# EFFICIENCY ASSESSMENT OF SMR DEVELOPMENT AS A NON-CARBON ENERGY SOURCE IN THE RUSSIAN ELECTRICITY AND DISTRICT HEAT SUPPLY SYSTEMS

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**Abstract**

The paper discusses the economic and technical possibilities and limitations of SMR development in the Russian energy system. The results of an economic comparison of nuclear plants with SMR units and large reactors (LR), low-carbon thermal power plants (CCS) and renewable energy sources are presented. The assessment of SMR capital costs (based on LR cost) takes into account various factors of their reduction, including the technological learning, multiunit effect, the grid connection cost. The SMR competitiveness analysis has been extended to district heating systems. Coal and gas cogeneration plants (CHP), as well as a carbon-free “joint scheme” of energy supply using a combination of electric boilers and LR nuclear power plants or hydroelectric power plants as sources of electricity, are considered as competitors of nuclear CHP with SMR. An analysis of "switching to nuclear" condition has been performed to assess the scale of support measures (for example, carbon payments) that are necessary for the mass implementation of SMR as an option for district heating. Optimization of the low-carbon transformation of Russian electricity and district heating supply systems has made it possible to study the effective scale of SMR development for the period up to 2050. The optimization took into account different levels of carbon emissions quotas. The impact of carbon payments on “switching to nuclesr” decisions and the development of nuclear energy sources, including SMR, was also studied.

## INTRODUCTION

Russia is one of the most significant emitters of greenhouse gases (GHGs) in the world and an important participant in the Paris Agreement. The Climate Doctrine, adopted in 2022, provides for achieving carbon neutrality of the national economy by 2060. The Strategy for the Development of Russia with Low GHG Emissions (SNUR), adopted in 2021, provides that by 2050 net emissions should decrease by 2.5 times compared to the level of 2019 (1.58 billion tons of CO2-eq), to 0.63 billion tons of CO2-eq [1]. At the same time, by 2050, the absorptive capacity of ecosystems is expected to increase by more than 2 times – up to 1.2 billion tons of CO2-eq. In this case, the physical annual GHG emissions over 30 years (from 2019 to 2050) should decrease by 0.29 billion tons of CO2-eq. This is less than 14% of the level in 2019. However, if GHG absorption volumes remain constant, physical emissions will have to be reduced by three times more by 2050 - by 0.95 billion tons of CO2-eq [2].

The electric power industry is the largest GHG emitter in the country and the sector where decarbonization can be most active. In 2021, 1,159 TWh of electricity (or 4.17 EJ) was produced in Russia, of which almost half (49%) was provided by gas-fired thermal power plants (TPPs) and about 13% by coal-fired ones. The share of nuclear power plants (NPP) is estimated at 19%, which is comparable to the contribution of hydroelectric power plants. The share of other renewable sources (RES) is still less than 1%. Due to geographical factors, the Russian economy and population consume a large amount of district heat, mainly for space heating. In 2021, its production volume amounted to 5.62 EJ, while 45% was produced at combined cycle power plants (CHP) using gas or coal. About 48% of the district heat was produced in gas or coal-fired boilers. The remaining 7% was provided by secondary heat recovery resources and carbon-free sources. At the same time, about 16 PJ of heat is supplied to consumers from operating NPPs.

Currently, more than 60% of electricity and 92% of district heat is produced using fossil fuels, mainly natural gas, and the total GHG emissions associated with electricity and heat production amount to about 0.78 billion tons of CO2-eq. This amount is twice as much as the target reduction of GHG emissions in the country's economy as a whole by 2050 with an optimistic increase in the absorption volumes. Thus, the SNUR targets may be achieved through the active development of carbon-free sources of electricity (including NPP), as well as the replacement of fossil fuels in the production of district heat with nuclear energy (SMR CHP) or electricity also produced from carbon-free sources (including hydro or nuclear power plants).

## TECHNOLOGICAL PROFILE OF RUSSIAN NUCLEAR POWER PLANTS OF LARGE AND SMALL unit CAPACITY

The traditional priority for the development of NPPs in Russia is large reactor units (LR) with a capacity of up to 1000+ MW. The National Power System (the UPS of Russia) is one of the largest in the world (the total installed capacity is about 250 GW). The rapid development of LR NPP in this power system is possible taking into account the balance and system requirements (including available reserves and flexibility resources) and reasonable based on economic considerations. By 2045, the share of NPP in total electricity production should grow to 25% (in 2021, it was about 19%). The capacity of all NPPs will increase from 30 to 50+ GW. At the same time, projects with VVER-1200 units with an installed capacity of 1,250 MW will be actively developed. It is also planned to build 600 MW VVER units for a number of zones of the UPS with lower balance needs in baseload capacity. After 2035, it is planned to increase the share of fast reactors (also 1,250 MW units), which will allow in practice to begin the transition to a closed fuel cycle in nuclear energy [3,4].

In Russia, the areas of application of LR and SMR nuclear power plants are now geographically separated. The development of SMR nuclear power plants is strategically considered for areas in the north and east of the country, as well as in the Arctic zone, where the cost of energy supply is traditionally high due to fuel supply costs. Since 1974, the Bilibino nuclear power plant with 12MW EGP-6 reactors has been operating in the Arctic. In 2019, the Academic Lomonosov floating NPP with KLT-40S reactors was put into operation in the same area. Currently, the adapted icebreaker reactor RITM-200 is being considered as a base solution for SMR power plants. The construction of an onshore SMR NPP with a 55 MW unit based on the RITM-200N reactor has begun. A typical floating power module with two RITM-200S reactors with a capacity of 110 MW has also been designed. Two of four such power modules are under construction for new mineral mining projects in the Arctic zone. For the power supply of large industrial nodes remote from the national power grid, SMR NPP with 80 MW units based on RITM-400 reactors are being considered. The peculiarity of the energy supply of settlements in these territories is the distribution of electrical and thermal loads and their relatively small values. This narrows the scope of mass application of SMR plants with units of 50-100 MW, but makes it relevant to promote smaller units. Pilot projects with Shelf (10 MW) and Elena (200 kW) reactors have now been launched.

In Russian conditions, taking into account the full cycle of own production of equipment, design and construction of nuclear power plants, the specific capital cost of LR NPP units turns out to be about 1.5-2 times lower than the global average. The national market regulator estimated their specific capital cost (CAPEX) based on the cost of the first VVER-1200 units at 186 million rubles/MW or about $2,700/kW (in 2021 prices). Technological learning can reduce these costs by another 10-15% (moreover, based on the historical analysis of the implementation of NPP development programs [5-8], this assessment is not the most optimistic). When designing fast reactor units, the goal is to ensure that their CAPEX are comparable to VVER-1200 units. With such cost indicators, LR NPP turn out to be the cheapest carbon-free technology in comparison with new gas combined-cycle (CCGT) and even more so coal-fired units and a priority for solving the problem of decarbonization of electricity production (Fig. 1).

Due to the scale effect, SMR NPP will have noticeably higher CAPEX than LR NPP (when using the same type of technology, for example, PWR). If we apply the classical formula of a power-law increase in CAPEX as the unit capacity decreases [9], then for 100 MW units their level should be 3.5-5.5 times higher than that of the 1200 MW unit, and for 50 MW unit – 5-8 times. In recent years, the possibilities of mitigating this effect have been actively discussed and very broad estimates of the possible reduction in CAPEX for SMR due to the simultaneous action of several factors [6, 10-12], including modularity and high integrity of production, optimization and simplification of design, more intensive technological learning due to the mass serial production of equipment and in-line construction, optimization of regulatory procedures and requirements. The analysis showed that the cumulative effect of these factors can significantly reduce the capital cost gap between LR and SMR. But the CAPEX for 50 and 100 MW units will still remain 3.5 and 2.5 times higher than for 1200 MW units, respectively (for comparable conditions of a two-unit plant). An additional (up to 15-20%) reduction in CAPEX is achieved by placing a larger number of units (up to 8-12) on one site.

Such a solution makes it possible to create a plant with a capacity of 400-600 MW on the basis of RITM reactors. It is comparable to the capacity of VVER-600 units, which are planned to be built in the peripheral zones of the UPS of Russia. The uncertainty in the increase in the CAPEX of VVER units with a change in unit capacity from 1200 to 600 MW creates a potential opportunity to choose alternative solutions based on multi-unit SMR plant (Fig.2). Even if the capital costs in this case turn out to be higher, system effects can play an important role, including lower power reserve requirements, as well as easier adaptation of the power system and grid to a more uniform capacity increase, adapted to demand growth. However, the potential amount of such projects for multi-unit SMR NPP is quite limited.

*FIG. 1. Annual impact of low- and non-carbon technologies on reducing of СО2 emissions from thermal plants (a), per 1 GW and changes in LCOE from 2025 to 2040 due to technological factors and discount rate (b), USD 2023Y/MWh*

*FIG. 2. Difference in the CAPEX of LR NPP and SMR and an impact of multiunit effect, times to 1200 MW unit CAPEX*

Thus, in the UPS of Russia, SMR plants are generally economically inferior to LR NPPs (Fig.1). However, another major area of SMR application could be district heating, where, as noted above, fossil fuels dominate. The transition to a low-carbon economy will inevitably affect this sector as well. In the district heat supply, the technological possibilities of replacing fossil fuels with carbon-free sources are more limited than in the production of electricity. Electric boilers can replace gas and coal boilers. Combined power and heat generation at gas and coal-fired CHPs can be replaced by nuclear CHPs (NCHP) or a combination of an electric boiler and LR NPP. Thus, the area of competition between small and large nuclear reactors remains here, but the conditions of this competition are significantly different. Let's look at them in more detail.

## ECONOMIC COMPARISON OF SMR NPP TECHNOLOGIES AND ALTERNATIVE CARBON-FREE HEAT SUPPLY OPTIONS

For an economic comparison of various district heating technologies, the indicator of the levelized cost of heat – LCOH [13, 14] can be used. Its structure is similar to the LCOE indicator for power plants, but the denominator takes into account the heat output from the source, not electricity. A certain methodological difficulty is the comparison of CHP that simultaneously produce both electricity and heat. For these technologies, LCOQ indicator can be calculated, in which the formula of the levelized cost is modified so that the denominator takes into account the total useful energy output to consumers (both electricity and heat, expressed in Joules or MWh) [15]. An alternative to CHP is a “join scheme” of energy supply, which considers the supply of electricity from a single-product power plant (j) and supply of heat from a boiler house (k). In this case, a similar LCOQ indicator is determined. Total cost of energy supplied in the numerator is defined by the volumes of electricity and heat supplied, LCOEj of power plant and LCOHk of boiler house.

In this study, the analysis includes technologies of SMR NCHP with 50 MW units, comparable power units of gas CCGT CHP and coal-fired CHP. In addition, a “joint scheme” is also being considered, where the heat source is an electric boiler, and the source of electricity (including for an electric boiler) is a LR NPP or a hydroelectric power plant. The cost of electricity for an electric boiler is determined by the LCOE of the nuclear or hydro power plant feeding it. The calculated LCOQ for nuclear and conventional CHP and heat supply technologies are shown in Fig.3. Due to the page limitation the paper cannot provide a detailed description of the LCOQ formula and key input data. More information is available in [15] and [16].

*FIG. 3. Changes in LCOQ from 2025 to 2040 due to technological factors and discount rate (b), USD 2023Y/MJ*

By 2050, coal and gas-fired CHPs will be able to provide approximately twice the cost of electricity and heat supply than alternatives using nuclear energy. Reducing the discount rate will improve the situation to a certain extent, especially for a combination of electric boiler and LR NPP. The LCOQ of SMR NCHP will be 10-15% higher than from a combination of electric boiler and LR NPP. Thus, NCHP with 50 MW SMR can also lose out in the competition with large nuclear power plants in the heat supply. The transition to larger SMR units (with a capacity of 100 MW) aligns the competitive positions of NCHP and LR NPP with electric boilers in heat supply.

However, the results obtained do not mean that the SMR NCHP will not appear in the power system during intensive decarbonization in district heating. A strong limitation for the scale of LR NPP development in the power system is the limit of sites for the placement of such large facilities. In Russian conditions, the investigated potential sites allow the construction of about 100 GW of NPPs. As will be shown below, with strong carbon regulation, all these sites need to be fully utilized to produce carbon-free electricity. Under these conditions, NCHP will be able to additionally substitute of fossil fuels in the production of district heat (and, in part, electricity). The economic parameters of such a "switch" to nuclear sources can be estimated by calculating the carbon avoided cost level and thereby determining the CO2 price level at which the LCOQ of a conventional CHP plant will be equal to the LCOQ of an NCHP or a “joint scheme” with an electric boiler and LR NPP. The cost of such a switch to nuclear technologies will be different for gas and coal-fired thermal power plants due to their levelized costs, as well as specific CO2 emissions [16].

Table 1 shows the CO2 price levels at which switching from gas and coal to nuclear technologies in heat supply becomes economically efficient. These values are quite high, especially for 2030. At the same time, the price of switching from gas is about twice as high as from coal. This is primarily due to the higher specific CO2 emissions from coal-fired CHP, as well as the difference in LCOQ with coal and gas power plants. A lower discount rate (and a concomitant decrease in LCOQ) makes it possible to significantly reduce the price of CO2 for switching, especially from coal-fired CHPs. In general, the transition to carbon-free technologies in the production of district heat will require fairly strict carbon regulation, unlike switching to nuclear power in the electricity generation sector (Table 1). Even in 2030, the LCOE of a LR NPP is only 15% higher than that of a CCGT and lower than that of a coal-fired TPP. Therefore, the calculated values of carbon avoided cost show that the price of CO2 for switching from a CCGT to a LR NPP does not exceed $ 30/t CO2, and for switching from a coal-fired power plant it is even negative (because the LCOE of a nuclear power plant is lower than that of a coal-fired TPP and the economic choice in favor of an NPP does not require mandatory carbon regulation).

TABLE 1. CO2 PRICES (ESTIMATED AS CARBON AVOIDED COSTS) REQUIRED FOR SWITCHING TO THE NUCLEAR TECHNOLOGIES, INCL. CHP WITH SMR, $ 2023Y/T CO2

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Nuclear technology | Substituted conventional technology | Required CO2 price in 2030, 8% discount | Required CO2 price in 2050, 8% discount | Required CO2 price in 2050, 5% discount |
| Nuclear (SMR) CHP | Coal CHP | 132 | 103 | 67 |
| Nuclear (LR) + electric boiler | Coal CHP | 113 | 80 | 47 |
| Nuclear plant (LR) | Coal plant  | -9 | -19 | -21 |
| Nuclear (SMR) CHP  | CCGT-CHP | 253 | 232 | 145 |
| Nuclear (LR) + electric boiler | CCGT-CHP | 200 | 169 | 94 |
| Nuclear plant (LR) | CCGT | 20 | 27 | -2 |

## MODELING OF THE EFFECTIVE SCALE OF DEVELOPMENT OF NUCLEAR CHP WITH SMR IN THE RUSSIAN POWER SYSTeM IN SCENARIOS OF INTENSIVE DECARBONIZATION

Comparing of electricity and district heat production technologies (or co-generation power plants) in terms of the levelized cost of production is an important, but only the first step in energy planning. Such a comparison makes it possible to identify economically priority types of energy sources and assess cost gaps with alternative technologies. However, the scale and speed of the transformation of the technological structure in the electric power industry and heat supply depends on the dynamics of many factors. The most significant are: demand for electricity and district heat, fuel prices, decommissioning of existing capacities. The uneven change of these parameters (as well as capital costs) across UPS territorial zones (the European part, the Urals, Siberia, the Far East) also plays an important role. Carbon regulation mechanisms constitute a separate group of factors. Within the framework of the study, two of the most "strong" mechanisms are considered: direct emission quotas from power plants and boiler houses and payment for CO2 emissions.

Modeling of changes in the structure of electricity and district heat production until 2050 was performed using the EPOS long-term capacity planning model developed at the ERI RAS [17]. The EPOS model can take into account limits on CO2 emissions from power plants and boilers, or set targets for the carbon intensity of electricity and heat production [18]. The cost function of the model corresponds to the classical least-cost planning approach, and carbon payments are also included in the total discounted costs of energy supply. Table 2 presents the results of several scenarios of the electricity and heat production mix in the UPS of Russia with the introduction of carbon regulation, which allow us to assess, among other things, the effective scale of development of NCHP with SMRs.

The baseline scenario assumes that by 2050 CO2 emissions from power plants and boilers will be 13.4% lower than in 2019, in accordance with the SNUR target. In this scenario, only LR NPP capacity will increase to 60 GW, and their share in electricity production will increase to 30% by 2050. SMRs appear in the energy supply mix if CO2 emissions are reduced by more than 30% by 2050. Table 2 shows the simulation results for the 40% and 50% quotas. To implement these scenarios, LR NPP will increase to 100 GW by 2050 and 10-14 GW of the SMR NCHP will additionally need to be added. Totally, NPPs in these scenarios will produce more than 50% of electricity, and their share in the structure of district heat production will be 5-7%.

TABLE 2. CHANGES IN THE ELECTRICITY AND DISTRICT HEAT PRODUCTION STRUCTURE BY 2050 UNDER DIFFERENT SCENARIOS OF CO2 QUOTAS (% OF 2019 YEAR) AND CO2 PRICES

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | 2021 | 2050 CO2 limit at 84,6%  | 2050 CO2 limit at 60%  | 2050 CO2 limit at 50%  | 2050 CO2 price 100$/t CO2 | 2050 CO2 price 200$/t CO2 |
| Electricity production, TWh | 1159 | 1482 | 1610 | 1821 | 1532 | 1669 |
| the same, PJ | 4172 | 5335 | 5796 | 6556 | 5515 | 6008 |
| Electricity production structure, %, including | 100,0 | 100,0 | 100,0 | 100,0 | 100,0 | 100,0 |
| Hydro and RES | 19.5 | 19.7 | 21.5 | 29.4 | 21.2 | 25.4 |
| Nuclear | 19.2 | 21.8 | 55.0 | 50.4 | 55.0 | 55.1 |
| Thermal (gas and coal) | 61.4 | 58.5 | 23.5 | 20.3 | 23.6 | 19.4 |
| District heat production, PJ | 5623 | 4517 | 4517 | 4517 | 4517 | 4517 |
| District heat production structure, %, including | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| CHP | 51.1 | 65.9 | 42.9 | 37.9 | 43.6 | 36.7 |
| Boilers (gas or coal) | 48.2 | 33.0 | 43.6 | 32.0 | 49.4 | 37.8 |
| Electric boilers | 0.3 | 0.5 | 8.6 | 22.9 | 3.3 | 18.5 |
| Nuclear plants | 0.4 | 0.6 | 4.9 | 7.2 | 3.7 | 7.0 |

The introduction of carbon payments is an equally effective mechanism that changes inter-fuel competition and helps strengthen the position of NPPs, including those with SMR. At a price of $25-50/t CO2 LR NPP capacity increases to 70-90 GW, and emissions are reduced by 20-30%. At a price of $100/t CO2, the LR NPP capacity increases to 100 GW and, about 8 GW of NCHP with SMR will be introduced, which will provide about 4% of the total district heat production. If the carbon price is doubled (up to $ 200/t CO2), the volume of NCHP with SMR will increase to 15 GW, and their share in the structure of heat production will increase to 7%. If we assume that a NCHP will consist of 3-4 SMR units of 50 MW each, then this means commissioning 75-100 nuclear power plants to achieve an effective volume of 15 GW. Thus, SMR can really become a mass energy supply technology in the UPS of Russia.

## CONCLUSION

Nuclear power plants with large reactors occupy a significant share in the Russian electric power industry. Given the relatively low capital costs within the country, they are the strongest carbon-free competitor to conventional thermal power plants even in conditions of low fuel prices, and, depending on the intensity of carbon regulation, they can provide from 30 to 50% of the electricity produced in the country by 2050.

Nuclear power plants with SMR, even taking into account the reduction in cost due to optimization of design, modularity of production, and faster rates of technological learning with mass implementation, will not be able to overcome the "curse" of economies of scale. 50-100 MW SMR units will remain 3.5-2.5 times more expensive than 1200 MW LR units. This makes their direct competition in the production of electricity in the UPS of Russia unrealistic.

An important regional niche for the development of NPP with SMR are the areas in the north and east of the country, as well as in the Arctic zone, where the cost of energy supply is traditionally high due to transportation costs for fuel delivery. Within the borders of the UPS of Russia, the development of a NPP with SMR may be in demand in scenarios of deep decarbonization of district heat.

Together with electric boilers (powered by LR NPP or hydroelectric power plants), nuclear CHP with SMR are perhaps the key technologies for replacing fossil fuels in district heating. Such a switch will require the introduction of high carbon prices (more than $100/t CO2 to replace coal sources and more than $200/t CO2 to replace gas heat sources) or strict quotas for CO2 emissions (up to 40-50% of the 2019 level). Model calculations showed that under these conditions, the capacity of NCHP with SMR by 2050 can reach up to 15 GW.

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