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EDITORIAL

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Energy mix management: A new look at the utilization of renewable sources from the perspective of the global energy transition

The processes of global energy transformation are currently considered the strongest determinants of social, economic, institutional and technological changes in modern economies (Balcerzak & Pietrzak, 2017; Igliński *et al*., 2021; Igliński *et al*., 2023a; Pietrzak *et al*., 2021; Pietrzak *et al*., 2022). The socio-economic changes of at least the last thirty years have contributed to the possibility of the energy transformation in its current form. Undoubtedly, a necessary condition was the occurrence of the phenomenon of world globalization in the 1990s. The dynamic development of world globalization processes has had a positive impact on the strong increase in interdependence between various markets, predominantly at the international level (Fałdziński *et al*., 2016; Stantana *et al*., 2023; Lv *et al*., 2023). This affected primarily the change in the conditions for the functioning of markets, in particular financial markets and macroeconomic financial governance, which resulted in the need to introduce many institutional changes to lower the risks of global crises (Balcerzak *et al*., 2016; Balcerzak & Rogalska, 2016; Gustafsson *et al*., 2022; Balcerzak *et al*., 2023 Karimli *et al*., 2024; Duta *et al*., 2023a; 2023b; 2024). The development of globalization processes has translated into a significant increase in the level of socio-economic development of world economies, including an unprecedented increase in the level of competitiveness and innovation (Lewandowska *et al*., 2023). On the one hand, these processes have contributed to a significant increase in the wealth of society, and on the other hand, to the emergence of new technologies and a significant decrease in the costs of their application (Kolupaieva & Tiesheva, 2023, including the production of systems for the production of renewable energy. However, it must be remembered that the cost and benefits of these processes has not been distributed evenly. Ultimately, the process of changing consumption patterns in the society observed over the last decade has opened the way to the beginning of the global energy transformation (Pal *et al*., 2024).

When considering the course of energy transformation processes, it should be emphasized that they contributed most to the creation of the renewable energy market (Singh *et al*., 2024). Renewable energy sources include primarily solar energy, wind energy, hydropower and bioenergy.

Additionally, the reactions inside the Earth allow for the production of geothermal energy, and the use of the phenomenon of attraction of celestial bodies allows for the development of tidal energy (Igliński *et al.*, 2022). The widespread use of renewable energy sources improves security on a local scale and contributes to improving energy supply, especially in areas with poor energy infrastructure (Uddin *et al.*, 2023). Currently, the production of renewable energy is available even to small enterprises and households, especially in the aspect of solar or wind energy production (Igliński *et al.*, 2016; Pietrzak *et al.*, 2021, Igliński *et al.*, 2022). The development of the renewable energy market is created for each economy individually at the national level, but is also institutionally strengthened by cooperation between countries at the international level and international legislation. In this case, the newly created institutions and legislation are intended to ensure the socially fair nature of energy transformation processes and a positive impact on the implementation of sustainable development goals (Pietrzak *et al.*, 2022; Brodny & Tutak, 2023; Cheba *et al.*, 2023; Jakubelskas & Skvarciany, 2023, López-Serrano *et al.*, 2023). The plans of international institutions are ambitious and assume that in the next 10 years the energy transformation processes will have a positive impact on changes in the energy policies of all countries.

The dynamic development of the renewable energy market is undeniably evidenced by the fact that within a few years, the renewable energy capacity in the world has increased from approximately 1,200 GW to approximately nearly 4,000 GW in 2023. The increase in power is currently mainly due to photovoltaics (PV) and the power wind industry (REN21, 2023). The described changes have an impact on the energy policy of most of the countries, where the need to diversify energy sources by establishing the appropriate structure of the energy mix is emphasized (Kumi & Mahama, 2023; Jonek-Kowalska, 2023). A question arises here — how to manage the energy mix within the state's energy policy, especially taking into account the dynamically developing energy transformation processes (Bakhsh *et al.*, 2024)? It should be emphasized that the process of managing the energy mix involves not only determining its optimal structure, but also determining the ways of its practical use, i.e. the ways of using the produced energy. Over the years, various countries have systematically focused on the idea of energy mix as part of economic management. In addition to national plans, strategies and regulations at the supranational

level are also created, for example in communities of countries such as the European Union (Caglar & Yavuz, 2023).

The development of the renewable energy market is important as a part of the state policy, as energy is a key element of the functioning of modern economies (Igliński *et al.*, 2021; Pietrzak *et al.*, 2021, Igliński, *et al.*, 2023a; 2023b; Zheng *et al.*, 2023). All mentioned renewable energy sources are an alternative to conventional energy and nuclear energy (Rehman *et al.*, 2021; Jonek-Kowalska, 2022). A rational state's energy policy should allow for the establishment of an appropriate structure of the energy mix, where currently there is an increasing emphasis on increasing the share of energy from renewable sources. It is worth to point that the need to diversify energy sources is argued not only by climate change, but also by the need to ensure energy security of the national economy (Triguero-Ruiz *et al.*, 2023). Both scientists and political decision-makers promote the development of alternative renewable energy sources and independence from traditional energy resources in order to reduce the adverse impact of high emissions of harmful greenhouse gases on the environment (García & Gómez, 2023; López-Serrano *et al.*, 2023). One of the key contemporary challenges is finding the optimal structure of the energy mix, where the deployment of various renewable energy systems would allow the production of clean energy while eliminating negative consequences, including: the local landscape or society. Another key challenge is managing the energy mix in terms of its practical use (Michalak & Wolniak, 2023). The fundamental issues are related to the decision regarding the methods of transmitting energy from selected sources, the methods of storing it and the purposes of its final use. In this case, a new perspective on energy mix management from the perspective of energy transformation must be proposed (Igliński *et al.*, 2023a, 2023b).

It should be emphasized that the structure of the energy mix at the national level affects the use of energy and the creation of the value chain in the economy, which translates indirectly into socio-economic development (Ram *et al.*, 2022). Determining the structure of the energy mix in accordance with the sustainable development approach will lead to reducing the share of traditional energy sources, such as coal, gas or oil, in favor of renewable energy sources (Zha *et al.*, 2023). The main motive of these activities is to reduce the negative effects of human activity on the environment (Galimova *et al.*, 2023). Of course, it should be emphasized that the structure of the energy mix, in addition to the state's energy policy, may also be

shaped by the activities of local governments, enterprises and households. Local governments can take over state functions in the field of large-scale energy production but also, together with enterprises and households, they can produce energy from renewable sources as a prosumer, especially in the field of solar and wind energy (Filho *et al.*, 2024).

Choosing the optimal structure of the energy mix and then managing the introduction of the produced energy into the economy is not an easy task. Undoubtedly, the production of energy from conventional sources should be replaced by the production of nuclear energy and the production of energy from renewable sources (Paraschiv, 2023). The optimal structure of the energy mix, especially in the field of renewable energy sources, is a specific issue for each country, due to the physical terrain and weather conditions. However, in most countries, the production of renewable energy is dominated by solar and wind energy. It should be emphasized that energy production from these two main energy sources is closely related to weather conditions, which affects the occurrence of seasonality and, therefore, it creates additional challenges and often fundamental problems (Jiang *et al.*, 2023). In this case, the seasonality of electricity production consists in negative or positive deviations from the trend level in selected periods of time (depending on the type of data, it may be quarters, months or weeks). The consequence of the occurring seasonality is a significant overproduction of electricity in selected periods and the occurrence of periods when energy production is at a very low level (Li *et al.*, 2024). In such a situation, an important issue is to forecast the values of average surpluses and average values of deficits of energy production in selected periods. It is particularly important to determine the average values of surplus energy production due to the quality and efficiency of transmission networks in most countries, because high daily or hourly excess energy production may cause a serious network failure, even across an entire country. The abovementioned overproduction may also generate negative prices for energy fed into the grid by prosumers, which is, of course, a factor inhibiting the development of the renewable energy market.

Therefore, taking into account the identification of periods of overproduction and shortage of energy from renewable sources, the issue of managing the energy mix becomes crucial. In the event of a period of shortage of energy from renewable sources, the best solution is to supplement it from conventional sources. If the average values of production shortfall are known in the selected period, this solution is easy to implement and does

not constitute a burden on the existing energy network. However, the real challenge is the problem of discharging surplus energy from renewable sources from the grid in very short time frames related to extraordinary weather conditions or in long periods lasting up to 5 months in the case of summer months. In this case, the only solution is to create new sidings with appropriate capacity in the existing network, and then dissipate the energy and store it skillfully in energy storage facilities (Wei *et al.*, 2024). However, the limited capacity and high costs of installing energy storage exclude this solution in practice (Wu *et al.*, 2024). The second solution is the possibility of converting the resulting surplus energy from renewable sources into green hydrogen (Ahmad *et al.*, 2021). This solution should determine the direction of energy mix management in the light of the ongoing global energy transformation processes, especially in the aspect of consumption of energy from renewable sources in the economy. Given the current advancement of green hydrogen production technology, the construction of efficient green hydrogen production and storage systems is feasible as part of the economic calculation (Awad *et al.*, 2024). The advantage of green hydrogen is also its transportability (d'Amore-Domenech *et al.*, 2023). During periods of energy production shortages, or at any time, green hydrogen can be converted back into electricity. The combination of green hydrogen's mobility properties with the potential for energy production is a strong argument for its widespread use in the country's energy policy. An equally important argument for the use of green hydrogen in global economies is the possibility of obtaining fuels and raw materials for the production of plastics based on it (Ramakrishanan *et al.*, 2024). This means that green hydrogen can have real applications in most sectors of the economy, including heavy industry and the chemical industry (Kullmann *et al.*, 2023). Ultimately, the way of managing the energy mix based on the production of green hydrogen from renewable energy should contribute to the acceleration and further development of energy transformation processes.

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