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DEVELOPMENT OF DIRECTIONS FOR INCREASING THE EFFICIENCY OF INNOVATION MANAGEMENT TAKING INTO ACCOUNT DECARBONIZATION TRENDS IN THE CONTEXT OF INTERNATIONAL COOPERATION

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The most important area in the fight against negative climate changes and ensuring sustainable development is the decarbonization of the economy. The object of this study is the development trends in decarbonization to enable effective innovation management processes under the conditions of international cooperation. Decarbonization involves reducing carbon dioxide emissions by switching to renewable energy sources, increasing energy efficiency, and introducing innovative technologies. As a global trend, it requires coordinated actions at all levels – from national governments to the private sector and international organizations. The possibilities of ensuring decarbonization through the use of climate-neutral energy complexes have been assessed. A feature of the approach is the use of statistical analysis to identify trends in the development of decarbonization of the economy. This has made it possible to prove with a probability of 98.6 % that if the trends of recent years regarding the increase in the number of operating nuclear reactors prevail, by the end of 2030 their number in the world will reach 489 units. The practical value of using wind power plants of different capacities and small modular reactors (SMRs) to provide electric vehicles with energy has been substantiated. This is confirmed by calculations of the number of cars that can be supplied with electricity from wind stations of various capacities at certain values of the capacity factor. In contrast to conventional approaches, determining the areas of innovative management allows the implementation of decarbonization processes under the conditions of international cooperation. The use of wind power plants of various capacities is of practical interest; the expediency of using small modular reactors and supplying electric vehicles with energy has been assessed

Keywords: innovative management, international projects, international cooperation, statistical analysis, decarbonization, sustainable development

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1. Introduction

The modern world faces numerous challenges related to the negative consequences of climate change. In recent decades, the level of global warming has reached critical indicators, which requires immediate action from the international community to reduce anthropogenic emissions of greenhouse gases and ensure sustainable development. The progress of world civilization, its particularly rapid economic development in recent decades has led to negative and extremely visible and tangible climatic and socio-economic changes, which are growing at a rapid rate.

One of the most important areas in the fight against negative climate changes and ensuring sustainable development is the decarbonization of the economy. The latter involves reducing carbon dioxide emissions by switching to renewable energy sources, increasing energy efficiency, and introducing innovative technologies. Decarbonization, as a global trend, requires concerted action at all levels – from national governments to the private sector and international organizations.

Achieving decarbonization goals is possible through the use of renewable energy sources (RESs), such as solar, wind, hydro, and bioenergy. In this context, the role of international cooperation is extremely important since many countries do not yet have sufficient technological and financial potential for the independent transition to "green" energy. Important aspects are the exchange of knowledge and experience, technological support, as well as investment in projects that will contribute to reducing dependence on fossil fuels.

No less important is the development of innovative management, which will ensure the effective implementation of new technologies and solutions under conditions of rapid changes. Innovative management in the process of decarbonization includes project management in the field of renewable energy, modernization of infrastructure, introduction of new business models and energy generation technologies. In addition, it requires the active participation of public and private investors, scientific institutions, and public organizations to create favorable conditions for sustainable development.

Special attention should be paid to the management of the transport sector, which is one of the biggest sources of environmental pollution. The introduction of electric cars, the development of public transport based on renewable energy sources, the use of hydrogen technologies – all these measures are aimed at reducing CO_2 emissions and improving the quality of life of people. Successful decarbonization of transport requires close cooperation between countries, as modern transport systems often transcend national boundaries and require concerted action.

Ensuring effective processes of innovation management under the conditions of decarbonization requires the creation of favorable conditions and economic incentives for the introduction of innovations. Only close international cooperation will make it possible to achieve the goals of sustainable development and prevent the negative consequences of climate change. Therefore, research on the theoretical substantiation of an integrated approach to improving the efficiency of innovative management under the conditions of decarbonization of the economy and international cooperation is relevant.

2. Literature review and problem statement

In [1], the results of analysis of modern trends, features, and processes of decarbonization and eco-modernization of energy and industry under the conditions of global climate change are reported. It is shown that decarbonization is a set of measures, methods, and technologies aimed at limiting the rate of global warming. There are two basic provisions:

1) restrictions on extraction and use of carbon-containing raw materials;

2) reduction of emissions of greenhouse gases (primarily CO_2 and H_2O vapors) into the atmosphere.

The author believes that climate mobilization of all countries is necessary, and business and the state should be allies in the decarbonization process. But issues related to the transition to carbon neutrality remained unresolved.

A likely option to overcome the difficulties is considered in work [2], in which the importance of the transition to carbon neutrality for reducing the impact of greenhouse gases on the environment is emphasized. Accelerated decarbonization of national economies becomes necessary to reduce dependence on hydrocarbon imports and political pressure. The development of green energy will provide reliable and affordable sources of energy, contributing to sustainable economic growth. It is shown how the USA and the EU actively finance green technologies to facilitate their implementation in other countries, but geopolitical instability slows down this process. However, the development of the decarbonization infrastructure and the strengthening of international cooperation regarding the transfer of innovations in this area require further justification.

However, in [3], solving the decarbonization problem is considered key to ensuring a climate-neutral future. All this gives reason to analyze the challenges and form directions for the decarbonization of the economy, focusing on the need to reduce CO_2 emissions through the use of renewable energy sources, "green" technologies, and electric vehicles. It is this approach that highlighted the progress and threats faced by the countries of the world in the implementation of decarbonization projects, programs, and strategies. It has been proven that the improvement of the legislative field and ensuring the consistency of requirements with EU legislation are key to the successful implementation of projects under the conditions of polycrisis. Nevertheless, the issue of attracting investments and innovations on the basis of sustainability, which is promising for further research development and requires scientific justification, has been neglected.

Paper [4] proves that decarbonization is a vital solution to reducing global warming and presents an assessment of the impact of green energy on reducing greenhouse gas emissions and addressing climate change. By analyzing various renewable energy technologies such as solar, wind, hydro, and biomass, their advantages and disadvantages in combating global warming are assessed. The effectiveness and sustainability of green technologies in comparison with conventional energy sources are analyzed, and strategies for the spread and implementation of green energy are proposed. However, the directions of innovation transfer development in the context of decarbonization have not been substantiated, and the main participants of this process in the international environment have not been identified.

In work [5], to overcome obstacles on the way to decarbonization, it is proposed to study the experience of European companies in implementing carbon pricing programs. This can assist businesses in voluntary pricing and emissions reductions at the national level. The scientist analyzes tools for reducing climate risks that can be applied in individual countries, and also considers the advantages and limitations of existing emission pricing programs. A methodical approach to the application of the "shadow price" for the assessment of investments in decarbonization and practical recommendations for climate risk management have been devised. The question of attracting investments to meet the needs of electricity consumers, in particular territorial communities and the development of electric mobility, remains unresolved.

Supplementing previous studies is the vision of the importance of the development of an innovative personnel management system and "green" corporate culture as a key direction for the effective functioning of enterprises, which is presented in [6]. Smartization and decarbonization require new approaches to corporate culture that combine elements of corporate, digital, and "green" culture, which will ultimately accelerate the transformation of enterprises to achieve the goals of sustainable development and decarbonization of production. But the issue of using international experience in decarbonization and energy supply of cities and other settlements with "green" energy remained unresolved.

In work [7], the results of research on the impact of decarbonization in the industrial domain are given and relevant statements are highlighted:

1) decarbonization is necessary for environmental management;

2) environmental regulations can contribute to decarbonization efforts;

3) innovations in greening processes can improve environmental indicators;

4) decarbonization is a connecting chain between innovation and the environment.

In order to prove the above statements, it is advisable to conduct a study of innovative management as a tool for strengthening efforts at decarbonization. Innovation further improves environmental management and environmental performance. This is exactly the kind of approach needed to create a road map for reducing the burden on the environment in the post-Covid era.

Our review of problems, trends, processes of energy decarbonization proves the necessity of energy transition to carbon neutrality in order to reduce the negative impact on the environment. The incompleteness of studying the processes of decarbonization with the use of effective tools of innovative management under the conditions of international cooperation is explained by many factors. Among them are the multifaceted and contradictory nature of climate change problems in different countries, the need to implement the best practices of European companies in ensuring sustainable development, and the need to take into account the process of globalization, particularly in the economic domain. All of the above gives reason to consider the research into ways to improve the efficiency of innovative management taking into account the trends of decarbonization development in the context of international cooperation to be a relevant task.

3. The aim and objectives of the study

The purpose of our study is the theoretical justification of an integrated approach to improving the efficiency of innovative management under the conditions of decarbonization of the economy and international cooperation in order to activate innovative actions to achieve the goals of sustainable development. This will make it possible to implement the imperative of decarbonization of the economy and prevent the catastrophic consequences of climate change.

To achieve the set goal, the following tasks were solved in the work:

– to determine the dynamics of renewable energy capacities and global trends in changing the capacities of generation facilities of various types of energy;

– to assess the possibility of ensuring decarbonization through the use of climate-neutral energy complexes;

– to demonstrate the practical application of wind power plants of various capacities and to assess the feasibility of using small modular reactors to provide energy to electric vehicles;

– to define the main participants and areas of innovative management under the conditions of international cooperation for the implementation of decarbonization processes.

4. The study materials and methods

The object of our study is the development trends of decarbonization to ensure effective innovation management processes under the conditions of international cooperation. The hypothesis of the study assumes the possibility of determining the dynamics of renewable energy capacities; assessment of the possibility of ensuring decarbonization through the use of climate-neutral energy complexes. The practical application of wind power plants of various capacities has been demonstrated to provide energy for electric vehicles. It has been proven that decarbonization has a leading place in establishing effective innovation management processes in the context of international cooperation.

The materials for the study were the Paris climate agreement of 2015 [8] and the World Meteorological Organization (WMO) report "State of the Global Climate 2023" [9]. The Paris Agreement calls on the international community to limit global warming to 2 °C or to limit temperature rise to 1.5 °C to avoid catastrophic climate change. According to the WMO report, 2023 was the warmest year on record, with global temperatures rising by 1.45 °C. Concentrations of greenhouse gases, as stated in [10], have reached record levels, which accelerates the melting of glaciers and leads to an increase in the level of the World Ocean. Scientists predict an increase in hurricanes and continued loss of glaciers, especially in the Alps and North America. The world ocean is also experiencing the global consequences of climate change, for example, a noticeable warming of the water in the Atlantic Ocean, the presence of the La Niña climate phenomenon, and the predicted intensification of hurricanes and storms.

The international community has proposed a road map for overcoming global climate change [9] – the production and use of renewable energy, primarily wind, solar, and water energy, which is the most promising area in the fight against climate change. At the same time, the growth of renewable energy production was noted, which in 2023 increased by 50 % compared to 2022.

In the process of researching the problems of energy development, statistical analysis methods are widely used, in particular, the method of dynamic series analysis (the study of trends based on the construction of a predictive model) and correlation-regression analysis. The latter, as stated in [11], is used to determine the dependence of electricity consumption on various factors: the volume of electricity production, the capacity of the energy system in Ukraine, the energy intensity of electricity production, the cost of electricity, etc. Also, this method was used to build a multiple regression model, on the basis of which electricity consumption is forecasted in view of possible changes in the factors taken into account.

Various methods are used to describe the current state of the load on the country's energy system, including taking into account energy generation by wind and solar plants according to [12]. In particular, analysis of variance and methods of mathematical statistics are applied to assess the range and intensity of fluctuations in the indicators characterizing energy consumption. Trend analysis (based on moving average and autoregressive models) is used to identify trends in electricity consumption and changes in its generation, as well as to identify periodic fluctuations in electricity consumption. Regression analysis is employed to build a model of load dependence on a number of factors included in it in the form of variables.

In [13], statistical trend modeling and forecasting was used to study the dynamics of electricity production from renewable sources. Determining the characteristics of energy generation trends from renewable sources for Ukraine, EU countries, and other countries of the world became the basis for identifying the global trend of countries switching to renewable energy sources. The importance of energy development for the purpose of decarbonization of the economy, reduction of CO_2 emissions, and improvement of the Earth's climate was noted. With regard to energy development trends, it is stated that the promising area of further decarbonization is the introduction of technologies within the framework of "10 Breakthrough Technologies". According to European programs and initiatives, those technologies include "hot" solar cells in the areas of their production and use; lithium-metal batteries, "green" hydrogen. Also, such areas include carbon-free natural gas as a substitute for natural gas, new wave nuclear energy as a replacement for conventional nuclear power plants, and carbon dioxide traps.

In order to evaluate the dynamics of electricity production in Ukraine, indicators of the series of dynamics are used [14]. At the same time, statistical modeling of dynamics (analytical alignment) is carried out to identify trends in the development of phenomena that change over time. It is based on establishing the functional dependence of the levels of a series of dynamics on time (building a trend model), identifying seasonal and random components.

5. Results of analyzing trends in the development of decarbonization in the context of international cooperation

5. 1. Dynamics of renewable energy capacities and renewable energy sources

Statistical data on the renewable energy of the world are given in [15], published by the International Agency for Renewable Energy Sources IRENA (International Renewable Energy Agency). Over the study decade (2013–2023), the dynamics of renewable energy capacities (Fig. 1) and the dynamics of the share of renewable energy in electric power generation (Fig. 2) demonstrate a steady upward trend with a high level of approximation reliability R^2.

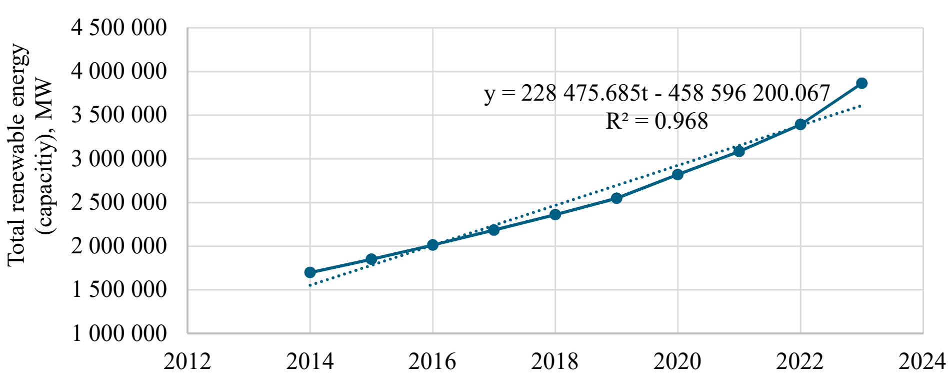

Fig. 1. World capacities of renewable energy, MW

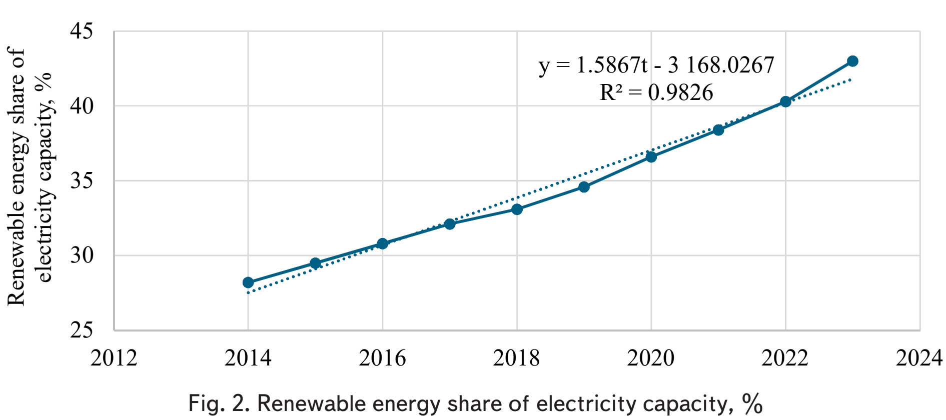

Fig. 2. Renewable energy share of electricity capacity, %

The change in global capacities of renewable energy is described by the trend equation y=228,475.685t–458,596,200.067. If this trend is maintained, the capacity of renewable energy sources will increase to 5,209,440 MW by 2030. The share of renewable energy in the electric power industry, if the trend described by the trend y=1.5867t–3,168.0267 is maintained, will increase to 53 % in 2030.

Among the various sources of renewable energy, hydropower facilities are characterized by the largest total capacity, and the capacity of wind and solar energy generation facilities is also high (Fig. 3). The dynamics of the capacity of various types of renewable energy facilities in the world indicate a significant increase in the capacity of solar and wind energy in the last decade.

While preserving the trends of changes in the capacities of solar energy and wind energy, described by the corresponding trends $y_{\text{solar energy}}$=127,220.8t–256,167,537.4 and $y_{\text{wind energy}}$=72,221.8364t–145,138,522.6, shown in Fig. 3, by 2030, the capacity of solar energy generation facilities in the world will be 290,687 MW, and the capacity of wind energy generation facilities will equal 1,471,805 MW.

In October 2023, the European Commission issued a press release [16], which identified the need to support the European wind energy industry. The agreed EU goal for the share of renewable energy in the total volume by 2030 is 45 %. In order to achieve it, it is necessary to significantly increase the installed wind capacity from 204 GW in 2022 to more than 500 GW in 2030. The existence of a unique set of problems was also indicated. These are insufficient and uncertain demand, a slow and complicated permitting procedure, lack of access to raw materials, high inflation and raw material prices, increased pressure from international competitors, and a lack of skilled labor.

It is known that offshore wind energy is more efficient because the intensity of the wind in the sea is greater, and it happens more often. The power factor of offshore wind turbines is significantly higher. However, their construction is much more difficult and has higher costs. The decisive role of offshore wind energy determines measures for its further rapid growth.

As for nuclear energy generation facilities, according to data [17] presented by the International Atomic Energy Agency (IAEA), the number of operating reactors at the end of the year in the world decreased from 2018 to 2021, reaching at the end of 2021 410 units, and increased to 413 reactors by the end of 2023 (Fig. 4, *a*).

If the trends of 2022–2023 prevail regarding the increase in the number of operating nuclear reactors (Fig. 4, *b*), it can be assumed with a probability of 98.6 % that their number in the world by the end of 2030 will be 489 units.

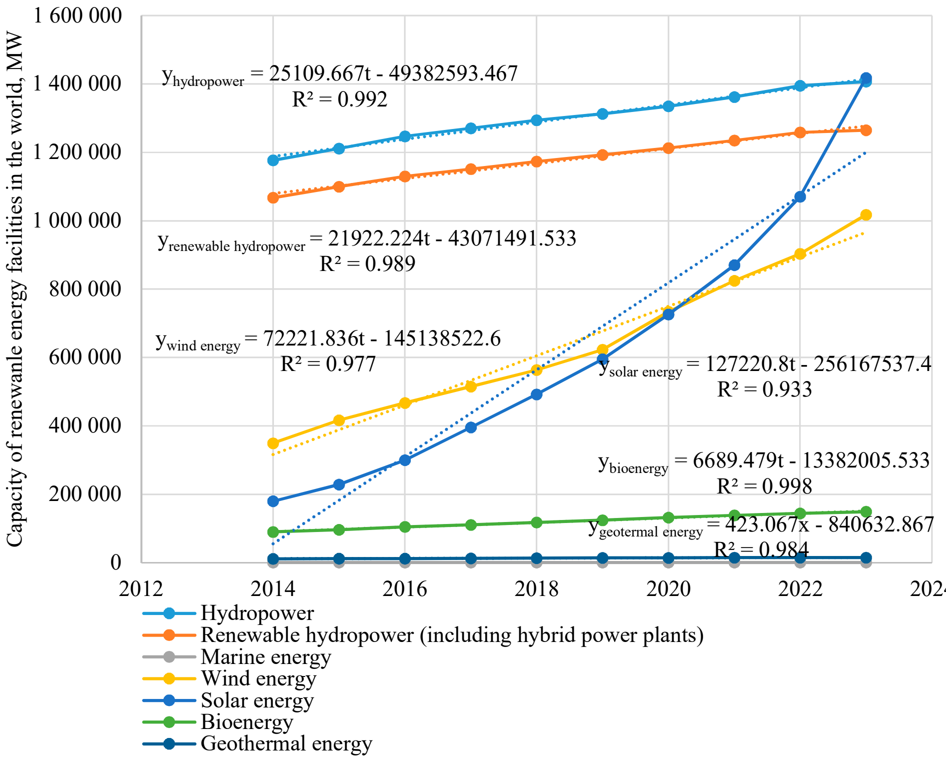

Fig. 3. Capacity dynamics of various types of renewable energy facilities in the world, MW

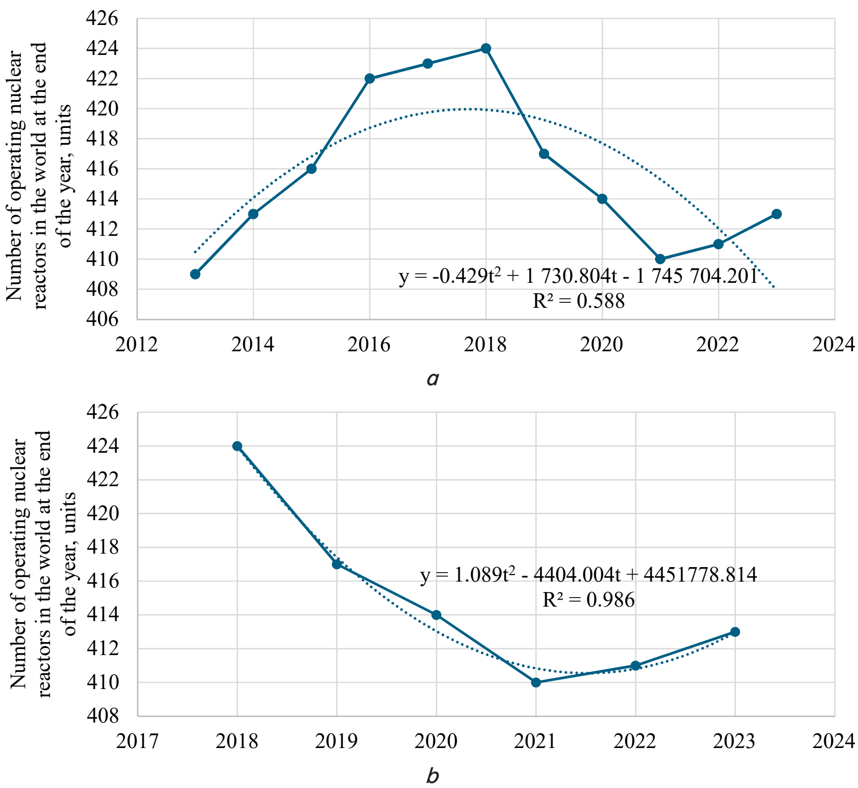

Fig. 4. Dynamics in the number of operating nuclear reactors in the world at the end of the year, units: *a* – since 2013; *b* – since 2018

The total net electric power of nuclear power generation facilities increased during 2014–2018 and slightly decreased by 2022 (Fig. 5). Further growth in 2022–2023 is associated with the search by global international organizations for means of countering the monopoly of the Russian Federation in the supply of oil and gas, and the use of oil and gas pipelines. This involves increasing the use of liquefied gas and resuming the operation of nuclear power plants. Focusing on the trend $y=2.196t-4{,}060.403$, it is possible to predict an increase by 2030 in the electrical capacity of nuclear power generation facilities to 397 GW.

According to Euronews [18], during a meeting in Brussels on March 21, 2024, EU leaders from 11 member states endorsed a declaration of support for nuclear energy. It was decided to expand international cooperation to ensure the timely construction and start-up of modern nuclear reactors, including small modular reactors (SMRs). Coordination of cooperation in the field of nuclear fuel supply, equipment production and resource security was also discussed. This is necessary to ensure the stability of supply chains and the overall development of nuclear energy. To that end, a declaration was adopted, which called on regulatory authorities to provide full access to information about the potential of nuclear energy and to ensure its financing, as well as to extend the service life of operating nuclear reactors. This document was signed by such leading countries as Belgium, Bulgaria, Croatia, the Czech Republic, Finland, France, Hungary, Italy, the Netherlands, Poland, and Sweden. So, the declaration confirms the role of already existing nuclear power plants in providing energy needs.

According to [19], countries that are actively developing or planning to implement nuclear technologies increasingly recognize the key role of nuclear energy. It is it that must enable the reduction of greenhouse gas emissions, ensure energy stability and security, as well as the ability for long-term sustainable development and the transition to clean energy. International world organizations advocate joint support for nuclear energy as an important element of the global strategy to combat climate change. We emphasize the importance of international cooperation in the field of civil nuclear potential development in order to reduce dependence on fossil fuels. In this context, international cooperation is a crucial factor for accelerating the transition to clean energy sources and introducing innovations in the field of nuclear power generation. It will contribute to the implementation of safe and effective solutions to meet the growing needs for electricity while simultaneously reducing the impact on the environment. At the same time, it is necessary to take into account the level of interaction between countries and the peculiarities of the realization of economic interests, depending on the economic and institutional conditions present in them.

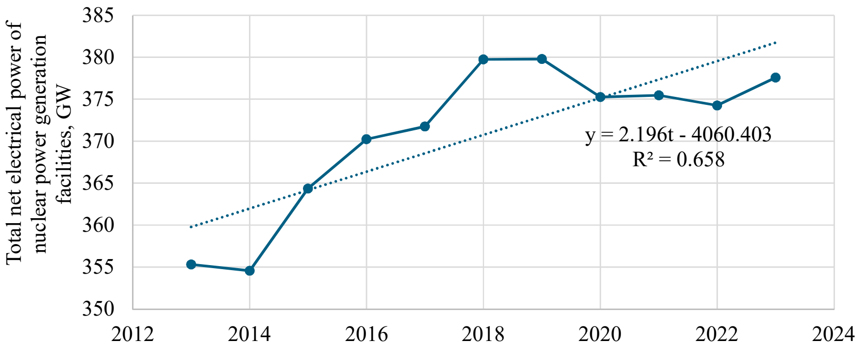

Fig. 5. Total net electrical power of nuclear power generation facilities, GW

5. 2. Ensuring decarbonization through the use of climate-neutral energy complexes

A new area of decarbonization, which has recently received much attention, is the use of small modular reactors (SMRs), which can be one of the important and promising vectors for the development of world energy. The European Commission [20] recognizes the potential contribution of small modular reactors to the achievement of the energy and climate goals of the EU "Green Deal", as reflected in its recommendations for reducing emissions by 2040.

A feature of small modular reactors is the possibility of using one or more modules, which allows changing the power of the power plant within reasonably wide limits and choosing the power required for certain conditions. There is no need to build a nuclear power plant with deliberately excessive capacity, which involves significant investments and is economically inefficient. If necessary, in the future it is possible to build an additional number of modules and increase the total power of the power plant. The construction of a nuclear power plant with small modular reactors is much cheaper than a conventional nuclear power plant, and its duration is significantly shorter. The safety of small modular reactors is higher than the reactors currently in use. This is due to a number of factors, including their modern innovative design and application technology, and small size. At the same time, most of the conventional reactors were built a long time ago, and some of them must be decommissioned due to the exhaustion of the operational resource.

Cooperation between EU countries allows for the implementation of the decarbonization policy by maintaining an energy balance between them. Small modular reactors can provide grid stability in a system with a higher share of renewable energy sources and growing demand for electricity. Small modular reactors are compact, their installation requires much less territory, which expands the geography of their placement, and much less water is needed for their cooling. The European Commission in [20] emphasizes that such modular reactors can be manufactured in series, and this ensures the economic efficiency of their construction due to the effect of scale. Since the individual components of such stations can be assembled at the factory, they can be transported to the site in the form of modules or even whole units, which reduces installation costs. The process of replacing power plants that use coal and brown coal with climate-neutral power plants is becoming widespread in the world. This process is associated with the dismissal of a large number of highly qualified specialists. Such specialists can find their new workplace at stations with small modular reactors, which are being built in areas where environmentally harmful thermal stations used to work.

Small modular reactors can be used as part of so-called climate-neutral energy systems (Fig. 6) in combination, for example, with wind and solar power plants and energy storage, as well as hydrogen production plants. At the same time, hydrogen in a liquid state can be used in various ways, directly on site or even in geographically distant places, for example, as a fuel in cars, buses, trains, and airplanes.

According to the International Energy Agency (IEA) [21], the power of electrolysis for the special production of hydrogen has been increasing in the last few years. The pace slowed in 2022, when about 130 MW of new capacity came online, down 45 % from the previous year. However, the production capacity of electrolyzers increased by more than 25 % compared to last year, reaching almost 11 GW per year in 2022. The implementation of all projects can lead to an installed electrolysis capacity of 170–365 GW by 2030.

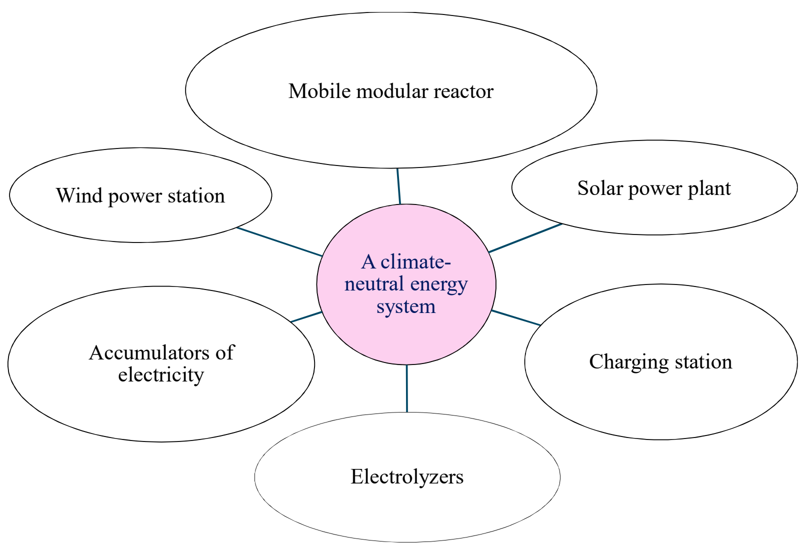

Fig. 6. Climatically neutral energy systems

SMRs make it possible to level out electricity generation to a large extent but to improve this process, especially in cases of moderate changes in consumption, it would be advisable to integrate energy storage systems into the composition of energy systems.

The European Commission document [20] emphasizes that the EU supports research and development in the field of SMRs within the framework of the Euratom Research and

Training Program (2021–2025). It also examines nuclear safety, security, guarantees, radiation protection and radioactive waste management, and pays considerable attention to the development of nuclear energy. To ensure the successful deployment of the first SMRs projects by the early 2030s and thus take Europe's important position in global competition, the Commission will create a European Industrial Alliance for SMRs.

Table 1

Possibilities of providing energy for electric vehicles

Power, MW		2			18			20		
Capacity factor 30 %										
Production per day, kWh		14,400 kWh			129,600 kWh			144,000 kWh		
Daily mileage, km		40	100	200	40	100	200	40	100	200
Number of cars										
Costs, kWh·year/100 km	14	2,571	1,028	514	23,139	9,257	4,628	25,710	10,285	5,142
	20	1,800	720	360	16,200	6,480	3,240	18,000	7,200	3,600
	25	1,440	576	288	12,960	5,184	2,592	14,400	5,760	2,880
	30	1,200	480	240	10,800	4,320	2,160	12,000	4,800	2,400
Capacity factor 40 %										
Production per day, kWh		19,200 kWh			172,800 kWh			192,000 kWh		
Daily mileage, km		40	100	200	40	100	200	40	100	200
Number of cars										
Consumption, kWh/per 100 km	14	3,428	1,371	685	30,852	12,340	6,170	34,280	13,713	6,856
	20	2,400	960	480	21,600	8,640	4,320	24,000	9,600	4,800
	25	1,920	768	384	17,280	6,912	3,456	19,200	7,680	3,840
	30	1,600	640	320	14,400	5,760	2,880	16,000	6,400	3,200
Capacity factor 50 %										
Production per day, kWh		24,000 kWh			216,000 kWh			240,000 kWh		
Daily mileage, km		40	100	200	40	100	200	40	100	200
Number of cars										
Consumption, kWh/per 100 km	14	4,285	1,714	857	38,565	15,426	7,713	42,850	17,142	8,571
	20	3,000	1,200	600	27,000	10,800	5,400	30,000	12,000	6,000
	25	2,400	960	480	21,600	8,640	4,320	24,000	9,600	4,800
	30	2,000	800	400	18,000	7,200	3,600	20,000	8,000	4,000

5. 3. Practical application of wind power plants and small modular reactors to provide electric vehicles with energy

The possibility of providing electric cars with energy, which will be produced with the help of wind power plants of various capacities, is considered here. Currently, wind turbines with a capacity of 2 MW, which can be combined into a group, are quite common in the world. In addition, according to available information [22], installations have already been developed and manufactured, in particular, in China, which have a very high capacity of 18 MW, and in Europe, research and development of wind installations with a capacity of 20 MW are being conducted. The efficiency of wind power plants depends on the intensity of the wind. At the same time, for installations that are located in the sea (are offshore), such efficiency is usually higher than for those located on land since the wind force and its duration are greater in the sea.

The consumption of electricity per 100 km of car mileage largely depends on the speed of the electric vehicle: at a relatively low speed, energy consumption can be significantly lower than the average consumption for a certain car. The problem is that it is difficult to ensure such a low speed due to high time costs. However, maintaining moderate driving speeds is advisable in the context of energy savings within the limits of a moderate consumption strategy.

To determine the possibility of providing energy for electric cars, the following criteria were considered: electricity generation per day, daily mileage, number of cars, electricity consumption per 100 km (Table 1). The efficiency of electricity generation is characterized by the value of the capacity factor (Capacity factor) and is considered at values of 30, 40, and 50 %. Electricity consumption per 100 km of mileage is taken as 14, 20, 25, and 30 kWh, which reflects the use of, firstly, relatively economical electric cars, secondly, electric cars with average consumption and, thirdly, sufficiently powerful electric cars.

The daily mileage is taken as 40, 100, and 200 km and reflects the different operating conditions of electric vehicles in the city or during country trips over moderate distances, which is typical for the conditions of Western Europe.

In the option of generating electricity with a 2 MW plant at a power factor of 30 % (Table 1), it is possible to generate 14,400 kWh energy, which is the minimum value in research according to its conditions. In this case, with a consumption of 14 kWh/per 100 km and a daily mileage of 40 km, the daily energy production of the wind turbine is capable of providing energy for 2,571 electric cars. In the case of consumption of 20 kWh/per 100 km of mileage, it is possible to provide 1,800 cars. Under the most unfavorable conditions (consumption of 30 kWh/per 100 km of mileage), the possibilities are reduced to 1,200 electric cars. With a daily mileage of 100 km and other things being equal, it is possible to provide energy from 1,028 to 480 electric cars. The least favorable conditions are observed with a daily mileage of 200 km: the maximum number of electric cars will be 514, and the minimum will be 240.

For the option of generating electricity with a 2 MW installation at a capacity factor of 40 % (Table 1), 19,200 kWh energy can be produced. In this case, with a consumption of 14 kWh/per 100 km of mileage and a daily mileage of 40 km, the daily production of energy by the wind turbine is capable of providing energy for 3,428 electric cars. In the case of consumption of 20 kWh/per 100 km of mileage, it is possible to provide 2,400 cars. In the most unfavorable case, with a consumption of 30 kWh/per 100 km and a daily mileage of 200 km, it will be possible to provide energy for 240 electric cars.

For the option of electricity production, a 2 MW installation with a capacity factor of 50 % (Table 1) can produce 24,000 kWh energy. In this case, at a consumption of 14 kWh/per 100 km of mileage, the energy is sufficient for 4,285 electric vehicles with a mileage of 40 km, 1,714 electric vehicles with a mileage of 100 km, and 857 electric vehicles with a mileage of 200 km. Under the most unfavorable conditions, it is possible to provide energy for 400 electric cars.

When generating electricity with an installation with a capacity of 18 MW (Table 1), it is possible to produce a very significant amount – 129.6 thousand kWh of energy at a capacity factor of 30 %, 172.8 thousand kWh of energy at a capacity factor of 40 %, and 216,000 kWh energy at a capacity factor of 50 %. In this case, for the considered range of conditions, there are possibilities for functioning from 38,565 (maximum number) to 2,160 (minimum number) cars.

Research on the possibility of providing electricity for electric vehicles with the help of small modular reactors (SMRs) needs attention. When using SMRs with a capacity of 80 MW with a Capacity factor of 90 %, the generated energy will be sufficient to drive in various cases from 308,520 electric vehicles under the most favorable conditions (energy consumption of 14 kWh/per 100 km of mileage and a daily mileage of 40 km) to 28,800 electric vehicles under the most unfavorable conditions (energy consumption 30 kWh/day 100 km mileage and 200 km daily mileage). Thus, the specified SMRs can provide for the use of electric vehicles on the scale of a small or even a medium-sized city. For a city with a large population, several modules of SMRs can be used. Of particular interest is the integrated use of wind, solar power plants, and SMRs, which allows for a synergistic effect.

5. 4. Defining the main participants and areas of innovative management for the implementation of decarbonization processes

The rhythmic course of decarbonization processes, as emphasized in [23], requires effective innovative management under the conditions of international cooperation (Fig. 7), which will make it possible, in turn, to implement the strategy of transition to an environmentally friendly economy.

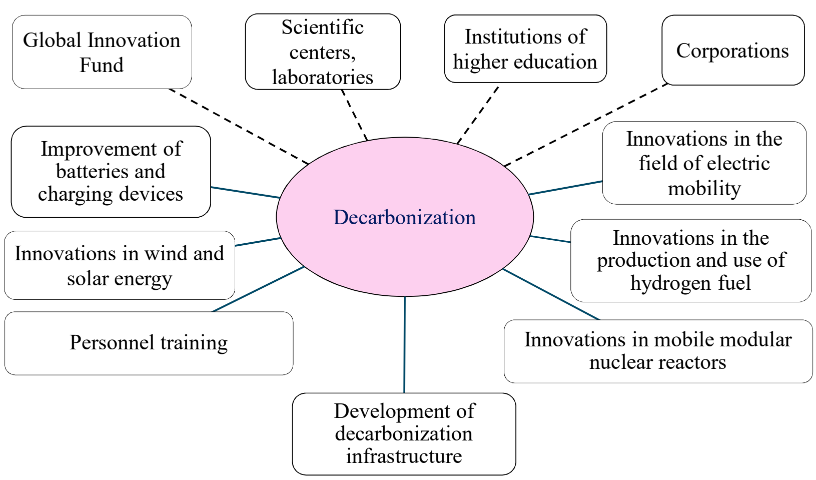

Fig. 7. Main participants and areas of innovative management under the conditions of international cooperation for the implementation of decarbonization processes

Similar conclusions were drawn in [24], in which carbon emissions were investigated with the help of artificial intelligence with the aim of further decarbonization to balance profitability and compliance with environmental and social goals. At the same time, a special role is given to the partnership between many interested parties, including in the framework of international cooperation for the exchange of knowledge, experience, technologies, and financial resources to achieve the goals of sustainable development.

In [25], attention is focused on electrification and decarbonization, the use of geothermal energy, and the storage of thermal energy in a heat pump. A thermo-economic analysis of the thermal system of buildings was carried out, the industrial policy of developing low-emission technologies and investments in mineral extraction was investigated.

In [26], it was noted that most countries of the world are increasing efforts to decarbonize the economy for the energy transition by increasing the amount of investments in research and development (R&D) related to energy. These strategic tools are aimed at decarbonizing the economies of partner countries.

According to [27], innovative activity is a research process aimed at creating and implementing innovations for profit at the enterprise, which leads to an increase in its innovative potential, ensuring financial stability and economic security. In addition to the development of state programs and innovation infrastructure, it is important to provide enterprises with scientific and methodological and advisory support, which will help correctly formulate the mission, goals, and stages of innovative activity for its successful organization. In [28], in turn, it was proved that the management of innovations should take into account the real conditions and trends of economic development, in particular, the peculiarities of production and its location. The main problem of innovative activity is insufficient funding. However, the appropriate level of financing of innovative activities can become a factor of socio-economic growth, both of individual enterprises and of the state as a whole, helping to solve various problems: social, economic, ecological, and technological.

The success of the world's leading companies is due to the continuous development of the innovation management system both within the organization and in its external environment. According to [29], they are building a management structure and culture, where innovative areas become part of strategic plans, with an emphasis on the development of new products and the creation of new areas of activity. At the same time, it was noted in [30] that a special place is given to participation in international projects, the management of which should take into account their uniqueness, high risk, limited resources for implementation, a wide range of tasks, cross-cultural features, etc. Regarding the possibilities of Ukraine's participation in international scientific and technical cooperation, it is recommended [31] to strengthen the dialog with the EU for the use of experience and financial support for the development of innovative, science-intensive, and high-tech industries. Cooperation with the EU in the field of energy is aimed at the introduction of renewable energy sources, the development of ecological transport and safe nuclear energy, which will increase Ukraine's energy independence and integrate it into the EU energy system.

6. Discussion of results based on examining approaches to increasing the efficiency of innovative management

The results of our study on increasing the efficiency of innovative management under the conditions of decarbonization of the economy and international cooperation are explained by a comprehensive approach to determining the dynamics of renewable energy capacities and global trends in changing the capacities of generation facilities of various types of energy (Fig. 1, 2). The largest total capacity among renewable energy sources is inherent to hydropower, wind, and solar generation facilities (Fig. 3). A trend towards a decrease in the number of operating nuclear reactors in the world has been revealed (Fig. 4, *a*). The possibility of ensuring decarbonization through the use of climate-neutral energy systems was also assessed. A feature of the approach is the use of statistical analysis to identify trends in the development of decarbonization of the economy. This made it possible to prove with a probability of 98.6 % that if the trends of recent years regarding the increase in the number of operating nuclear reactors prevail (Fig. 4, *b*), by the end of 2030 their number in the world will be 489 units. The total net electrical capacity of nuclear power generation facilities increased during 2014–2018 and slightly decreased by 2022 (Fig. 5), which was the result of efforts to reduce the use of oil and gas as energy sources. Small modular reactors can be used as part of so-called climate-neutral energy systems (Fig. 6). The practical value of using wind power plants of various capacities and small modular reactors to provide electric vehicles with energy has been substantiated (Table 1). It was established that for the considered values of the capacity factor of wind generation installations with a capacity of 18 MW, it is possible to provide electricity to 2,160 to 38,565 cars. Unlike studies [1–4], which consider exclusively the transition to carbon neutrality, the proposed comprehensive approach emphasizes the transfer of innovations in the field of energy generation in the context of international cooperation. This confirms the hypothesis about the need to implement economic and social levers of influence on the decarbonization process [5, 6], which must be taken into account when planning innovative management measures. The use of climate-neutral energy systems, wind power plants of various capacities, and small modular reactors is proposed, which differs from the proposals in [25]. Our solutions prove the possibility of providing electricity for electric vehicles with the help of small modular reactors (SMRs). Of particular interest is the integrated use of wind, solar power plants, and SMRs, which allows for a synergistic effect. Effective innovation management in the context of decarbonization of the economy is possible under the condition of close international cooperation (Fig. 7).

A limitation of our study is the consideration of only trends in the development of wind, solar, and nuclear energy, which may affect the results of innovation implementation. The shortcomings of the study include the insufficient justification of the influence of external environmental factors and their dynamics, which may negatively affect the prospects of decarbonization of the economy. In the future, it would be appropriate to assess the influence of political, economic, social, technological, legal, and environmental factors. This can be eliminated by conducting a PESTLE analysis and applying the McKinsey 7S model based on the Triple Bottom Line (TBL). The development of the research may consist in the expansion of methodological principles for evaluating the effectiveness of innovations for the development of energy-generating enterprises in the context of decarbonization. This includes a detailed analysis of the practice of transfer of innovations under conditions of polycrisis, legal regulation of transfer of intellectual property rights, fundraising under conditions of international cooperation.

7. Conclusions

1. Climate changes on the planet caused by human economic activity are becoming more and more noticeable and negative in their impact, which indicates the need for decisive actions regarding the decarbonization of the global economy. The world capacity of renewable energy in the last decade shows a tendency to increase; the dynamics of the capacity of various types of renewable energy facilities in the world indicate a significant increase in the capacity of solar and wind energy. A high level of total capacity of hydropower facilities is observed. In 2022–2023, the prevailing trends were towards increasing the capacity of nuclear power generation facilities and increasing the number of operating nuclear reactors.

2. The expediency of ensuring decarbonization through the use of climate-neutral energy systems has been revealed. Notable among them are small modular reactors (SMRs), which can be used both separately and in combination with, for example, wind and solar power plants and energy storage, as well as hydrogen production facilities. The use of small modular reactors makes it possible to change the capacity of the power plant within sufficiently wide limits by using one or more modules. This ensures greater safety than conventional nuclear plants, allows the implementation of the decarbonization policy, and makes a certain contribution to the achievement of energy and climate goals.

3. Small modular reactors (SMRs) could be an effective means of providing electricity for electric vehicles on the scale of a small or even medium-sized city. And their use in a combination with wind and solar power plants allows one to get a synergistic effect. Also, the use of wind power plants makes it possible to provide energy for a significant number of electric cars. We have estimated possible volumes of electricity production by wind turbines of different power at a certain value of the capacity factor. The number of electric cars that can be supplied with electricity under the conditions of different options for electricity consumption per 100 km of mileage under different variations of the mileage of an electric car has been determined.

4. In the context of the imperative of decarbonization of the world economy, the main participants and areas of innovative management under the conditions of international cooperation have been highlighted. Effective innovation management is an indispensable condition for the further development of electric mobility in order to replace gasoline and diesel cars. This involves the implementation of a set of technological and management solutions to solve the problem of the high cost of electric cars, increase the capacity of batteries, and improve charging devices in order to speed up the charging process. The concentration of innovation efforts requires the transition to hydrogen fuel for trains on lines where there is no electricity, the replacement of diesel fuel, fuel oil with hydrogen on sea and river vessels, as well

as the development of decarbonization infrastructure. Under the conditions of international cooperation, the use of scientific centers, laboratories, institutions of higher education, the provision of the necessary personnel training, and the involvement of the potential of corporations and innovation funds will contribute to the improvement of the efficiency of innovation management in order to ensure global decarbonization. Broad international cooperation together with the efforts of state institutes, universities, scientific institutions, corporations, mass media, public organizations, and conscious citizens makes it possible to realize the imperative of decarbonization and prevent the catastrophic consequences of climate change.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

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Data availability

All data are available, either in numerical or graphical form, in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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