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Short Communication

Potential role of nuclear power in a carbon-free world

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Abstract

Thermal Power Plants (ThPP), along with transport facilities, are the major sources for industrial emissions of carbon dioxide (CO_2) believed to be responsible for the greenhouse effect leading to overheating of the lower atmosphere. In the opinion of many scientists, there is a threshold value of the average atmospheric temperature exceeding, which entails the potential for the development of irreversible processes threatening the existence of humankind. To avoid this danger, governments in nearly 200 countries have chosen voluntarily to reach net-zero CO_2 emissions by 2050. Renewable Energy Sources (RES), including wind and solar power plants, have been selected as substitutes for ThPPs. However, energy systems based on RES only need to be multiply redundant in terms of installed capacity due to their efficiency being heavily dependent on daily, seasonal and weather factors, leave alone the scale of the required material resources (metals, polymers, concrete, glass, etc.). The major drawback of such energy systems is, however, the RES common-cause failure, e.g., in the event of a global volcanic eruption, when no energy-security requirement can be met to provide energy for satisfying the most vital needs. A need is fully evident for furnishing such energy system with another power source to be not dependent on the event that has caused the mass RES failure. With the net-zero-carbon requirement taken into account, Nuclear Power (NP) appears to be the best option in this respect. Modern NP does not however fully suits this role due to its inherent drawbacks (limited fuel resources, pending Spent Nuclear Fuel (SNF) and RadioActive Wastes (RAW) handling and nuclear-material nonproliferation issues). A potential solution to these drawbacks is a two-component NP technology in a closed nuclear-fuel cycle currently in the process of development. In Russia, where the greatest progress has been achieved in this field of development, under construction is a pilot and demonstration energy complex with the BREST-OD-300 nuclear unit expected to be started up in 2026–2027. Another promising designs to be developed are Small Modular Reactors (SMRs) / Small Nuclear Power Plants (SNPPs).

Keywords

Global warming, renewable energy sources, decarbonization, window of opportunities for nuclear power, small nuclear power plants

Introduction

Power generation forms the basis for the economy of any modern state and the world economy as the whole. Electric power is known to be the most ‘convenient’ type of energy for common use. Currently, fossil fuel power plants (fired by coal, natural gas or oil) account for more than a half of electricity generation. The situation can, however, change dramatically as soon as in the first half of this century thanks to the efforts by our planet’s climate advocates.

Indeed, as shown by the weather observations from recent decades, there is rather a pronounced trend for the growth in the average temperature of the Earth’s lower atmosphere. According to estimates from many anxious scientists, overheating of the Earth's atmosphere by more than 2 °C can lead to irreversible catastrophic climate changes threatening the very existence of human civilization (Global Warming 2023).

Some scientists believe that this potentially dangerous dynamics in the average temperature of the lower atmosphere is the result of the greenhouse effect they think to be caused by industrial emissions of carbon dioxide (CO_2), the major product of the fossil fuel combustion in an oxygen-containing environment. The main sources of such emissions are thermal power plants and transportation (ground-, sea- and air-based).

As in the event of any scientific theory or hypothesis, the greenhouse-effect proponents are opposed by those believing the scales of current industrial factors cannot lead to the global overheating of the lower atmosphere. The opponents think this phenomenon to be more likely caused by a cyclic nonindustrial natural process with such a lengthy period, as compared with the history of the regular monitoring for the atmospheric temperature dynamics, that this cycle has not been yet determined scientifically.

As experts in a somewhat different field of knowledge, the authors do not think they have the right to intervene in the debate between the undoubtedly competent and honorable greenhouse effect proponents and their no less competent opponents. However, the energy of the Earth's climate defenders has led to the threat of a catastrophic climate change and the ways to avert these having been discussed at different climatic forums, including at the top political level. There have been signed the Kyoto Protocol on Climate Change (1997), the Paris Climate Agreement (2015), and the Glasgow Climate Pact (2021) ratified by governments of nearly 200 states. These documents provide for a reduction in the global emissions of greenhouse gases to prevent the Earth's atmosphere temperature from increasing by more than one degree Centigrade and a half by the end of the 21st century.

The key step in implementing the plans to reduce the global emissions of greenhouse gases is phased abandonment of ThPPs since it is exactly these plants that use fossil fuel in the form of coal, natural gas or oil. The governments in nearly 200 states have voluntarily chosen to reach by 2050 net zero emissions of carbon or, more exactly, CO_2 into the atmosphere. Thus, for example, in his video address to the UN General Assembly in February 2020, Chinese President Xi Jinping said China's goal was to "be past the CO_2 emission peak in 2030, and achieve the coal neutral status by 2060". It is worth noting though that China accounts for nearly 30% of the world's CO_2 emission.

At the same time, the abandonment of ThPPs with the annual generation of over a half of the electricity produced worldwide is really possible only if there is a replacement generating capacity. The so-called Renewable Energy Sources (RES), namely Wind Power Plants (WPPs) and Solar Power Plants (SPPs), have been chosen as such. NPPs have somehow turned to be in a grey zone. In the EU, for example, some states, specifically France, Hungary, Great Britain and 13 more of the 27 EU members, advocate for nuclear power, whereas Germany, Austria and Luxemburg strongly oppose it. Their own far-reaching nuclear power evolution programs are under way in Russia, China, India, Turkey, Egypt and some other countries.

Expecting RES to substitute all other types of electricity generation with a surplus, the advocates of decarbonization intend to change dramatically the entire structure of modern economy by making transportation, metallurgy and other energy-consuming branches of the world economy powered by electricity. In their opinion, it will be possible to use some of the RES-generated electricity for electrolysis of water to produce 'green' hydrogen. This hydrogen can be used both by way of combustion and more rationally, e.g., in fuel elements providing transportation and other energy-consuming industries with electricity. In combination with large-scale production and application of green hydrogen, the climate advocates believe, carbon-free electricity generation will serve the basis for a new world economy often referred to as hydrogen economy.

Abbreviations

ACP	Advanced Chinese Pressurized-water reactor
BR	Breeding Ratio
BREST-OD	Fast Reactor with Inherent safety Lead Coolant – Experimental Demonstration (БРЕСТ-ОД – Быстрый Реактор Естественной безопасности со Свинцовым Теплоносителем – Опытно-Демонстрационный or Быстрый Реактор ЕСТественной безопасности – Опытно – Демонстрационный (in Russian abbreviations) (Russia))
CAREM-25	Central ARgentina de Elementos Modulares-25
EU	European Union
FPU	Floating Power Unit
FNR	Fast Neutron Reactor
HPP	Hydroelectric Power Plant
HTR-PM	High-Temperature Reactor (helium-cooled) Pebble-bed Module (China)
ICUF	Installed Capacity Utilization Factor
IEA	International Energy Agency
INPRO	International Project on Innovative Nuclear Reactors and Fuel Cycles
KLT	Container-carrier cargo-Lighter Transport (reactor) (Контейнеровоз Лихтеровоз Транспортный (реактор) (in Russian abbreviations)) (Russia)
NFC	Nuclear Fuel Cycle
NM	Nuclear Materials
NP	Nuclear Power
NPP	Nuclear Power Plant
PDEC	Pilot and Demonstration Energy Complex
PWR	Pressurized Water Reactor
RAW	RadioActive Wastes
RES	Renewable Energy Source
RF	Reactor Facility

RITM-200M	Reactor Integral Type Modular 200-MW_{el} Modernized (РИТМ-200М – Реактор Интегрального Типа Модульный мощностью 200 МВт Модернизированный (in Russian abbreviations) (Russia))
RITM-200H	Reactor Integral Type Modular 200-MW_{el} land-based (РИТМ-200Н – Реактор Интегрального Типа Модульный мощностью 200 $МВ_{тэл}$ Наземного размещения (in Russian abbreviations) (Russia))
SMR	Small Modular Reactor
SNF	Spent Nuclear Fuel
SNPP	Small Nuclear Power Plant
SPP	Solar Power Plant
SPR	Small Power Reactor
ThPP	Thermal Power Plant
UN	United Nations
USA	United States of America
WPP	Wind Power Plant

Topical issues of exclusively RES-based electricity generation

Some of the aspects involved in the transition to carbon-free electricity generation and the associated hydrogen economy were dealt with earlier by the authors in (Kaplienko and Gabaraev 2023); specifically, issues were discussed concerning the implementation of RES in the required scope and the energy security of an exclusively RES-based energy system. The key advantage of renewables is that they constitute an energy resource renewed continuously by nature independently of man, allow electricity generation with no CO_2 emissions, and do not require fuel purchasing, delivery, storage and waste disposal costs. This is exactly why the climate defenders have turned to RES to address the issues of limited resources and environmental safety.

At the same time, there are drawbacks of RES some of which are apparent while the others can manifest themselves in specific consequences. Thus, for example, the following obvious drawbacks can be mentioned as applied to HPPs (Gabaraev and Lutovinov 2013):

- limited hydropower resources, especially in states with a small territory (e.g., many EU countries);
- alienation of large territories, sometimes with flooding of residential areas;
- difficulty of fish migration to breeding grounds.

Some of not so obvious RES drawbacks are:

- potential catastrophic breakdown of reservoir dams in the event of improper dam integrity monitoring and maintenance;
- extraordinary costs of the dam disposal or renovation, and reclaiming the exposed reservoir bed to avoid an environmental or infectious disaster.

One can judge the scale of loss in the wake of the hydropower dam breakdown from the example of an accident in 1975 in China caused by the failure of a comparatively small (25-m high and 120-m long) earth dam of the Banqiao HPP on the Ru River, when 26 thousand people died as the result of the flood and 145 thousand more were killed by the famine and epidemic that followed (Banqiao China 1975).

With this taken into account, many countries refrain from building large hydropower stations. Some of the exclusions are countries with a large territory and full-flowing rivers, such as China, Russia, Brazil, India and others.

It is because of this that WPPs and SPPs have been given special attention among different RES types. Their obvious drawbacks include:

- alienation of large territories for the WPP and SPP construction;
- low Installed Capacity Utilization Factor (ICUF) values due to a strong dependence on daily, seasonal and weather factors;
- requirement for using energy storage systems;
- high material/output ratio of RES and energy storage systems.

The first of the above drawbacks is current concern for small densely populated countries with no access to sea incapable to build sea-based WPPs or SPPs.

The second drawback can be compensated by reservation of the generating capacity. A graphic example is provided in (Kaplienko and Gabaraev 2023): *"in 2021, the total capacity of all WPPs and photovoltaic SPPs in the world amounted to respectively 825 and 849 GW_{el}, and their cumulative contribution to the global generation of electric power has turned to be equal to 10.3%, of which 6.6% are generated by wind power and the rest 3.7% are generated by solar power. Nearly the same contribution of 9.9% was made by all NPPs in the world to the global electricity generation also in 2021 with a total power of 400 GW_{el}, this being at least four times as small as the total power of WPPs and photovoltaic SPPs: (825 + 849) = 1674 GW_{el}. In other words, the ICUF of the world's NPP fleet has turned out to be four times as large as that of the world's WPP and photovoltaic SPP fleet."* This leads to a conclusion that the replacement of ThPPs and NPPs will require the RES generating capacity to be at least quad redundant.

Such large-scale redundancy of the RES generating capacity and energy storage systems may turn out to be questionable to implement since the transition from fuel-intensive power of today's world economy to material-intensive carbon-free power of the future world will require huge material resources, these to include not only steel and concrete but also much more difficult-to-obtain materials such as copper, aluminum, polymers and such rare metals as lithium, nickel, platinum, cobalt, cadmium and others. Of interest in this respect is the information provided in (Tesla's Master Plan Part 3, 2023). Achieving a sustainable energy economy by 2050 will require ~30.3 TW_{el} of the SPP and WPP power and ~240 TW_{el}·h of the storage battery energy content which means a 15-fold increase against the current level of these parameters.

With regard for the material consumption involved in electricity generation as such, storage batteries and power transmission, this means the following total demand (million tons): nickel – 40, aluminum – 412, lithium ($LiOH \cdot H_2O$) – 118, zinc – 66, silicon – 39, silver – 0.07, magnesium – 18. The figures for copper, declared the 'base green power metal', are: mining (2019) – 24 million tons, consumption in SPPs – 5.5 t/MW_{el}, consumption in WPPs – (4–10) t/MW_{el}.

Some of the unobvious drawbacks of the world's electricity generation based exclusively on RES are:

- failure to comply with the net zero carbon and environmental friendliness principles at the front and back ends of the RES lifecycle (mining and fabrication of RES materials, RES disposal after the end of life);
- failure to comply with the requirement for uninterruptible power supply, or, in other words, the energy security requirement.

A note can be made with respect to the former that present-day fabrication of RES materials involves large CO_2 emissions. The disposal of RES, e.g. polymer wind turbine blades or solar panels, will inevitably involve the release of harmful substances much more harmful than CO_2.

The second of the above-mentioned drawbacks is seen by the authors as that of most concern. Normally, ensuring that any function of the energy system under consideration is uninterruptible requires such measures as redundancy (in terms of generating capacity) or diversification (e.g., in terms of the principle of operation). Seemingly, exclusively RES-based electricity generation fully meets these requirements. However, the redundancy and diversification of the energy system components meet their objective only provided these do not fail due to a common cause.

Meanwhile, apart from unfavorable daily, seasonal and weather factors that affect the RES functionality and efficiency, extreme situations are possible. An example of such extreme event is the February frost of down to -20 °C in the state of Texas that led to ~75% of the RES generating capacity lost due to the wind turbine blade icing. A hypothetical global-scale eruption of a volcano (e.g., the Yellowstone Supervolcano in the USA) can be called as one of the most unlikely extreme situations though not altogether excluded.

Therefore, ensuring the energy security (meeting at least just the most important vital needs) requires any future energy system to include, in addition to RES, another electricity source which is stable to the factor that has caused the RES common-cause failure. At the present time, ThPPs or NPPs can claim the role of such a stable electricity source. The former are automatically declined by the advocates of the carbon-free hydrogen economy, so only NPPs remain.

It is possible to include cutting-edge nuclear reactor designs–like small modular reactors, or SMRs–into a grid that produces no carbon emissions for example in conjunction with WPP or SPP. However some issues have to be resolved including: legal frameworks for widespread enriched-fuel utilization and its interstate transportation; elimination of potential for plutonium production; sabotage and terrorist-attacks prevention; accounting and remote monitoring of nuclear materials; assured cooling of spent nuclear fuel during transportation; and equipment operating without maintenance for a time commensurate with core lifetime (Pioro et al. 2019; Pioro et al. 2020; Handbook of Generation IV Nuclear Reactors 2023).

In a grid consisting of RES, SMR, electrolyzers for hydrogen generation, energy and hydrogen storage systems, it is quite possible to ensure the baseload operation mode of SMR by maneuvering the share of energy supplied to electrolyzers (Locatelli et al. 2018; Poudel and Gokaraju 2021).

NP has a noticeable negative impact on the environment at the initial stage (extraction and processing of raw materials) and the final stage (waste management). To be fair, the same pattern occurs in the case of RES, and even more so given the series production of RES. It should be noted that NP and RES are continuously improving their technological processes in order to reduce the negative impact on the environment. Nuclear energy, renewable energy and innovative technology protect environmental quality while globalization and economic growth degrade the environmental sustainability. It should be noted that currently there is a transition from a carbon economy to a carbon-free (hydrogen) economy, from a linear economy to a circular economy (Hassan et al. 2020; Hassan et al. 2022; Hassan et al. 2023; Sadiq et al. 2023).

In developing countries, the urgent task is to increase per capita electricity generation. The use of NP, with its very low carbon footprint, will make it possible to avoid the use of ThPPs, which are a major contributor to CO_2 emissions. The implementation of an appropriate energy policy requires the political will of the decision-makers (Hassan et al. 2022).

The roadmap (IEA 2021) of such a competent organization as the IEA presents the results of the studies, according to which net zero carbon emissions in the world's electricity generation will be reached by 2050 with 88% of the electricity being RES-generated and the rest 12% generated by NPPs. It is difficult for the authors to answer the question if 12% will be enough for satisfying the vital needs but they believe the possibility for excessive nuclear electricity to be rapidly 'transferred' for being used in electrolysis cells for hydrogen production will make it possible to keep the reactor power continuously at a level close to the nominal value. As a result, the permissible NPP contribution is expected to exceed, with time, the above 12% without a damage to the energy system as the whole. This leads to a conclusion that a certain 'window of opportunities' still exists for nuclear power in the future world of hydrogen economy.

Prospects of using the window of opportunities for nuclear power

The most radical climate defenders are resolute to close up this window of opportunities or just leave it slightly opened for a certain transitional period. As stated in the Introduction, there is an uncompromising confrontation within the EU between the advocates of nuclear power and their opponents.

Opinions also differ in the world's scientific community with respect to the outlook for nuclear power. An article was published in 2021 in an international journal, *Energy Policy*, by a team of Austrian scientists (Muellner et al. 2021). They compared the nuclear power evolution forecasts for different periods of time developed by the IAEA and other international organizations with the actual dynamics of the parameters for the power industry under consideration in the same time periods and have found the actual dynamics to have always been near the lower boundaries of the forecast corridor. They also noted the limited resources of ^{235}U and the predominant contribution of the reactors designed in 1960–1980 and built in 1970–1990, and reminded about the residual risk of severe accidents, major release of radioactive materials during such accidents, and nuclear material proliferation risks. At the same time, the (Muellner et al. 2021) mentioned in a casual manner the developers of innovative energy technologies promising a ten-fold decrease in the risk of severe accidents but complained right away about long innovative reactor development, planning and construction times they expect to extend to beyond 2050.

They have come to a conclusion that the contribution of nuclear power to mitigating the climate changes does not exceed 2 to 3% of the total CO2 emission and it is better to be abandoned and replaced by other electricity sources. It only remains to guess that these other sources are RES. The energy security issue of an exclusively RES-based energy system discussed above has been left outside the focus of attention of (Muellner et al. 2021).

The drawbacks of present-day nuclear power have been looked at not only in (Muellner et al. 2021). It was understood as early as by the beginning of the 2000s that large-scale evolution of nuclear power required the following four key issues to be resolved in an integrated manner: energy generation cost reduction, safety improvement, RW and SNF handling, nonproliferation of nuclear materials. With new nuclear power plants and nuclear fuel cycle facilities continued to be built under the existing designs, even the most advanced of the Generation III+ designs, the above problems will be only growing. It is only nuclear power based on novel principles will be capable to resolve the above-mentioned issues and become a stable source of power for many years to come.

Accordingly, two major international forums, the Generation IV International Forum (Generation IV, 2014) and the INPRO Project (IAEA-TECDOC-1575, 2008), were organized in the early 2000s for intensifying the activities to build reactors of a new type devoid of the above drawbacks. The former's goals were to search for and implement new designs of nuclear energy systems. The INPRO Project aims at shaping the consumer requirements with respect to designs of nuclear systems and technologies and developing a methodology to assess the quality of new designs as applied to consumer requirements.

A variety of reactor technologies (concepts), capable to satisfy, potentially, the developed requirements, were analyzed as part of the Generation IV Project. As a result, six promising reactor concepts were chosen and recommended for further R&D studies:

- SFR (Sodium-cooled Fast Reactor);
- VHTR (Very-High-Temperature helium-cooled Reactor);
- SCWR (Supercritical Water-Cooled Reactor);
- GFR (Gas-cooled Fast Reactor);
- LFR (Lead-cooled Fast Reactor);
- MSR (Molten Salt Reactor).

Activities for any of the above six reactor concepts have been under way in a number of countries (Russia, China, India, USA, and EU), while a note should be made that they are undertaken at an accelerated pace in Russia and China.

The most graphic and advanced example of the nuclear energy technology developed as part of the Generation IV Project is *Proryv*, a Russian nuclear project aiming to develop, build and deploy commercially a closed nuclear fuel cycle (CNFC) based on fast neutron reactors for the purpose of developing large-scale nuclear power meeting the following requirements (Adamov 2020; *Proryv* Project 2020):

- exclusion of severe accidents requiring evacuation of the population;
- competitiveness in the market of electricity generation;
- use of the full potential of natural raw uranium;
- radiation equivalent disposal of radioactive waste;
- strengthening of nuclear material proliferation resistance.

The construction of a pilot and demonstration energy complex has been started at the Siberian Chemical Combine's site as part of the *Proryv* project, comprising a power unit with the BREST-OD-300 innovative lead-cooled reactor and an onsite backend plant.

The energy technology with a fast neutron reactor in a closed NFC meets the above requirements to large-scale nuclear power as the one that:

- excludes severe accidents requiring evacuation of the population. This is achieved through the principle of 'inherent safety', without upgrades to expensive engineered barriers and safety systems, only thanks to the peculiarities of the chain fission

reaction balance in a fast reactor, the natural regularities, properties and qualities of its key components (lead coolant and fuel), as well as the designs that contribute to their implementation. The risk of the most severe accidents can be reduced dramatically or even avoided naturally;
- resolves the problem of limited fuel resources thanks to the use of ^{238}U (and possibly ^{232}Th);
- offers low-waste SNF reprocessing with radiation equivalent RW disposal;
- supports technologically proliferation resistance (no uranium enrichment, no blanket, onsite fuel cycle, BR of ~1, SNF reprocessing technology without uranium and plutonium extraction).

The BREST-OD-300 nuclear unit is expected to be started up in 2026–2027. And it is as soon as in the 2030s that the technology is expected to begin to be duplicated.

Another area for the evolution of nuclear power is intensive development of SNPP designs currently under way in many countries (Zohuri and McDaniel 2019; IAEA ARIS 2022; Soloviev et al. 2022; WNA 2022; Citi GPS 2023; Snobeiti et al. 2023). The SNPP advantages are:

- Possibility for being used in relatively small grids (small countries, remote areas in large countries or island territories);
- Possibility for being used in hybrid energy systems with a predominance of RES;
- Reduction of risks and economically competitive growth due to nearly full fabrication of modules in factory conditions with the smallest possible scope of onsite construction and assembly operations;
- Series effect as compensation for the power scale effect;
- Short construction times and possibility for phased NPP scale-up via deployment of further units;
- Modular and compact design, small radius of the area planned for safety measures around the SNPP (up to 300 meters as a rule);
- A higher level of safety achieved through a smaller power density, natural circulation of coolant and extensive use of passive safety systems;
- Possibility for subsurface and underwater deployment, which provides better protection against natural disasters and offers a safer solution;
- Cheaper and easier decommissioning, including via the module removal from the site and its centralized disposal;
- Increased motivation for investors to fund the SNPP construction project due to a smaller cost of the module, shorter construction times, the resultant risk reduction, and a shorter payback period as compared with a large NPP;
- Substitution of the steam supply systems of nonnuclear (hydrocarbon) plants to give up combustion of fossil fuel;
- Nonelectric applications: desalination, district heating, hydrogen production, conversion of organic fuel, etc.;
- Longer fuel lifetimes (10 years or more without refueling);
- Reduction of licensing costs due to only the initial unit being comprehensively inspected by regulatory authority. In addition, the ‘learning curve’ starts to act thanks to which each further unit will be cheaper to build and operate than the previous one.
- Simplified systems and structures in the SPR allow accidents to be excluded with the coolant lost via major pipeline breaks due to the absence of large-diameter pipelines in the SPR primary circuit.

As of 2023, there are dozens of SNPP designs of different power in the world. The overwhelming majority of the designs are at different development and licensing stages (Zohuri and McDaniel 2019; IAEA ARIS 2022; Soloviev et al. 2022; WNA 2022; Citi GPS 2023; Snobeiti et al. 2023). At the same time, some SNPPs are under construction now or have already been commissioned.

Thus, for example, an SNPP is under construction in China with a 125 MW_{el} integral PWR reactor (ACP-100) expected to be commissioned in late 2026 (WNN, July 2023). Argentina is going on with the construction of an SNPP with a 30 MW_{el} integral reactor (CAREM-25), the first criticality for which is expected to be reached in 2026 (WNN, October 2023). This reactor is the prototype of the further reactor the power for which will be chosen in a range of 150 to 300 MW_{el}. In 2023, the US regulator licensed the design of a multimodule NPP with the NuScale energy modules of 77 MW_{el} each (WNN, January 2023). The first NPPs of this type are expected to be put into operation in Poland (2029) and the USA (2030).

Plans are being implemented in Russia to build a number of pilot NPPs based on different reactor technologies (Rosatom July 2023). Russia’s first ground SNPP will be built in Yakutia based on the RITM-200N reactor facility with a power of 55 MW_{el} (Rosatom, April 2023). In 2022, the design received go-ahead from the State Environmental Expert Review Committee, and the plant deployment was licensed in 2023. The plant commissioning is scheduled for 2028.

A 10 MW_{el} prototype SNPP based on the Shelf-M reactor facility will be built in the framework of the federal project “New Nuclear Power Including Small Reactors for Remote Areas”, as part of the integrated program “Evolution of Machinery, Technology and Research in the Field of Using Atomic Energy in the Russian Federation” (Rosatom, July 2023). The SNPP is expected to be put into commercial operation in 2030.

Along with the SNPPs under construction, there are already examples of SNPPs in operation. In May 2019, Akademik Lomonosov, the world’s first FPU of the total electric power 70 MW_{el} with two water-cooled KLT-40S reactors, was connected to the grid. A Russian project with 4 floating power units is at the implementation stage for powering the Baimskoye gold and copper deposit on the Chukotka Peninsula (Росатом 2021). In December 2021, China's first SNPP with two HTR-PM high-temperature gas-cooled reactors of the total power 210 MW_{el} was connected to the grid (WNN 2022).

Conclusion

The increase in the average temperature of the lower atmosphere observed in recent decades is explained by some scientists as being the result of the greenhouse effect they believe to be caused by industrial CO_2 emissions and to threaten the existence of humankind. Nearly 200 states have voluntarily chosen to achieve by 2050 net zero carbon or CO_2 emissions into the atmosphere. The major sources for industrial release CO_2 emissions are thermal power plants and transportation (ground-, sea- and air-based).

Renewable Energy Sources (RES), the focus of attention for accelerated development in most of the countries worldwide, are viewed by the climate advocates as the substitution for Thermal Power Plants (ThPP). As estimated by the IEA (International Energy Agency), net zero CO_2 emissions are expected to be reached by 2050 provided 88% of electricity will be RES-generated, and the rest 12% will be generated largely by Nuclear Power (NP).

The most radical advocates of 'green' power insist that NP needs to be abandoned in a phased manner because of the potential short supply of ^{235}U, the experience of the nuclear accidents that have taken place, and the SNF (Spent Nuclear Fuel) and RAW (RadioActive Waste) handling and NM (Nuclear Material) nonproliferation issues. They ignore the fact that an exclusively RES-based energy system will require to be multiply redundant in terms of installed capacity. Even with this requirement met, a question remains unanswered as to if the energy security is ensured in the event of the RES common-cause failure, say, in the event of a hypothetical global volcanic eruption. Apart from RES, a sustainable energy system needs to include another electricity source to be not dependent on the event that has caused the mass RES failure.

Out of the number of the currently deployed sources of electricity, it is only NP that may claim this role provided the requirement of net zero carbon emissions is met. Therefore, there is somewhat of a 'window of opportunities' still existing for NP, and a question remains for the time being unanswered as to if the 12% of the electricity generated by NPPs, as shown in the IEA report, will be enough for ensuring the energy security. At the same time, many aspects of the unbiased criticism against NP need to be acknowledged and done away with for NP to become acceptable to the public.

It is exactly the elimination of the actual NP drawbacks that the efforts to develop an energy technology with FNRs (fast neutron reactors) in a closed NFC (Nuclear Fuel Cycle) focus on. The activities in this field have already been under way in Russia, China, the USA and the European Union. The greatest progress has been achieved in Russia where the construction of a Pilot and Demonstration Energy Complex (PDEC) has been started at the Siberian Chemical Combine's site as part of the *Proryv* project. The BREST-OD-300 nuclear unit is expected to be started up in 2026–2027, and the technology is expected to begin to be duplicated as soon as in the 2030s.

Another promising area for the NP evolution is intensive development of Small Nuclear Power Plant (SNPP) designs currently under way in Russia, China, the USA, Argentina, the Republic of Korea and some other countries. The greatest advances have been achieved in Russia and China where these countries' first SNPPs have been built and further SNPP deployment plans are being implemented. In Russia, for example, a project is under way for building 4 FPUs (Floating Power Units) to power the Baimskoye gold and copper deposit on the Chukotka Peninsula, the first ground SNPP based on the RITM-200N reactor facilities of 55 MW_{el} each has been scheduled for commissioning in 2028, and an SNPP based on the 10 MW_{el} Shelf-M reactor facility will be put into operation by 2030.

Against the background of the pessimistic forecasts from the NP opponents about new nuclear energy technologies to be 'late' for the coveted 2050, it is very important to note that nearly all of the most important advanced designs have already passed successfully the point of no return and are expected to be practically implemented in the foreseeable future. Naturally, the political will of the governments in leading countries and the investor support can be also vital.

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