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Ecological and economic assessment of nuclear power as a low-carbon energy source

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Abstract. The research has carried out a multi-criteria assessment of nuclear power as a low-carbon energy source. The peculiarity of the research lies in the comparative analysis of nuclear power with both renewable energy sources and sources using fossil fuels with carbon dioxide capture technologies. The assessment uses three criteria: specific carbon dioxide emission, specific value of material consumption in MI-numbers, and electrical power costs value in LCOE/LEC. The criteria make it possible to characterize nuclear power in a holistic way while comparing it with other sources of low-carbon energy in terms of reducing carbon dioxide emissions possibility, capital and operating costs for electrical power production, and minimizing overall negative impact on the transformation and violation of biosphere material and energy flows. The work reveals that the integrated ecological and economic efficiency of nuclear power is higher than that of gas and coal-fired power stations with carbon dioxide capture technologies, but it is lower than that of renewable energy sources. The reasons are the increased cost of nuclear power and its relatively high specific water consumption.

1 Introduction

At present many countries consider the transition to low-carbon energy as a key task and are implementing it; we can see investments in the energy industry to reduce CO_2 emissions and transit to more environmentally friendly energy sources. This “green transition” to such an energy system is expected to bring numerous benefits for public health and global economy, ensure long-term ecological and economic development, and allow implementing sustainable development goals. In addition, low-carbon energy industry can help reduce existing dependence on exhaustible fossil fuel sources and significantly decrease environmental pollution. However, economic activities show that there is a wide range of approaches to the transition of energy industry to “carbon neutrality”. The key role in this process is played by renewable energy sources such as solar, wind, geothermal power and hydropower. At the same time, it is often overlooked that the goals of low-carbon development can be achieved not only by renewable energy, but also by traditional energy sources using innovative carbon capture and storage technologies. Nuclear power is debatable in particular [1]. Its share in the world power balance currently reaches 10.9%, in some countries it is the dominant energy source: France

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(70.6%), Slovakia (53.9%), Hungary (49.2%) [2]. In Russia the share of electrical power generated at nuclear power plants (NPPs) has steadily increased over the past decades and has reached 19.7%. Nuclear energy sources have an important feature, i.e. almost complete absence of CO_2 emissions during normal operation, which renewable energy industry also does. The point causing a heated discussion, in addition to the issues of safety and nuclear waste disposal, involves serious capital expenditures to construct and operate power facilities as well as the use of fossil uranium fuel, the extraction of which has a significant negative impact on the environment. To a large extent, it is determined by the low uranium prospect in the earth depths, which leads to large-scale mining and technical work during its extraction and enrichment. Further, it gives rise to a transformation of existing material and energy biosphere flows. The change can result in the global environmental problems escalation, in particular, reducing the areas occupied by natural ecosystems, decreasing biomass volumes and losing biodiversity. Consequently, the ecological and economic assessment of nuclear power as promising and low-carbon one requires taking into account several factors at once: the total cost of electrical power resulting from capital and operating costs, the volume of CO_2 emissions reduction, and the amount of material flows in ecosystems during the extraction and enrichment of nuclear fuel, as well as the operation of power plants. Only considering transformed biosphere material flows in detail, one can draw an adequate conclusion about the overall environmental “trace” of nuclear power. Nowadays the attention is paid exclusively to generated emissions, which ultimately leads to distorted assessments of ecological and economic efficiency.

Based on the author's methodology, the research carries out a comprehensive assessment of nuclear power as a low-carbon energy source. It uses three parameters: the specific value of reduction in CO_2 emission during electrical power generation, the volume of transformed material flows in ecosystems when nuclear fuel is operated, the cost of electrical power resulting from capital and operating costs. The results obtained are subjected to comparative analysis with other low-carbon energy sources, which makes it possible to draw a conclusion about the overall ecological and economic efficiency of nuclear power.

2 Materials and methods

The methodology applies a comprehensive assessment which allows the authors to identify the effectiveness of nuclear power comparing it with other low-carbon energy sources by three ecological and economic parameters.

Since reducing CO_2 emissions is a primary goal of low-carbon energy industry, the authors select specific carbon dioxide emissions per kilowatt of generated electrical power as the main parameter and make reference to their previous research on specific carbon dioxide emissions for various methods of electrical power generation as well as approaches proposed by the Intergovernmental Panel on Climate Change (IPCC) [3]. These approaches hold that CO_2 emissions are caused by the combustion of various types of fuel containing carbon and depend on the type of technology used in electrical power generation. Whilst stationary fuel combustion, carbon dioxide emissions are calculated by multiplying fuel combustion data by the corresponding emission factor [4]. Emission factors can vary quite significantly depending on the type of fuel and technologies, for these reasons the authors use averages for different low-carbon energy sources.

The following parameter is the specific value of material consumption which characterizes the volume of material flows in ecosystems. Nuclear energy power places emphasis on it in the production and enrichment of nuclear fuel, as well as in assessing material costs for capital structures. However, the assessment of this parameter was based on the total MI (Material Input)-numbers. The calculation of values was carried out using the MIPS methodology for identifying material input per unit service, which was developed at the Wuppertal Institute for Climate, Environment and Energy (Germany). Within the framework of this methodology, it is possible to estimate the volumes of transformed material flows operating in the natural environment during the production of almost any product, including electrical power generation [5]. Nowadays there is a significant database of MI-numbers characterizing the specific value of material consumption for various manufactured products; it is freely available on the Institute's website and is used in the research. It helps establish the specific value of material consumption of nuclear energy industry, expressed in kilograms per kilowatt of generated electrical power. The comparative analysis requires similar values for other low-carbon energy sources, which the authors have identified. It should be noted that MI-numbers allow for a broad analysis of the material costs of natural materials, therefore, they are initially divided into several categories, depending on which natural resource is most used. The research purposes consider such a categorization redundant and use the total MI-numbers characterizing the total consumption of all natural materials.

The third parameter characterizes the cost of electrical power as a result of capital and operating costs for generated capacity and is called Levelized Cost of Energy/Levelized Energy Cost (LCOE/LEC). This parameter is actively used by various research groups when assessing the cost of generated electrical power; it is of particular importance in justifying investments, including nuclear energy power [6]. The peculiarity of modern low-carbon power industry lies in not only renewable energy sources, but also traditional ones that use fossil fuel and apply carbon capture technologies. Their efficiency can be quite high and amount to more than 90% of captured carbon dioxide in total emissions [7]. This is achieved by significant energy costs for CO_2 capture equipment operating, which ultimately affects the cost of electrical power. Since assessing the ecological and economic efficiency of nuclear power industry as a low-carbon energy source requires a comparative analysis with traditional energy sources that capture carbon dioxide, the authors make appropriate additions to the generally accepted formula LCOE/LEC for calculating their efficiency.

$$\mathrm{LCOE/LEC_{CarbonCapture}} = \sum_{t=1}^{u}\left(\frac{k_t+K_{Ct}+O_t+O_{Ct}+T_t+T_{Ct}}{(1+R)^t}\right) \Big/ \sum_{t=1}^{u}\left(\frac{V_t}{(1+R)^t}\right) \quad (1)$$

Where $\mathrm{LCOE/LEC_{CarbonCapture}}$ – Levelised Cost of Energy when using Carbon capture; K_t – capital investments for electrical power generation;; K_{Ct} – capital investments for CO2 capture; O_t – operating costs for electrical power generation; O_{Ct} – operating costs to prevent CO2 emissions; T_t – fuel costs; T_{Ct} – fuel costs for CO2 absorption; V_t – volumes of electrical power generation; R – discounting rate; u – the time period of the power plant existence.

To determine the ecological and economic efficiency of nuclear power industry, the authors have developed a methodology based on multi-criteria analysis, where specific CO2 emissions, specific material consumption in MI-numbers, and cost of electrical power expressed in LCOE/LECCarbonCapture values are used as criteria. This allows for a comprehensive comparative analysis of nuclear power industry with other low-carbon energy sources.

3 Results and Discussion

The study specifies that nuclear power industry currently has a fairly high cost of electrical power, its LCOE/LEC indicator is 0.155 $/kWh [8]. It should be noted that the cost of nuclear power has increased by 26% over the past decade, which significantly distinguishes it from other sources of low-carbon energy, where, on the contrary, there has been a significant decrease in cost. The cost of solar power has decreased by 89%, the one of wind power has decreased by 70%, and even gas and coal-fired power industry with CO2 capture technologies have noticed a slight reduction in cost, by 33% and 2%, respectively [8]. The main reason for cost development of nuclear power is the significantly increased requirements for environmental safety being imposed on facilities under construction after the accident at the Fukushima Daiichi Nuclear Power Plant in 2011. These measures require an increase in capital costs, which in the long term affects the competitiveness of nuclear power compared with other sources of low-carbon energy.

The high capital intensity of nuclear power industry facilities and the need to transfer a huge amount of substances during the extraction, use and disposal of nuclear fuel also determine the high level of specific material consumption. In total MI-numbers it is 79.815 kg/kWh, which is significantly more than wind power (0.938 kg/kWh) and solar power (5.051 kg/kWh) have, however, it is slightly less than that of electrical power generated by gas (80.657 kg /kWh) and coal-fired (81.88 kg/kWh) power plants with carbon dioxide capture technologies [9]. The case is largely explained by the very high water intensity of nuclear power industry; to generate power it is necessary to expend 79.5 kg/kWh of water resources. To some extent, one can observe a similar situation in geothermal power which also has high water intensity, but its material consumption in MI-numbers is almost two times less and amounts to 44.609 kg/kWh.

There is one important feature of nuclear power industry, that is during its operation, as well as during the operation of renewable energy sources, one can notice the complete absence of carbon dioxide emissions. In gas and coal-fired power plants with CO_2 capture technologies there are little emissions. Currently, technological methods for capturing CO_2 make it possible to achieve an efficiency of more than 90%, but this inevitably affects the cost of the electrical power generated [10]. Averaged figures for modern power plants with similar technologies have revealed that the residual emission for gas power plants is 0.049 kg CO_2/kWh and for coal-fired power plants it is 0.082 kg CO_2/kWh [11].

Based on these three criteria, the authors have carried out a comprehensive comparative analysis of nuclear power with solar, wind and geothermal power, as well as electrical power generated at gas and coal-fired power plants with CO_2 capture technologies. All criteria have different units of measurement and they are initially reduced to a dimensionless form. Since the number of low carbon energy sources compared is 6, the ranking is done on a scale of 1 to 6. The value 6 is considered the most preferred and the value 1 is considered the least preferred. The total value of preference for a particular low-carbon energy source is determined by summing the obtained score values for all three criteria.

$$F_i = \sum_{i=1}^{m} B_i S_i \tag{2}$$

where F_i is the summing value of points for the assessed low-carbon energy source (i); B_i is the criterion score in points; S_i is the value characterizing the significance of the criterion; m is the number of criteria to be assessed. The results are presented in Figure 1.

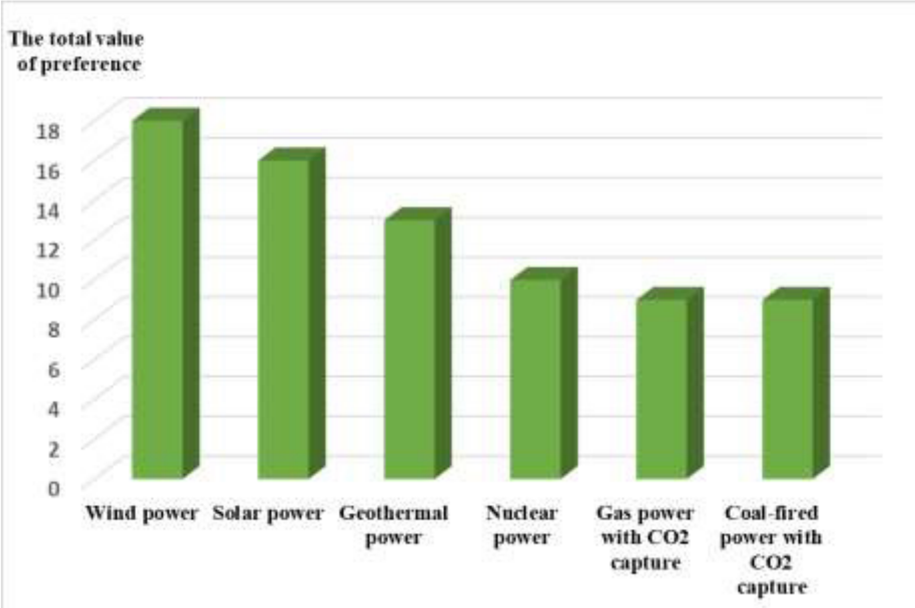

Fig. 1. Comprehensive ecological and economic assessment of low-carbon energy sources.

Wind power industry receives the highest score of 18 points; with the indicators being the highest possible for all three assessed criteria. Solar and geothermal power industries share the second and third place, scoring 16 and 13 points respectively. Nuclear power as a low-carbon energy source is close to renewable energy sources, but does not surpass them, receiving 10 points. Gas and coal-fired power plants with CO_2 capture technologies score equal 9 points, showing slightly lower ecological and economic efficiency compared to nuclear power industry.

4 Conclusions

The comparative analysis reveals that nuclear power as a source of low-carbon energy falls in between renewable and traditional energy sources. Its integrated ecological and economic efficiency is higher than that of gas and coal-fired power stations with CO_2 capture technologies. Nuclear and renewable power industries are similar in the almost complete absence of carbon dioxide emissions, which is important in the transition of power industry to "carbon neutrality." However, its efficiency is slightly lower than that of solar, wind and geothermal energy sources. One of the main reasons for the current situation lies in the relatively high costs value of electrical power, which has increased in recent years, due to the increased requirements for the environmental safety of nuclear power plants, with LCOE/LEC value having reached 0.155 $/kWh. Other modern energy sources that use fossil fuels and carbon dioxide capture technologies have seen some cost reductions, although not very significant. At the same time, the cost of solar power industry has fallen by 9 times over the last decade, and the cost of wind power industry has fallen by more than 3 times, which creates a completely new situation. It should also be noted that nuclear power industry has a significant impact on biosphere material and energy flows, having a very high specific water consumption. In some cases it may lead to an increase in environmental problems of water bodies in regions where this industry is located, which must be taken into account when making decisions about its development.

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