhance a country's energy supply security when nuclear energy is part of its energy mix. Uranium is a uniquely concentrated energy source, meaning that the required quantities are much smaller compared to coal or oil.

Table 1 – Nuclear fuel types

Fuel type	**Low-enriched uranium (LEU)**	**High-assay low-enriched uranium (HALEU)**	**Highly enriched uranium (HEU)**
Enrichment U-235	less than 5 % U-235	5-20% U-235	above than 20% U-235
Utilization	Conventional reactors	For advanced reactors to achieve smaller designs that get more power per unit of volume. HALEU will also allow developers to optimize their systems for longer operating cycles, increased efficiencies, and better fuel utilization.	Often associated with weapon-grade uranium, which is commonly considered to have been enriched above 90 % U-235

Source: Author‘s systematization

Currently, there are 439 operational reactors worldwide, providing 398,108 MWe. The nuclear share of global electricity generation is 9%. The top 10 countries by total operable reactor net capacity are: USA (96952 MWe), France (63000 MWe), China (56888 MWe), Japan (31679 MWe), Russia (26802 MWe), South Korea (25825 MWe), Ukraine (13107 MWe), Canada (12669 MWe), India (7425 MWe) and Spain (7123 MWe). In Europe, France, Russia, Ukraine, and Spain lead in nuclear energy production, but other countries also utilize nuclear energy or have plans to develop it. In Serbia, in 2024, amendments to the Energy Law lifted the moratorium on the use of nuclear energy, and the Nuclear Energy Development Program was included as part of the revised law. The program is divided into three phases: assessing the feasibility of adopting nuclear energy development, developing the program, and its implementation.

Overview of Operational Reactors in Europe

In European countries, there are currently 157 operational nuclear reactors, representing 35.8% of the total number of operational reactors worldwide.

Table 2 – Operable reactors in European countries

Country	**Total operable nuclear capacity (MWe)**	**Nuclear share of generation (%)**	**Nuclear generation (GWh) 2023**	**Number of units**
Belarus	2220	29	10997	2
Belgium	3463	41	31289	4
Bulgaria	2006	40	15488	2
Czech Republic	4212	40	28728	6
Finland	4369	42	32759	5
France	63000	65	323773	57
Hungary	1916	49	15092	4
Netherlands	482	3	3771	1
Romania	1300	19	10312	2
Russia	26802	18	203957	36
Slovakia	2308	61	17005	5
Slovenia	688	37	5332	1
Spain	7123	20	54371	7
Sweden	7008	29	46648	6
Ukraine	13107	15	49550	15

Source: Author‘s systematization

Stances and actions toward the use of nuclear energy vary from reactor shutdowns, as seen in Germany, to the construction or planning of nuclear energy implementation. However currently, 15 countries in Europe utilize nuclear energy: Belarus, Belgium, Bulgaria, Czech Republic, Finland, France,

Hungary, Netherlands, Romania, Russia, Slovakia, Slovenia, Spain, Sweden and Ukraine. Countries with a capacity below 1,000 MWe are: Netherlands and Slovenia.

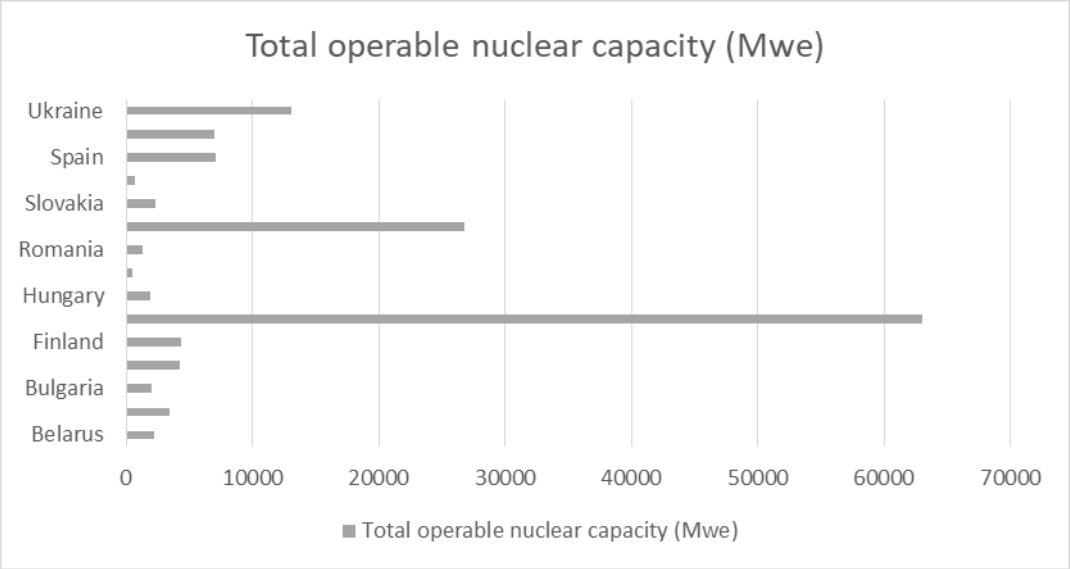

Figure 2 – Total operable nuclear capacity in MWe by country
Source: Author's figure

France is the largest producer of nuclear energy in Europe, Russia and Ukraine also have substantial nuclear capacities. France, Russia, and Ukraine each have a capacity of over 10,000 MWe. The majority of selected countries fall within the range of 1,000 to 9,999 MWe, and this group includes 10 countries: Belarus, Belgium, Bulgaria, Czech Republic, Finland, Hungary, Romania, Slovakia, Spain and Sweden.

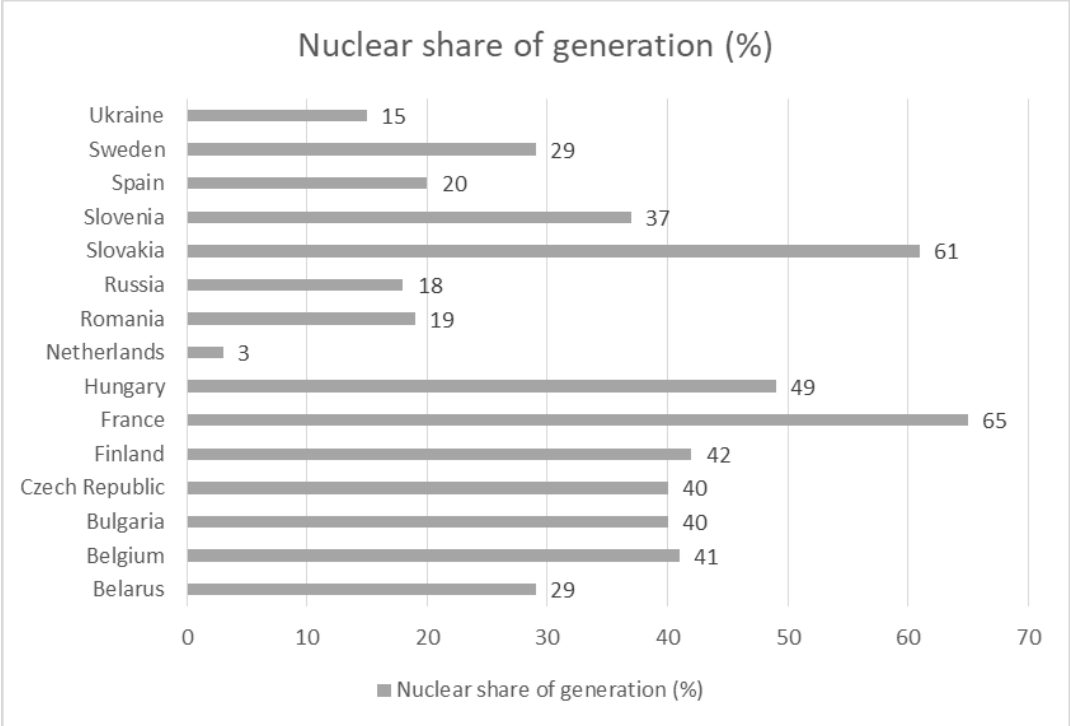

Figure 3 – Nuclear share of generation in %
Source: Author's figure

By researching nuclear share of generation the highest share has France, Slovakia and Hungary. The average share of nuclear generation in Europe is 33.86%. Above the average are 9 of 15 countries.

In achieving green goals, Serbia is primarily focused on the development of RES technologies and energy generation from renewable sources. However, as global uncertainty over energy resources grows, and despite the existing moratorium on the use of nuclear energy, interest in reopening this issue is emerging once again.

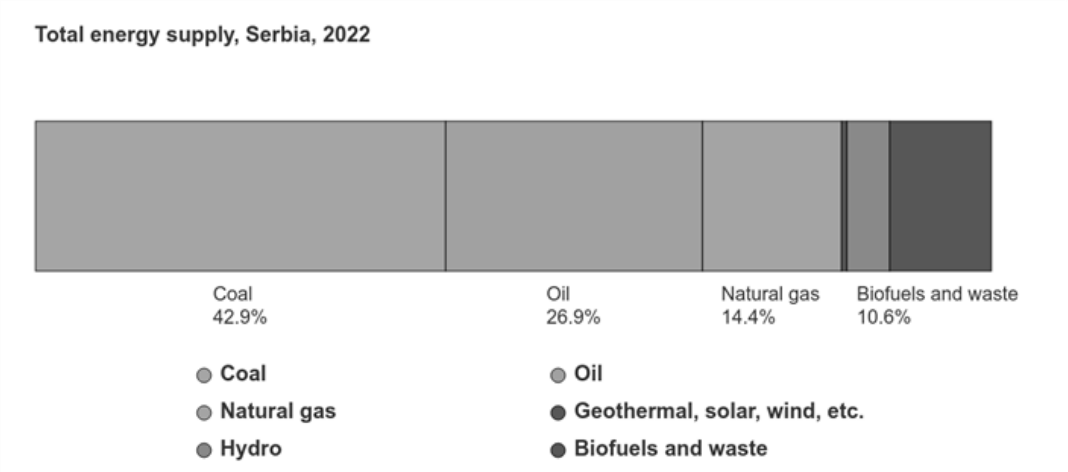

Figure 4 – Energy mix of Serbia (2022)
Source: IEA, 2025

By reviewing Serbia's energy mix, it is clear that fossil fuels play a significant role, accounting for 42.9% and development of RES is slow and unpredictable. The development of RES requires investments, and the same applies to nuclear energy. Nuclear energy brings both risks and benefits, and in this regard, a SWOT analysis has been conducted for the use of nuclear energy in Serbia.

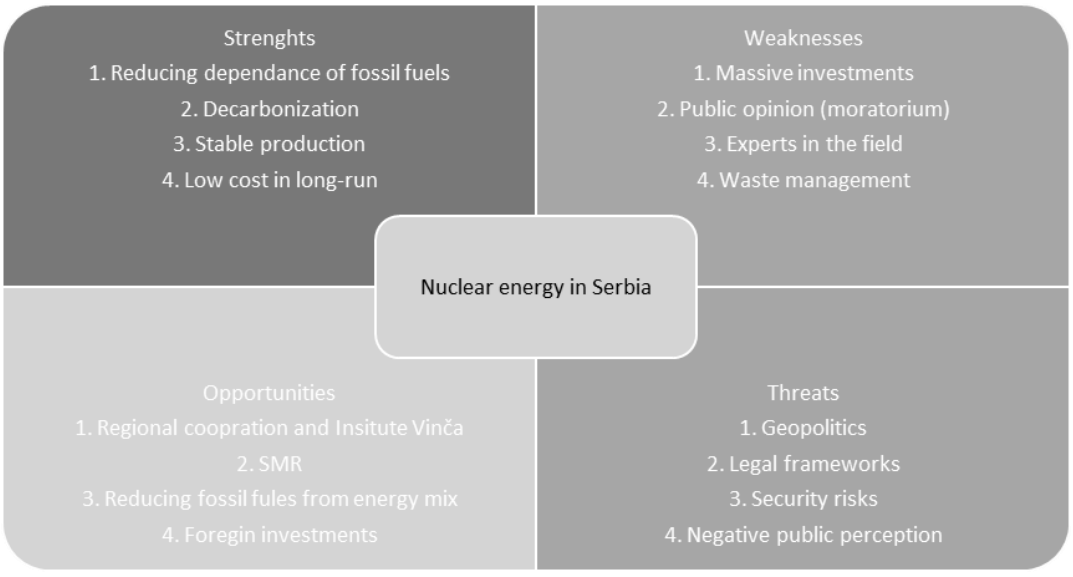

Figure 5 – SWOT analysis for nuclear energy utilization in Serbia
Source: Author's research

Serbia needs to decarbonize its energy mix, and nuclear energy could be one of the solutions for transitioning to renewable energy sources. In examining the current climate regarding nuclear energy, the SWOT analysis highlights the Institute of Nuclear Sciences Vinča, which has experts in this

field, as well as the accident in 1958, which could influence public opinion about nuclear energy. This issue requires further investigation in light of the growing energy needs and climate changes caused by the use of fossil fuels.

CONCLUSION

By reviewing the status of nuclear energy through a comparative analysis of European countries that utilize nuclear energy and analyzing the development of these technologies in Serbia, it appears that nuclear energy is emerging as one of the solutions. SMR technologies are promising, both in the context of the European nuclear energy challenge and when considering their application in Serbia. Another option could be international cooperation with neighboring countries such as Bulgaria or Hungary, which have a significant share of nuclear energy in their energy mixes, thus alleviating the pressure on the environment and represent an example of good practice.

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