Nuclear power in a decarbonized and electrified economy. A look into 2060

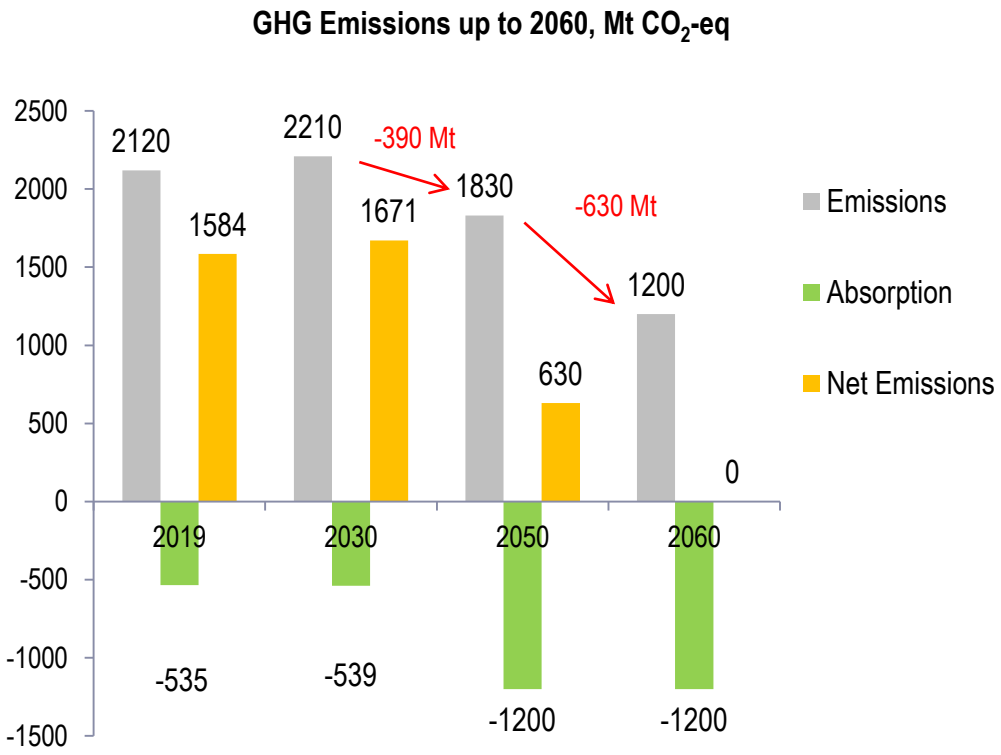
Fedor Veselov

Energy Research Institute of the Russian Academy of Sciences

IAEA Technical Meeting on Modelling the Contribution of Nuclear Power to Clean and Secure Transitions

Vienna, Austria, 14-18 July 2025

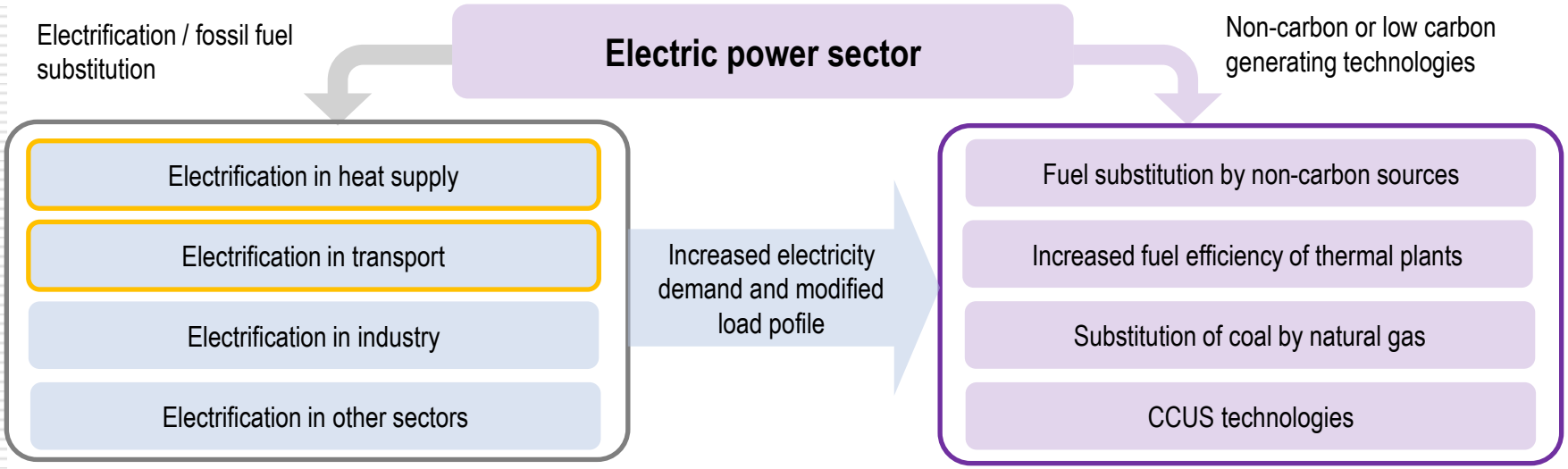
National decarbonization and carbon neutrality goals



- The Low-emission Strategy for the Development of the Russian Economy aims to reduce net GHG emissions by 60% from 2019 levels by 2050.
- It is expected that absorption capacity of ecosystems will be doubled and physical GHG emissions will decrease by 390 million tons over the next 20 years (-13.6%),
  - which is about two-thirds of the reported emissions from power plants.
- The Climate Doctrine of the Russian Federation sets the goal of achieving carbon neutrality for the economy by 2060.
- In this case, annual emissions should decrease by another 630 million tons by 2060, which is 1.5 times more than the reduction in 2030-2050.
- The total emissions reduction by 2060 is 1,120 million tons,
  - which is 1.9 times higher than the current emissions from power plants.

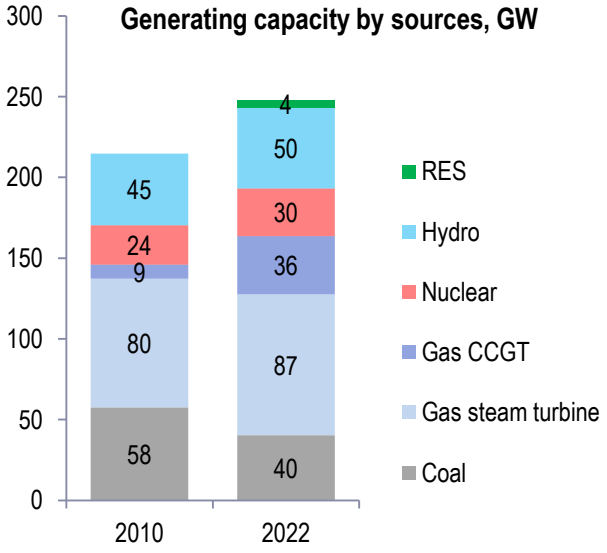
Source: ERI RAS analysis based on the official documents

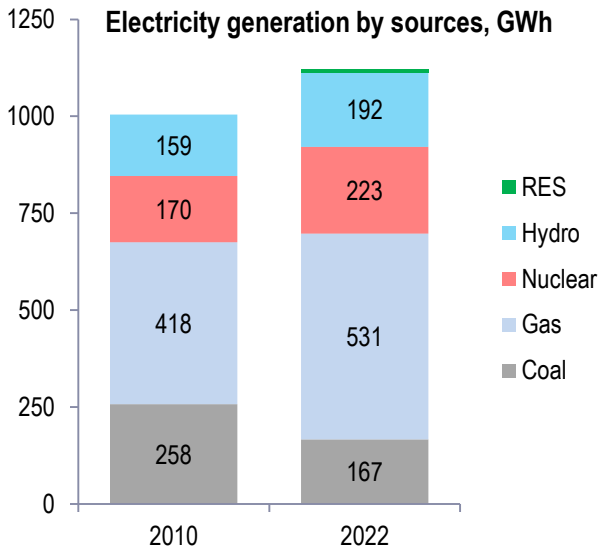
Electric power sector: technological opportunities for decarbonization of the economy



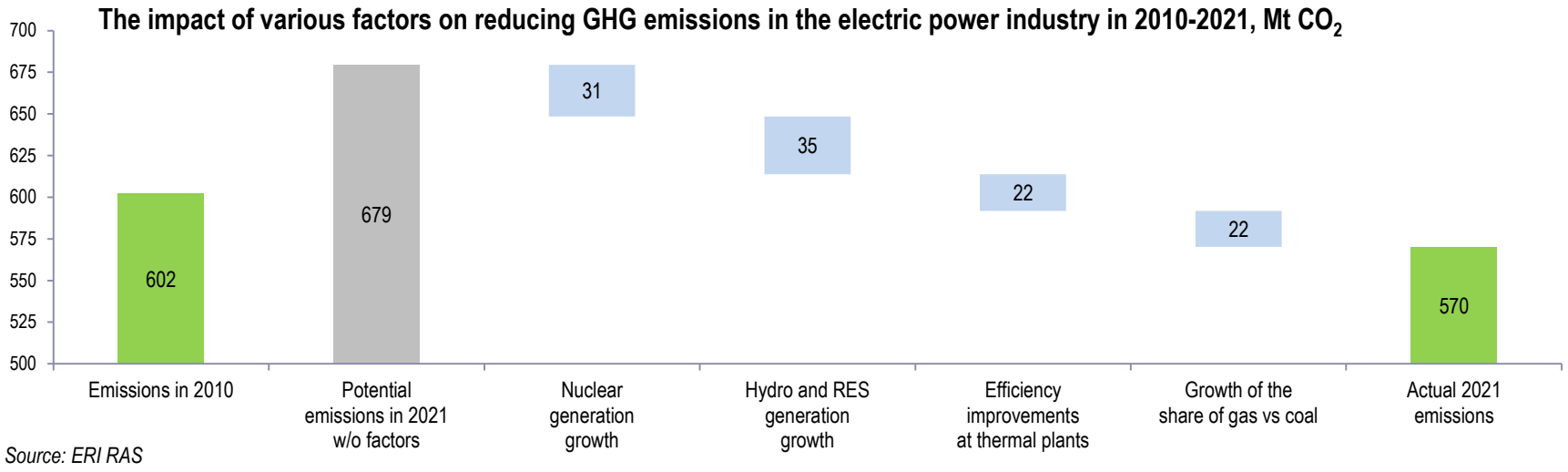
- The electric power sector plays a unique role in achieving carbon neutrality of the economy by 2060 (according to the Climate Doctrine)
- Currently, about 25% of GHG emissions in Russia are associated with power plants. About 2/3 of the country's electricity is produced by thermal power plants, mostly gas-fired. The average fuel efficiency is only 39%
- The possibilities of direct reduction of emissions from power plants are associated with the replacement of fuels with carbon-free sources (including nuclear power plants), increasing the efficiency of thermal power plants, as well as the use of CCUS technologies.
- At the same time, in other sectors of the economy, active electrification is being considered to reduce GHG emissions – replacing fossil fuels with electricity.
- Electrification is a significant challenge for the electric power sector, which must adapt to increased demand and changing patterns of electricity load. At the same time, it is essential to reduce emissions from the sector itself.
- There are vast technical opportunities for the electric power sector to contribute to the decarbonization of the economy. However, implementing such a strategy on a large scale requires careful analysis and energy modeling to ensure its cost-effectiveness and affordability

Decarbonization of the electricity generation. Current achievements





- **The total capacity has increased by 15%**
- Nuclear +21%, Hydro&RES + 22%, CCGT in 4 times
- **The total generation has increased by 12%**
- Nuclear +31%, Hydro&RES + 26%, gas-fired plants +27%

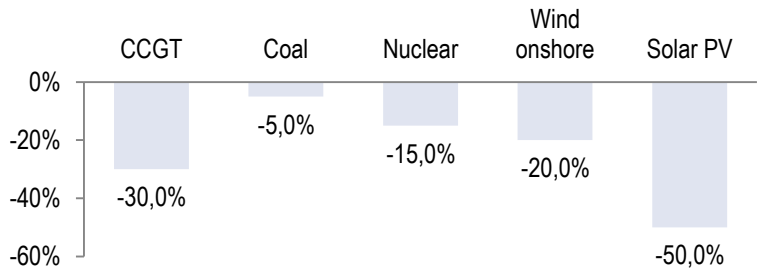


Source: ERI RAS

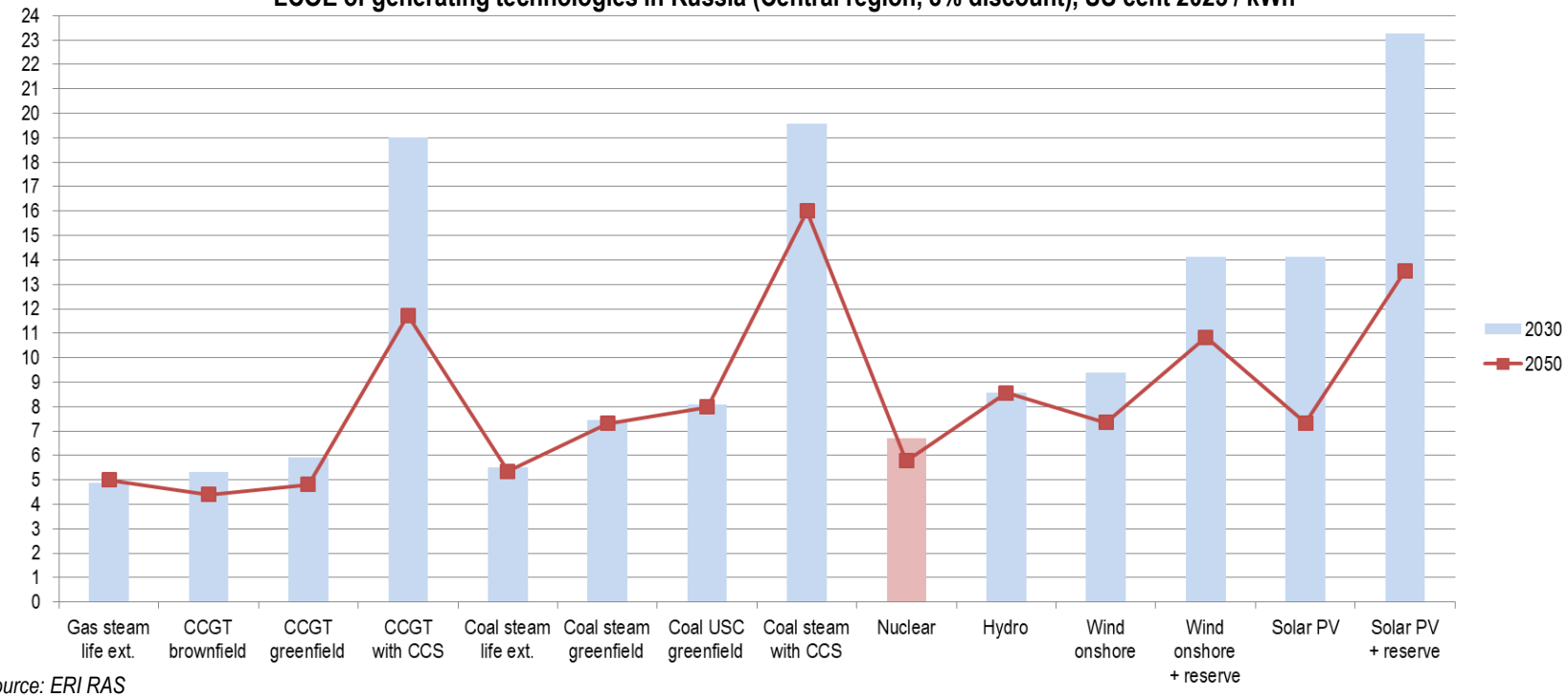
Decarbonization of the electricity generation. Competitiveness of nuclear

- Russia is one of the few countries with domestic competencies and industrial capacities for the mass production and construction of nuclear power units.
- Even today, with low gas prices, nuclear power plants are considered the least expensive carbon-free technology for generating electricity in the Unified Energy System (UES) of Russia. But regional specific (capital and fuel costs) matters
- The competitive position of nuclear power plants will remain strong in the future, given the technological development of domestic equipment.

CAPEX reduction by technologies from 2030 to 2050



LCOE of generating technologies in Russia (Central region, 8% discount), US cent 2023 / kWh



Source: ERI RAS

Decarbonization of the electricity generation. Competitiveness of nuclear

- Carbon prices could stimulate the transition to the less carbon-intensive electricity generation. The appropriate "switching" CO_2 price values can be estimated using the carbon avoided cost approach

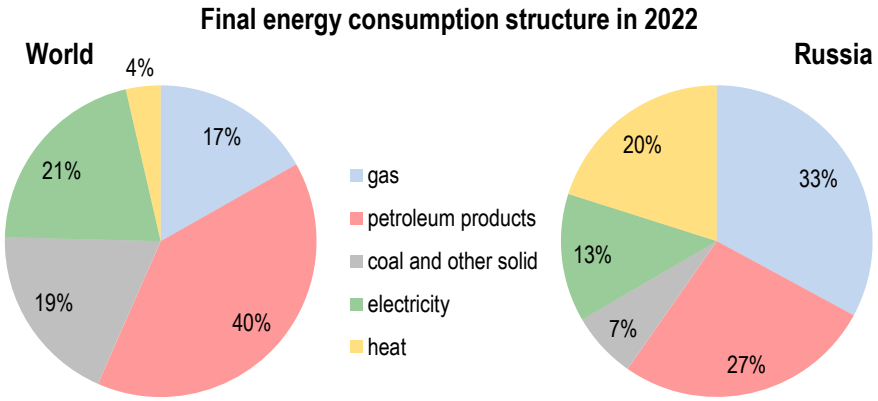
$$CarbonAvoidedCost = \frac{LevelizedCost(1) - LevelizedCost(2)}{CO2Emiss(2) - CO2Emiss(1)}$$

Non/low-carbon technology	Substituted conventional technology	Required CO_2 price		
		2030, 8% discount	2050, 8% discount	2050, 5% discount
Nuclear (LR)	Coal steam	-9	-20	-20
Hydro	Coal steam	14	15	-7
Wind onshore	Coal steam	26	5	-3
Wind onshore + reserve	Coal steam	84	44	31
Solar PV	Coal steam	83	4	-2
Solar PV + reserve	Coal steam	197	78	59
CCGT + CCS	Coal steam	154	58	56
Coal + CCS	Coal steam	174	123	100

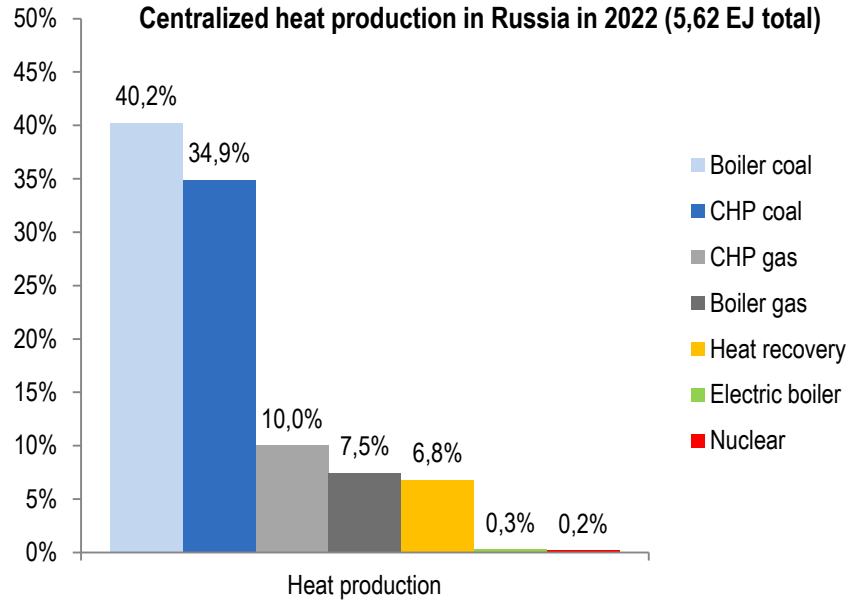
Non/low-carbon technology	Substituted conventional technology	Required CO_2 price		
		2030, 8% discount	2050, 8% discount	2050, 5% discount
Nuclear (LR)	CCGT	20	27	-2
Hydro	CCGT	66	104	29
Wind onshore	CCGT	88	71	39
Wind onshore + reserve	CCGT	206	168	115
Solar PV	CCGT	207	70	41
Solar PV + reserve	CCGT	436	244	178
CCGT + CCS	CCGT	375	219	185

Source: ERI RAS

Decarbonization of the district heating. Competitiveness of nuclear

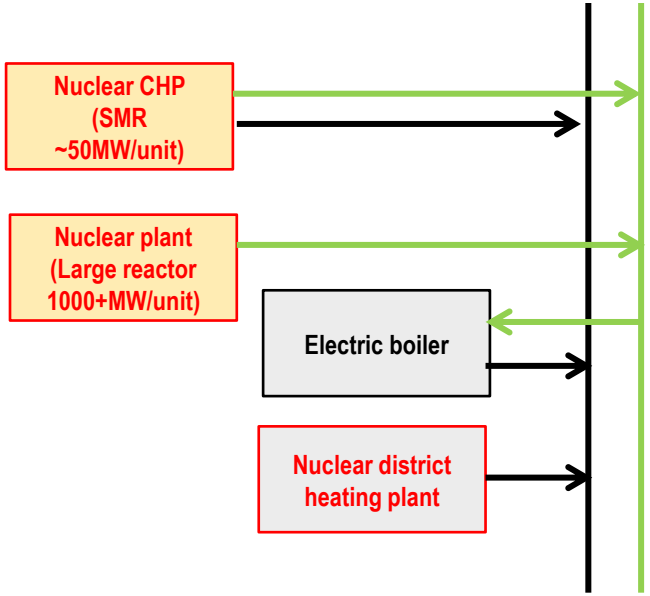


Source: IEA database



Source: RF State Statistic Service

- Due to geographical factors, the Russian economy and population consume a large amount of district heat, mainly for space heating.
- In 2022 heat accounted for 20% of total final energy consumption (non-energy sectors of the economy). It is in 1,5 times more than electricity!
- 90% of heat is produced from gas and coal-fired sources. There is a huge potential for decarbonization (even more than in electricity supply)
- Nuclear plants in Russia already supply heat to internal needs and neighboring settlements (16 PJ)
- There are 3 alternative ways to enhance the role of nuclear energy in heat supply



Decarbonization of the district heating. Competitiveness of nuclear

Levelized cost approach should be adjusted for the screening-analysis of two-product technologies

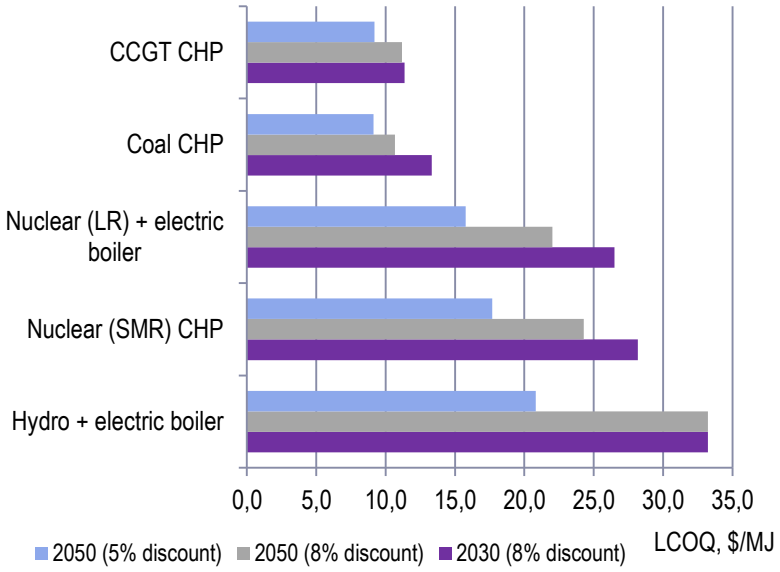
- Two-product (combined heat and power) plant or CHP

$$LCOQ_i = \frac{\sum_t (CAPEX_{i,t} + Fuel_{i,t} + VarOM_{i,t} + FixedOM_{i,t} + Carbon_{i,t}) \cdot (1+d)^{-t}}{\sum_t (Electr_{i,t} + Heat_{i,t}) \cdot (1+d)^{-t}}$$

- Alternative electricity and supply combination of one-product power plant and boiler/electric boiler

$$LCOQ = \frac{\sum_t (LCOE_j \cdot Electr_{j,t} + LCOH_k \cdot Heat_{k,t}) \cdot (1+d)^{-t}}{\sum_t (Electr_{j,t} + Heat_{k,t}) \cdot (1+d)^{-t}}$$

Changes in LCOQ from 2025 to 2040 due to technological factors and discount rate



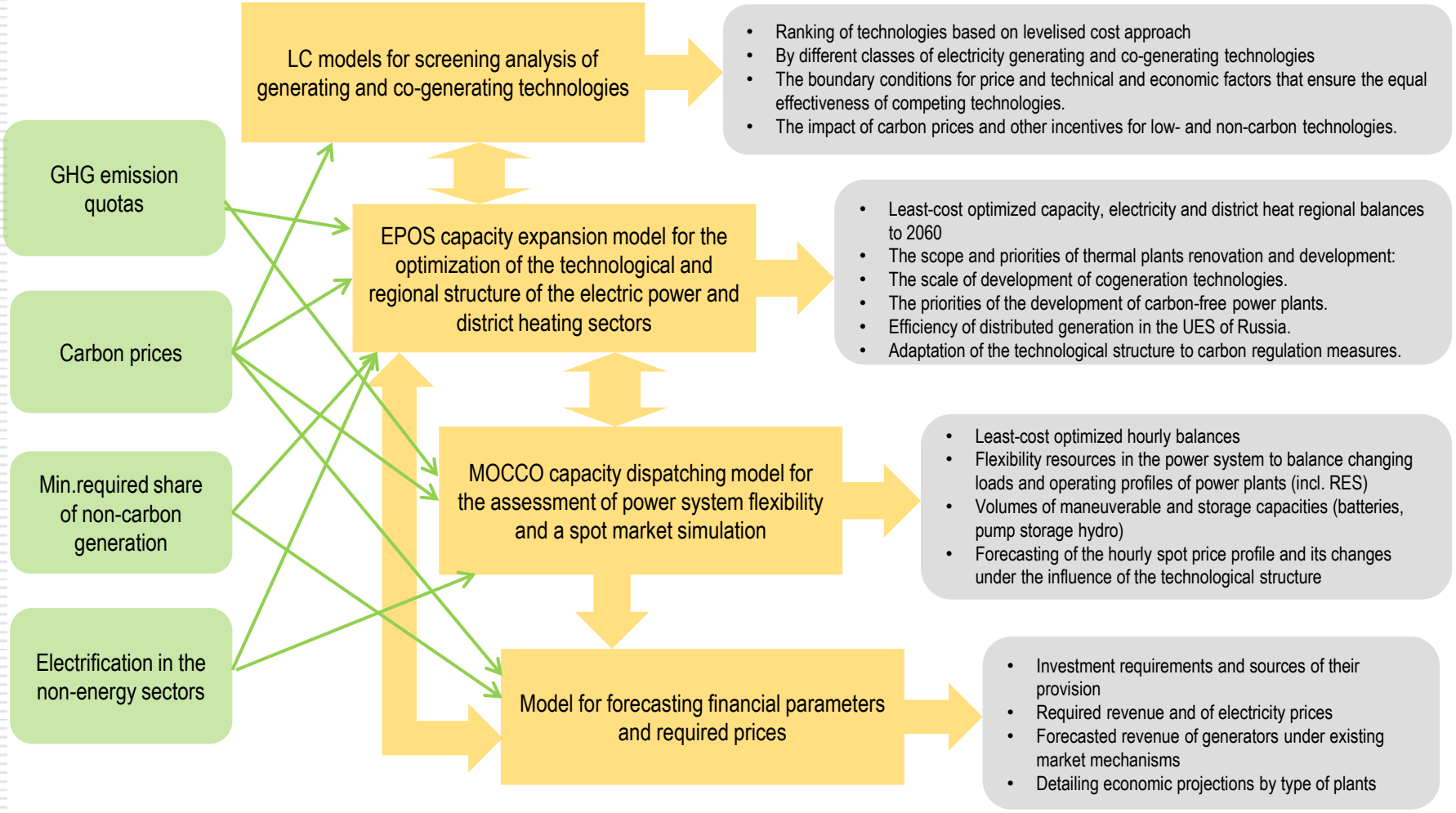
- By 2050, coal and gas-fired CHPs will be able to provide approximately twice lower the cost of energy supply than nuclear alternatives
- Lower discount rate will improve the situation to a certain extent, especially for a combination of electric boiler and LR NPP
- Just strong low-carbon requirements for heat or carbon prices can help bring the LCOQ values of gas and coal-fired CHP in line with nuclear technologies
- The cost of energy supply from a nuclear CHP (50 MW SMR units) will be 10-15% higher than from a combined electric boiler and LR NPP scheme. But regional grid tariffs and losses may strongly affect the competitiveness

Nuclear technology	Substituted conventional technology	Required CO_2 price		
		2030, 8% discount	2050, 8% discount	2050, 5% discount
Nuclear (SMR) CHP	Coal CHP	132	103	67
Nuclear (LR) + electric boiler	Coal CHP	113	80	47
Nuclear (SMR) CHP	CCGT-CHP	253	232	145
Nuclear (LR) + electric boiler	CCGT-CHP	200	169	94

Source: ERI RAS

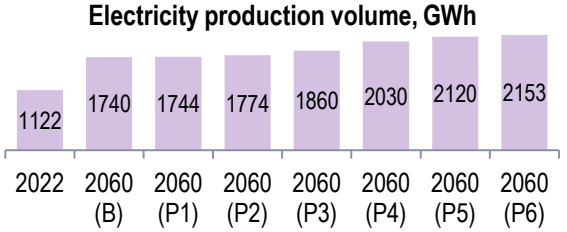
ERI RAS modeling tools for the scenarios of Russian electric power sector development

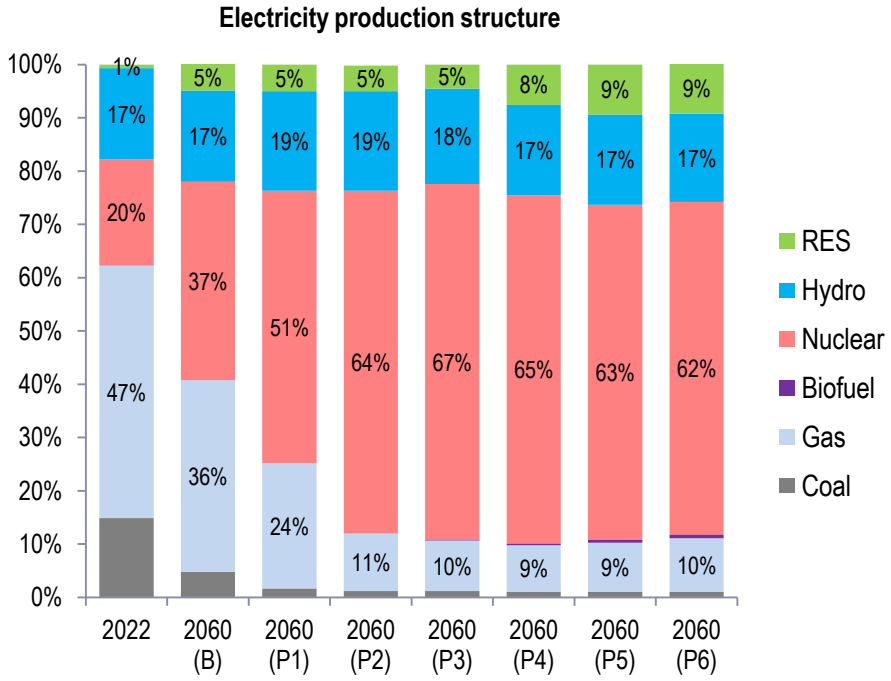
- A systematic approach to the formation of scenarios for the development of the electric power sector provides for careful modeling of conditions for the development and use of capacities, as well as financing investments in market conditions

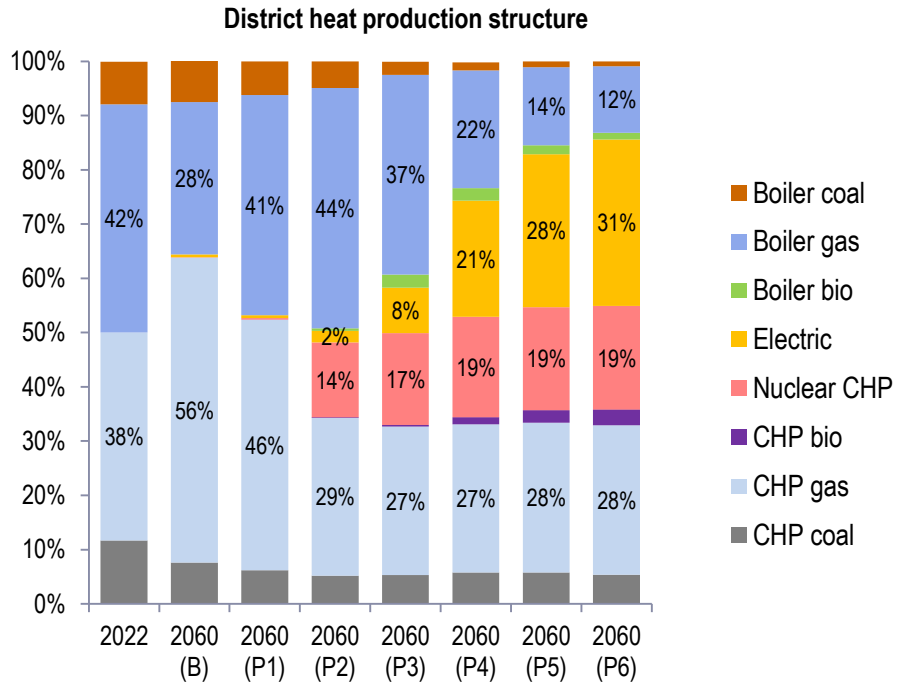


The impact of carbon pricing on the structure of electricity generation

Carbon price by scenarios, $/t CO_2	Base (B)	P1	P2	P3	P4	P5	P6
2030	0	25	25	25	38	50	75
2050	0	25	50	100	150	200	250
2060	0	25	67,5	125	200	275	325
CO2 emissions in 2060, % to 2019 level	86%	67%	50%	44%	38%	34%	33%







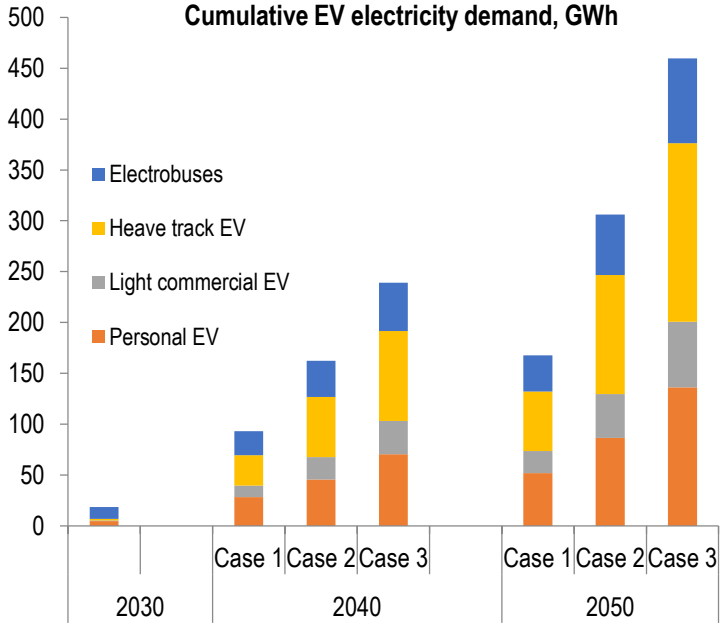
- Carbon prices help nuclear to be a dominant in the electricity production structure; the share of RES will also increase, but remain insignificant
- They also stimulate a low-carbon transformation of district heat production, creating opportunities for nuclear CHP and electrification
- As a result, 16-25% more electricity will be required in 2060 (in respect to the Base case) to ensure fuel substitution in district heating

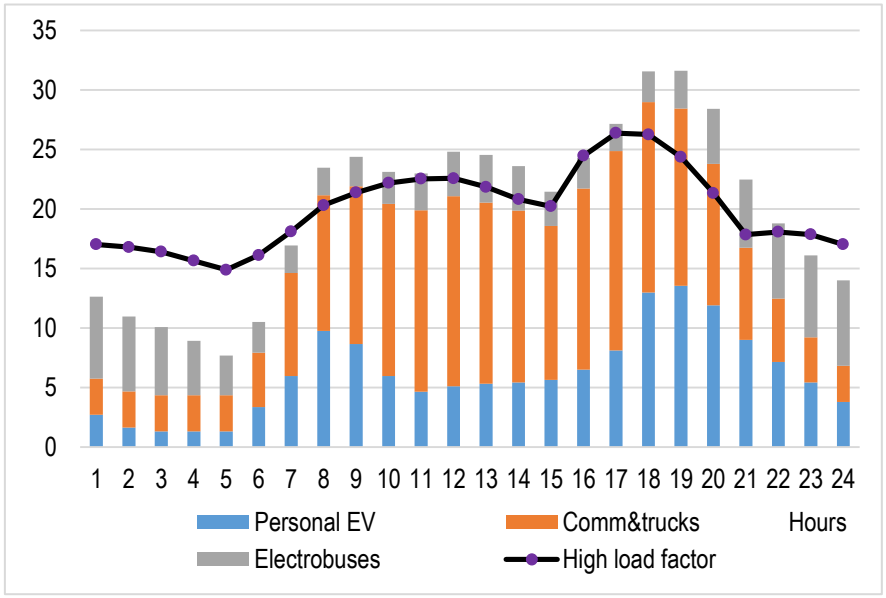
Source: ERI RAS, EPOS model

Transportation sector. Potential impact of electricity demand and load profile

Transportation technology	Share of EV in the total amount of vehicles in 2050		
	Case 1	Case 2	Case 3
Personal EV	30%	50%	70%
Light commercial EV	10%	20%	30%
Heavy track EV	10%	20%	30%
Electrobuses	30%	50%	70%

- At present personal EV accounts less 0.15% of total cars in Russia. Electrobuses accounts of 4.5% of total buses (and ~30% in Moscow city)
- To 2050, additional electricity demand from EV will may be 170-460 GWh
- Electrification in transportation sector will cause a serious distortion of load profile. Depending of the charging behavior (affecting the load factor), additional 170 GWh demand will also add 26-32 GW of capacity requirements in 2050



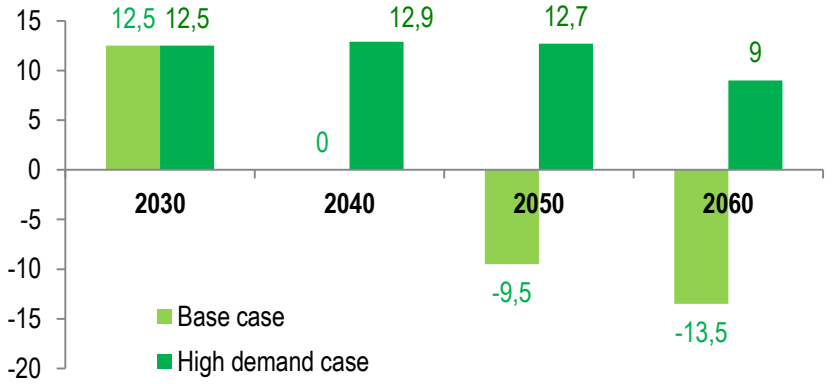


Source: ERI RAS

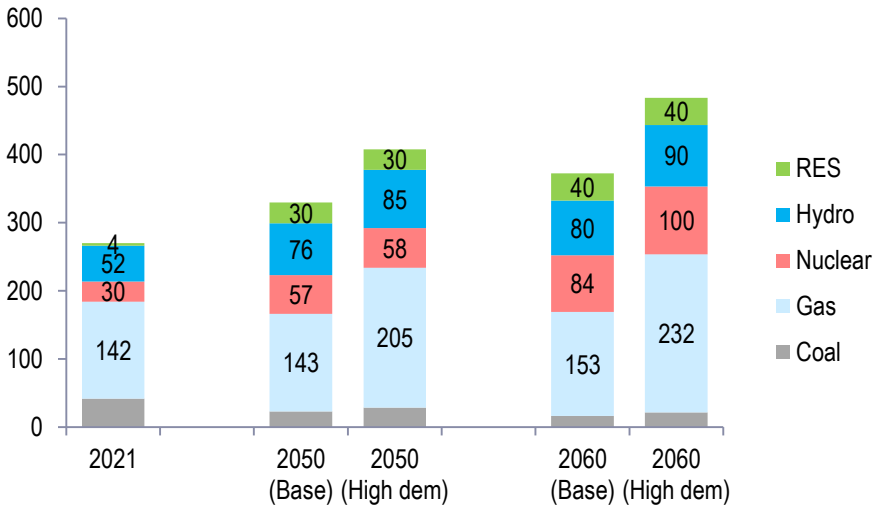
Adaptation of the electric power sector to accelerated demand growth due to "new electrification"

- To meet the domestic demand in a Base case, electricity production will increase by a third by 2050 and 55% by 2060
- An active transition from fuel to electricity in the end-use sector can additionally increase the required production volumes against the Base case by a 25% by 2050 and by a 30% by 2060
- Without carbon regulations, gas would provide the main increase in power generation, with a smaller but significant contribution from nuclear and hydroelectric sources.
- As a result, emissions from electricity and heat production would remain at 9% above 2019 levels, reducing the overall impact of electrification-oriented decarbonization efforts in other sectors.

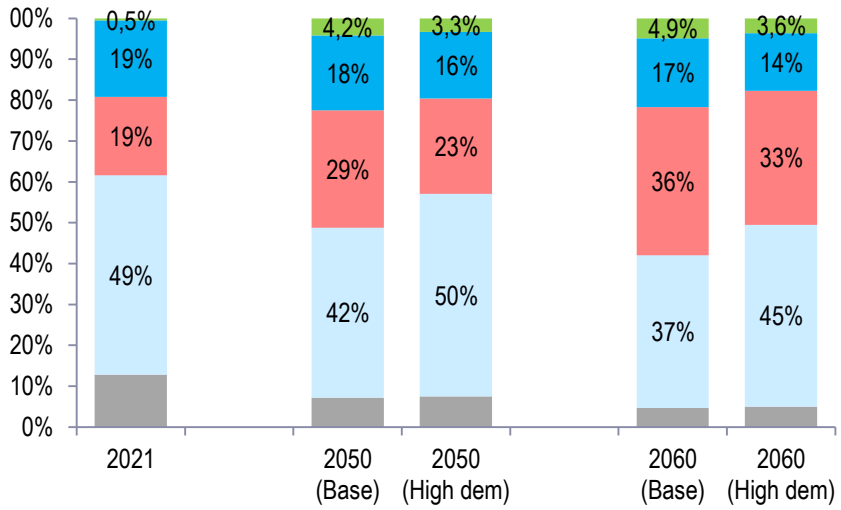
Change in annual CO_2 emissions from power plants and boilers (relative to 2019)



Installed capacity structure, GW



Electricity production structure, %

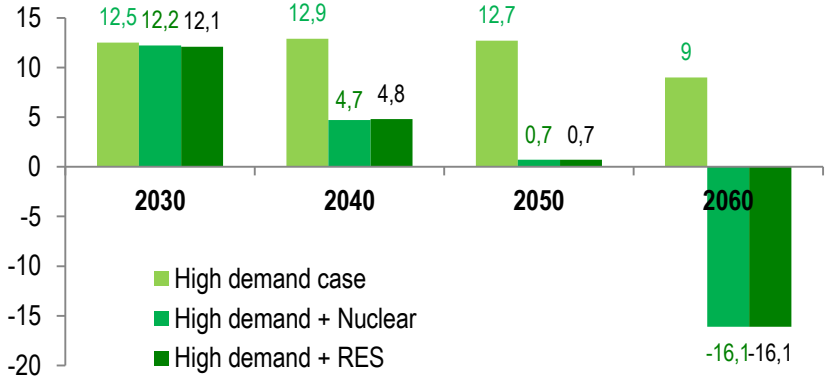


Source: ERI RAS, EPOS model

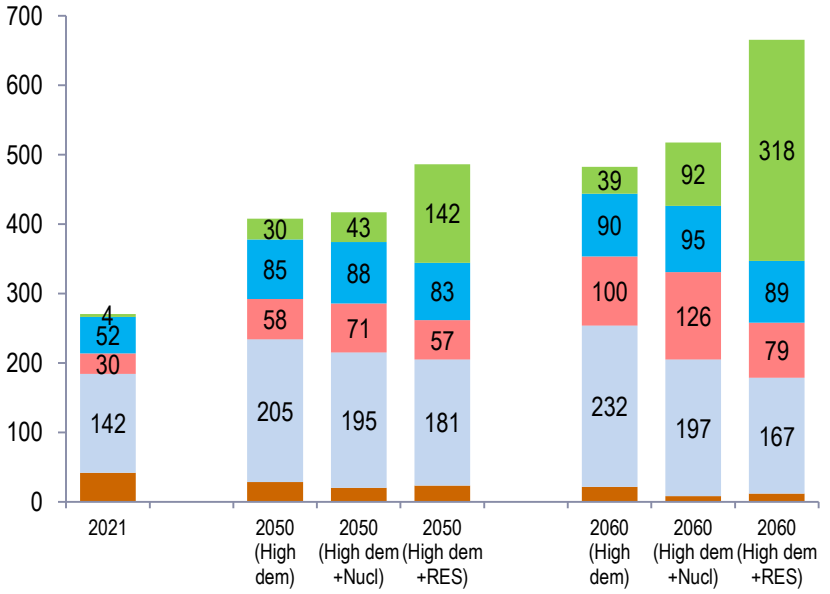
Options for reducing CO_2 emissions from power plants with an accelerated increase in electricity consumption

- A higher level of electricity production with simultaneous reduction of CO_2 emissions from power plants can be achieved by different technological strategies, for example, based on nuclear power plants or renewable energy sources.
- Using both strategies, the same level of CO_2 emissions can be achieved.
- Upper limits on the rates of commissioning of nuclear units and limited amount of sites for construction will require to develop other types of power plants.
- Focusing on renewable energy sources will require a drastic increase in reserve peaking or storage capacities

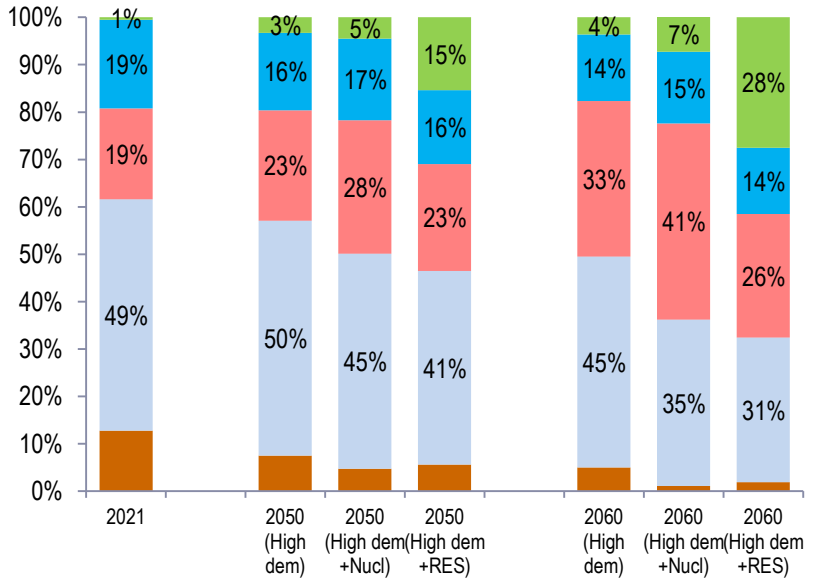
Change in annual CO_2 emissions from power plants and boilers (relative to 2019)



Installed capacity structure, GW

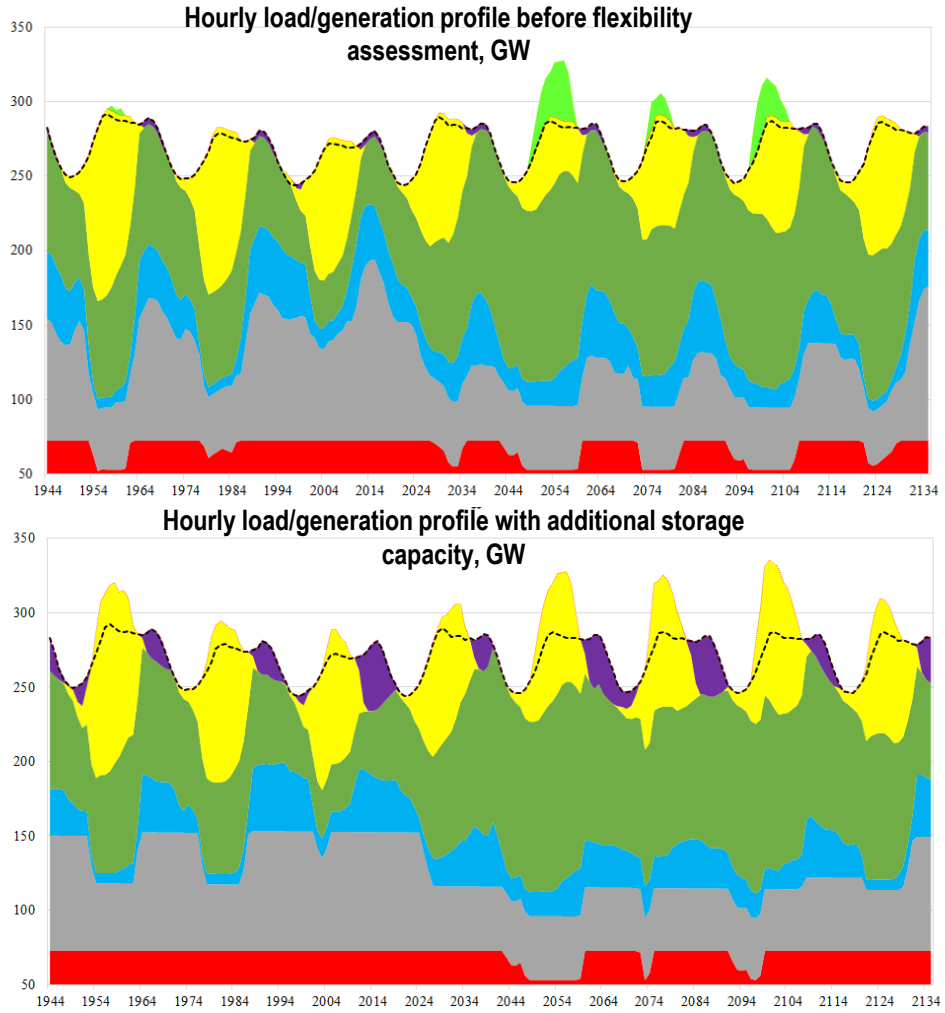


Electricity production structure, %



Source: ERI RAS, EPOS model

Assessment of additional flexibility requirements in the High demand+RES case

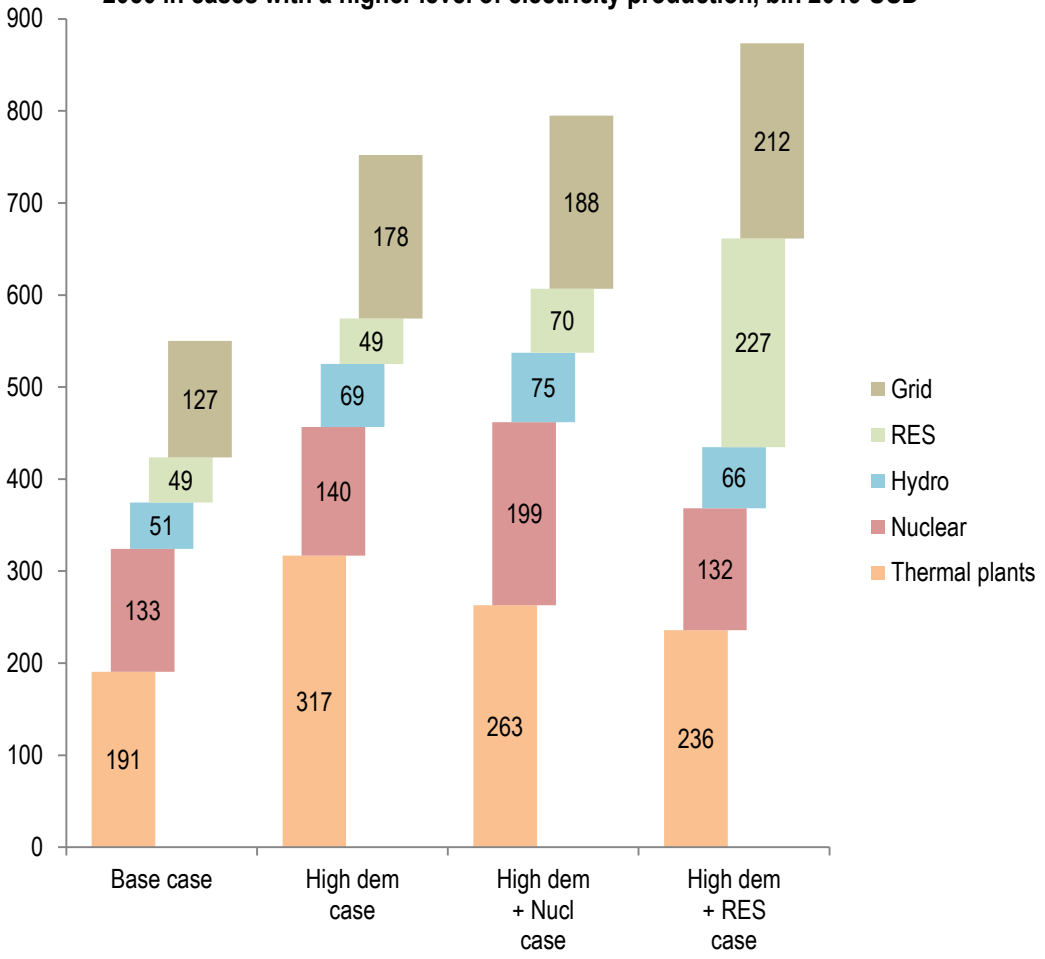


- Focusing on renewable energy sources will require a drastic increase in reserve peaking or storage capacities
- In 2060 RES will be near 50% of total capacity. The unstable operation will affect on the capacity factors of other plants as well as deficits and curtailments
- An additional assessment of flexibility using the capacity dispatching model makes it possible to find optimal storage capacity volumes to minimize imbalances.

Source: ERI RAS, MOCCO model

Economic consequences of the electric power industry's adaptation to the "new electrification" and decarbonization

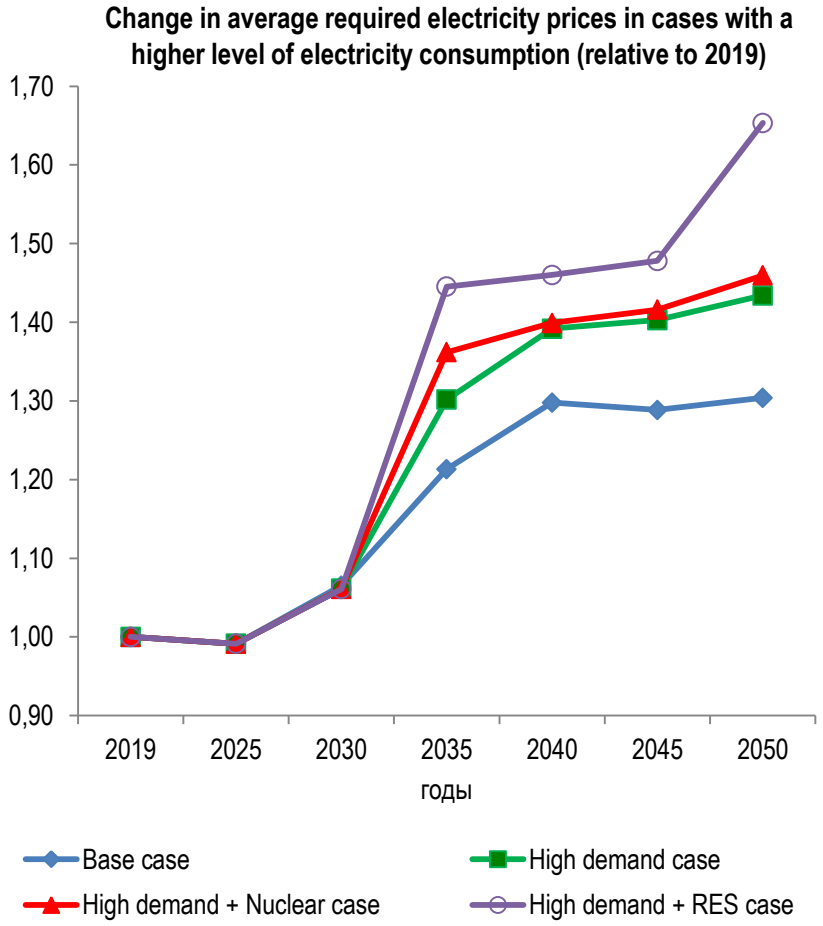
Total investment in the development of the electric power industry until 2050 in cases with a higher level of electricity production, bln 2019 USD



- A 30% increase in electricity production due to electrification by 2060 will require an increase in capital investment of almost 40%.
- At the same time, investments in gas-fired power plant development will increase by 65%.
- An additional decarbonization factor, with a higher volume of production, will require an increase in capital investment by:
  - 6% (Nuclear strategy), while investments in nuclear power plants will increase 1.5 times
  - 16% (RES strategy), while investments in renewable energy sources will grow 4 times, while in nuclear power plants they will remain at the base scenario level

Source: ERI RAS

Economic consequences of the electric power industry's adaptation to the "new electrification" and decarbonization



- Base case - significant investments in upgrading the existing power units (thermal and nuclear) will require an increase in electricity prices by 30% in real terms by 2040, followed by stabilization at this level.
- High demand case - With higher demand, the increase in investments, together with an increase in fuel costs due to the intensive development of gas-fired power generation, will require an increase in the price of electricity (in real terms) by 40% by 2040-50.
- High demand + Nuclear case - The increase in capital intensity to meet additional decarbonization goals will have little effect on the additional increase in electricity prices due to lower fuel costs.
- High demand + RES case - Higher capital investments with lower fuel cost savings will increase the price more when choosing a strategy focused on nuclear or gas
- Electrification generates negative feedback among end users through electricity prices
- Rising electricity prices may increasingly constrain the cost-effective scale of fuel substitution with electricity (or increase the amount of subsidies).
- In addition, the cost of electricity, as a key energy product, will increasingly affect the level of costs in the economy, restraining its growth.
- Estimates for Russian conditions show the elasticity of GDP to the price of electricity (-0.106). However, as electrification expands, this negative elasticity will increase.

Source: ERI RAS

Final remarks

- The electric power (EP) sector plays a unique role in the national decarbonization strategies due to (1) the provision of a resource for replacing fuels with electricity in other sectors of the economy and (2) its own technological capabilities for development of carbon-free energy sources or capturing CO_2 at the thermal plants.
- Nuclear power plants are considered the least-cost carbon-free technology for generating electricity in Russia. Even in the absence of strict carbon regulation their capacity will almost double by 2050 and triple by 2060. As a result of evolutionary change of generation mix in a Base case, CO_2 emissions from power plants and boilers in 2050-60 will be 10-15% lower than in 2019
- District heating (DH) is a second one area of fuel substitution with electricity, as well as nuclear (CHP with SMR units). But economic incentives, like carbon pricing, are required. Modeling results show that carbon prices may reduce CO_2 emissions from electricity and heat production by 50-70%, taking into account the additional demand for electricity from decarbonized DH systems.
- The electrification of the transportation sector may require 170-450 GWh in 2060. There is also high uncertainty about the impact on the load profile and peak demand depending on the EV charging behavior and infrastructure.
- The electrification in the end-use sectors may add 30% to the Base case electricity demand in 2060 and double the 2020 level. Gas-fired electricity generation is the least-cost option, but at the same time, CO_2 emissions remain high, which reduces the effect of replacing fuel with electricity in other sectors. Electrification will be accompanied by the 40% growth of investments and 40% (real) price increase by 2040-50
- Additional decarbonization targets for the EP+DH sector will require more intensive growth of nuclear or RES capacity. In the case of a strategy based on renewable energy, investment requirements and price levels are maximized due to the need for additional reserves and flexibility.
- Electrification will have the natural economic limit because of the negative feedback among end users through electricity prices, the availability and attractiveness of switching from fuel to electricity, as well as GDP growth (despite the opposite multiplier effect of investments).

Energy Research Institute of the Russian Academy of Sciences
www.eriras.ru
info@eriras.ru, erifedor@mail.ru

The research was carried out at the expense of a grant from the Russian Science Foundation No. 21-79-30013-P, https://rscf.ru/project/21-79-30013/

Thank you for your attention!