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EDITORIAL

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Towards cleaner energy transition: Small modular reactors as a feasible revolutionary step in the economics of nuclear energy

The topic addressed in the current editorial relates to the impact of the installation of small modular reactors on the development of nuclear energy, which is in line with the issues of contemporary energy transition processes (Tzeremes *et al*., 2022; Pietrzak *et al*., 2022; Mukhtarov, *et al*., 2023;

Balcerzak *et al*., 2023; 2024). The energy transition is a global phenomenon that undoubtedly has the most significant impact on economic, social, institutional, environmental, and political changes in all economies (Liu *et al*., 2022; Yin *et al*., 2023; Bakhsh *et al*., 2024; Delcea *et al*., 2024). One of the main problems of the development of world economies is currently ensuring adequate energy supplies, especially electricity, while meeting appropriate environmental conditions (Streimikiene, 2022; Igliński *et al.*, 2022; Jakubelskas & Skvarciany, 2023; Štreimikienė, 2024; Oesterreich & Barej-Kaczmarek, 2024). Nowadays, energy policy and energy security undoubtedly have a global dimension, which, on the one hand, carries numerous threats but, on the other hand, creates conditions for their limitation or elimination (Nihal *et al*., 2024). However, from the very first and fundamental perspective, it is impossible to create assumptions for any national energy policy without considering the broadly analyzed specificity of a given region and the energy policy of neighboring countries. This naturally raises questions about the main energy sources on which national energy policy can be based (Gao & Chen, 2023). More and more countries are assuming a transition process to nuclear power as the sole conventional energy source in their long-term energy strategies. However, it should be remembered when taking into account the current development of energy transition processes — worth remembering its political context — that equally strong emphasis in parallel with the development of nuclear power is still placed on the development of renewable energy, which to some extent allows for the diversification of the national energy mix of each economy (Cheba *et al*., 2023; Ullah & Lin, 2024).

Traditionally, nuclear energy strategic plans have been based on the assumptions of building the nuclear energy sector with the starting of construction of a single, large nuclear power plant. In recent years, however, a viable alternative of building a network of small nuclear power plants has emerged (Tuler & Webler, 2024). Compared to large nuclear power plants, the purpose of building nuclear units of this type is to reduce investment costs and provide electricity to areas where the construction of large power grids is difficult or economically unjustified. In the case of planning nuclear power plants, various models are considered depending on the adopted solutions and technologies (Adamov *et al.*, 2025). Light water reactors dominate among them, based on many years of experience in the operation of nuclear-powered submarines (Chen *et al.*, 2025). The idea is slowly making its way into the national strategic plans of the world's economies, and it

seems that conventional energy based on small nuclear power plants may be the next evolutionary — or maybe even possible to claim — revolutionary step of the energy transition.

Three groups of energy carrier producers can be distinguished in the electricity generation sector. The world's most developed energy production subsector is composed of power plants using traditional coal and hydrocarbon fuels: hard coal and brown coal, liquid fuels, and natural gas (Dam *et al.*, 2025). The second group consists of installations using natural sources, mainly solar and wind; these are the so-called renewable energy sources and "large" water power (Solangi *et al.*, 2025). The third part of the sector under consideration are large nuclear power plants using heavy fissile isotopes (Ghisellini *et al.*, 2025). Power plants of this type constitute the basis of electricity production in the world's largest economies, e.g., the USA, France, and Russia.

As already mentioned, each national economy has its own specific energy mix structure, where traditionally the largest share goes to energy generated from conventional sources, which are most often fossil fuels in the form of coal and hydrocarbon fuels (Balcerzak *et al*., 2024). A few countries rely on nuclear energy as a main conventional source. Subsequently, renewable sources have a much lower share of the energy mix (Abbasi *et al*., 2022; Michalak & Wolniak, 2023). From year to year, the share of energy from renewable sources is steadily increasing, where solar and wind energy mainly dominate (Igliński *et al*., 2023; Uddin *et al*., 2023). However, due to the instability of renewable energy production, mainly due to geographic conditions, it is recommended to develop green hydrogen production (Amin, 2022; Lebrouhi *et al*., 2022). It is possible that shortly green hydrogen will become another element in the structure of the energy mix, and its share will grow dynamically (Capurso *et al*., 2021). Many world economies base their energy policies on buying energy from other economies. This is often for economic reasons, but it significantly reduces energy security due to energy dependence on other economies. Having one's own properly diversified energy mix is currently the most relevant national energy policy and security issue (Bashir, 2022; Triguero-Ruiz *et al*., 2023).

Currently, most of the world's economies still use coal and hydrocarbon fuels as a source of conventional energy. In many economies, the share of this energy source is very high, often approaching 100%. This situation is problematic from the point of view of regional policy, as it can be a source of various types of problems in each of the key areas of development of

modern economies, including economic, social, institutional, environmental, and political areas. In addition, it should be noted that the listed energy sources significantly lead to environmental degradation. Also, the size of the reserves of coal and hydrocarbon fuels is limited. As a result, increasing their extraction within time may become on the verge of profitability or may become unprofitable. Last, but not least, one must point to the international political context related to the doctrine of CO2 reduction, which must also be taken into consideration. These are the next important arguments for building energy systems based on renewable and nuclear energy together with energy storage and/or green hydrogen (Chen & Nouseen, 2025). Undoubtedly, in the long term, there will be a move away from the energy subsector using only traditional coal and hydrocarbon fuels. This process leads to the challenge or problem of building stability of the energy system, which currently, due to technological and economic factors, cannot be ensured by the single expansion of renewable energy production. Based on technological and economic characteristics, nuclear energy is the most feasible solution to this problem, which can provide a stable foundation for the energy sector (Dong *et al.*, 2025). Therefore, as part of the process of transitioning to nuclear energy as a stable conventional source, it is worth asking about the trend in the development of nuclear energy, which will be consistent with the ongoing processes of energy transition and the implementation of the national energy policy of world economies, while at the same time maintaining an appropriate level of energy security. One of the possible directions is further development of sizeable nuclear energy, which will allow for the possibility of reducing the amount of energy obtained from coal and hydrocarbon fuels. However, considering the socio-economic changes related to the energy transition, it seems likely that the nuclear energy sector will also develop effectively using small modular reactors (SMR).

Analyzing the historical, technological, and economic development of the nuclear energy sector, one can find the path leading to the so-called evolutionary projects, which are aimed at increasing competitiveness and streamlining the operation process, as well as further improving the level of safety in power plants. The first two goals are achieved by simplifying the design of both the reactors themselves and the elements of the reactor system, especially the primary circuit, i.e. the elements directly cooperating with nuclear reactors. In the case of safety systems, the so-called passive systems, i.e., systems that do not require the use of devices using mechani-

cal drive work, are becoming increasingly important (Nian, 2024). The final goal here is to reach the widespread use of so-called inherently safe reactors. In such reactors, the role of safety systems is played by appropriately used laws of nature, thanks to which, in emergency situations, phenomena occur spontaneously, leading to the safe shutdown of the reactor and then its sufficiently effective cooling to collect the so-called residual heat (Ho *et al*., 2019).

Traditional nuclear power plants are very large units with a capacity of 600–1500 MW, which brings a number of benefits (e.g., economies of scale), but also makes their construction and financing a very complex process. Therefore, in the last decade, there has been an increase in interest in low-power nuclear units, the so-called SMRs, which may enter the market at the end of the current decade. Such reactors, with a capacity of less than 300 MW, are to be manufactured in series in production plants and delivered to the place of target operation in the form of successive modules, which can be added successively, depending on local needs and conditions (Hussein, 2020). The new modular reactors are to have a simpler design to reduce costs and construction time. Many private investors are involved in the work on SMR reactors, which is a new trend in the nuclear energy sector (Ashoori & Gates, 2024).

Depending on local needs, small and larger energy complexes can be created. This is mainly due to the increase in capital costs associated with the construction of large nuclear units (with capacities above 1 GWe) and the need to ensure energy supplies in small power grids and remote or inaccessible regions. SMR can occur individually or in a group of many modules put into operation successively, making the entire investment easier to finance (Kim *et al*., 2024).

As a result, when asking about the development trends of the nuclear energy sector in recent years, it is more often stressed that the sector may move away from the construction of large nuclear power plants, whose huge energy potential will be replaced by a suitably designed network of small nuclear power plants. Modern low-power reactors for energy and special applications, besides the already mentioned characteristics such as simple, integrated design, manufacturing in series in a short time, and low construction costs (Ishaq & Dincer, 2024), will have passive safety features resulting from the laws of nature (gravity, convection). Many of them are designed to be placed in the ground, which increases their resistance to terrorist and proliferation threats. The radius of the danger zone around

such nuclear facilities will not exceed 300 m (Steigerwald *et al.*, 2023). Currently, it is assessed that SMR construction should take about 1/3 of the time needed to build a traditional large nuclear power plant. In addition, the costs of building such a unit are expected to be about 30 percent lower, calculated per installed megawatt of power. An SMR with a capacity of about 300 MW can generate electricity annually necessary to power a city of 150 thousand people. So, the cost of producing 1 MWh of electricity should be 30 percent lower than in the case of gas-steam blocks (Ramana & Blaise, 2024).

The economic potential of SMR reactors lies mainly in the following factors (Xie *et al.*, 2024):

- small size and modular design enable them to be manufactured in specialist factories in conditions that ensure compliance with high technical standards and production quality,
- the possibility of installing subsequent identical units in one location significantly reduces the financial burden of investment and also enables adjustment to the current local demand for energy and flexible response to its growth,
- small size and passive safety features predispose them to countries with small power grids and little experience in implementing nuclear energy,
- The size of the facility, simplicity, compactness, and integrity of the structure, as well as the use of innate, passive safety systems, will reduce the use of complex and multiple emergency systems. This leads to lower construction costs compared to large power units,
- the economics of the production series will allow for further reduction of manufacturing costs,
- the possibility of placing the nuclear unit underground or underwater increases its resistance to natural hazards (earthquakes, tsunamis) and external hazards (aircraft crashes, terrorism, non-proliferation),
- lower requirements for access to cooling water enable the deployment of facilities close to the potential recipient, not only on the coast but also inland, in remote and inaccessible areas for energy supply or for various extraction projects (mines, gas, and oil wells),
- the diversity of technologies and obtained coolant temperatures enable the design of facilities not only for energy purposes. They can also be used for water desalination, heating, chemical processes (including hydrogen production), and the disposal of radioactive waste, with the pos-

sibility of removing the facility in its entirety after its end of use or dismantling it on-site (Ingersoll, 2016).

Even though technology and the whole sector are still at a relatively early stage of development, with their typical problems and challenges, SMRs may become an innovative way to generate low-emission, climate-neutral, safe, and reliable electricity. SMRs can be the answer to many problems that characterize traditional nuclear power. The smaller scale of the investment and the ability to adjust its size to the needs mitigate the risk of budget overruns and delays in project implementation. Less stringent location conditions minimize potential costs. This technology is an attractive choice for investors from the private sector. The increasing number of projects implemented successfully will positively impact their economic effectiveness and, therefore, the interest in financing SMRs by financial institutions.

From the perspective of national security, which in the current times becomes a priority in building any energy system, distributed SMRs and renewable energy sources guarantee security of supply. A centralized energy system based on a dozen or so large power plants is vulnerable to serious failures, whether "natural" or deliberate physical or IT attacks. A distributed energy system based on thousands of diverse, distributed, and independent sources of renewable and nuclear energy, creating energy clusters that can operate independently, is similar in its resistance to the Internet, which was designed at the time as a structure resistant to attacks that destroy its fragments. In a distributed energy system, a total blackout scenario will not occur or is much less feasible.

To sum up, from the socio-economic perspective, the future may belong to SMR, or at least they can become the second important pillar of the nuclear energy production system. Therefore, they can become a key step in the energy transition, improving the energy security of economies and optimizing and diversifying their energy mix.

Undoubtedly, at the current stage of technological development, but at the same time not less important from the perspective of the political context, one of the most important issues is the regulation and financing of the construction of small modular reactors. From the technological and economic perspective, these investments can be treated as compatible with the idea of long-term sustainable development goals (Ramzan *et al*., 2022; Shuguang *et al*., 2022; Zheng *et al*., 2023; Niță *et al*., 2024; García-Agüero *et al*., 2024). However, looking at the political context is not a less important is-

sue, and probably one of the biggest challenges is ensuring the same status for technology and the whole sector in terms of national and international regulation and policy.

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Compliance with ethical standards

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Data availability statement

All data generated or analyzed are included in the published article. The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation. The raw anonymized data can be provided by emailing the primary author.

Author contributions

All listed authors have made a substantial, direct and intellectual contribution to the work, and approved it for publication. The authors take full responsibility for the accuracy and the integrity of the source analysis.

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The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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