Scales and Consequences of Deep Decarbonization of the Russian Electric Power Industry

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Abstract—The article considers possible scales of changes in Russia’s Unified Energy System (UES) generation capacity structure and the associated costs necessary for adapting the electric power industry to various, in terms of stringency, requirements for reducing carbon emissions and decreasing the electricity production carbon intensity in 2040–2050. To this end, production and economic indicators are predicted for the so-called “boundary” industry’s development scenarios, which differ essentially in the scales of such changes, and provide different contributions in decarbonization of the country’s economy. One of the scenarios was drawn up based on the assumption that the existing trends and rates of changes in the technological structure would remain the same, with which a stable level of electricity price and amount of СО2 emissions will be reached by 2050. The second scenario implies that a transition will be made after 2030 to more intensive changes due to increasing the number and capacity of carbon-free power plants, improving the energy efficiency of thermal power plants (TPPs), and substituting their use of coal. Taken in combination, these measures will make it possible to reduce the CO2 emissions from power plants by almost 40% by 2050. Two electric power industry development scenarios are compared with respect to the following indicators: installed capacity and electricity production, and their mix (share distribution) by power plant types, necessary amounts of commissioning the capacities of thermal and carbon-free power plants and the required capital investments, demand for fuel, financial requirements of the electric power industry, and electricity price variation dynamics. The capital intensity of reducing the СО2 emissions and electricity production carbon intensity is estimated, and the scales of unavoidable growth in the price of electricity for its consumers in Russia are shown.

Keywords: decarbonization, carbon emissions, carbon intensity, thermal power plants, carbon-free power plants

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Russia, which is among the parties to the Paris Agreement and one of the largest (after China, the United States, and the European Union) greenhouse gas (GHG) emitters, adopted an official strategy for decarbonizing its economy up to 2050 called the Low-Carbon Development Strategy to 2050 (LCDS-2050) only in the fall of 2021; According to it, the net carbon emissions are supposed to be reduced over 30 years by 60% (954 million t CO2 (equiv.)). Supposedly, this reduction will mainly be achieved owing to increasing, by several times, the absorption capacity of ecosystems, and the amount of GHG emission will be reduced for the period from 2019 to 2050 by 13.6%.

Although the economy’s decarbonization target indicators have been defined, the ways for achieving them and the contribution that the individual industries have to make in the reduction of GHG emissions still remain a subject of discussions [1–3] and need serious systematic, technological, and economic substantiation. The growing long-term influence of external geopolitical factors, which aggravate the financial and technological risks of adopted decisions, adds difficulty to the problem of efficiently decarbonizing the economy. Such a problem is also faced to a full extent by the electric power industry of Russia, the country’s largest consumer of fossil fuel, which accounts for approximately one quarter of the national annual amount of CO2 emissions.

An analysis of the International Energy Agency data has shown that, in the last two decades, the CO2 emissions produced by the electric power industry in the majority of developed countries that actively implement low-carbon strategies showed a noticeably faster reduction than the total CO2 emissions from fuel combustion in these countries (Table 1). At the same time, an opposite situation is observed in developing countries, including the largest economic states that are members of the BRICS group, in which the elec-
electric power industry’s main developing force is providing energy support to their stable economic growth owing to the use of all kinds of energy resources. As a result, the growth of CO₂ emissions in the electric power industries in the majority of these countries is noticeably faster than the growth of total CO₂ emissions from fuel combustion. Russia occupies an intermediate position in this regard: the total CO₂ emissions from fuel combustion in the country have been increased since 2000 by slightly more than 10%, whereas its emissions in the electric power industry have been decreased by 7%.

It should be noted that, as is shown in [5, 6], a fairly low carbon intensity level of electricity production has already been reached in Russia in comparison with similar indicators of other countries. In 2019, its value (depending on the numerical analysis procedure) was by 20—40% lower than the world’s average value but by 20—45% higher than the average European value. This is facilitated by a high (more than one-third) share of noncarbon resources in electricity production, domination of natural gas as the main fossil fuel for thermal power plants (TPP), and also a significant share of combined heat and power plants (CHPs) in the generating capacity mix.

Of course, all these factors create a significant potential for further reduction of CO₂ emissions in the electric power industry of Russia. There is a variety of preferred technologies used for decarbonizing the electricity production (see, for example, [7, 8]). However, the choice of technologies should, first, be based on assessments of economic feasibility of using them and, second, it should take into account the technological independence requirements, existing limitations, and timeframes within which the necessary domestically produced power, electrical, and other equipment can become available.

In this article, we took one more step in studying the limit scales of the technological low-carbon transformation of Russia’s electric power industry, the possibilities for intensively reducing the CO₂ emissions and the resulting economic consequences. To this end, we elaborated and compared—in terms of energy and economic characteristics for a time horizon of up

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**Table 1.** Changes of CO₂ emissions from fuel combustion in the economic and electric power industry of some countries around the world for the period 2000–2019 with respect to 2000 (according to the data of [4])

| Country               | Total CO₂ emissions, times with respect to 2000 | in electric power industry |
|-----------------------|-----------------------------------------------|---------------------------|
|                       | from fuel combustion 2000 2005 2010 2015 2019 | in electric power industry 2000 2005 2010 2015 2019 |
| World, total          | 1.00 1.17 1.32 1.39 1.45                     | 1.00 1.17 1.34 1.43 1.50 |
| Including: OECD Member countries*: | |
| United States         | 1.00 1.00 0.93 0.86 0.83                     | 1.00 0.99 0.92 0.78 0.67 |
| Canada                | 1.00 1.07 1.05 1.09 1.14                     | 1.00 0.93 0.82 0.73 0.63 |
| Australia             | 1.00 1.09 1.14 1.11 1.14                     | 1.00 1.13 1.18 1.06 1.01 |
| Japan                 | 1.00 1.03 0.99 1.01 0.92                     | 1.00 1.11 1.18 1.34 1.19 |
| United Kingdom        | 1.00 1.02 0.92 0.76 0.66                     | 1.00 1.08 0.94 0.65 0.38 |
| EU-27, total          | 1.00 1.04 0.95 0.85 0.79                     | 1.00 1.07 0.98 0.84 0.67 |
| Including:            | |
| France                | 1.00 1.02 0.93 0.83 0.81                     | 1.00 1.20 1.10 0.80 0.76 |
| Germany               | 1.00 0.97 0.93 0.90 0.79                     | 1.00 1.05 1.01 0.96 0.71 |
| Spain                 | 1.00 1.20 0.94 0.89 0.83                     | 1.00 1.20 0.74 0.84 0.56 |
| Italy                 | 1.00 1.09 0.93 0.79 0.74                     | 1.00 1.17 1.00 0.80 0.71 |
| Countries that are not OECD Members: | |
| Brazil                | 1.00 1.06 1.27 1.55 1.40                     | 1.00 1.10 1.45 2.97 2.10 |
| India                 | 1.00 1.21 1.77 2.29 2.60                     | 1.00 1.22 1.71 2.30 2.56 |
| China                 | 1.00 1.74 2.51 2.91 3.16                     | 1.00 1.66 2.42 2.95 3.63 |
| Indonesia             | 1.00 1.25 1.54 1.78 2.29                     | 1.00 1.50 1.94 2.76 3.63 |
| Russia                | 1.00 1.01 1.04 1.04 1.11                     | 1.00 1.01 1.02 0.93 0.93 |

* The Organization for Economic Cooperation and Development.
to 2050—two “boundary” electric power industry development scenarios, as a result of which the CO\textsubscript{2} emissions should become stabilized by 2050 at the reporting level (2019) (the base scenario) or essentially lower (the intensive scenario). In contrast to the majority of predictive assessments, the aim of this study is not to determine the range of most probable quantitative electric power industry development characteristics but to estimate the possibilities of and consequences from reaching the ambitious objectives of its low-carbon transformation.

### CARBON-FREE AND THERMAL POWER PLANTS’ DEVELOPMENT SCENARIOS UP TO 2050

Elaboration of the base and intensive power industry development scenarios was an integral part of the comprehensive study of ways and rates of low-carbon energy transition in Russia that was carried out at the Energy Research Institute of the Russian Academy of Sciences in 2021 [9]. In so doing, long-term trends in the changes of external conditions for the electric power industry (demand and fuel prices) were determined within the framework of interaction between the modules of the SCANER modeling and information system based on the country’s economic development forecasts. In turn, the main energy and cost characteristics of the electric power industry development scenarios made it possible to determine the long-term influence of the sector on the energy balance structure and economic development dynamics with taking into account the necessary capital investments and electricity prices. Such “feedback” (from the electric power industry to economy) was especially important in drawing up the intensive scenario, for which the economic and energy sectors’ development parameters had to be matched in the course of several model computation iterations [10].

The external conditions of the electric power industry’s development within the framework of the Unified Energy System of Russia for the two scenarios considered are briefly characterized in Table 2.

In the base scenario, the dynamics of the demand for electricity and centralized (district) heat supply from power plants is estimated proceeding from the trends of changes in the country’s economic energy and electricity intensities that have been formed for the last two decades. The scenario also took into account the influence of the corona virus pandemic-related crisis with subsequent recovery of the economy and stable growth of gross domestic product (GDP) at a level of 3\% per annum. Obviously, the growing pressure of sanctions will entail certain corrections of these indicators in the nearest 3–5 years, although an adaptive transformation of the country’s economy and also the principles and priorities of managing it, which will be revised in the future, may noticeably decrease the duration and scale of the new crisis and the economy’s restorative growth rates. It is also important that the demand for electricity in the crisis periods is essentially less volatile than the GDP dynamics. Thus, the data given in Table 2 can be regarded as the upper boundary of balance requirements for the electric power industry development in 2030 and beyond (up to 2050).

After 2030, in the transition to the intensive scenario involving active development of electrification technologies in various economic sectors, even with account for a more large-scale energy saving, the demand for electricity in the UES of Russia will grow more rapidly than it will be in the base scenario, and it will exceed the reporting level by 52\% (against its growth by 41\% in the base scenario) by 2050. Both scenarios assume a growth in the amounts of electricity export (up to 50 billion kW h in 2050) in the eastern direction to the countries of Asia and the Asian-Pacific region.

However, these two scenarios differ essentially in the dynamics of heat supply from power plants. In the...
base scenario, this indicator increases by 25% with decaying growth rates (with the corresponding growth of power plant share in the centralized heat production). In the intensive scenario, the heat supply from power plants grows only to 2035, after which it decreases by 2050 to almost the reporting level owing to intensive heat saving and energy substitution (including electric space heating).

Up to 2030, the changes in the generating capacity mix in both scenarios are determined by investment projects, which are implemented within the framework of existing investment supporting mechanisms\(^1\) and also by the commenced construction projects of hydroelectric and nuclear power plants (HPPs and NPPs).

After 2030, according to the base scenario, it is supposed to retain the existing price policy in the fuel market (primarily the growth of prices for gas within the inflation rate limits) and extend the validity terms of existing investment support mechanisms in the electric power industry. The influence of these factors will lead to moderate dynamics of introducing new technologies in updating thermal power plants and developing RES. As a result, in the prospect to 2040–2050, the changes in the mix of generating capacities will remain within the limits of existing trends.

In contrast to the base scenario, the intensive scenario after 2030 is implemented under the conditions of a faster growth of domestic prices for gas to reach their parity with the export prices. The new price policy in the fuel markets is supplemented by the economic carbon regulation measures: the introduction, after 2030, of carbon payments with increasing the payment rate to $95/t CO\(_2\) by 2050. Given a successful industrial policy on mastering and mass-scale production of modern types of equipment for TPPs, NPPs, and RES power plants and appropriate readjustment of investment mechanisms, all these measures will facilitate the following:

1. a growth of competitiveness of carbon-free power plants (HPPs, NPPs, and RES-based power plants) substituting thermal power plants (primarily coal-fired ones); and

2. improved energy efficiency of the gradually decreasing thermal power generation segment, in which incentives emerge for making a large-scale transition to combined (combined cycle and cogeneration) fuel utilization technologies and introduction of equipment with improved fuel efficiency indicators instead of repeatedly using previous technical solutions.

The list of main lines in the technological transformation of Russia’s electric power industry in the intensive scenario will include:

- 1. mass-scale replacement in 2035–2040 of the existing steam turbines at TPPs by modern equipment on the basis of gas turbines for various capacity of a single unit;
- 2. a growth of distributed cogeneration substituting boiler houses or large CHPs in regions with a low heat load on the basis of gas turbine and gas piston units firing natural gas and also those utilizing industrial, agricultural, and municipal waste, timber harvesting and processing biomass, and biogas obtained from agricultural waste;
- 3. transition to new-generation thermal and fast neutron NPP reactors with improved technical and economic characteristics;
- 4. active development of wind and solar power plants (WPP and SPP), including small- and micro-generation units, which, taken in combination with electric energy storages, will be able to change the technological pattern of individual regional power systems in the UES of Russia (primarily in the country’s southern and eastern regions);
- 5. development of new hydroelectric power plants in the country’s eastern part and small HPPs in its European part, and also a more extensive use of pumped storage plants (PSP) to meet the increasing demand for peaking and storage capacities in the rapid development of renewable energy.

The differences in the amounts and technological mix of generating capacities in the UES of Russia for its two development scenarios are given in Table 3.

A comparison between the base and intensive scenarios shows that there are essential differences in the installed capacities of power plants. In the base scenario, its amount will increase, with respect to 2019, by 9.7% by 2040 and by 23.9% by 2050, whereas it will increase in the intensive scenario by 19.5 and 57.6%, respectively (a faster growth). These differences are determined not as much by the electricity consumption amounts but to a larger extent by the dynamics of nonguaranteed power output of RES power plants and the need of additionally backing them up (especially in the intensive scenario) by highly maneuverable capacities of gas turbine units (GTU), gas piston units (GPU), and development of PSPs and other types of electric energy storages.

In both scenarios, the capacity of carbon-free types of power plants and electric energy storages will grow most intensely (by a factor of 1.81 in the base scenario and by a factor of 3.44 in the intensive scenario with respect to 2019). Their share in the generating capacity mix will increase from 33.2% in 2019 to 48.5 and 72.5% by 2050 in the base and intensive scenarios, respectively (with the share of RES-based power plants growing from 0.6% in 2019 to 9.9 and 28.5% by 2050).

Also, the role of thermal power plants will decrease in both scenarios: in the base scenario, the thermal power plants will still account for more than

\(^1\) Competitive bids of TPP modernization projects are carried out, including those involving innovative Russian gas turbines and also renewable energy development projects (based on RES) with a high degree of using domestically produced equipment.
a half of installed capacities in the UES of Russia by 2050, while their share will be less than 30% in the intensive scenario by 2050. However, thermal power plants will, as previously, play an important role in providing reliable energy supply to consumers. This relates both to the use of CHPs for combined supply of electricity and heat and backing up the nonguaranteed power output of RES-based power plants (at least for the nearest 15–20 years up to commencement of commercial-scale production of large-capacity energy storages).

The changes in the technological structure of TPPs (especially in the intensive scenario) stem from the need of actively reducing the amount of CO2 emissions with achieving more efficient use of fossil fuel and decreasing the consumption of coal, which is characterized by the highest carbon content indicators. To achieve these goals, it will be necessary to give priority to the development of CHPs and increase the share of gas-fired power plants on the basis of combined cycle and gas turbine technologies (their share will increase from 21.7% in 2019 to 89.3% by 2050). The required amounts of commissioned generating capacities in the thermal power sector will be determined by the timeframes of reaching the limit service life of the equipment of existing TPPs and also by the launched programs on its modernization with extending the service life by another 15 years. In the base scenario, the capacity of existing TPPs (with taking into account their modernization projects) will decrease by 42% by 2040, and 22% of TPP capacities operated in 2019 will remain in operation by 2050 (Table 4). In the

### Table 3. Dynamics of change in the installed capacity of power plants in the UES of Russia (reporting data are from the Rosstat RF and UES SO and predicted data are ERI RAS assessments)

| Power plants                           | Installed capacity, million kW |
|----------------------------------------|--------------------------------|
|                                        | reporting data | predicted data            |
|                                        | 2000  2010  2019  2020  2030  2040  2050  2040  2050 | base scenario | intensive scenario |
| Total                                  | 200.1 214.7 246.3 245.3 244.1 270.0 305.2 294.4 388.3 |
| Including:                             |                  |
| carbon-free power plants, total        | 63.7 68.8 81.7 82.0 86.9 112.7 148.0 145.7 281.5 |
| Including:                             |                  |
| HPPs (including PSPs)                  | 42.0 44.5 49.9 49.9 51.9 55.4 59.1 58.4 69.0 |
| NPPs                                   | 21.7 24.3 30.3 29.4 26.1 37.7 58.7 41.8 83.9 |
| RES                                    | – 0.0 1.5 2.7 8.9 19.6 30.2 40.5 110.6 |
| storages                               | – – – – – – – 5.0 18.0 |
| thermal power plants, total            | 136.4 145.9 164.6 163.3 157.2 157.3 157.2 148.7 106.8 |
| Including:                             |                  |
| CHPs, total                            | 73.2 80.9 89.6 89.6 90.6 93.2 95.9 85.3 78.5 |
| Including:                             |                  |
| Gas-and-oil fired ones, total          | 41.5 48.0 59.1 59.1 62.4 68.1 72.0 66.1 73.6 |
| Including:                             |                  |
| Steam turbine ones                     | 41.5 42.6 38.9 38.6 38.3 17.5 6.4 17.5 6.4 |
| CCGT and GTUs                          | – 5.4 20.2 20.5 24.1 50.6 65.6 48.6 67.2 |
| solid fuel fired ones                  | 31.7 32.9 30.5 30.5 28.2 25.1 23.9 19.4 4.9 |
| CPPs, total                            | 63.2 65.0 75.0 73.7 66.6 64.1 61.3 63.4 28.3 |
| Including:                             |                  |
| gas-and-fuel oil fired ones, total     | 38.5 40.3 52.2 52.1 47.7 45.5 46.4 49.6 28.3 |
| Including:                             |                  |
| Steam turbine ones                     | 37.3 36.9 36.6 36.6 28.1 17.2 2.5 13.4 0.1 |
| CCGT and GTUs                          | 1.2 3.4 15.6 15.5 19.6 28.3 43.9 36.2 28.2 |
| solid fuel fired ones                  | 24.7 24.7 22.8 21.6 18.9 18.6 14.9 13.8 – |

* CCGT are combined cycle units, CPPs are one-product condensing TPPs, producing electricity only.
intensive scenario, a faster decommissioning of the operating TPP equipment will be necessary, especially condensing thermal power plants (CPPs). By 2040, 52% of the reporting amount of CPP capacities will remain in operation, while only 14% by 2050.

The growth in the amounts of substituted and new capacities for CHPs will be limited by the centralized heat supply dynamics, and that for CPPs will be limited by the marginal (residual) role of these power plants in the capacity balance (with the expected development dynamics of the other power plant types). Therefore, in the intensive scenario, the total (for the period) substituted and new capacity of TPPs in 2050 will be by one-third smaller than it will be in the base scenario; these differences will be most noticeable for the capacities of CPPs.

The total amount of generating capacity commissioned in the UES of Russia until 2050 in the base scenario will exceed 200 million kW and it will be a factor of 1.5 larger (310 million kW) in the intensive scenario. In the base scenario, TPPs will account for approximately 60% of the total amount for the entire period up to 2050, whereas they will account for only 30% in the intensive scenario (Table 5), and the main increase of capacity will be owing to carbon-free types of power plants.

The capital investments required for implementing these two scenarios differ from each other by 36% (36.8 trillion rubles in the base scenario and 50.1 trillion rubles in the intensive scenario for the period from 2019 to 2050). In the base scenario, the thermal power plants accounts for the largest amount of investments, which corresponds to the role of TPPs in the mix of commissioned capacities. The nuclear power plants and networks go next in the scale of investment requirements. In the intensive scenario, which implies a drastic decrease in the amounts of commissioned TPPs, RES-based power plants account for the main share in the mix of new capacity. However, the role of renewable energy will not dominate in the structure of capital investments, which is owing to the already achieved quite low capital intensity of new WPPs and SPPs (and further reduction in the construction cost of these power plant types). In the intensive scenario, with decreasing the investment outlays in the thermal power plants, the share of NPPs in the capital investments grows, becoming close to 30%.

### Table 4. Dynamics of installed capacity at thermal power plants in the UES of Russia (reporting data are from the Rosstat RF and UES SO and predicted data are ERI RAS assessments)

| Power plants | Installed capacity, million kW |
|--------------|--------------------------------|
|              | reporting data | base scenario | intensive scenario | predicted data | predicted data |
|              | 2019 | 2020 | 2030 | 2040 | 2050 | 2040 | 2050 |
| TPPs, total  | 164.6 | 163.3 | 157.2 | 157.3 | 157.2 | 148.7 | 106.8 |
| Including:  | | | | | | | |
| existing and modernized | 164.6 | 163.3 | 145.3 | 94.1 | 36.2 | 90.3 | 23.4 |
| replaced and new | — | — | 11.9 | 63.2 | 121.0 | 58.4 | 83.4 |
| CHPs, total  | 89.6 | 89.6 | 90.6 | 93.2 | 95.9 | 85.3 | 78.5 |
| Including:  | | | | | | | |
| existing and modernized | 89.6 | 89.6 | 84.8 | 50.9 | 25.4 | 50.9 | 20.1 |
| replaced and new | — | — | 5.8 | 42.3 | 70.5 | 34.4 | 58.4 |
| CPPs, total  | 75.0 | 73.7 | 66.6 | 64.1 | 61.3 | 63.4 | 28.3 |
| Including:  | | | | | | | |
| existing and modernized | 75.0 | 73.7 | 60.5 | 43.2 | 10.8 | 39.4 | 3.3 |
| replaced and new | — | — | 6.1 | 20.9 | 50.5 | 24.0 | 25.0 |

### FUEL CONSUMPTION AND CO2 EMISSION SCENARIOS IN THE ELECTRIC POWER INDUSTRY UP TO 2050

The contribution power plants of different types make in the electricity production reflects the above-mentioned technological changes in the UES of Russia; however, in view of different annual capacity utilization modes (capacity factor, CF), it differs from the generating capacity mix indicators. Table 6 shows the changes in the electricity production characteristics to 2050.

In the nearest decade, the contribution of carbon-free power plants in the total electricity production in the UES of Russia will slightly decrease in both scenarios (from 37.1% in 2019 to 35.4% in 2030) in view of advance decommissioning of a number of power units at existing NPPs. After that, this share will grow steadily to reach by 2050 46.7% in the base and 67.5%
in the intensive scenarios. It should be noted that it is particularly NPPs that will become the most important technology for decarbonization: by 2050, their share in the electricity production will increase from the reporting 19.3 to 36.1%. Unlike NPPs, in view of their rather low CF, RES-based power plants, despite their having a significant share in the generating capacity mix, will provide, even in the intensive scenario, only 15.4% of the total amount of electricity produced in the UES of Russia by 2050.

As is shown in Table 6, only one-third of electricity will be produced using fossil fuel in the intensive scenario in 2050 and, with fast (especially after 2040) substitution of coal, 95.7% of this amount will be produced by gas-and-oil-fired power plants. In the base scenario, TPPs will account for slightly more than half the total electricity production in 2050, and gas-and-oil-fired power plants will produce 3/4 of this amount. In the total amount of electricity produced by thermal power plants, the share of TPPs with equipment on the basis of gas turbines (combined cycle and gas turbine units) will grow drastically by 2050: from 29.5% in 2019 to 70.7% in the base scenario and up to 90.8% in the intensive scenario.

Another trend is connected with the development and efficient use of cogeneration capacities: the share of CHPs in the total amount of electricity produced by TPPs will increase from 57.7% in 2019 to 63.5% in the base scenario and to 82.0% in the intensive scenario by 2050. An essential decrease in the CF of CPPs in the intensive scenario points to transformation of their role in the power system into intermediate and peaking sources.

Changes in the mix of capacities and in the electricity production structure have an effect on the specific and absolute indicators of fuel consumption and, as a consequence, CO₂ emissions. The technological transformation of the thermal power plants makes it possible to achieve its noticeably better energy efficiency: the weighted average heat rate for electricity supply will decrease by 2050 (depending on the scenario) by 21–25% with respect to 2019 (from 308.4 to 242.0 or 229.0 gce/(kW h)). It should be noted that the target heat rate reduction specified in the Energy Strategy up to 2035 (255 gce/(kW h)) will be reached after 2040 even in the intensive scenario. This points to the need of correcting the Energy Strategy target indicators with taking into account the optimal contribution of this partial result (improvement of the TPP energy efficiency) in solving the general problem of low-carbon development of the electric power industry and economy as a whole.

### Table 5. Comparison of the scales of capacity additions and required capital investments for different UES of Russia development scenarios

| Indicator | Base scenario | Intensive scenario* |
|-----------|---------------|---------------------|
|           | 2021–2030 | 2031–2040 | 2041–2050 | 2031–2040 | 2041–2050 |
| Commissioned power plant capacities, million kW: | | | | | |
| cumulative for the last year in the decade, total | 24.3 | 108.2 | 205.4 | 135.2 | 309.2 |
| by decades, total | 24.3 | 83.9 | 97.2 | 110.9 | 174.0 |
| Including: | | | | | |
| HPPs and PSPs | 1.5 | 3.6 | 3.7 | 6.5 | 10.6 |
| NPPs | 4.8 | 18.4 | 25.0 | 22.4 | 46.2 |
| RES | 6.2 | 10.6 | 10.6 | 29.8 | 70.1 |
| storages | – | – | – | 5.0 | 13.0 |
| TPPs | 11.8 | 51.3 | 57.8 | 47.1 | 34.1 |
| Capital investments, trillion rubles in 2019 prices (with VAT): | | | | | |
| cumulative for the last year in the decade, total | 8.1 | 21.9 | 36.8 | 25.0 | 50.1 |
| by decades, total | 8.1 | 13.8 | 14.9 | 16.5 | 25.0 |
| Including: | | | | | |
| HPPs and PSPs | 0.5 | 0.7 | 0.7 | 1.2 | 1.7 |
| NPPs | 1.6 | 3.8 | 4.2 | 5.0 | 7.9 |
| RES | 0.6 | 0.9 | 1.0 | 2.3 | 4.8 |
| TPPs | 3.3 | 5.0 | 4.4 | 3.6 | 2.3 |
| electric networks and storages | 2.1 | 3.4 | 4.6 | 4.4 | 8.3 |

* The data for 2021–2030 coincide with the data for the base scenario.
In view of the change in the role of TPPs in the UES of Russia with simultaneous improvement of their energy efficiency, the consumption of fossil fuel at power plants in the first 10–15 years will grow more slowly than the electricity production, and then it will decrease. In the base scenario, in 2050, the demand of power plants for fuel will remain slightly higher than it was in 2019, with retaining the share of gas in the structure of this demand at a level of 72–73%. In the intensive scenario, the total consumption of fossil fuel at TPPs in 2050 will be by 28.0% lower than the reporting level. The demand for gas after 2035 will decrease more slowly than the total fuel consumption, and it will be by only 9.4% smaller by 2050 than it was in 2019.

The technological changes in the generating capacity mix are reflected to a larger extent on the use of fuel for electricity production. Therefore, the CO₂ emissions connected with fuel consumption for electricity production will decrease, in both scenarios, more rapidly than the total amount of CO₂ emission from power plants. The carbon intensity of electricity production, which is the specific indicator of emissions, will show a still more rapid decrease. Since the growth of electricity production even in the base scenario will be noticeably faster than the dynamics of CO₂ emissions entailing this production, the carbon intensity of electricity production will by 2030 remain at the 2050 to the values of the reporting level. In the intensive scenario, the peak of emission will be reached earlier—in 2030 (with the increase by 8.2% with respect to 2019), and the subsequent reduction of annual CO₂ emissions will go more rapidly than the decrease of fossil fuel consumption at TPPs. As a result, in this scenario, the CO₂ emissions from power plants in 2050 will be by 39% lower than the reporting level and by almost 40% lower than in the base scenario.

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| Indicator | Reporting data | Base scenario | Intensive scenario |
|-----------|----------------|---------------|--------------------|
|           | 2000 | 2010 | 2019 | 2020 | 2030 | 2040 | 2050 | 2040 | 2050 |
| Electricity production, billion kWh, total | 847.4 | 1004.5 | 1080.6 | 1047.1 | 1196.7 | 1367.6 | 1538.1 | 1400.2 | 1661.0 |
| Including: | | | | | | | | | |
| HPPs (including PSPs) | 155.4 | 158.9 | 190.3 | 207.4 | 195.6 | 209.7 | 227.4 | 222.5 | 267.2 |
| NPPs | 129.9 | 170.2 | 208.8 | 215.7 | 205.3 | 283.0 | 429.6 | 306.6 | 599.6 |
| RES | — | 0.0 | 1.5 | 3.4 | 17.8 | 38.8 | 62.0 | 87.0 | 255.0 |
| TPPs, total | 562.1 | 675.4 | 680.0 | 620.6 | 778.0 | 831.6 | 819.1 | 784.1 | 539.2 |
| Including: | | | | | | | | | |
| gas-and-fuel oil fired ones | 331.7 | 417.8 | 473.4 | 434.5 | 563.7 | 613.2 | 608.6 | 633.3 | 515.9 |
| solid fuel fired ones | 230.4 | 257.6 | 206.6 | 185.7 | 214.3 | 222.9 | 210.5 | 150.8 | 23.3 |
| Heat rate for electricity supply, gce/(kWh) | 340.6 | 335.8 | 308.4 | 306.3 | 297.9 | 263.6 | 242.2 | 266.5 | 228.6 |
| Fuel consumption, million tce, total | 265.6 | 292.2 | 275.7 | 254.3 | 302.8 | 307.0 | 290.6 | 286.0 | 198.6 |
| Including: | | | | | | | | | |
| gas | 166.1 | 199.1 | 199.1 | 184.8 | 221.3 | 220.2 | 209.4 | 223.0 | 180.4 |
| fuel oil | 13.1 | 4.1 | 1.1 | 0.9 | 0.9 | 0.9 | 0.2 | 0.9 | 0.2 |
| coal | 78.0 | 79.0 | 63.9 | 57.0 | 68.0 | 70.1 | 58.9 | 47.8 | 1.1 |
| other | 8.4 | 10.0 | 11.6 | 11.6 | 12.6 | 15.8 | 22.1 | 14.3 | 16.9 |
| CO₂ emissions, million t, total | 535.2 | 576.2 | 534.8 | 491.6 | 582.1 | 586.0 | 535.8 | 528.9 | 328.1 |
| Including: | | | | | | | | | |
| for electricity production | 347.1 | 408.3 | 373.3 | 337.2 | 410.3 | 395.2 | 343.2 | 360.9 | 191.6 |
| for heat supply from CHPs | 188.1 | 167.9 | 161.5 | 154.4 | 171.8 | 190.8 | 192.6 | 168.0 | 136.5 |
| Carbon intensity of electricity production, kg CO₂/(kWh) | 0.41 | 0.41 | 0.35 | 0.32 | 0.34 | 0.29 | 0.22 | 0.26 | 0.12 |
reporting level of 2019 and it will decrease by 35% by 2050. In the intensive scenario, the carbon intensity will drop much more rapidly, and it will decrease by a factor of three by 2050 to make only 33% of the values in the 2019 reporting (and will be half the value specified in the base scenario).

A more detailed analysis of the change in the amounts and structure of electricity production and fuel consumption made it possible to determine the contribution of the main technological factors that help (depending on the scenario) constrain the growth and/or decrease the amounts of CO₂ emissions from power plants. In performing such assessment for each scenario, we first estimated the potential growth of CO₂ emissions subject to retaining, at the reporting level, the electricity production structure by the types of power plants, the structure of fuel demand by the kinds of fuel used, and heat rates for electricity and heat supply. After that, we sequentially added in the analysis each of the above-mentioned factors in the amount supposed by the relevant scenario: up to achieving the predicted indicators of the electricity production structure and fuel demand structure. Figure 1 shows the most important integral results relating to 2050.

In the base scenario, given the specified demand for electricity and heat supply from TPPs, the potential growth of CO₂ emissions by 2050—with the TPP production structure and energy efficiency indicators kept at the reporting level—would make 784 million t CO₂, which is by almost 47% higher than in 2019 (see Fig. 1a). The predicted level of emissions in 2050 in this scenario is almost the same as the reporting level—536 million t CO₂. The most significant contribution in constraining the CO₂ emissions in the base scenario is due to improvement of the TPP energy efficiency. This factor accounts for more than half the difference between the potential and predicted amounts of emissions in 2050. The factor second in importance is the development of the nuclear power plants, which accounts for another 30% of the difference between the potential and predicted amounts of emissions in 2050. In comparison with them, the contribution of renewable energy and hydroelectric energy sources in the formation of this difference, as well as the changes in the structure of power plants fuel balance, is several times smaller in this scenario.

In the intensive scenario, the potential growth of CO₂ emissions by 2050—with the TPP production structure and energy efficiency indicators kept at the reporting level—would make 748 million t CO₂, which is by almost 40% higher than in 2019 (see Fig. 1b). A lower, in comparison with the base scenario, amount of potential emissions is due to a smaller predicted amount of heat supply from CHPs in 2050. The predicted level of emissions in 2050 will make 328 million t CO₂; i.e., it will be a factor of 2.3 lower than the potential level, and the difference between them will reach 420 million t CO₂. Under these conditions, carbon-free power plants will make the major contribution in constraining the CO₂ emissions: almost 37% will be due to accelerated development of NPPs and approximately 30% owing to rapid development of RES-based and hydroelectric power plants. The contribution owing to improvement of the TPP energy efficiency will be lower than it is in the base scenario (approximately 20%), which is connected with smaller scales of technological updating of the thermal power plants in substituting TPPs (especially coal-fired ones) with carbon-free power plants. The remaining 13% will be due to a radical change in the fuel consumption structure at TPPs, namely, an increase of the share of gas in it.

ECONOMIC CONSEQUENCES AND COMPARATIVE ANALYSIS OF THE SCENARIOS

The assessments of capital investments given above, which are necessary for implementing each of the UES of Russia development scenarios, and the achieved indicators of absolute and specific CO₂ emissions from power plants make it possible to evaluate the capital intensity of possible decisions on carrying out more or less intensive decarbonization policy in the country’s electric power industry. The dependence of the achieved level of emissions on cumulative capital investments is fairly well approximated by a linear function (Fig. 2). An analysis of incremental characteristics shows that every trillion rubles of investments (with VAT) in the base scenario results in that the CO₂ emissions are reduced by 3 million t. In the intensive scenario, these indicators are almost a factor of 2.5 higher, so that the amount of CO₂ emissions is reduced by 7.2 million t with every trillion rubles of investments, and vice versa: to decrease the CO₂ emissions by 1 million t, approximately 330 billion invested rubles will be required (with VAT) in the base scenario and only 135 billion rubles in the intensive scenario.

Similarly, the amount of investments required for decreasing the carbon intensity of electricity production (with respect to its level in 2019) was estimated. With every additional trillion invested rubles (with VAT), the carbon intensity level is decreased by 1.3% in the base scenario and by 1.6% in the intensive scenario, and vice versa, for the carbon intensity of electricity production to be additionally decreased by 1%, it will be necessary to invest 610 and 750 billion rubles (with VAT) in the intensive and base scenarios, respectively.

For estimating how the structural changes in the base and intensive UES of Russia development scenarios influence the dynamics of electricity price, we calculated the total revenue required (TRR) for each of the electric power industry production segments (hydraulic, nuclear, thermal, and renewable generation, and also the networks) with aggregating them

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into the total amount of the TRR for the whole industry. To this end, we used an original system of combined production and financial models [11], which makes it possible to calculate—proceeding from the specified parameters of production and investment programs for each segment—the dynamics of operational costs (fuel, other operating and maintenance, and depreciation allowances), required profit, and financial outlays. The amounts of these financial outlays depend on the rational structure of investment resources and capital structure meeting the financial stability requirements (primarily by the credit burden parameters). The analysis also takes into account tax payments in accordance with the existing legislation.

The average price for electricity supplied for the consumers in the UES of Russia was calculated as the ratio of the sector’s total TRR (minus the costs of TPPs for heat production) to the electricity supplied to end users. In the base scenario, the price will increase slowly to 2040 (on the whole for this period by 9% in real terms, i.e., without taking inflation into account). After 2040, with relatively stabilized amounts of investments and gradual decrease of fuel consumption in the UES of Russia, the price will slightly decrease, and it will be only by 6% higher in 2050 than the reporting level (in 2019). In the intensive scenario, high capital outlays for deep technological transformation of the industry taken in combination with a higher level of domestic prices for fuel and introduction of carbon

Fig. 1. Contribution of main technological factors in constraining the CO₂ emissions from power plants in the UES of Russia by 2050 in the (a) base and (b) intensive scenarios. 1—Emissions in 2019; 2—potential growth of emissions in 2050; reduction of emissions as a consequence of: 3—growth in the NPP share; 4—growth in the share of RES and HPPs; 5—TPP energy efficiency; 6—fuel structure; 7—predicted emissions in 2050.
payments will require an essential growth of prices. Accordingly, in the intensive scenario the price for electricity in real terms will already increase by 50 and 60% by 2040 and 2050, respectively, with respect to its reporting value in 2019 (and by 51% higher with respect to the base scenario).

The obtained results confirm once again the statement that the ambitiousness of the plans for decarbonizing Russia’s electric power industry should be carefully balanced with the readiness and ability of consumers to withstand an essentially higher price of electricity in the case of its production at low-carbon power plants (Fig. 3). In the conditions under which the consumers will have to implement their own large-scale decarbonization plans and also face the risks of external (cross-border) carbon regulation [12], the cost of electricity will be of significant importance for their competitiveness in external and domestic markets. The negative price effect can be partially smoothed out through efficiently using the carbon payments from power plants. The available assessments [13] show that goal-seeking forwarding of part of this money to encourage investments in the development of carbon-free power plants will make it possible to decrease the growth of electricity price by several percent, and the major part of the money can be used for supporting low-carbon transformation in other sectors of the country’s economy.

CONCLUSIONS

(1) The results of elaborating the UES of Russia base development scenario show that there will be relatively stable capital investment levels and electricity prices for consumers in the long-term prospect with moderate rates of renewing thermal generation and development of carbon-free generation capacities; in this case, however, the CO₂ emissions from power plants by 2050 do not decrease below the reporting level (in 2019). Thus, the objective of stabilizing the level of emissions but not decreasing them is solved in this scenario.
(2) The elaboration of the intensive scenario shows that it will not be possible to achieve a several times lower amount of CO₂ emissions from power plants in the 30-year horizon even with a radical change in the electricity production structure. By implementing the power industry technological transformation scenario considered in the article, it will be possible to decrease, by 2050, the amounts of CO₂ emissions from power plants with respect to the base scenario by 40% and the carbon intensity of production by a factor of two. In this case, on the one hand, there will be a serious change in the mix of the country’s energy balance and conditions for development of the gas and coal industries, because the demand of power plants for fuel decreases by one-third (with the consumption of coal decreased fully to zero). On the other hand, the implementation of this scenario will require by 37% larger amount of capital investments. Finally, it will be rather costly for consumers: the price for electricity in 2050 will be a factor of 1.5 higher in comparison with the base scenario. But the intensive scenario also noticeably increases the amount of incomes into the country budget from the electric power industry, including the possibility of using the money received due to carbon payments from power plants in the economy.

(3) This totality of environmental and economic consequences, which are different in their directions, from the active efforts on decreasing the CO₂ emissions in the electric power industry obviously shows the necessity and importance of inter-sectoral assessment of its development as part of more general scenarios of the entire economy and the country’s energy sector. Such assessment includes the influence on the competitiveness and possibilities of making transition to low-carbon development in the other sectors of Russia’s economic and power industry. A matter of key importance is achieving technological independence over the entire range of the kinds of main and auxiliary equipment for low- and carbon-free electricity sources.

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

REFERENCES

1. I. A. Bashmakov, “Russian low carbon development strategy,” Vopr. Ekon., No. 7, 51–74 (2020). https://doi.org/10.32609/0042-8736-2020-7-51-74

2. B. Porfir’ev, A. Shirow, and A. Kolpakov, “Low-carbon development strategy: Prospects for the Russian economy,” Mirov. Ekon., Mezhdunar. Otn. 64 (9), 15–25 (2020). https://doi.org/10.20542/0131-2227-2020-64-9-15-25

3. G. Safonov, V. Potashnikov, O. Lugovoy, M. Safonov, A. Dorina, and A. Bolotov, “The low carbon development options for Russia,” Clim. Change 162, 1929–1945 (2020). https://doi.org/10.1007/s10584-020-02780-9

4. IEA. Data and Statistics (2021). https://www.iea.org/data-and-statistics

5. F. Veselov, T. Pankrushina, and A. Khorshev, “Comparative economic analysis of technological priorities for low-carbon transformation of electric power industry in Russia and the EU,” Energy Policy 156, 112409 (2021). https://doi.org/10.1016/j.enpol.2021.112409

6. B. N. Porfir’ev, A. A. Shirow, and A. Yu. Kolpakov, “Comprehensive approach to the strategy of low-carbon socio-economic development of Russia,” Georesursy 23 (3), 3–7 (2021). https://doi.org/10.18599/grs.2021.3.1

7. A. Lagerev and V. Khanaeva, “Impact of restrictions on CO₂ emissions on innovative development of thermal power plants,” Energ. Polit., No. 7 (161), 16–25 (2021). https://doi.org/10.46920/2409-5516_2021_7616_16

8. E. O. Adamov, D. A. Tolstoukhov, S. A. Panov, F. V. Veselov, A. A. Khorshev, and A. I. Solyanik, “Role of NPPs in the Russian electricity industry taking into account carbon emissions limits,” At. Energy 130, 127–135 (2021). https://doi.org/10.1007/s10512-021-00783-y

9. A. A. Makarov, “Means and cost of achieving carbon neutrality of the economy for the Russian energy sector,” Therm. Eng. 69 (10), 727–737 (2022).

10. Study of the Ways and Pace of Development of Low-Carbon Energy in Russia, Ed. by A. A. Makarov (Inst. Energ. Issled. Ross. Akad. Nauk, Moscow, 2022) [in Russian].

11. F. V. Veselov and A. I. Solyanik, “Methodological approach for harmonization of the investment and pricing policy options in the electric power industry,” in Proc. 10th Int. Conf. on Management of Large-Scale Systems Development (MLSD), Moscow, Russia, Oct. 2–4, 2017 (IEEE, Piscataway, N. J., 2017), pp. 1–5. https://doi.org/10.1109/MLSD.2017.8109704

12. I. A. Bashmakov, “CBAM and Russian export,” Vopr. Ekon., No. 1, 90–109 (2022). https://doi.org/10.32609/0042-8736-2022-1-90-109

13. F. V. Veselov and A. I. Solyanik, “Modeling of carbon payment impacts on electricity prices and possibility for mitigation of negative effects on consumers,” in Proc. 14th Int. Conf. on Management of Large-Scale Systems Development (MLSD), Moscow, Russia, Sept. 27–29, 2021 (IEEE, Piscataway, N. J., 2021), pp. 1–4. https://doi.org/10.1109/MLSD52249.2021.9600129

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