Adv Syst Sci Appl 2019; **02**; 33-43
Published online at http://ijassa.ipu.ru/index.php/ijassa/article/view/709

Potential scales of structural transformation of the Russian electric power system based on low-carbon distributed generation

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Received March 3, 2019; Revised May 5, 2019; Published July 10, 2019

Abstract: This article considers conditions and scenarios of transformation of the traditional structure of generating capacity in the Russian electric power system in the next 10-15 years considering the mass decommissioning of operating thermal power plants (TPPs) and active development of low-carbon distributed generation (DG) technologies. For this purpose, the ultimate development potential of Russia's key distributed cogeneration technology was assessed, taking into account the forecast of capacity balance situation in the national electric power system. In addition to it, the possible scales of the involvement of renewable power (RES) plants, as well as the potential impact of consumer's demand response (DR) programs to replace large-scale generating facilities are considered.

Keywords: electric power system, distributed generation, low-carbon technologies, cogeneration, renewable power plants, demand response, capacity balance.

1. INTRODUCTION

For many decades, the development of the electric power industry in most countries has mainly relied on large power plants that produce power to high voltage transmission grid. However, in recent years, the development of small power sources[†] connected to the distribution network has been more and more intensive, and this is becoming one of the key trends in the transformation of the electric power industry of the 21st century worldwide. Distributed generation (DG) becomes significant, and in some countries, such as Denmark, [1] – it is also the dominant component of the national electric power system.

The rapid growth of this segment is facilitated (to varying degrees in different countries) by several drivers that are of regulatory, technological and market nature. The most significant regulatory drivers are formed by purposeful public actions to implement the priorities of the national energy policy. Many countries, having raised the level of energy security, increase in the energy efficiency and environmental acceptability of the electric power industry as political goals, have chosen to maximize the involvement of local (primarily renewable) energy resources and the intensive development of other low-carbon cogeneration technologies using gas, biomass and biofuel, as one of the main ways to achieve these goals. The regulatory framework and economic (tariff-based, tax-related or credit-based) mechanisms for supporting such projects have made the new sector attractive for large-scale investments.

Technological drivers that have provided for a significant improvement in the DG competitiveness in recent years, based on the fold reduction in the cost of wind and solar power as a result of technological improvements and the scale effect due to the multifold equipment production growth [2-4]. According to recent estimates, in a number of countries, renewable

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[†] In this article, distributed generation includes all types of power plants with an installed capacity of up to 25 MW and that are connected to a distribution grid

energy technologies have equalized or even surpassed traditional technologies for levelized cost of electricity (LCOE), even without special incentive measures provided by the state (for example, [5]) or a higher price of carbon; for other countries, this parity is expected in the next decade.

Finally, a significant role in DG development is played by market drivers associated with the development of competitive electricity markets, due to which distributed energy supply often becomes more attractive to consumers. The opportunity to choose the supplier, the differentiation of the final price of electricity with the allocation of competitive and tariff component, the transition to hourly and even shorter pricing periods stimulate consumers to a wider, more active influence on market conditions. The demand curve for electricity is becoming more elastic, and it is distributed power that offers consumers additional options for choosing power supply conditions, based on a combination of price, reliability and quality of services. Often, consumers' own generation sources are combined with storage devices, as well as other mechanisms for price-dependent demand response (DR). It is necessary to note one more important feature of the DG, making it a more attractive investment solution in the context of slowly growing demand for electricity. Unlike power plants with large power units, distributed sources due to small power gains can more accurately balance supply and demand for electricity and capacity both in amount and territory. This significantly reduces the risks of over-investment and excess capacity.

Finally, in conditions where competitive market mechanisms are limited mainly by the wholesale level, the public regulatory actions in the retail market, the rules and validity of approval of network tariffs, the practice of cross-subsidizing in the interests of certain consumer groups (usually, population) is another incentive for consumers to the abandonment of the traditional format of energy supply through a common grid and full or partial switching to own energy sources. This driver is, for example, the main incentive for the development of the DG in the Russian energy system, since distortions in prices introduced by non-economic factors (in particular, keeping energy prices low for the population while having higher prices for other consumers) are the main economic reason for industrial and commercial consumers to choose an alternative model of energy supply [6].

Combinations of causes and incentives that contribute to the DG development in different countries are unique and affect both the technological priorities and the overall scale of this new segment of the electric power industry. One of the countries, where the influence of regulatory and technological drivers is most significant, is Germany. The active policy on the structural transformation of the electric power industry introducing renewable energy sources (RES) led to the fact that in 2015 the installed capacity of the latter exceeded 90 GW. And the majority of RES plants with a capacity below 25 MW connected to the distribution grid approached 79 GW [7]. Together with 6 GW of small thermal power plants, this amounts to more than 40% of the total installed capacity of the national electric power system. A significant DG segment was created in the UK (25 GW, or 25%, of the installed capacity) [8]. Unlike these countries, for example, in the USA, the active development of renewable energy is mostly linked with large wind farms and solar farms [9]. With a total RES plants capacity of more than 100 GW, only 18 GW have a capacity below 25 MW. Most of the DG sources in the US are thermal, cogeneration plants (17.5 GW), and the total share of the DG in the installed capacity of the national electric power system is still insignificant and does not exceed 5%.

As we shall show below, compared to other countries, the DG role in the energy system of Russia is still negligible; however, the growth rate of the small-scale power sources is noticeably higher than that of large power plants. The purpose of this article is to analyze key drivers, priorities and possible scales of the DG development for the Russian electric power industry, based on current forecasts of growth in demand for electricity, the status of existing capacities, price factors in the wholesale and retail markets.

2. DISTRIBUTED GENERATION IN THE ELECTRIC POWER SYSTEM OF RUSSIA AND THE POTENTIAL FOR ITS DEVELOPMENT

The Unified Energy System (UES) of Russia is one of the largest in the world, occupying the fifth place in the world in terms of the installed capacity and the volume of electricity production in 2016, according to EIA [10]. Staged UES formation in the 20th century took a traditional way of generating capacities concentration, construction of large power plants (up to thousands of megawatts) and development of a high voltage network (330-750 kV). At present, thermal power plants (67.7%), nuclear power plants (11.7%) and large hydro (20.3%) play the main role in the structure of installed capacity. One feature of the UES of Russia is the significant spread of cogeneration technologies (CHP), which constitute about 50% of the total capacity of all thermal power plants (TPP). Another feature is the extremely low level of renewable energy – the total capacity of wind, solar, geothermal and small hydro power plants in 2016 was about 0.5 GW or 0.3% of the total volume in the UES. At present, Russia is pursuing a rather cautious policy to stimulate renewable energy. In accordance with the current decisions of the regulator, until 2024, about 5 GW of wind and solar power will receive tariff support, but subsequently the volume of RES plants that receive support will be reduced due to the tariff growth limitations for the final consumers.

According to state statistics, in 2016, Russia had 36,000 power plants with a capacity below 25 MW (that are considered as DG in this article), and their total capacity was about 13.0 GW. Over the past 10 years, the total installed capacity of DG power plants in Russia increased by 30% (Table 1), which is twice as much as the increase in installed capacity of large power plants (15.5%). However, to date, the DG is only a small, albeit an actively growing segment of the electric power industry: for 10 years, its share in the total capacity of Russia's power plants increased from 4.5 to 4.9%, and in electricity production – from 2.0 to 2.6%.

Table 1. Assessment of the scale of the DG development in Russia in 2006 and 2016

	2006			2016		
	Installed capacity, GW	Production of electricity, TWh	Quantity, pcs.	Installed capacity, GW	Production of electricity, TWh	Quantity, pcs.
DG – total, including:	9.97	19.76	23625	12.96	27.85	36002
% of total values for Russia	*4.5*	*2.0*		*4.9*	*2.6*	
in the zone of centralized power supply	2.76	8.38	261	4.47	13.65	445
TPP	2.39	7.05	196	3.38	11.18	256
RES	0.37	1.33	65	1.09	2.48	189
in the zone of autonomous power supply (TPP)	7.21	11.38	23364	8.50	14.19	35557
The share of total indicators for the Russian electric power industry	4.5%	2.0%	-	4.9%	2.6%	-

Source: Russian State Statistical Service

In the DG structure of Russia, the dominant role is played by thermal power plants used for autonomous power supply of settlements isolated from the national electric power system (UES). Approximately 8.5 GW (that is, about 2/3 of the entire DG capacity) is operated outside any connection to the UES of Russia. The remaining 4.5 GW are used by consumers connected to the UES, to reserve supplies from the grid and to provide for themselves with electrical energy and heating. The most common types of DG are diesel, gas turbine, gas piston units, which are used as backup or peak, but mostly as cogeneration sources.

In remote and isolated from power system areas distributed generation is a natural and non-alternative investment solution, whereas within the UES boundaries its development takes place in conditions of economic competition with the traditional schemes of electricity (and also heating) supply from the grid. In recent years, the growth of the DG in Russia in the absence of special measures of their regulatory support is due to the insufficiency of market mechanisms in the retail market, because of which the cost of supplying electricity from the grid (and for new consumers – also the level of connection fee) is higher than the cost of their own production.

An important role is played by the imperfection of regulation in the heating market, where heat tariffs are less attractive for many consumers compared to the cost of heating produced from an own boiler house or a small CHP. The planned transition to the heating price formation model based on long-term marginal costs envisages that the cost of heating will be determined by a competing technology – a new boiler house. Such a change in the heating market will also contribute to the growth of its price and commercial attractiveness of distributed cogeneration power plants. This will reduce the risks of unprofitable sales of heating and will reduce the cost of electricity for consumers, based on the LCOE for CHP based on the calculation of total discounted costs for electricity and heat production.

Thus, market drivers are key factors in the DG growth in Russia, and the pace of this development depends on government regulatory actions in the retail electricity and heating markets that can make distributed generation an effective alternative to the traditional supply chain. However, speaking about the restructuring of the electric power system, it is necessary to assess the technically possible potential for changing the proportions between large and distributed sources in the context of a possible change in the balance of supply and demand in the UES.

At present, the UES of Russia has a capacity surplus, due to a suboptimal configuration of incentive mechanisms for investment into new power plants in conditions of stagnant demand. At present, it is estimated at 32 GW, and the actual power reserve in the power system is 38% and more than 2 times higher than the normative (17%).

Despite the extremely moderate forecast of demand growth, already in the period until 2025 this excess capacity may disappear, and in the subsequent period the capacity deficit in the UES will rapidly increase. The reason for this is the deterioration of a significant proportion of the existing thermal power plants, which equipment has already reached or will soon reach the service life limit. Accordingly, investment decisions on reconstruction, replacement of equipment with more efficient or final dismantling and replacement with new capacities, should be made for these objects.

Currently, the wholesale market prices of electricity and capacity are insufficient to pay back investments in the reconstruction of existing large thermal power plants. The special mechanism to support investments in such projects will be launched in 2019 but any case it will not cover the entire volume of capacities that require replacement. Under these conditions, there are high risks that significant volumes of the TPP's existing capacity will leave the market. This opens up good competitive prospects for a distributed generation to replace the retiring capacity of large power plants. First of all, this refers to the replacement of large CHPs, many of which, as a result of a sharp decline in industrial demand for heat, are forced to contain excess heat capacity. The substitution of such power plants with smaller units, which heating capacities are adequate to actual heating demand, is one of the important directions for the DG development (the quantitative estimates of such substitution are given below).

In order to assess the growing capacity deficit in conditions when the existing TPPs are shutting down, it is necessary to compare the capacity requirements of the UES of Russia with the volume of the guaranteed installed capacity of all types of power plants (Table 2). With the macroeconomic expectations of the Ministry of Economic Development of Russia[‡] the demand for electricity in the UES of Russia will increase by an average of 1.2% per year and by 2035 it will amount to more than 1300 billion kWh. Taking into account the normative

[‡] The assessment of the change in demand for electricity and the demand for installed capacity was performed on the basis of the basic version of the long-term forecast of the socioeconomic development of the Russian economy for the period until 2035, submitted to the Government of Russia by the Ministry of Economy in May 2017.

reserve margin, as well as various restrictions on the use of installed power plant capacity, the demand capacity requirement by 2035 corresponding to this forecast will exceed 250 GW.

The value of the guaranteed installed capacity of all types is determined by the following components:

- the capacity of the existing TPPs that have not yet reached the service life limits and do not require investment decisions (Table 2), which by 2035 will decrease by 71 GW and will amount to about 55% of the 2016 level. The main reduction in the size of this segment will have to occur already in the period until 2025;
- the capacity of the TPPs already under construction, the commissioning of which will be implemented in the coming years (until 2020) in the amount of 9 GW, based on the mid-term UES development plans for 2017-2023, approved by the System Operator and by the Ministry of Energy of the Russian Federation. [11];
- capacity of all types of non-carbon power plants (hydro, nuclear and RES), adopted in accordance with the long-term UES development plans approved by the Government of the Russian Federation in 2016 [12]. The capacity of nuclear power plants in the UES will increase by 7.3 GW by 2035 (by 26% from the level of 2016), the growth of large hydro plants will be about 4 GW (8% from 2016), mainly in Siberia and the Far East. The growth in the RES capacity is expected to be about 6.5 GW, mainly in the European part of the country.

Table 2. Characteristics of the forecast balance situation in the UES of Russia in the period until 2035, GW

	2016	2020	2025	2030	2035
Demand for electricity	1048.5	1096.4	1165.7	1234.8	1308.0
Demand for centralized heating	1235	1260	1285	1242	1310
Demand for installed capacity	205.0	216.1	226.8	239.6	252.0
Guaranteed installed capacity of power plants – total	236.6	245.8	188.4	186.8	189.5
Operating TPP	157.2	153.1	93.6	89.2	86.2
TPPs under construction	2.9	9.0	9.0	9.0	9.0
Nuclear	27.9	30.6	29.7	30.5	35.2
Hydro	48.1	50.7	51.2	52.1	52.1
RES plants	0.5	2.4	5.0	6.0	7.0
Excess capacity	31.6	29.7	-	-	-
Capacity deficit after 2020 – total	-	-	-38.6	-52.7	-62.5
Including due to the growth in demand	-	-	-10.7	-23.5	-35.9

Thus, the amount of the guaranteed generating capacity in the UES of Russia by 2025 will be reduced by almost 50 GW, remaining approximately at this level until 2035. Taking into account the expected in demand for electricity and capacity requirements, the need for additional (newly commissioned) capacity, which at least partially can be provided by DG sources, can reach 39 GW by 2025, and 63 GW by 2035. Based on these estimations of the potential needs for the DG, several scenarios for the mix of distributed energy technologies will be further considered, including:

I. Distributed cogeneration technologies;

II. RES based microgeneration

III. Demand management technologies.

3. SCENARIOS FOR THE DEVELOPMENT OF THE DG BASED ON COGENERATION SOURCES

From the perspective of the end-users, the problem of efficient heating supply in Russian climatic conditions is no less (and perhaps more) relevant than reliable and high-quality power supply. That is why the development of distributed energy now and in the future will, first of all, focus on new small-scale cogeneration (and in the southern regions – also trigeneration) sources. In this study, when assessing the development potential of the DG based on cogeneration, three groups were identified.

The first group consists of the DG units, which substitute the heating supply in the service area of the existing CHP plants, while the latter's capacity is reduced due to the decommissioning of the deteriorated equipment. With the introduction of market mechanisms supporting the reconstruction of existing TPP that do not take into account the low efficiency of their operation in the heating market, the reduction in their capacity as a whole in the UES of Russia by 2025 may be about 28 GW, and by 2035 – more than 30 GW. Accordingly, heating supply to consumers will decrease relative to 2016 by 30% by 2035. If this reduction in supplies is compensated for by DG cogeneration sources with a full load in the heating mode, the capacity of such plants can be about 20 GW by 2025-2030.

The second group consists of the DG units which can respond to the additional demand for heating. Given the continuing decline in the heat intensity of the Russian economy, the increase in demand for heating relative to 2016 is estimated to be a modest amount – only 2% by 2025 and about 6% by 2035. Taking into account the fact that cogeneration, as the most energy efficient way of electricity and heat supply, is a priority for the national energy policy, its share in the heat balance will increase, replacing traditional boiler houses. At the same time, heating output from CHP will grow faster than the total demand for heating, and will increase by 7% by 2025 and by 26% by 2035. In the event that all this increase in heat supply from the CHP will be provided exclusively by small sources of combined generation of electricity and heating, this will make it possible to additionally use about 5 GW of cogeneration plants by 2025 and about 18 GW by 2035.

In total, two groups of DG considered above can provide input of more than 23 GW of cogeneration plants by 2025 and 39 GW by 2035. However, this value is less than the potential balance capacity deficit that may arise in the UES during this period (Table 2). One of the ways to eliminate this deficit is an even more intensive development of distributed cogeneration. In this connection, the third group of DG is identified in this assessment, which will have to substitute the existing boiler houses in the heat balance, instead of their capital intensive reconstruction. One of the options for this replacement of boiler houses is their reconstruction into small CHP plants with the installation of gas turbine or gas piston units. According to Russian experts, the economically feasible potential of such a reconstruction of boiler houses is estimated at 60-70 GW [13]. However, based on the capacity requirements, the reasonable substitution scales should be 2-3 times smaller and will result to 17 and 25 GW of additional small CHP capacity in 2025 and 2035 (Table 3, scenario 1), respectively. This will lead to a serious structural rearrangement of the centralized heat balance with a sharp increase in the share of cogeneration (totally large and distributed CHP) from 45% in 2016 to 70% by 2035. Taking into account the high fuel utilization factor at CHP plants (up to 80-90%), even partial implementation of such scenario and structural reorganization of not only the electric power industry, but also the district heating system is attractive from the point of view of energy efficiency and ecological compatibility.

Another concomitant effect with such an active development of the CHP plants may occur in the electricity market. In general, according to the UES, the share of distributed generation can reach 21% in 2025 and more than 29% in 2035. The high efficiency of cogeneration sources, mainly based on the heating load profile, will result in their annual capacity factor (50-57%) being significantly lower than the annual load factor of the UES (about 75%). To bridge this gap in the electricity balance, it will be necessary to increase the capacity factor of the most efficient large TPPs with the lowest fuel costs, from 48% in 2016 to 64% by 2035 (Table 3, Scenario 1). In addition to the increased volumes of electricity generation at the CHP in the cogeneration mode with minimal fuel costs, this change in the electricity balance structure will help reduce the price of the spot market, reshaping the profile of the electricity supply curve [14].

Table 3. Changes in the structure of installed capacity and electricity production in the UES under various scenarios for the DG development

			DG development scenarios					
			Scenario 1 (CHP)		Scenario 2 (CHP and RES)		Scenario 3 (CHP and demand management)	
	2016	2020	2025	2035	2025	2035	2025	2035
Capacity required – total, GW	204.1	214.5	227.0	252.0	227.0	252.0	227.0	252.0
Guaranteed installed capacity - total, including:	236.4	246.0	188.4	189.5	188.4	189.5	188.4	189.5
- existing DG	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5
Excess (+) / Deficit (-)	32.3	31.5	-38.6	-62.5	-38.6	-62.5	-38.6	-62.5
DG capacity additions								
I. Cogeneration, incl.			40.3	64.0	23.3	38.8	23.3	38.8
- substitution of existing CHPs			18.6	20.7	18.6	20.7	18.6	20.7
- ensuring the increase in demand for heating			4.8	18.1	4.8	18.1	4.8	18.1
- substitution of boiler houses			16.9	25.1	-	-	-	-
II. Micro-RES			-	-	16.9	25.1	-	-
additional capacity for RES reservation			-	-	13.5 / 0§	20.1 / 0		
III. Demand Management			-	-	-	-	16.9	25.1
Electricity production – total, TWh, incl.	1048.5	1096.4	1165.7	1308.0	1165.7	1308.0	1165.7	1308.0
Nuclear	196.4	205.8	222.7	245.3	222.7	245.3	224.1	274.4
Hydro	176.5	186.5	188.8	195.1	188.8	195.1	188.8	195.1
RES plants – total	1.8	6.2	12.0	18.0	62.8	93.5	12.0	18.0
incl. RES microgeneration			-	-	50.8	75.4	-	-
Large TPPs	662.6	686.7	529.6	518.6	563.5	568.9	604.2	598.5
Capacity factor, %	48	49	61	64	57 / 65	58 / 71	69	74
Distributed cogeneration	11.2	11.2	212.5	331.0	127.9	205.3	138.0	222.0
Capacity factor, %	38	38	55	56	55	56	60	60
Decrease in annual CO_2 emissions relative to the case without DG, mln tons			-26	-44	-40	-64	-18	-44
Share of DG in total installed capacity,%	2	3	21	29	20 / 21	27 / 29	15	22
Share of DG in electricity generation,%	1	2	19	27	16	23	13	18

4. COMBINED SCENARIOS FOR THE DG DEVELOPMENT WITH RES AND DR COMPONENTS

The development of the distributed cogeneration plants can be combined with other DG technologies, including wind and solar microgeneration, as well as demand response options. Each of these scenarios has its positive sides and risks and requires more detailed analysis, which is presented below.

In the scenario of DG development as a mix of cogeneration and RES units (Table 3, Scenario 2) there are additional risks associated with ensuring the reliability of energy supply.

§ The first value when reserving additional RES with traditional TPPs, the second – for the case of combination of RES with accumulators

One risk factor is the stochastic operation of RES plants and the need to reserve their capacity. In conditions of expected capacity deficit, this will require, along with commissioning of new RES plants, to put in operation additional peaking (gas turbine or gas piston) units or to develop a lot of power storage systems that are still expensive for such mass use, including the pumped hydro storage plants.

Another risk factor is the low capacity factor of RES plants (about 20-25% for onshore wind and 10-15% for solar plants on average for the conditions in Russia). Therefore, in addition to their reservation with peaking capacities to balance the growing electricity demand in the UES, it will be necessary to increase the electricity production of thermal power plants and their capacity factor to 58% (Table 3, scenario 2). In this scenario, the replacement of large plants by a combination of distributed cogeneration and renewable sources can potentially provide for the whole UES, about 16% of the total electricity production in 2025 and about 23% by 2035.

An alternative option is a combination of RES plants with storage systems to provide controlled output of generated (and stored) electricity to the power system for a long time (4 to 6 hours). Such a solution, as in the case of the reserve capacity additions, will require more capital and maintenance costs (system integration costs), and also involves losses of about 10% of the electricity in the storage systems. As a result [15-16], the levelized cost of electricity (LCOE) at renewable energy plants in Russia, already exceeding these indicators of traditional generation (gas and coal-fired TPP and nuclear), increases by another 1.5 times (Table 4).

Table 4. Relative competitiveness of thermal, nuclear and RES plants in Russia (relative to LCOE of CCGT – 100%)

	2015	2035
Coal-fired TPP	137%	126%
Nuclear	171%	103%
Wind (capacity factor 23%)		
- without system integration costs	327%	199%
- with cost of peaking plants reservation	412%	258%
- combined with storage systems	605%	322%
Solar (capacity factor 17%)		
- without system integration costs	501%	248%
- with cost of peaking plants reservation	615%	346%
- combined with storage systems	879%	442%

The results for Scenario 2 provided in Table 3 show that integration of RES plants with storage systems will not require additional capacity reserves in the UES, but for the compensation of losses in storage process, the TPPs capacity factor will increase to 65% in 2025 and up to 71% by 2035.

Another scenario, in contrast to the two previously discussed, provides that the remaining capacity deficit is eliminated not by capacity additions, but by reducing the peak load of consumers through demand response programs. At this it is assumed that in spite of the load profile changes the forecasted electricity demand will remain the same as in other scenarios, i.e. the impact of the energy saving programs is not considered. In this scenario, to balance the electricity demand it will be required to strongly increase the utilization of practically all types of generating capacities (Table 3, scenario 3), including not only large TPPs (capacity factor will grow to 74%), but also nuclear power plants (capacity factor growth to 89%) and the sources of distributed cogeneration commissioned to compensate the retirement of large CHP plants and the increase in demand for heating (capacity factor growth from 56 to 60%).

These estimates show that intensive demand response measures can in extremis lead to a tense balance situation in terms of marginal (and effective) modes for the operation of generating capacities and, if possible, should be accompanied by energy saving measures, resulted to the demand reduction, but not only reshaping of its hourly and seasonal profile.

Otherwise, especially given the large share of CHP in Russian electric power industry, this will lead to an increase in the marginal costs of electricity generation and, as a result, an increase in electricity prices in the spot market.

Taking into account the possible implementation of DR programs, the contribution of DG to the required capacity will be the same as in previous versions, but due to the smaller volume of electricity production, its share in the total electricity production in the UES of Russia will be slightly lower: up to 15% in 2025 and about 22% in 2035.

5. CONCLUSION

The estimates of the potential for transformation the Russian electric power industry based on the use of DG sources, provided in the article, can be considered as the upper limit of its impact on the structure of the installed capacity and electricity production in the UES. Clarification of these estimates, determination of cost-effective potential will require more detailed analysis of costs and benefits, comparison of additional costs for the construction and operation of different types of DG sources, costs savings of developing large power plants, also taking into account the possible increase in environmental charges. Despite the significant differences in the mix of technological solutions, all three scenarios considered for restructuring the UES on the basis of distributed generation sources (low-carbon gas power plants, wind and solar power plants) are united by the fact that they provide a significant reduction in greenhouse gas (GHG) emissions compared with the "case as usual" option, within which the existing technological structure of generating capacities on the basis of large thermal power plants is preserved.

The main reason for this is a gain in the fuel savings of cogeneration plants having a higher efficiency in the contrast with existing steam turbine thermal power plants (on average 38.5% for gas and 34% for coal-fired TPP), which in the "case as usual" scenario will remain in operation after equipment replacement with the same one. Fuel savings makes it possible to reduce GHG emissions by 2035 by more than 40 million tons of CO_2, and the growth of microgeneration based on RES will increase this effect by about 1.5 times (Table 3). Given the possible development of economic mechanisms for constraining GHG emissions to meet Russia's national obligations under the Paris Protocol, this effect creates an additional competitive advantage for distributed generation, which can significantly facilitate the implementation of the scenarios considered.

The economic effects in the grid will be ambivalent: on the one hand, the DG development allows reducing the costs of strengthening the transmission and distribution network within the traditional “vertically-oriented” (or “up-down”) scheme of energy supply. On the other hand, the rapid growth of the DG will require additional investments into the strengthening of “horizontal” electrical connections in the distribution grid, as well as the adaptation of the electric power system to bi-directional electricity flows. Another important fact is that a significant part of the DG is the investment projects of electricity consumers, mainly industrial and commercial. Their willingness and financial ability to invest in electricity generation assets that are not related to their main type of economic activity is a separate research task that requires micro- and macroeconomic modeling.

At the same time, the state itself, as a regulator of the electricity market, can both stimulate and restrain the growth of the DG, primarily by liberalizing the rules of the retail market and reducing (albeit gradual) the amount of cross-subsidies that distort the economically feasible cost of electricity for consumers, influencing their investment choices. On the other hand, the state can ensure effective competition between the DG and large generation in the framework of the new economic mechanism for renewing large thermal power plants, which will enable them to identify the most effective locations for their replacement by new technologies.

ACKNOWLEDGEMENTS

The study was carried out with the financial support of the Russian Science Foundation (project No. 17-79-20354).

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