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MODERN TRENDS IN GLOBAL ENERGY IN THE CONTEXT OF SUSTAINABLE DEVELOPMENT AND DECARBONIZATION

СУЧАСНІ ТРЕНДИ СВІТОВОЇ ЕНЕРГЕТИКИ В УМОВАХ СТАЛОГО РОЗВИТКУ ТА ДЕКАРБОНІЗАЦІЇ

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The article presents data from authoritative international organizations on the noticeable change in the planet's climate compared to the pre-industrial period. It is emphasized that in recent years, climate change has become especially intense. One of the results of climate change is the increase in the frequency and destructive effects of hurricanes in various parts of the planet, droughts and crop losses in agriculture, floods, and rising sea levels, which leads to large economic losses. An important area of decarbonization of the global economy is the production of electricity using climate-neutral energy sources. The article provides a comprehensive comparative analysis of the efficiency of traditional large nuclear reactors and small modular reactors (SMRs). Significant technological, environmental and economic advantages of SMRs are noted. A comprehensive model for the development of global energy in the context of decarbonization is proposed, which includes innovative areas: SMRs, large nuclear power plants, wind, solar energy and the use of biofuels.

Keywords: management, decarbonization, climate change, small modular reactors, innovation, investment, sustainable development, wind power plants, bioenergy.

У статті наводяться дані авторитетних міжнародних організацій про помітну зміну клімату планети порівняно з періодом доіндустріального розвитку. Наголошується, що в останні роки кліматичні зміни набувають особливо інтенсивного характеру. Одним із результатів кліматичних змін є збільшення частоти та руйнівних наслідків ураганів у різних районах планети, посух та втрати врожаїв у сільському господарстві, повеней, підвищення рівня Світового океану, що призводить до великих економічних втрат. Важливим напрямком декарбонізації світової економіки є виробництво електроенергії за допомогою кліматично нейтральних джерел енергії. У статті виконано комплексний порівняльний аналіз ефективності традиційних великих атомних реакторів та малих модульних реакторів (SMRs). Як параметри порівняння розглянуті наступні: тривалість будівництва, вартість робіт, безпека станцій, гнучкість потужності, інноваційність, можливості розміщення, терміни окупності будівництва, вартість енергії, екологічні переваги, комплексність використання з іншими видами енергії, перспективи та привабливість різних видів станцій. Вказується, що навіть невеликі міста, їхня влада, для забезпечення потреб населення і господарства цих міст і прилеглих околиць здатні власним коштом муніципальних утворень будувати малі модульні реактори. Відзначаються значні технологічні, екологічні та економічні переваги SMR. Показано, що зараз у світі розробляється близько 80 проектів різних типів SMRs. Розглянуто плани будівництва атомних електростанцій у Східній Європі, які передбачають інвестиції у розмірі 130 млрд євро. Особливе місце у цьому процесі займають Польща та Чехія, з інвестиціями відповідно 56,5 та 24 млрд. євро. Показано перспективи атомної енергетики у глобальному масштабі з урахуванням думки авторитетних експертів. Запропоновано комплексну модель розвитку світової енергетики в контексті декарбонізації, яка включає інноваційні напрямки: SMRs, великі атомні станції, вітрову, сонячну енергетику та використання біопалива.

Ключові слова: менеджмент, декарбонізація, зміна клімату, малі модульні реактори, інновації, інвестиції, сталий розвиток, вітрові електростанції, біоенергетика.

Formulation of the problem. Numerous data from authoritative international organizations clearly indicate the rapid increase in global climate change, which is already leading to significantly more frequent and destructive hurricanes, floods, droughts, and crop losses than was the case before. Joint and rapid efforts by the world community are needed to ensure sustainable human development, economic growth, and preservation of the natural environment.

Analysis of recent research and publications. The problems of sustainable development, global economic growth, analysis of the negative consequences of climate change, and the study of innovative climate-neutral energy sources attract constant attention from experts, researchers, and numerous publications. Among the authors of expert opinions and studies, it is necessary to note such experts and scientists as: Fatih Birol, Adrian Rinscheid, Jens Turau, Christian von Hirschhausen, Patrick Greenfield, Claudia Kemfert, Rolf Wüstenhagen, Megan Fisher, Ravi Kotecha. The authors make an important contribution to the study of current issues of global development and its improvement.

Previously unsolved parts of the overall problem. Even very extensive studies by climate and global energy experts cannot examine in detail all the problems of developing such an important area as energy. Of great scientific and practical interest is the analysis of promising areas and decarbonization of the economy in the context of sustainable development, the most important innovation and investment goals. Research into the interaction of various areas of decarbonization may be relevant.

Presentation of the main research material. The past months of 2024 clearly show the active processes of global warming.

Data published by the authoritative international organization – Copernicus, in July 2024 show (Fig. 1): «June 2024 was warmer globally than any previous June in the data record, with an average ERA5 surface air temperature of 16.66°C, 0.67°C above the 1991–2020 average for June and 0.14°C above the previous high set in June 2023. This is the thirteenth month in a row that is the warmest in the ERA5 data record for the respective month of the year. While unusual, a similar streak of monthly global temperature records happened previously in 2015/2016. According to ERA5 data, the month was 1.50°C above the estimated June average for 1850–1900, the designated pre-industrial reference period, making it the twelfth consecutive month to reach or break the 1.5°C threshold. The global-average temperature for the past 12 months (July 2023 – June 2024) is the highest on record, at 0.76°C above the 1991–2020 average and 1.64°C above the 1850–1900 pre-industrial average. The average European temperature for June 2024 was 1.57°C above the 1991-2020 average for June, making the month the joint-second warmest June on record for Europe [1].

Climate change on the planet leads to devastating hurricanes, floods, droughts, sharp decline in harvests and food shortages, melting glaciers, rising sea levels and other negative consequences. A clear example is the enormous hurricane Milton in October 2024 in the United States on the coast of Florida. Scientists believe that the frequency and intensity of such hurricanes will increase under the influence of climate change on the planet. The economic consequences of climate change are already very large and are constantly growing.

Humanity is noting climate change, outlining plans to curb it, but the decarbonization process

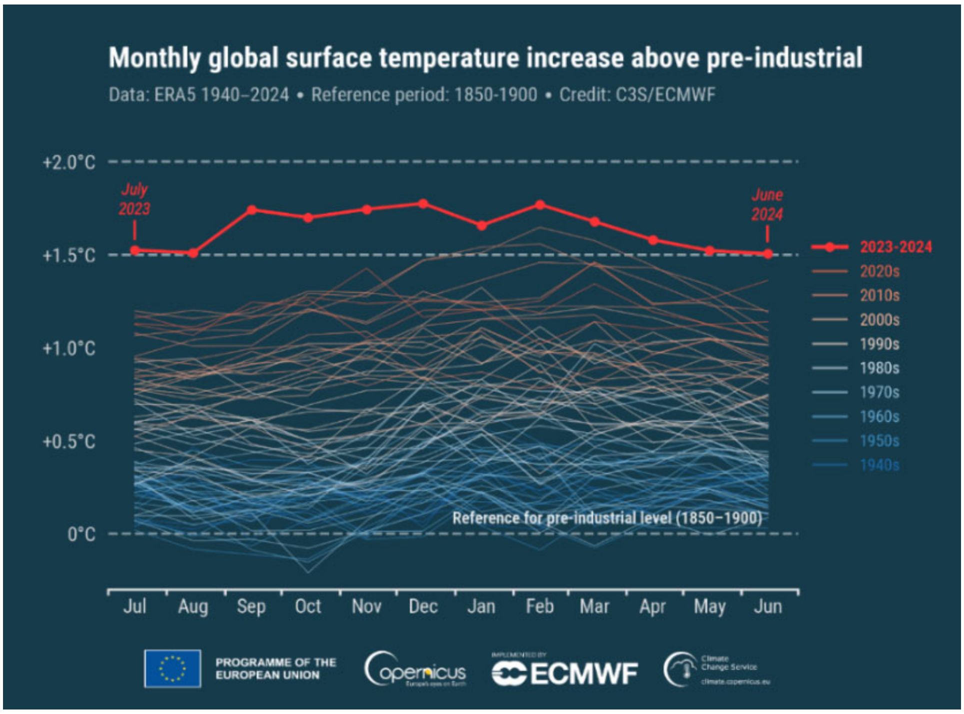

Figure. 1. Monthly global surface air temperature anomalies.

Monthly global surface air temperature anomalies (°C) relative to 1850–1900 from January 1940 to June 2024, plotted as time series for all 12-month periods spanning July to June of the following year. The 12 months from July 2023 to June 2024 are shown with a thick red line, while all other 12-month periods are shown with thin lines shaded according to the decade, from blue (1940s) to brick red (2020s). Data source: ERA5. Credit: Copernicus Climate Change Service /ECMWF [1].

Source: [1]

needs to be radically accelerated. One of the most important areas of decarbonization of the global economy is energy. A new factor in it can be considered the emergence of small modular reactors (SMRs). Let us analyze a set of data on traditional large SMRs and those designed in different countries (Table 1).

Duration of construction of nuclear power plants. Plants where large nuclear reactors are installed have a significant construction time of even one unit of the plant, which is at least 5-7 years. Due to the great complexity of the work, there is a high probability that the construction time will exceed the design time. Installation of equipment is also a complex and very responsible task, delays in the manufacture of equipment are possible. In general, it can be stated on the basis of extensive world experience that there are extremely significant difficulties with the timing of commissioning of such reactors. A long construction time may be a condition against making a decision to develop large nuclear power plants.

The construction time of SMRs is expected to be relatively short. Due to the comparative simplicity of the work compared to traditional nuclear reactors, the probability of exceeding the design construction time is significantly reduced. Equipment installation is also comparatively simple. There is no experience in constructing such reactors, so estimates of their construction time are preliminary. Construction cost. Large nuclear reactors are expensive. The cost of constructing even one unit of a station with a capacity of approximately 1000 MW can be around $5 billion or more. Quite common stations with 4-5 units can cost $20-30 billion or more. Since traditional large nuclear power plants are among the most complex and critical construction projects of humanity as a whole, in this case there is a high probability of exceeding the construction time and a significant increase in cost compared to the design indicators. According to Deutsche Welle, the first EPR reactor in France is scheduled to be launched in test mode in mid-2024 at the Flamanville

Table 1

Comparative comprehensive analysis of types of nuclear reactors

№	Indicator	Large nuclear reactors	Small modular nuclear reactors
1	2	3	4
1	Construction duration	They have a significant construction time of even one power plant unit, which is at least 5-7 years. Due to the high complexity of the work, there is an extremely high probability of exceeding the construction deadlines over the design ones. Installation of equipment is also a complex task, there is a high probability of financing problems and delays in the manufacture of equipment.	Presumably, they have a very short construction time. Due to the comparative simplicity of the work in relation to traditional nuclear reactors, the probability of exceeding the construction time over the design is significantly reduced. The installation of equipment is also comparatively simple. There is no history of the construction of such reactors in the world, therefore, estimates of the duration of their construction are of a forecast nature.
2	Cost of construction	The cost of building even one unit of a station with a capacity of approximately 1000 MW can be about 5 billion dollars or more. Quite common stations with 4-5 units can cost 20-30 billion dollars or more. It is possible to assume with a fairly high probability that the cost of construction will increase during its period. There may be factors increasing the cost of construction that will arise unexpectedly and cannot be predicted.	Due to the significantly lower performance of such reactors compared to traditional large reactors, simpler design, lower power, high technology of module production, use of smaller areas for placement, location, in many cases, near places of energy consumption, it is possible to predict significantly lower cost of work.
3	Safety	Based on extensive global experience, it can be stated that if existing safety measures are observed, the likelihood of emergency situations that pose a significant danger to people and the environment is extremely low.	Due to their innovative design features and the operating technologies used, such reactors appear to be safer than traditional nuclear reactors.
4	Power flexibility	Large nuclear power plants are designed to generate significant amounts of electricity. Reducing reactor power is a problem and cannot be done quickly and regularly enough when energy consumption is reduced, such as at night and on weekends. Excess energy can be generated in large enough quantities, it can be transferred to other regions, accumulated to a certain extent, hydrogen can be produced for use or storage, and transferred in a liquefied state to places of consumption.	SMRs initially have a small capacity and are very flexible in terms of changing capacity, there is a significant control capability, which is largely determined by the innovative design of such reactors. In addition, the capacity and number of SMR units will probably be selected in such a way that energy production in a certain region will approximately correspond to the needs of this region, there will be no significant excess capacity, a small excess capacity can be accumulated in energy storage devices, transmitted to other regions.
5	Innovativeness	Nuclear power plants were the biggest innovation at the time of their appearance. Later, new types of reactors, special equipment, energy production technologies, safety systems, technologies and equipment for nuclear fuel production, its storage, processing and storage of spent fuel, other elements and systems were developed. Nuclear energy, of course, is still a very innovative sphere.	SMRs are an important example of advanced innovations of the 21st century, which develop previous innovations of the middle of the last century. Such innovations largely optimize nuclear reactors of the past, giving them new qualities. These qualities are aimed at increasing economic efficiency, safety, manufacturability of manufacturing, construction and installation of equipment.

(End of Table 1)

1	2	3	4
6	Accommodation options	Nuclear power plants were designed taking into account the location where they were to be located. An important condition was the availability of a sufficiently large reservoir for cooling the plant. Construction of plants in remote areas, hard-to-reach or mountainous terrain was an extremely difficult task and cannot be considered a typical phenomenon.	SMRs do not require a large area for placement, they can be placed in close proximity to cities or in rural areas. There is no need for natural water bodies to be nearby for such reactors to operate. At the same time, SMRs can be placed in remote and hard-to-reach areas, such as mountainous areas, deserts. In addition, SMRs can be placed next to other sources of electricity, such as wind, solar stations in addition to them.
7	Payback periods	The payback period of a large nuclear power plant depends on the number of units, their type and capacity, construction conditions, price and cost of electricity, as well as many other factors and can be 20-25 years or more. The conditions for building stations can become more complicated, construction periods can be extended, significantly increasing the cost of the station. This can increase the payback period.	There is no experience of SMRs payback, since such reactors have not yet been built and are not in operation. There are a number of positive factors for payback: simplicity of design, modularity, small size and power, relatively low cost, possibility of serial production of modules, use of existing energy infrastructure allow us to predict a short payback period for SMRs.
8	Cost of energy	The cost of energy depends on many factors, including the high costs of building a nuclear power plant.	The lower projected cost of electricity from SMRs compared to traditional large nuclear power plants is determined by many positive factors.
9	Environmental benefits	Large conventional nuclear reactors are a significant source of zero-emission electricity on a global scale, making them an important contributor to the decarbonization of global civilization.	SMRs build on the environmental benefits of traditional large nuclear power plants. Because they are innovative, they have a number of advantages over large reactors and can be more widely deployed worldwide, underlining their critical contribution to decarbonising the global economy.
10	Complexity of use with other types of energy	It is very advisable to use such stations in combination with wind and solar power stations, stations that use biofuel.	SMRs have additional capabilities for use in conjunction with wind and solar power plants compared to traditional large reactors. More opportunities for joint operation with plants that use biofuels.
11	Prospects and attractiveness	Large nuclear reactors have significant development prospects as a source of zero-carbon electricity. Large nuclear power plants will be of greatest importance in those regions of the planet where energy consumption is particularly high. They can be a source of energy for hydrogen production. In a number of countries, governments and environmentalists have a negative attitude towards existing nuclear power plants. It is important to show their advantages in decarbonization and to point out the sufficiently high safety of the plants in order to form correct ideas about nuclear energy in people.	Like large nuclear reactors, SMRs have unique development prospects as a source of zero-carbon electricity. But they have even greater prospects for expansion due to the many advantages that SMRs have. Small cities and their municipal authorities can easily build small modular reactors at their own expense to meet the needs of their population and the economy of their cities and surrounding areas.

(End of Table 1)

1	2	3	4
12	Reasons for making a decision	For decisions on the construction of large nuclear power plants – energy requirements, adherence to decarbonization policies, availability of significant financial resources, feasibility of placement, public support.	There are more reasons for making decisions to build SMRs than for building large nuclear reactors – energy demand, adherence to decarbonization policies, availability of even limited financial resources, relatively short construction and cost recovery time, ease of deployment, higher public support due to innovation and higher safety, balance of power and energy demand, ability to increase capacity by quickly building new SMR units.

Nuclear Power Plant in Normandy, according to the French state-owned EDF. Its construction took 17 years and the cost was €12.7 billion, four times higher than originally estimated [2]. The high cost of construction could be a major factor against the decision to develop such plants.

Safety of nuclear reactors. The world has accumulated a great deal of experience in operating traditional large nuclear power plants. The experience of accidents and disasters has been taken into account. If strict safety measures are observed, the probability of accidents that pose a significant danger is extremely low. Due to their innovativeness and design features, as well as the operating technologies used, SMRs appear to be safer than traditional nuclear reactors. International Atomic Energy Agency (IAEA) points out the very significant safety advantages of SMRs: «In comparison to existing reactors, proposed SMR designs are generally simpler, and the safety concept for SMRs often relies more on passive systems and inherent safety characteristics of the reactor, such as low power and operating pressure. This means that in such cases no human intervention or external power or force is required to shut down systems, because passive systems rely on physical phenomena, such as natural circulation, convection, gravity and self-pressurization. These increased safety margins, in some cases, eliminate or significantly lower the potential for unsafe releases of radioactivity to the environment and the public in case of an accident» [3].

Power flexibility. Large nuclear power plants are designed to generate significant amounts of electricity. Reducing the reactor power is a problem and cannot be done quickly and regularly enough at times of reduced energy consumption, such as at night and on weekends. Excess energy can be generated in fairly large quantities, it can be transferred to other regions, accumulated to a certain extent, hydrogen can be produced for use or storage, and transferred in a liquefied state to places of consumption. SMRs initially have a small capacity and are very flexible in terms of changing the power, there is a significant controllability, which is largely determined by the innovative design of such reactors. In addition, the capacity and number of SMRs units will probably be selected in such a way that energy production in a given region will roughly correspond to the needs of that region, there will be no significant excess capacity, a small excess capacity can be accumulated in energy storage devices, transmitted to other regions, in case of excess electricity, for example, at night, hydrogen can be produced, liquefied and subsequently used or stored, and hydrogen can also be transported to other areas.

Innovativeness. Nuclear power plants were the biggest innovation when they first appeared in the 1950s. Later, new types of reactors, special equipment, energy generation technologies, safety systems, technologies and equipment for nuclear fuel production, its storage, processing and storage of spent fuel, other elements and systems were developed. Nuclear power, of course, is still a very innovative area.

SMRs are an important example of advanced innovations of the 21st century, which develop previous innovations of the middle of the last century. Such innovations largely optimize nuclear reactors of the past, giving them new qualities. These qualities are aimed at increasing economic efficiency, safety, manufacturability of manufacturing, construction and installation of equipment. An important innovative quality of such reactors is their high ability to meet the needs of energy consumers, the energy balance of the region in which the SMRs are located. A serious innovative quality is the ability of such reactors to have higher safety characteristics.

Possibilities of placing nuclear power plants. Designing the construction of traditional large nuclear reactors was a complex task. Nuclear power plants were designed taking into account the terrain where they were to be located. An important condition was the availability of a sufficiently large reservoir for cooling the station. Stations were located at a certain distance from cities. Construction of stations in remote areas, hard-to-reach or mountainous areas was an extremely difficult task and cannot be considered a typical phenomenon. SMRs do not require a large area for placement, they can be located in close proximity to cities or in rural areas. There is no need for natural reservoirs to be nearby for such reactors to operate. At the same time, SMRs can be located in remote and hard-to-reach areas, for example, in mountainous areas, in deserts, in permafrost zones, when it is necessary to provide energy to people or production. In addition, SMRs can be located next to other sources of electricity, for example, thermal, wind, solar stations in addition to them.

Payback periods. The payback period of a large nuclear power plant depends on the number of units, their type and capacity, construction conditions, price and cost of electricity, as well as many other factors, and can be 20-25 years or more. The conditions for the construction of stations can become more complicated, the construction period can be extended, significantly increasing the cost of the station. This can increase the payback period. A fairly high degree of uncertainty in the cost, duration of construction of large nuclear power plants and the uncertainty in the payback period caused by these and other factors can be a serious factor in making a management decision on the construction of such stations. The situation is significantly more complicated in the case of large stations with many units. There is no experience of payback of SMRs, since such reactors have not yet been built and are not in operation. However, many factors that are favorable for payback, namely, simplicity of design, modularity, small size and power, relatively low cost, possibility of serial production of modules at factories and related additional savings, small occupied area, no need for large volumes of water for reactor cooling, possibility of using existing energy infrastructure, absence of excess power and energy losses, allow us to predict with a fairly high probability a relatively short payback period for SMRs. This factor can be decisive when making a management decision on the construction of SMRs.

Cost of energy. For traditional large plants, the cost of energy depends on many factors, including the high costs of building a nuclear power plant. The lower predicted cost of electricity for SMRs compared to traditional large nuclear power plants is determined by many positive factors.

Environmental benefits. Large nuclear power plants are a very large source of electricity with zero emissions of harmful gases into the atmosphere. This determines their significant contribution to the decarbonization of the world economy. SMRs expand on the environmental benefits of traditional large nuclear power plants. At the same time, SMRs have many advantages and can be much more widespread, which will determine their special contribution to the decarbonization of the world economy.

Complexity of use with other types of energy. It is very advisable to use large nuclear power plants in combination with wind and solar power plants, plants that use biofuels, although in many cases the excess capacity of nuclear power plants will not cause the need for other energy sources. SMRs have additional opportunities for use in combination with wind and solar power plants compared to traditional large reactors. More opportunities for joint operation with plants that use biofuels.

Prospects and attractiveness. Large nuclear reactors have significant development prospects as a source of electricity with zero carbon emissions. They can be a major addition to the production of electricity for such types of power plants as wind, solar, and biofuel power plants. Large nuclear power plants will be of greatest importance in those regions of the planet where energy consumption is particularly high. They can be a source of energy for hydrogen production. In a number of countries, governments and part of the population, as well as the environmental community, have a negative attitude towards nuclear power plants that have existed for a long time. This is due to concerns about the consequences of accidents at large nuclear power plants. The public sometimes ignores the extremely important economic and environmental benefits of nuclear energy. As a paradoxical and erroneous decision in the field of nuclear energy, in our opinion, we should point out the decision of the German authorities to close all nuclear power plants in the country.

Like large nuclear reactors, SMRs have unique development prospects as a source of electricity with zero carbon emissions. But they have even higher distribution prospects due to the numerous advantages that SMRs have. To a much greater extent than traditional nuclear reactors, small reactors can be a power reserve for such climate-neutral primary energy sources that are most promising for the world energy sector, such as offshore and onshore wind, solar power plants, and biofuel plants. In addition, they can be a source of energy for the production of hydrogen for its subsequent use. Small cities and their municipal authorities can build small modular reactors at their own expense to meet the needs of the population and the economy of these cities and the surrounding areas.

Reasons for making a decision on construction. The decision to build large nuclear power plants is based on the need for energy, adherence to the decarbonization policy, the availability of significant financial resources, the possibility of placement, and public support. There are more reasons for making decisions to build SMRs than for building large nuclear reactors – energy demand, adherence to decarbonization policies, availability of even limited financial resources, relatively short construction and cost recovery time, ease of deployment, higher public support due to innovation and higher safety, balance of power and energy demand, ability to increase capacity by quickly building new SMR units.

A large number of nuclear reactors (415 as of the end of October 2024, [4]) in the world have mostly a long service life. For example, there are 3 reactors that are 55 years old, 38 reactors that are 50 years old or older, 27 reactors that are 40 years old, 163 reactors that are 40 years old or older, and 290 reactors that are 30 years old or older. Only 66 reactors are 10 years old or younger. Thus, it is obvious that the global nuclear energy industry needs to build new nuclear reactors not only to supplement existing reactors, but also to replace old reactors that need to be decommissioned.

The world community has plans to significantly increase nuclear power capacity by the middle of this century, but this is a complex issue, the World Nuclear Association reports: [5] «Tripling nuclear by 2050 is going to be a challenge, said World Nuclear Association Chairman Bohdan Zronek, who is chief nuclear officer of Czech

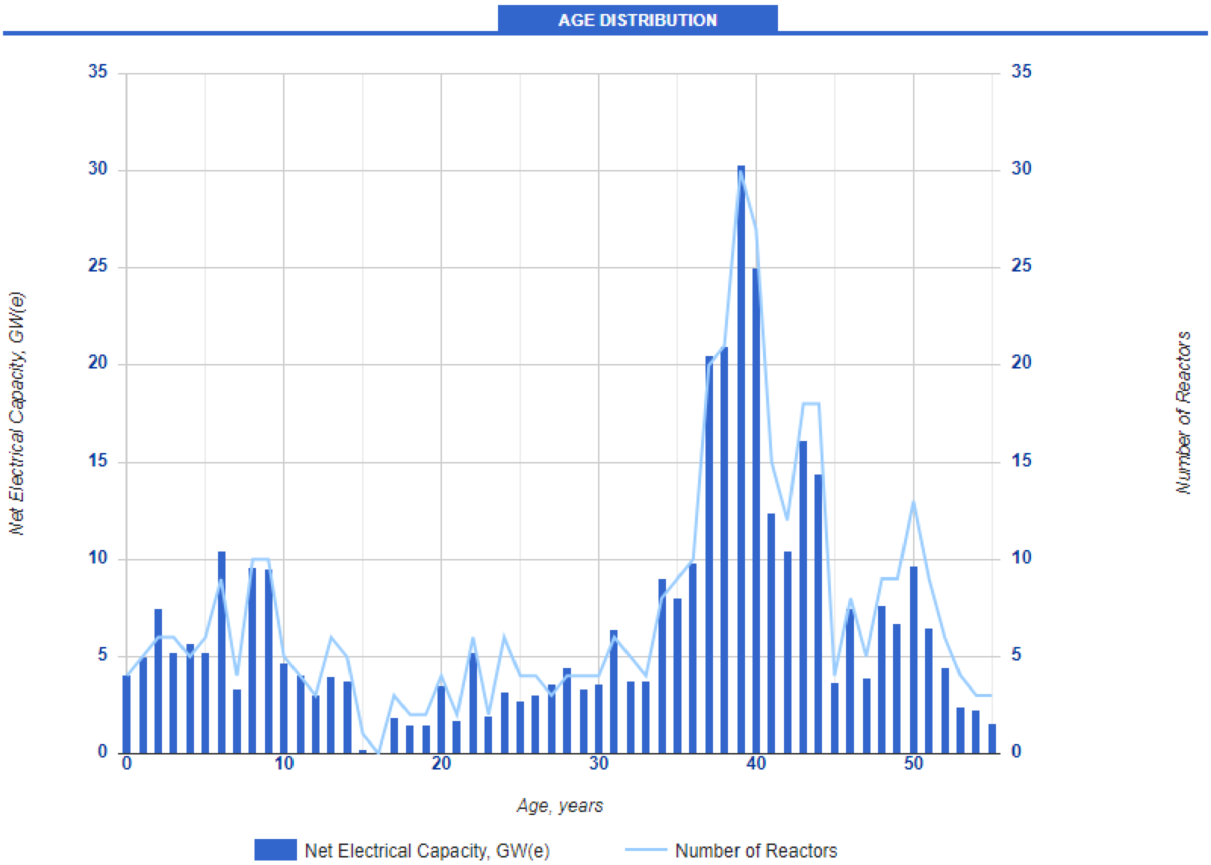

Figure 2. Age Distribution

Source: [4]

nuclear power plant operator ČEZ. "We are going to need to ramp up every aspect of the nuclear value chain to meet that challenge," he added. Alongside extending the operating lives of many existing reactors to 60 or even 80 years, this will still require the construction of about 1000 GWe of new nuclear in the next 26 years. "Essentially, what we are saying is that we need to build 40 GWe of new nuclear capacity every year for the next 26 years. Doing a 'back of the envelope' calculation, this would be about twenty 1000 MWe large reactors, and seventy 300MWe SMRs, every year," he added» [5].

Poland (Fig. 3) did not have nuclear power plants on its territory before, but the country is currently planning the largest-scale construction – commissioning of units with a total capacity of 6.55 MW, the cost of which will be 56.5 billion euros [6]. The Czech Republic also has very significant plans – construction and commissioning of 4.8 MW capacities, the cost of which will be 24 billion euros. This is a very serious contribution to the energy of both countries and an extremely large-scale investment, a contribution to decarbonization, nuclear energy will replace old coal-fired power plants. Other Eastern European countries are also planning to make large investments in the development of nuclear energy – in total more than 47 billion euros. The total investment of the countries of the group (Fig. 3), according to Bloomberg, will be about 130 billion euros [6].

Currently, various companies from many countries around the world are developing approximately 80 different projects of small modular reactors. France is showing significant interest in such reactors, and is also contributing to their development. As an illustration, according to [7], we can cite (Fig. 4) NUWARDTM (EDF, France).

It is indicated that «NUWARDTM is an integrated PWR design to generate 340 MWe from two independent reactor units, offering flexible operation. The NUWARDTM technology is being developed to replace fossil-fired power plants in the 300-400 MWe range; to supply power to remote municipalities and energy-intensive industrial sites; and to power grids with limited capacity. By design, it is a multipurpose SMR that can be used for cogeneration of heat and electricity, hydrogen production, district heating, and water desalination. The design offers baseload and load-following capability to enable integration with renewable energy sources» [7].

The following are the important qualities of this power plant: «NUWARDTM design is based on the proven PWR-technology that incorporates significant experience acquired in the fields of medium and high-power generation, alongside several key technological innovations, to achieve the following design objectives: acceptability: robustness of the design will maximise safety and minimise environmental impact; simplicity: simple architecture, enhanced manufacturability…» [7].

Eastern Europe Plans Almost €130 Billion of Nuclear Spending

New projects have been announced across the region

Country	Location	Planned Output	Estimated Cost
Bulgaria	Kozloduy	2,300MW	€13 Billion
Czech Republic	Dukovany	4,800MW	€24 Billion
Poland	Pomerania, Patnow	6,550MW	€56.5 Billion
Romania	Cernavoda	1,400MW	€7 Billion
Slovakia	Jaslovske Bohunice	1,200MW	€12 Billion
Slovenia	Krsko	1,650MW	€15.4 Billion

Source: Latest government estimates
Note: Excludes Hungary because the Paks plant is already under construction. Estimates for Czech Republic and Slovenia are for upper end of proposals.

Figure 3. Plans of Eastern European countries to build nuclear power plants

Source: [6]

NUWARD™ (EDF, France)

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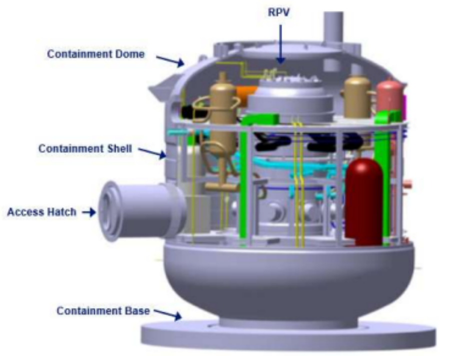

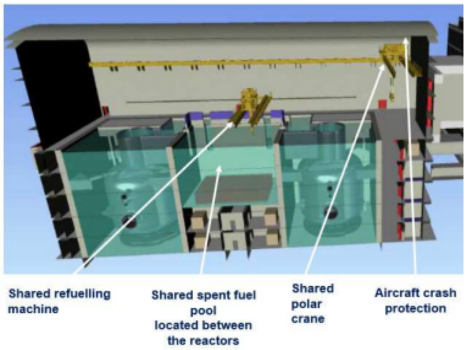

MAJOR TECHNICAL PARAMETERS

Parameter	Value
Technology developer, country of origin	EDF, France with major contributions from CEA, Naval Group, Framatome, TechnicAtome, and Tractebel-Engie
Reactor type	Integral PWR
Coolant/moderator	Light water / light water
Thermal/electrical capacity, MW(t)/MW(e)	2 x 540 / 2 x 170
Primary circulation	Forced circulation
NSSS Operating Pressure (primary/secondary), MPa	15 / 4.5
Core Inlet/Outlet Coolant Temperature (°C)	280 / 307
Fuel type/assembly array	UO_2 / 17x17 square pitch arrangement
Number of fuel assemblies in the core	76
Fuel enrichment (%)	<5
Refuelling Cycle (months)	24 (half core)
Reactivity control	Control rod drive mechanism (CRDM), solid burnable poisons
Approach to safety systems	Passive
Design life (years)	60
Plant footprint (m^2)	3500, nuclear island including fuel storage pool
RPV height/diameter (m)	15 / 5
RPV weight (metric ton)	310
Seismic Design (SSE)	0.3g
Distinguishing features	Integrated NSSS with pool submerged containment, boron-free in normal operation and in all Design Basis Conditions (DBC), semi-buried nuclear island
Design status	Conceptual Design

Figure 4. NUWARDTM (EDF, France)

Source: [7]

Directions and priorities of decarbonization in the global energy sector. Development model. For the purposes of sustainable development of world civilization, economic growth and combating climate change of the planet, it seems advisable, in particular, to follow the following key development directions.

1. Mass construction of small modular nuclear reactors and nuclear microreactors in the widest areas of the planet, primarily in Europe, which can be an important addition to such main sources of climate-neutral energy as wind, solar energy, biofuel energy. The greatest attractiveness of small modular reactors, including for the general public, is due to their innovativeness, increased safety, simplicity, low cost and construction time, technological advantages of manufacturing modules and their installation, the possibility of additional increase in capacity by rapid placement of additional units, high capacity factor, independence of energy production from climatic and weather factors. SMRs are a new and key factor in decarbonization.

2. Wind energy as the main source of climate-neutral energy in the future. Its advantages are obvious, but a two-fold lower capacity factor, dependence on weather, low capacity of a single wind turbine compared to SMRs, despite the many positive qualities of wind energy in the near future, assign it a slightly less important role in the energy sector. In the

long term, it can be said with high probability that when the number of wind turbines on the planet reaches an extremely large number, wind energy will become the most important for the global world.

3. Solar energy. Its importance is already very high today, but dependence on the intensity of sunlight and a relatively low capacity factor to a certain extent hinder its development. For many desert regions of the planet with intense lighting, solar energy can play an extremely important role.

4. Large nuclear reactors, traditionally used in nuclear energy. Over many decades of operation of such stations, an extremely large amount of energy has been generated. Such stations have important development prospects, a high capacity factor, but public support for their development is ambiguous. They are characterized by a very high cost and construction time; there is a high probability of a multiple increase in these parameters during the work. At the same time, large nuclear power plants have the prospect of development in places of high energy consumption, for example, near large industrial centers and densely populated cities.

5. Bioenergy. Humanity will not be able to refuse the development of animal husbandry, agriculture in general, forestry, the use of plant materials, and therefore the development of bioenergy is extremely promising. A very important area, for example, can be the production of methane from animal manure, which allows not only to produce fuel, but also to reduce greenhouse gas emissions into the atmosphere.

6. The most important factor in the development of global energy in the direction of decarbonization is the comprehensive development and use of all progressive types of energy in interaction, taking into account their advantages for various conditions: SMRs, wind and solar energy, traditional nuclear energy, bioenergy. The parameters for the use of various types of energy will be determined by specific economic, geographical, social and other circumstances.

Conclusions. Thus, the study showed that, based on reliable information from authoritative international organizations, negative climate change is becoming increasingly intense. Analysis of many factors of traditional large and small modular reactors showed the simplicity of designs, manufacturability, lower cost and high safety of SMRs. Such reactors require smaller investment and construction time. Their many properties, in particular, a high-capacity factor, make their development a priority for ensuring sustainable development and decarbonization. In combination with other types of energy, such as wind, solar, bioenergy, it is possible to provide optimal conditions for economic development in the global economy of the planet. The implementation of priority development areas requires adequate innovation management and efforts of the entire global community.

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