sustainability

Article

Paving the Way to Green Status for Nuclear Power

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Abstract: The paper considers a way to bring nuclear power into the category of "green" energy technologies; thus advertising its critical role in achieving the sustainable development goals adopted by the UN in 2015, and presents an option of nuclear power development based on a new technological platform (NTP) with two pillars: closed nuclear fuel cycle (CNFC), and fast reactors (FR). Provisions are formulated to break through the skepticism of nuclear power opponents. The "PRORYV" (the Russian equivalent for "break-through") project is focused on proving the industrial feasibility of the closed fuel cycle on-site of the NPP with fast reactor, thus giving the technological opportunity to establish nuclear energy systems environmentally friendly and free from the risk of proliferation of nuclear weapons. Such a nuclear energy system could contribute significantly in combating both looming energy crises and climate change.

Keywords: fast reactors; closed nuclear fuel cycle; inherent safety; non-proliferation; new technological platform; the PRORYV ("break-through") project

Citation: Pershukov, V.; Artisyuk, V.; Kashirsky, A. Paving the Way to Green Status for Nuclear Power. *Sustainability* **2022**, *14*, 9339. https://doi.org/10.3390/su14159339

Academic Editors: Michael I. Ojovan and Alexander V. Bychkov

Received: 6 July 2022
Accepted: 25 July 2022
Published: 29 July 2022

1. Introduction

Currently, there are at least three main factors that underlie global power development:

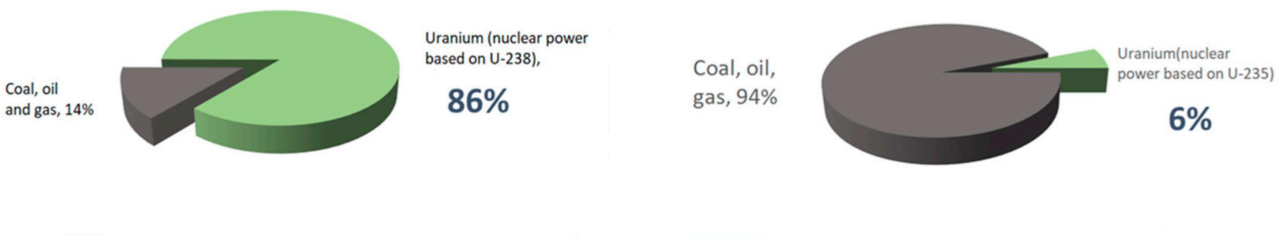
- the adoption by the UN of 17 Sustainable Development Goals (SDGs) for the period after 2015, among which are designated SDG 7 "Affordable and clean energy" and SDG 13 "Climate action" [1];
- the signing of the Paris agreements on climate, requiring as soon as possible to reach the peak of greenhouse gas emissions and begin to reduce it in an absolute global scale in order to bring net emissions to zero in the second half of the 21st century, i.e., to achieve a balance between anthropogenic greenhouse gas emissions and their absorption from the atmosphere [2];
- the retreat from globalization triggered by the coronavirus pandemic emphasized the need for robust national energy security system for individual states capable of providing uninterrupted power supply unchallenged by intermittency [3].

As a result of the adoption of climate agreements, most countries launched an active work on the formation of a list of technologies and technical solutions to comply with the green energy policy, contributing to a sharp reduction in the carbon impact on the environment. A typical example is the Taxonomy currently being developed by the European Commission, which defines a unified framework for assessing economic activity, encouraging investors and industry to develop technologies that contribute to the implementation of the Paris Agreements [4]. A similar document has been formed in the Russian Federation [5].

Three types of energy generation—solar, wind and hydropower—all related to renewable energy sources (RES) unambiguously can be included in the list of technologies that are worthy of subsidization. Fossil based power generation is also not excluded from the list if carbon capture and storage-CCS technologies are introduced, and convert green house gases into useful products for industry [6]. The nuclear case appears to be more complicated. In 2019 a group of experts confirmed the low carbon parameters of nuclear power, but did not recommend including it in the taxonomy at this stage [4]. The reason that was pointed out referred to the difficulty in assessing that nuclear power meets the broader criterion of no significant environmental impact ("do no significant harm"), which implies a minimum impact on water resources, conservation of biological diversity, and reliability of waste management (primarily nuclear), including the possibility of implementing the so-called "Circular economy", which is based on the principle of renewal of resources [6]. However, this notion was revised in a draft copy of the Complementary Delegated Act (CDA) that considered including nuclear power in the EU Taxonomy [7]. One of the most important messages contained in the CDA is recommendations to lay dawn screening criteria for new reactor technology and closed fuel cycles "in view of their potential contribution to the objective of decarbonisation and minimization of radioactive wastes". A closed nuclear fuel cycle regenerates the fuel after it is initially irradiated in the reactor by means of spent nuclear fuel reprocessing. In an open fuel cycle, spent fuel is not reprocessed and is constantly accumulated as the reactor continues operation, which is undesirable from political, environmental and social points of view. The recent additions in the CDA provide a meaningful illustration that closing the nuclear cycle to breed fuel and minimize the radiowaste accumulation is considered as a beacon for future power development. The subsequent chapters give the motivation and status of closing the nuclear fuel cycle in Russia.

2. Nuclear Power as a "Circular" Industry

The main attractive feature of RES is that their operation is relatively independent of fuels such as gas and coal. Electricity production today is extremely sensitive to the volatility of fossil fuel market prices. At the same time, the UN SDG 13 focuses on low-cost energy, which should minimize consumer dependence on fossil fuel prices and the availability of associated resources and thus reducing the speculative component in providing the market for electricity consumers. The existing nuclear power industry, based on an open fuel cycle and thermal reactors, uses mainly uranium-235 (whose share in natural uranium is 0.72%). Thus, the fuel base energy equivalent for such power based on uranium-235 is only 6% of the planet's total energy resources (Figure 1).



(a) (b)

Figure 1. Resource base for nuclear power in open and closed fuel cycles. (**a**) Open NFC is limited by the resource base of natural uranium. (**b**) Closed NFC based on fast reactors.

It is matter of fact that the cost of nuclear generation directly depends on the prices for uranium, which are formed on the commodity exchange. Uranium price over the past 20 years is presented in Figure 2. Despite the low component in the structure of the cost of raw materials, strong price fluctuations have a significant impact on the cost of electricity, which in many countries is a backbone of their national economic system and is to be regulated by state. The level of regulated generation tariffs set by state regulators are unable to provide a quick response to changes in exchange prices, which leads to the financial instability of the companies supporting nuclear power plants.

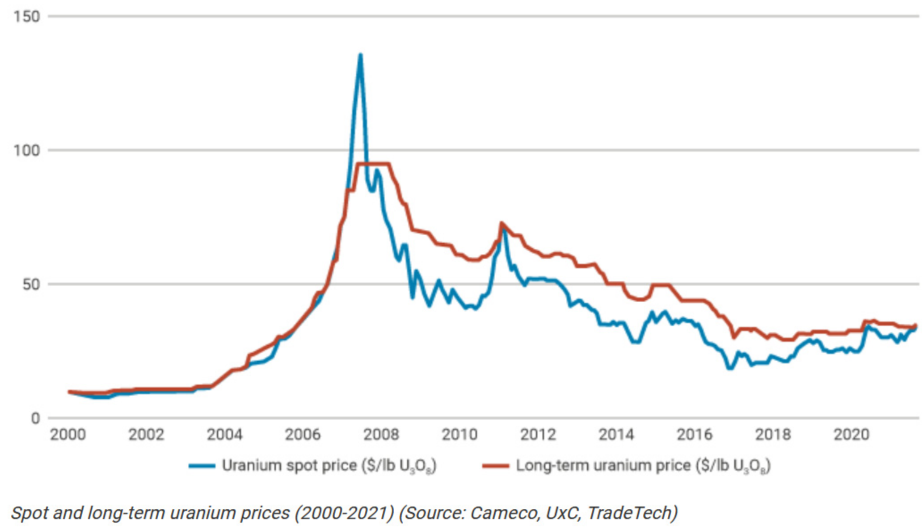


Figure 2. Dynamics of uranium prices (according to WNA data) [8].

Any power generation technology should ensure a minimum impact on the environment, including on the planet's atmosphere, which is possible only with a sharp decarbonization of electricity production. However, the consideration of RES through the prism of the broader criterion "do no significant harm" and the framework of the "circulation economy" raises a number of questions for their feasibility. Currently, publications have appeared that indicate significant problems during the decommissioning of expired RES, both in wind and solar energy [9–12]. When analyzing the occupied area during the construction of generation parks based on RES, a significant difference in the levels of alienated land also appears (Figure 3). Such a comparison favorably demonstrates the compactness of nuclear power facilities, which, of course, is due to the high concentration of natural energy. A similar conclusion can be drawn from the effect of natural climatic changes on the efficiency of generating plants. Only in 2020–2021 there was a significant number of unscheduled shutdowns of wind generators and solar panels when exposed to external weather conditions [13]. At the same time, the nuclear power plant (NPP) capacity factor practically does not depend on external conditions and is determined by the efficiency of the operators, the quality of the fuel and the design of the reactor core. With 393 GW of electricity installed (443 power units), the average capacity factor values for NPPs fluctuate in a range of 0.7–0.95, which is significantly higher than the typical values for RES [14].

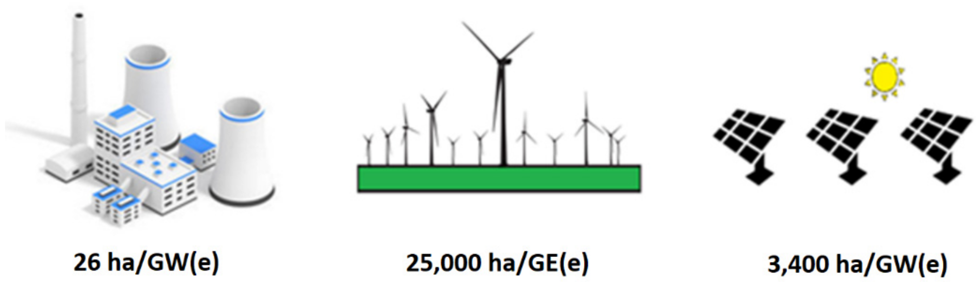


Figure 3. Comparison of occupied area for different energy generation parks.

An informative picture is obtained by comparing the dependence of various types of power generation of the main structural materials consumed, which affect the overall "green" component of the cost of electricity produced. As follows from Figure 4, the specific need for the main energy-intensive materials (metal, concrete, glass) is the lowest for NPP, which is undoubtedly due to the high concentration of initial energy in nuclear fuel.

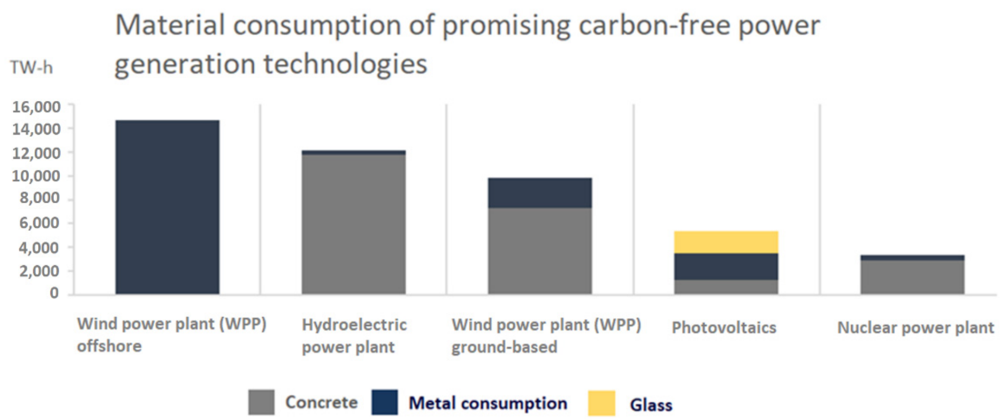


Figure 4. Specific material consumption for various power generating technologies.

Safety is a cornerstone of nuclear power development. It is one of the most sensitive issues in NPP operation that very much affects public perception of nuclear power. The past decades have characterized nuclear energy for many segments of the population as dangerous and leading to catastrophic consequences on human life and environment, which is associated with the initial military goals of using nuclear weapons as the most destructive weapon in the history of the mankind. Peaceful use of nuclear energy also reveals the chance for uncontrollable processes (Three Mile, Chernobyl, Fukushima), leading to accidents, associated with core damage probability at the level of 10^{-6} per reactor-year [15]. Of course, the degree of the impact of accidents at NPP is much less, compared to ordinary man-made accidents at coal, gas and hydro power plants, or the annual damage to health from coal thermal power plants, but the radiophobia developed in society multiplies the risks of using nuclear energy in public opinion.

As it was stressed above, the management of radiowastes from spent nuclear fuel (SNF) remains to be a bottleneck in expanding nuclear power globally. It is for lack of the long-term experience with the radiowaste disposal that made experts to suspend recommendation of including nuclear power in the EU Taxonomy despite the fact that CO_2 emissions during operation are practically zero. The effect of SNF accumulation illustrated in Figure 5 shows a twofold increase in amount in the next 20 years.

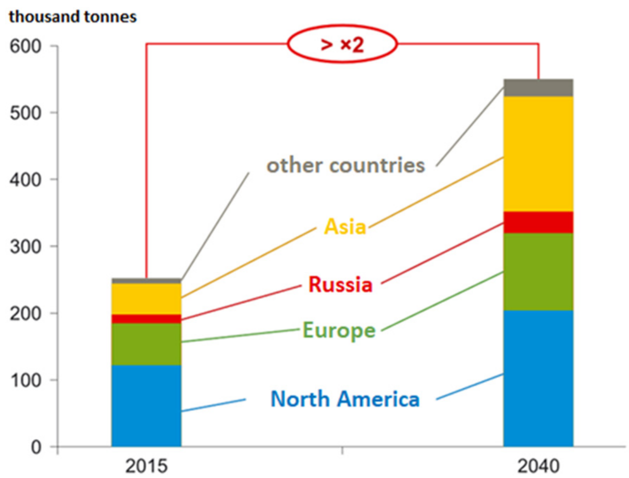


Figure 5. Forecast of SNF accumulation when using an open nuclear cycle [16].

The largest increase is expected in Asia where nuclear generation emerges at high rate (primarily in China). Many countries restrict development of SNF reprocessing in view of growing risk of proliferation of nuclear weapons mainly through the possibility to extract pure plutonium from SNF. It is for this reason that a number of countries (Germany, USA, etc.) are considering only deep geological storage as an option of SNF management. However, under the condition of primary processing, it is necessary to confirm the insulating characteristics of the matrices for the retention of radioactive isotopes (primarily minor actinides) for a period of up to several hundred thousand years. Humanity has no such experience, and that is why the discussions drag on for decades, leaving the issue unresolved [17–20].

At present, the bulk of nuclear electricity is generated by water cooled reactors operating in an open nuclear fuel cycle. Comparative analysis shows that nuclear power technologies look very economically attractive. Figure 6 gives this comparison in terms of LCOE calculated on the condition of a 5% discount rate, and generation life cycle of 60 years.

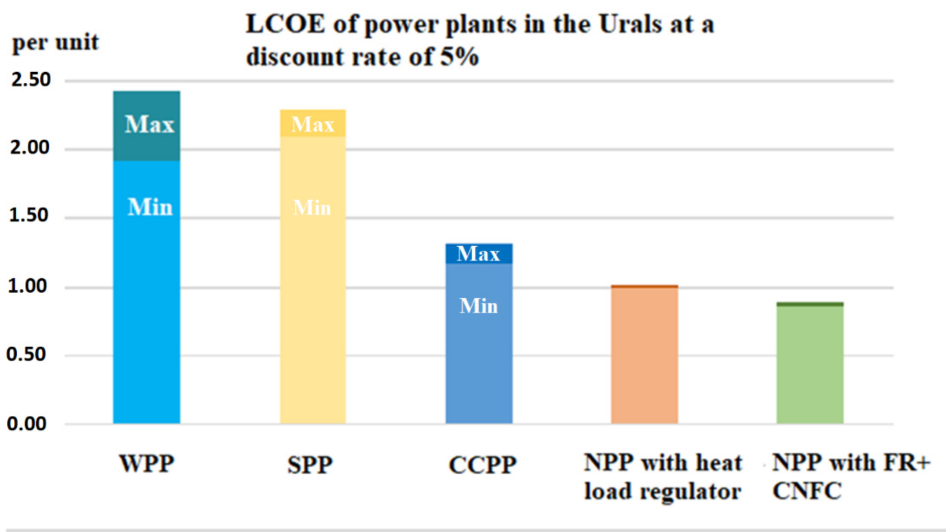


Figure 6. Levelized cost of electricity (LCOE) of power plants in the Ural Region of Russian Federation at a discount rate of 5% for techno-economic efficiency of 2035, in rel. units (the LCOE value of NPP with thermal reactor (TR) is taken as a unit, WPP—Wind Power Plant, SPP—Solar Power Plant, CCPP—Combine Cycle Power Plant, FR—Fast Reactor) [15].

RES is challenged by intermittency and is often considered as backed up by gas turbine installations. Such a power reservation will lead to an increase in LCOE and, accordingly, to a deterioration in the competitiveness. Nevertheless, many experts note that a further reduction in the capital costs of solar and wind power can be achieved by increasing the installed capacity as happened in India and China.

Obviously, nuclear power in the 21st century should be competitive when compared with any alternative generation technology. If it cannot prove the competitiveness at the current level of its development, nuclear power needs a new market product with higher requirements for economic efficiency thus restoring the competitive advantage. Such a product can be circular power producing economy that is generally referred to as Closed Nuclear Fuel Cycle (CNFC), which is constantly evolving with the accumulation of positive experience in the design, construction and operation of nuclear reactors and closed nuclear fuel cycle facilities. Calculations show that the level of capital expenditures of promising new generations of nuclear power plants in Russia will be 20% lower than the indicators achieved by the current generation of VVER reactors [16]. At the same time, the fuel component in the cost of electricity for a nuclear reactor with CNFC should not exceed the same parameter for a VVER operating in an open fuel cycle.

As it was mentioned above, nuclear power with traditional thermal reactors meets the situation of limited resources and is challenged by low public perception due to radiowaste accumulation. That continues to be true despite the low carbon footprint. So, the "green" color of nuclear power is an issue of contention. The R&D endeavors performed in Russian Federation within 2000–2020 by the institutes of State Atomic Energy Corporation "Rosatom", National Research Centre "Kurchatov Institute" and the Russian Academy of Sciences made it possible to form a new technological platform for nuclear power development, eliminating the problems above and confirming a number of technical solutions for building "green" nuclear power through closing the nuclear fuel cycle.

At the very dawn of the nuclear era, scientists were focusing on producing artificial fissile isotope Pu-239 from U-238 irradiated by neutrons. E. Fermi (in the USA) and A. I. Leipunsky (in the USSR) proved that a self-sustaining fission chain reaction initiated by high energy (fast) neutrons leads to a significant neutron excess generation, compared to one initiated by thermal neutrons. This neutron excess can be used to produce plutonium-239 (fuel breeding) or for transmutation of long-lived radioactive nuclei from spent nuclear fuel into short-lived or benign nuclei. It is this natural phenomenon that was laid down in the requirements for the design of fast reactors that make it possible to close the nuclear fuel cycle and drastically increase fuel resources for nuclear power (Figure 1). The involvement of plutonium from SNF of thermal neutron reactors in CNFC with fast neutron reactors makes it possible to completely remove resource limitations for centuries to come. In Russia the strategical transformation of nuclear power to a totally FR-based one will cost the integral consumption of uranium within 230 thousand tons. Recycling of plutonium, uranium and minor actinides drastically reduces the amount of radioactivity sent to deep geological storage. As a result, this will reduce the potential biohazard and lifetime radiation-related risk (LAR) of the possible induction of cancer from nuclear waste disposed to the level acceptable by safety standards and within acceptable time intervals [21].

In an open cycle, SNF is sent to intermediate storage with subsequent either final disposal as waste, or the separation of high-level nuclear waste from it, containing minor actinides with or without plutonium for final disposal in deep geological storage. For many countries, these options are unacceptable for political, environmental and other reasons. The radiotoxicity of spent nuclear fuel decreases over time, but it will take hundreds of thousands of years before its level drops to that of natural uranium needed for fabrication of fuel consumed for power generation. The purpose of the FR in this respect is to use U, Pu and MA from the spent nuclear fuel of thermal neutron reactors in such a way that only fission products would be disposed of. The radiotoxicity of this waste will also eventually reach the level of natural uranium, but this will only take a few hundred years, which is ultimately a much more manageable period than in open cycle option. This approach makes it possible to practically reduce the negative impact of spent nuclear fuel on the environment to zero, meeting one of the main requirements in terms of clean "green" energy.

3. Fast Reactors as a Heart of New Nuclear Technology Platform

One of the key advantages of FR is the possibility of applying fundamentally new approaches to ensuring safety. Fast reactors could obey the principles of inherent safety [22–24] being designed so as to eliminate accidents at NPPs requiring evacuation of population. That means exclusion of

- reactivity accidents;
- accidents with loss of heat sink;
- fires and explosions which may lead to the need to evacuate populations.

Inherent safety also makes it possible to reduce the number of various required engineering measures and safety systems at NPP that has a positive effect on the assessment of the economic competitiveness.

Summing up (Figure 7), it can be stated that innovative FR and closed nuclear fuel cycle will allow for the solving of the key systemic problems of existing nuclear power:

- technical safety of nuclear power: elimination of accidents requiring evacuation of the population;

- environmental safety of nuclear fuel cycle: solving the problems of handling long-lived highly radioactive waste and SNF accumulation;
- political neutrality of the nuclear fuel cycle: technological support for the nonproliferation regime;
- competitiveness of nuclear power;
- sustainable supply of raw materials (thousands of years) with the elimination of the need for uranium mining for the needs for generation of nuclear electricity.

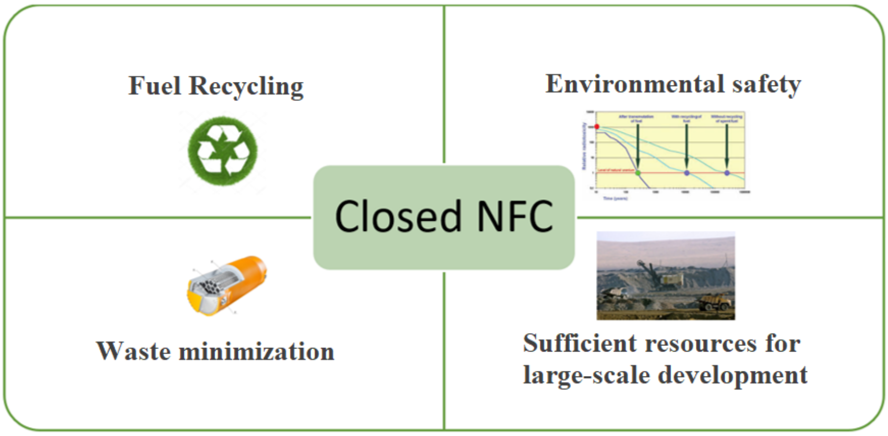


Figure 7. New technological platform—the path of nuclear power to the "green" economy.

In Russia within the framework of the ongoing Break-Through Project (PRORYV project—in Russian), a new technological platform for nuclear power is coming to reality with the construction of innovative fast reactors with a closed nuclear fuel cycle. In June 2021 the first concrete was poured into foundation of the building for the lead-cooled fast reactor BREST-OD-300 (electrical capacity of 300 MW € with a planned commissioning date in 2026 (Figure 8). The NPP will be a part of the pilot demonstration energy complex (ODEK) to be built in the city of Seversk, Tomsk region, Siberia (Figure 9). In addition to the reactor facility, ODEK will also have facilities for the on-site nuclear fuel cycle for fabricating and reprocessing of nuclear fuel, which ultimately should demonstrate the successful implementation of a closed nuclear fuel cycle within a single site. The construction of the facility for fabricating new uranium-plutonium nitride fuel has already been completed and the process of commissioning is going on (Figure 10). It starts in 2024 to manufacture on-site the first fuel assemblies for BREST-OD-300 reactor. Nitride fuel has a better thermal conductivity than the oxide fuel, but a similar melting point, and thus a larger safety margin to melting during operation. In addition, nitride fuels are denser with respect to fissile material, which gives a slight advantage in regards to Pu consumption for start-up.

Figure 8. First Concrete ceremony in construction of the NPP with lead reactor BREST-OD-300. 8 June 2021, Seversk, Tomsk Region, Siberia.

Figure 9. Lay-out of the experimental demonstration complex in Seversk to prove the feasibility of on-site closed fuel cycle.

Figure 10. Commissioning of uranium-plutonium nitride fuel fabrication facility.

The ODEK will be followed by industrial energy complexes (IEC), where within the same site there will be already commercial high-capacity power units linked to facilities for fabricating and reprocessing spent fuel, meeting international criteria for sustainable development and circular economy at a high level. The creation of such complexes will make it possible to minimize transport flows of potentially hazardous nuclear materials and implement a "short" external fuel cycle of fast reactors, which is effective from the point of view of optimizing Pu balances for the development of large-scale nuclear power. The industrial development of these technologies and their replication in Russia and the world will ensure an uncompromising transition of nuclear power to the category of green and renewable technologies already in the first half of the 21st century [25].

4. Conclusions

A closed nuclear fuel cycle with fast reactors has long been considered as a vital option towards the unlimited fuel resources for nuclear power deployment on a global scale. The transition to a "green" economy puts in focus nuclear radiowaste as an impediment to include nuclear in the list of sustainable energy sources. However, neutron excess available in fast reactors could be used for the transmutation of long-lived radiowastes as well. The present paper gives an overview of the advantages of closing the nuclear fuel cycle with an example of a new technology platform that is a basis for strategic nuclear power development in Russia. It is exemplified by the lead cooled FR technology with a closed fuel cycle within the perimeter of a single NPP that is coming now at the stage of construction and commissioning in Russia. The latest IAEA Conference on Fast Reactors and Related

Fuel Cycles: Sustainable Clean Energy for Future (FR22. 19–22 April 2022) [26] showed that similar approach is being implemented in China and India at the high level of transition to industrialization. It is worthwhile to mention that delegates and participants of the conference recommended to establish an Agency wide platform to promote the efforts on closing nuclear fuel cycle with fast reactors in the IAEA, thus giving the opportunity for a number of countries to consider advanced wasteless nuclear energy systems as a way to their transition to a "green" economy.

Author Contributions: Conceptualization, V.P.; resources, A.K. and V.A.; writing—A.K., V.A. and V.P., original draft preparation, V.A. and V.P.; writing—review and editing V.P., V.A. and A.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors acknowledge the critical comments by anonymous reviewers, which helped to improve the review.

Conflicts of Interest: The authors declare no conflict of interest.

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