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Industrial microgrids as tools for managing the energy efficiency in industrial regions

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Abstract

The integration of electricity grids with technologies for small-scale distributed generation based on natural gas consumption is one of the most important innovative directions for improving the reliability and energy efficiency of power systems. Synchronous operation of large energy consumers and distributed generation systems is a new element of the electricity system. This element is an industrial microgrid, which has a unique ability to control the operating modes of the electrical energy system compared to conventional industrial electricity consumers. The aim of this study is to develop a theory and methodology for the use of microgrids in industrial areas under the market-based conditions of electricity and natural gas purchase. An analysis of trends in the use of small-scale distributed generation shows that the operation of distributed generation based on renewable energy sources is not economically feasible in all countries. In some countries, such as Russia, for example, the use of distributed energy sources powered by natural gas is the most important. The study of pricing principles for the purchase of energy in the wholesale and retail electricity markets and for the purchase of natural gas from regional suppliers and on commodity exchanges shows that managing the volatility of energy demand schedules can have a significant impact on the prices of electricity and natural gas used by industrial companies and large consumers of energy resources. As part of a unified power system, industrial enterprises and small distributed generation systems simultaneously consume electricity from the Unified Energy System, generate electricity through a distributed generation system into the internal network of the enterprise and external network the power system, and consume natural gas through the enterprise consumption system and the distributed generation system. Synchronised operation of an industrial enterprise and a small system of distributed generation system in the unified control system of a microgrid enables the enterprise to reduce the combined costs of purchasing energy resources and increase the efficiency and reliability of power supply to equipment. The article presents a system of factors influencing the demand of microgrids for electricity and natural gas consumption and develops a model for the integrated control of industrial microgrids under their integration with the technology for managing the demand of industrial enterprises for electricity and natural gas consumption. The control algorithm developed for a microgrid takes into account the cross effects of changes in its energy and gas demand, energy market price factors, internal constraints for industrial load management, external external of the Unified Energy System and the Unified Gas Supply System, and the ability to meet the energy demand of external consumers of the microgrid. The paper is of scientific and practical importance and can be used in the process of developing, implementing and managing microgrids at industrial enterprises in Russia and around the world.

Keywords: industrial power supply, power cost, distributed generation, industrial energy management, energy consumption, natural gas consumption, electricity market.

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工业区域中作为能源效率管理工具的分布式发电工业系统

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简介
将电网与基于天然气消费的小型分布式发电技术相结合，是提高电力系统可靠性和能源效率的关键创新方向之一。 大型能源消费者与分布式发电系统的同步运行构成了电力系统的新元素。该元素即工业微电网，与传统工业用电消费者相比，具备独特的电力系统运行模式管理能力。 本研究的目的是在电力和天然气市场条件下，制定在工业区使用微电网的理论和方法。对小型分布式发电使用趋势的分析表明，基于可再生能源的分布式能源在所有国家中并不都是经济上可行的。 例如，在俄罗斯，使用以天然气为燃料的分布式能源是最为切合实际的。研究在批发和零售电力市场上采购电力以及向区域供应商和商品交易所采购天然气的定价原则表明，管理能源需求波动可以显著影响工业企业和大型能源消费者所用的电力和天然气价格。 工业企业和小型分布式发电系统作为统一能源综合体的一部分，同时从统一能源系统消耗电力，通过分布式发电系统向企业内部网络和外部能源系统网络发电，并同时通过工业企业的燃气系统和分布式发电系统消耗天然气。在统一的主动能源综合管理系统框架内，同步工业企业与小型分布式发电系统的运行，可以降低企业能源资源采购的综合成本，提高设备的能源供应效率和可靠性。本文提出了影响主动能源综合体电力和天然气消费需求的因素体系，并开发了一种在与工业企业电力和天然气消费需求管理技术相结合的条件下，对主动能源综合体进行综合管理的模型。所开发的主动能源综合体管理算法能够考虑主动能源综合体内电力和天然气需求变化的相互影响、电力和天然气市场的价格因素、工业企业内部负荷调节的限制要求、统一能源系统和统一供气系统的外部系统限制，以及满足主动能源综合体外部用户电力需求的可能性。研究结果可以在俄罗斯和全球工业企业开发、实施和管理主动能源综合体的过程中使用。
关键词： 工业电力供应、电力成本、工业能源管理、能源消耗、天然气消耗、电力市场。

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Introduction

Since the dawn of industrialisation, the global fuel and energy sector has undergone significant changes, creating a number of specific industries, such as electricity, oil, gas, and coal. The energy systems of most countries have become the most important infrastructure and backbone sectors of the economy, the efficiency of which determines the quality and cost of the products manufactured in a country. In today's conditions, the fuel and energy sectors determine the vector of strategic industrial and territorial development of the countries of the world. The global fuel and energy sector is characterised by ever-increasing demand for the consumption of energy resources. Over the past 50 years, the average annual increase in the world's consumption of fuel and energy resources has amounted to 2.1%. The economic development of any territorial entity is inseparable from an increase in the consumption of energy resources to ensure the functioning of growing industries and territorial agglomerations, as well as the growing needs of the population.

The main fuels and energy resources consumed in the world are oil, natural gas, coal, and nuclear energy, the use of which is converted into electricity and thermal energy. Electricity is generated by hydroelectric and renewable power plants, which are primarily based on the conversion of solar, wind and hydroelectric energy.

Figure 1 shows the world consumption profiles for different fuel and energy resources in the period 1965–2020. The consumption of fuel and energy resources is increasing in all cases, but at different rates. For example, the growth of natural gas consumption is characterised by the same rates for all 56 years, while the rate of an increase in consumption of oil, coal, and nuclear energy varies significantly.

Irregularities in the consumption patterns of different fuels and energy resources are mainly related to economic, technological and environmental characteristics. The decline in the rate of oil consumption since the early 1970s is due to rising prices on world oil markets. The decrease in the growth rate of nuclear energy consumption is due to environmental restrictions and the suspension of the construction of many nuclear power plants following the accident at the Fokushima-1 nuclear power plant in Japan in 2011. The increase in coal consumption since 2007 is due to the growth of Asia-Pacific economies with their access to coal reserves. The growth in electricity generation based on renewable energy technologies (RES) is due to the intensification of their development after the beginning of the 2000s.

The difference in the structure of consumption of fuel and energy resources is not only in the level of development of the world fuel and energy sector. The structure of the energy mix is highly differentiated in the territorial and national contexts. Figure 2 shows the structure of fuel and energy consumplion for electricity generation in the countries of the world in 2020. While natural gas accounts for 38% of electricity generation in North America, it accounts for 18% in South America. In the Middle East, 28% of electricity is generated from oil, and in Europe, APAC, and the CIS, the share is no more than 2%.

Taking into account the constantly increasing cost of primary energy resources on world markets, the depletion of primary fuel and energy resources in most countries, the intensive growth of energy demand and the significant environmental impact of the energy industry, most countries are currently developing the concepts of 'energy transition', or 'energy turnaround' (German: Energiewende). The concept of energy transition is based on the gradual replacement of fossil fuels with renewable energy sources.

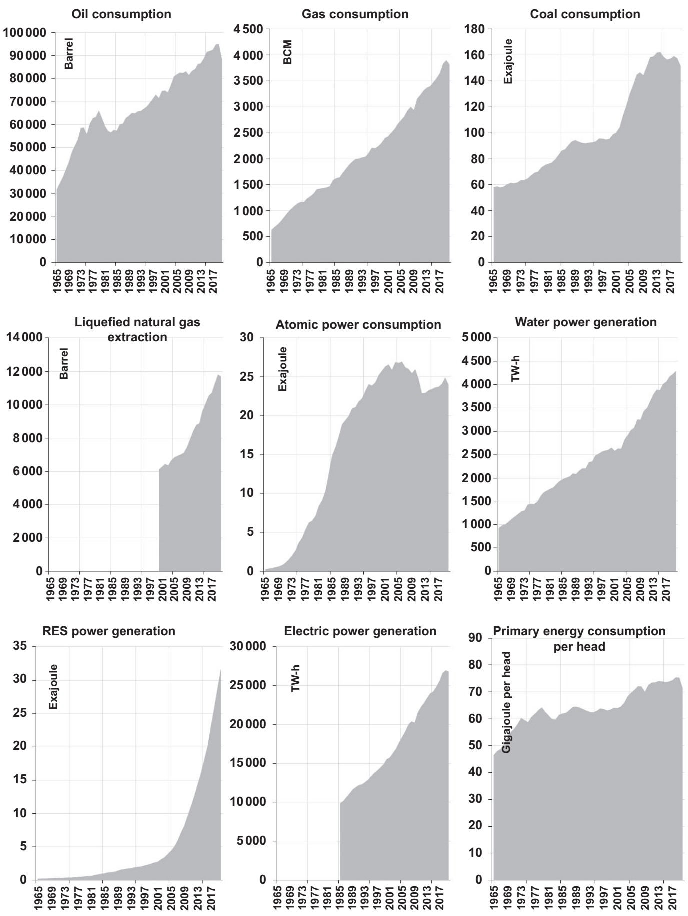
Figure 3 shows graphs of the installed capacity of RES power plants in 2011–2020. The growth rate of installed solar capacity in the last decade of the period was 29% per year, while wind generation averaged 14% per year. According to 2020 results, the share of electricity consumption based on RES was 98.4% in Norway, 84.1% in Brazil, 80% in New Zealand, 68.4% in Sweden, 67.7% in Canada, etc. These statistics include both large hydro plants and distributed generation. The fact that the share of renewable energy generation is high in many countries and is increasing year on year once again confirms the prospects for the development of distributed energy and RES around the world.

Figure 4 shows statistics on the volume of production and import (export) of different types of energy resources in 2020 for the top 10 largest countries. As can be seen from the graph, Russia is the third largest producer of energy resources in the world, after China and the United States. Russia's share in the global energy mix is 10% of the global energy resources consumed. In 2020, 47.6% of the energy produced was exported. Russia is the world's second largest oil producer after the United States. In 2020, 45.7% of oil produced was exported. In terms of natural gas production, Russia is second only to the United States, and well ahead of most of the world's economies that produce natural gas, accounting for 17.6% of the world market. The share of Russian exports of produced natural gas is 34.2% in 2020. Russia is the third largest exporter of liquefied natural gas (LNG), a market that is actively developing. Russia ranks sixth in the coal production market, with 45.9% of coal production exported. In 2020, Russia was the world's fourth largest electricity producer.

The share of natural gas consumption in the structure of fossil fuels used in Russia in 2020 was 75.5%. In most countries of the world, this figure is significantly lower, averaging 33.4%. The domestic production of natural gas in Russia determines the pricing policy for natural gas on the domestic market, the cost of which is one of the lowest in the world. It averages $ 100 per thousand cubic metres, which is more than 10 times lower than in Sweden, Spain, the Netherlands, Italy, France, etc., and more than 5 times lower than the average world price.

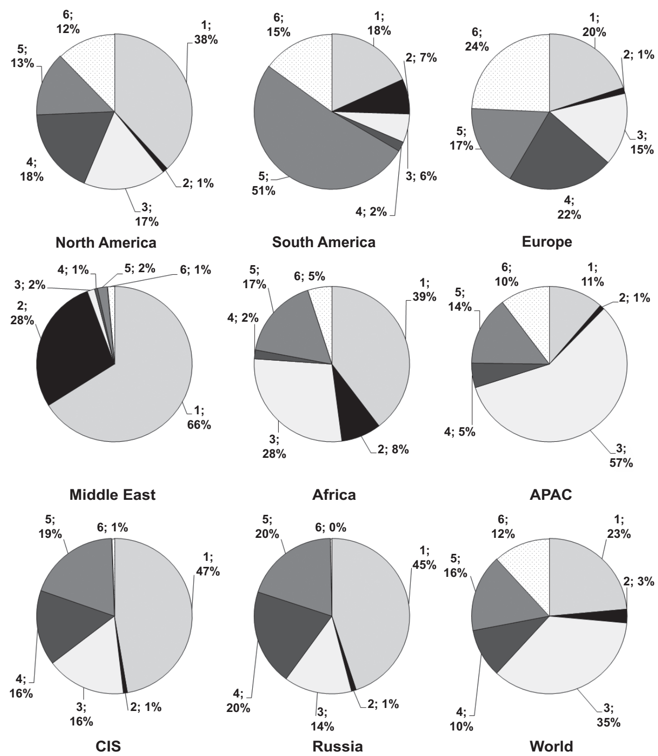
The cost of natural gas supplied to the Russian domestic market and the high share of natural gas consumption in the structure of electricity generation determine the prices of the supplied electricity sold to the country's domestic market. The average cost of a kilowatt-hour of electricity supplied in Russia is on average 8 cents, which is 2 times lower than in France, Spain, and Hungary and more than 3 times lower than in Great Britain, Germany, Denmark, etc.

Fig. 1. World consumption profiles for different fuel and energy resources for the period 1965–2020



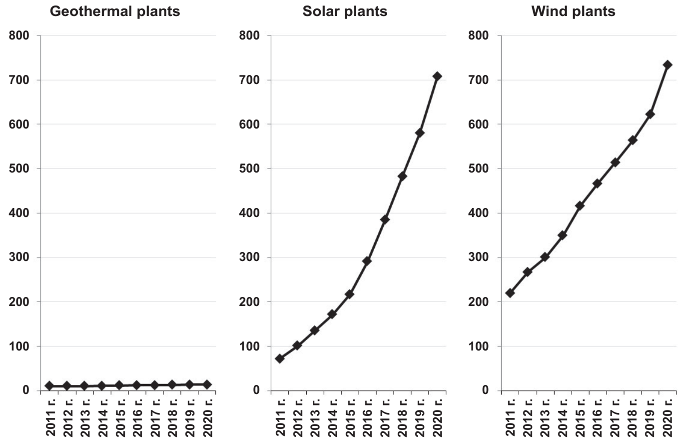
Source: Statistical review of world energy: Materials from the official British Petroleum website. https://www.bp.com/.

Fig. 2. Structure of consumption of fuels and energy resources for electricity generation in the regions of the world in 2020 (1 is natural gas, 2 is oil, 3 is coal, 4 is nuclear, 5 is hydro, and 6 is RES)



Source: Electricity information 2020 IEA. Report of International Energy Agency. http://data.iea.org.

Fig. 3. Installed capacity of RES power plants in 2011–2020 in GW



Source: Electricity information 2020 IEA. Report of International Energy Agency. http://data.iea.org.

The growing demands for electricity consumption and for the construction of new industrial facilities or increasing the capacity of existing technological links determine the need to find modern solutions to improve the efficiency of power supply to industrial enterprises. We believe that these circumstances determine the priority of the development of Russian small-scale distributed power generation based on natural gas.

The installation of small distributed generation systems (SDG) has a number of economic advantages.

- Payment for the cost of electricity transmission services and sales surcharges from regional electricity suppliers are excluded.
- Payment for the cost of electricity as part of electricity purchasing cost is excluded.
- Costs for technological connection and increase of operational connection capacity are excluded.
- Losses during the electricity and heat transportn are minimised [Abdulkareem et al., 2021].

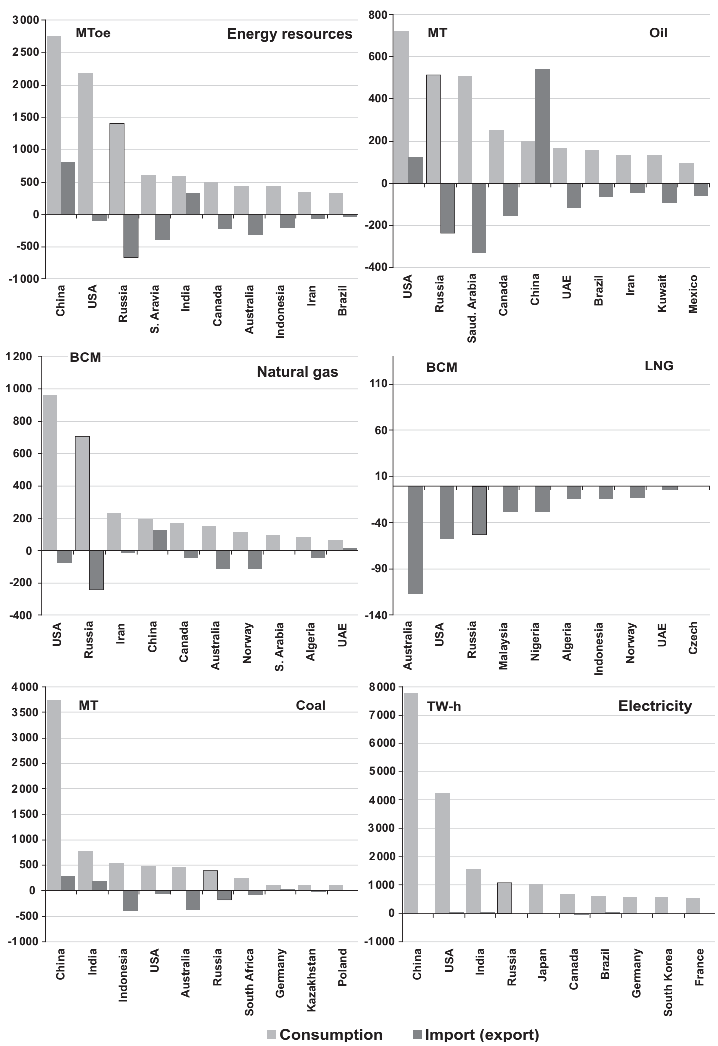
The low cost of electricity in Russia makes the global trend towards intensive deployment of renewable energy sources relatively less relevant for Russia. In 2020, the share of electricity generation from RES (excluding large hydroelectric power plants) was 41% in the UK, 28% in Finland, 19% in Brazil, 12% in Japan, but only 0.32% in Russia. The low share of RES electricity generation in Russia is related to the uncompetitive prices of RES electricity generation compared to conventional electricity sources using relatively cheap natural gas.

Now the trend in Russia is the growing demand for electricity from existing and new industrial enterprises. Russia's power grid infrastructure was built in the days of the USSR. Power transmission facilities are distributed among the industrial sites for which the power grids were built, and despite the fact that the distributed capacities are not fully utilised, their distribution in favour of other electricity consumers is impossible.

According to modern Russian and world legislation in the field of technological connection to power grids, with the exception of certain cases, the consumers of electricity pay all the costs of performing works to increase the permissible power for the consumer. Thus, if it is necessary to increase the permitted power consumption, the enterprise has to pay all the costs of increasing the power of supply transformers, strengthening cables, building cells, etc. In some cases, the cost of increasing the connected capacity of an industrial enterprise can be in excess of $ 1 million for 1 MW of additional allowable power.

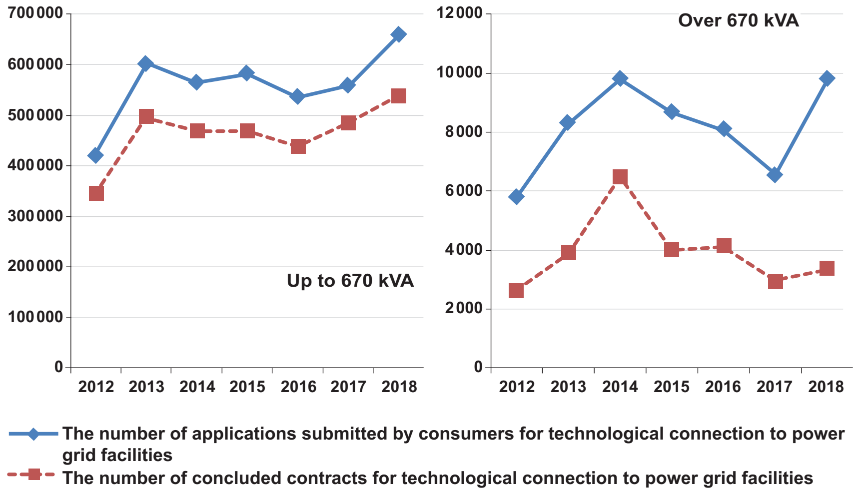
Figure 5 shows the number of submitted and satisfied applications for technological connections to power grids with a maximum power of up to and over 670 kVA in Russia in 2012–2018. The number of applications submitted by consumers for technological connection to power grid facilities of power grid organizations significantly exceeds the number of concluded contracts for technological connection to power grid facilities. The same trend is observed in many countries of the world.

Fig. 4. Production and import (export) volumes of energy resources for the top 10 largest countries in 2020



Sources: World energy balances 2020 IEA. Report of International Energy Agency. https://www.iea.org/reports/key-world-energy-statistics-2020/energy-balances; Russian statistical yearbook. Rosstat, 2020.

Fig. 5. Number of submitted and accepted applications for technological connections to power grids with a maximum power of up to and above 670 kVA



Sources: Ministry of Energy of the Russian Federation. https://minenergo.gov.ru/; PJSC "Rosseti". https://www.rosseti.ru/; Unified interdepartmental statistical information system. https://fedstat.ru/.

- The probability of overpaying for electricity and heat due to errors in the consumed energy resources is significantly reduced.
- Small distributed generation systems have the following technological advantages.
- It is possible to regulate the load of distributed generation according to the characteristics of a company's performance.
- The reliability of the energy supply increases.
- The quality of the electricity consumed increases.
- It is possible to control the reactive power balance [Liu et al., 2019].

According to the estimates of the EnergyNet Infrastructure Center, Russia, realising the potential of distributed energy will allow the Russian economy to receive economic benefits of up to 150 billion rubles ($ 2.5 billion) in 2020–2028, taking into account the deduction of investment costs [Lin et al., 2021]. One of the modern ways of using and developing the distributed generation (DG) systems is operate them as microgrids.

1. Analysis of research studies on the use of distributed energy

Modern foreign scientific research into the use of distributed generation technologies is largely devoted to simulating the operation of DG systems with a centralised power supply system and increasing the sustainability of consumer power supply. Studies [Beltrán, 2020; Matos et al., 2021] investigate increasing the stability of parallel operation of distributed generation systems with centralised power supply systems. Studies [Martínez et al., 2021; Sandhya, Chatterjee, 2021] focus on reducing failures and improving the quality of power supply for distributed generation systems. Studies [Anuradha et al., 2021; Baghbanzadeh, 2021] focus on reducing losses during operation and distribution of electricity generated by DG systems.

Many modern studies in the field of application of distributed generation systems deal with the problems of integration with modern digital control and management systems. The intelligent control of distributed generation systems is studied in [Howlader et al., 2015; Kakran, Chanana, 2018; Li, Chen, 2022]; the execution of digital behavior simulation of DG systems is carried out in [Belmahdi, El Bouardi, 2020; Valencia et al., 2021]; and the researches [Rahiminejad et al., 2016; Menke et al., 2019] focus on the improvement of digital monitoring and planning the operating modes of DG systems.

Since the development of electricity markets in most countries of the world has reached a high level, a significant part of the global studies in the field of distributed generation focuses on the integration of distributed energy with energy market pricing mechanisms. Examples of such works are studies [Craig et al., 2018; Abdulkareem et al., 2021] dedicated to improving the quality of planning and analysis of energy markets in the context of integration of the energy system with distributed generation sources. Studies [Yu et al., 2018; Liu et al., 2019] address the issue of economic modelling of options for the operation of DG systems in energy markets. Studies [Kumar et al., 2018; Lin et al., 2021] have contributed to the simulation of the distributed generation operation, taking into account the signals and characteristics of the energy market.

Much scientific research is devoted to the use of RES-based distributed generation [Garlet et al., 2019; Samper et al., 2021; Zhang et al., 2021] and industrial energy storage systems [Yanine et al., 2019]. Articles [Howlader et al., 2016; Nakada et al., 2016; Wang et al., 2018] focus on the integration of distributed energy with modern control and management technologies. The problem of improving the reliability of power supply to consumers, taking into account the operation of distributed generation systems based on demand response is studied in [Poudineh, Jamasb, 2014; Nejad et al., 2019].

Many Russian scientists have also devoted their work to the use of distributed energy systems. The problem of improving the reliability of power supply systems is studied in [Nepomnyashchiy, Ilyushin, 2013; Rytsova, 2018; Khudyakov et al., 2020]. Distributed energy systems in technologically isolated areas of the country are studied in [Chulyukova, 2019; Nurmukhametov, 2020; Sichevsky, Dolgopol, 2020]. The studies [Kuchin et al., 2010; Ragutkin, 2013; Abramovich, Sychev, 2016; Eljrushi et al., 2019; Pogodin, 2019; Tepchikov, Stashko, 2019; Lukyanov 2020] focus on improving the quality of electrical energy. Russian scientists devote their research to the issues of reducing power losses in distributed generation systems [Ilyushin et al., 2019; Myshkina, 2019]. The effectiveness of electricity cogeneration in distributed energy supply systems and highliting the advantages compared to generation of a single type have been evaluated in [Pivnyuk, 2008; Safonov et al., 2016; Dormidonov, 2019]. The problem of increasing the efficiency of distributed energy sources based on cogeneration technologies has been studied in [Lachkov, Fedyaev, 2015; Makarova et al., 2018; Nalbandian, Zholnerchik, 2018].

Despite the wide range of research areas in the field of distributed generation, not so many modern scientific studies pay attention to the use of microgrids and develop methodological approaches to the integrated control of electricity and natural gas purchase costs in the control of microgrids at Russian industrial enterprises [Dzyuba, Semikolenov, 2021a; 2021b; Dzyuba et al., 2022].

An industrial microgrid is an electric power generation facility with an installed generating capacity up to 25 MW, which has direct electrical connections with power receivers of an industrial electricity (power) consumer and only one electrical connection to the Unified Energy System and simultaneously regulates and controls power generation and consumption within a single balance flow. The control process takes into account the possibilities of pricing parameters for the purchase of electricity (power) and natural gas in the current conditions of the energy market and the existing technological restrictions on the permitted power consumption by the power receivers. All components of the industrial microgrid are synchronously controlled on the basis of intelligent functionally integrated devices.

2. Development of methodological foundations for microgrids of the electricity market

Distributed generation systems using natural gas are generally installed near the production sites of large industrial enterprises or directly on the territory of such enterprises. Usually, the electrical load of such enterprises is the main one for DG systems. When designing the power and operating conditions of a generation system, the characteristics of the electricity and power consumption of the base enterprises are taken into account.

It is advisable to locate distributed generation systems close to the sites of electricity consumers for the following reasons.

- Marketing of both electricity and heat energy is possible.
- The systems are located close to distribution gas pipelines.
- The generated electrical and thermal energy is transmitted directly to the consumer with low losses.
- It is possible to synchronise the operating modes of the plants when producing and consuming both electric and thermal energy.
- No need to pay for the transmission through regional electricity networks.
- No need to sell the generated electricity according to the rules for the subjects of the wholesale electricity (capacity) market.
- No need to control a power plant with the dispatching participation of regional and unified energy systems.
- The environmental impact when generating electricity and heat is reduced.
- It is possible to regulate the demand for electricity and natural gas consumption from the Unified Energy System and the Unified Gas Supply System (for enterprises operating in Russia) [Dzyuba, 2020; Dzyuba, Solovyeva, 2021a].

A distributed generation system has a direct electrical connection to the power receivers of an energy consumer, which provides a unified operating system for the consumer and the DG system. The power receivers of both the energy consumer and the DG system also have a parallel connection to the Unified Energy System, which determines the possibilities and limitations for controlling the microgrid system.

Figure 6 shows the structure of a microgrid based on a typical industrial enterprise. The industrial enterprise has consumers of electricity and natural gas that use energy resources for both basic production needs and for auxiliary needs of the enterprise.

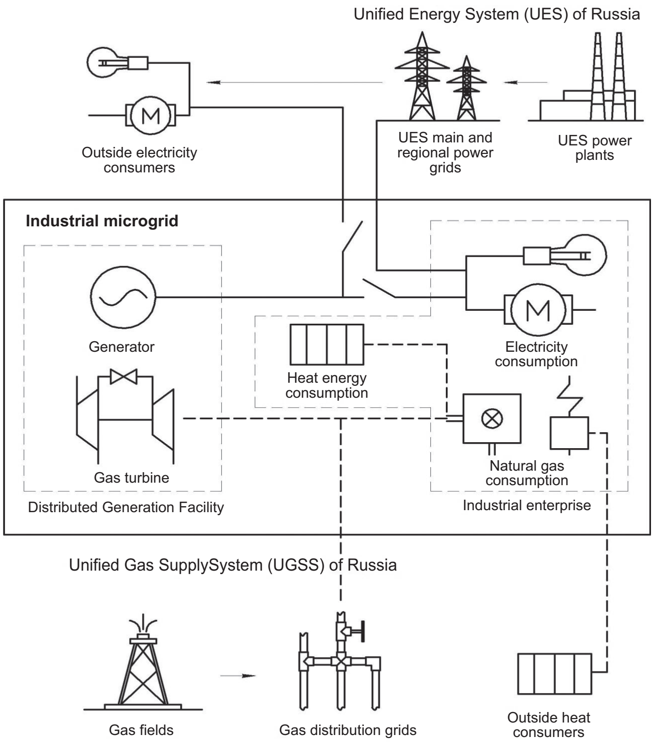
The distributed generation plant also has a generator that produces electricity and a gas turbine that produces high-pressure steam to run the generator. The gas turbine is connected to the gas supply system of an industrial enterprise and consumes natural gas to run the generator and generate electrical energy for the electrical network of an industrial enterprise. A system of electricity and gas supply to an industrial enterprise has technological connections with the Unified Energy System and the Unified Gas Supply System.

The operation modes of electricity and gas-consuming facilities of an industrial enterprise should be synchronised with each other not only directly, i.e. the generation of electricity by a generator, the consumption of electricity by an industrial enterprise, and gas consumption by a distributed generation system and the natural gas consumers of the enterprise, but also comprehensively, i.e. the system of generation and consumption of electricity should be synchronised with the consumption of natural gas.

The management of an industrial microgrid is further complicated by the fact that the power and gas supply systems of the industrial microgrid should be synchronised with the Unified Energy System and the Unified Gas Supply System, with which the industrial enterprise and the microgrid as a whole operate in parallel within a single technological, regulatory, and economic environmental control.

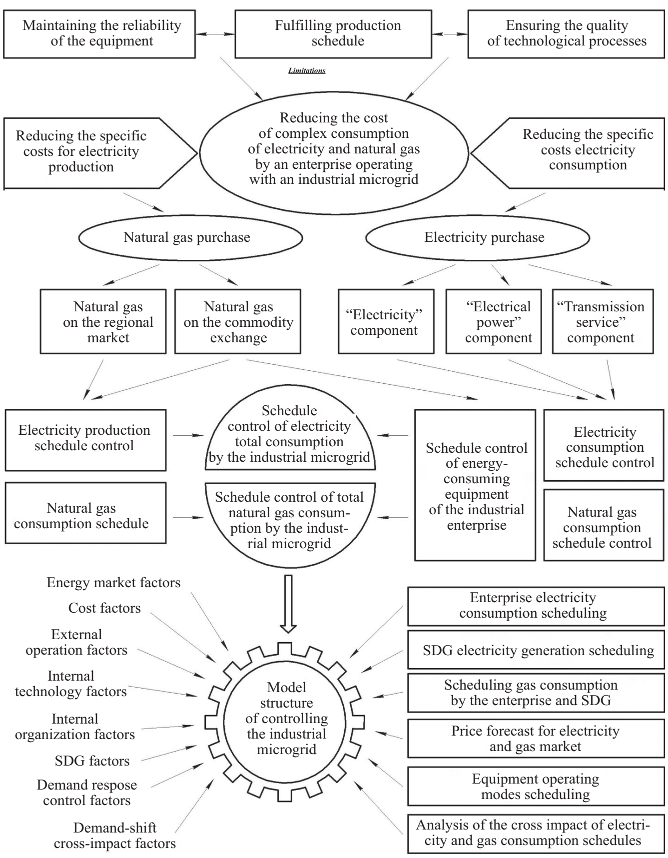
Figure 7 shows the proposed methodological approach to the control of industrial microgrids operating in industrial enterprises. The target function of implementing the methodological approach is to reduce the cost of complex consumption of electricity and natural gas by the industrial microgrid. The limits of the microgrid control are maintaining the reliability of the equipment of an industrial enterprise and

Fig. 6. Industrial microgrid structure



Source: compiled by the authors.

Fig. 7. Structure of a methodical approach to control microgrids of an industrial enterprise



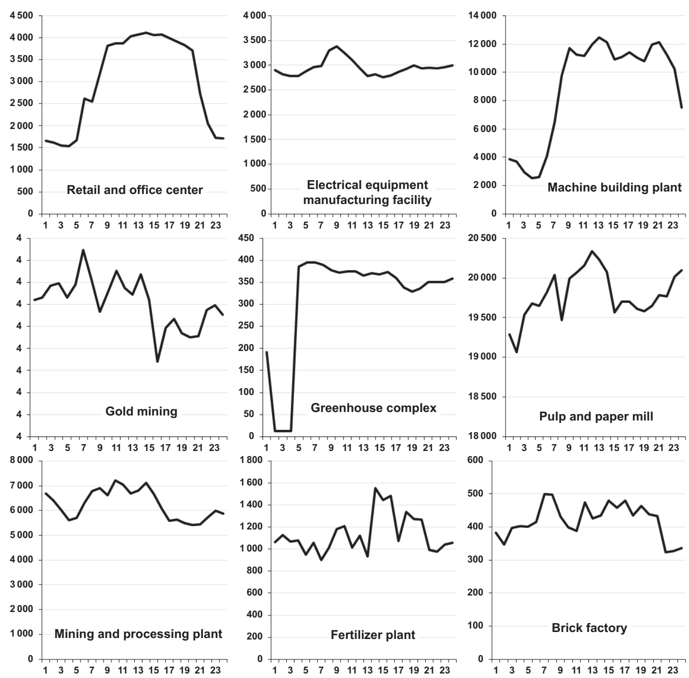
Source: [Dzyuba, Semikolenov, 2021b].

the distributed generation system, meeting the production schedule of the industrial enterprise and ensuring the quality of technological processes in the industrial enterprise and the DG system. In order to achieve the target function, it is necessary to achieve the conditions of synchronous simultaneous reduction of specific costs both for the electricity production by the DG system and for electricity consumption.

When controlling the cost of purchasing natural gas, it is necessary to take into account the cost of purchasing both on the regional market and on the commodity exchange. When purchasing electricity, it is necessary to take into account the purchase on both the wholesale and retail electricity markets for all main components: the cost of electricity and the cost of electricity transmission services.

The control of the electricity and gas purchase cost parts for an industrial microgrid is based on the total simultaneous control of the electricity production schedule of the distributed generation system. Electricity is supplied to the internal network of an industrial enterprise according to the schedule of electricity consumption of an industrial enterprise from the Unified Energy System and the schedule of natural gas consumption by a DG system and gas-consuming equipment of an industrial enterprise. This results in the control of the schedule of total electricity and natural gas consumption by the industrial microgrid. The proposed methodological approach to control the industrial microgrid of an industrial enterprise can be adapted to the infrastructure of energy markets in various countries of the world, where the circulation of electricity and natural gas is carried out within competitive pricing models.

Fig. 8. Hourly graphs of the standard day electricity demand for different types of consumers



Source: [Dzyuba, Solovyeva, 2021b].

3. Industrial microgrid control integrated with the demand management technology

The shape of the electricity demand curve for an industrial enterprise operating in any country in the world is uneven due to the peculiarities of the operation of the main and auxiliary power consuming equipment [Matos et al., 2021]. Figure 8 shows examples of hourly graphs of standard day electricity demand for different types of consumers. Depending on the specifics of an industrial enterprise, the shapes of the electricity demand curves are individual, which is expressed in the nature of the daily peak, the volatility of the load schedule, the ratio between the daily maximum and the night minimum, etc.

The characteristics of the daily demand curves for different types of industrial enterprises result from the characteristics of the energy-consuming equipment that forms the demand for electricity, and the characteristics of the production processes and equipment operation schedules. Figure 9 shows examples of an energy consumption schedule and industrial equipment operation shedules. It shows that, depending on the modes and operating times of the equipment operating in an industrial enterprise, electricity is consumed from the Unified Energy System with an unevenness formed by the operation of production equipment.

The unevenness of work schedules and control parameters of power-consuming equipment in industrial enterprises is associated with the influence of a number of the following factors.

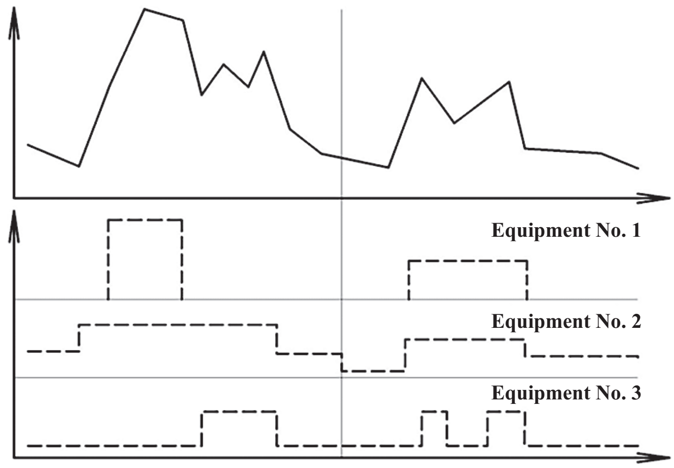
Production factors are factors that influence the change in the schedules of power consumption of industrial enterprises, related to the schedules of production processes and the schedules of the production equipment in an industrial enterprise.

Operational factors are factors influencing changes in the schedules of power consumption of industrial enterprises when controlling operating modes of equipment within the production of specified product groups.

Meteorological factors are factors influencing changes in the electricity consumption schedules of industrial enterprises caused by the influence of changes in environmental indicators, such as air temperature, illumination level, precipitation intensity, etc.

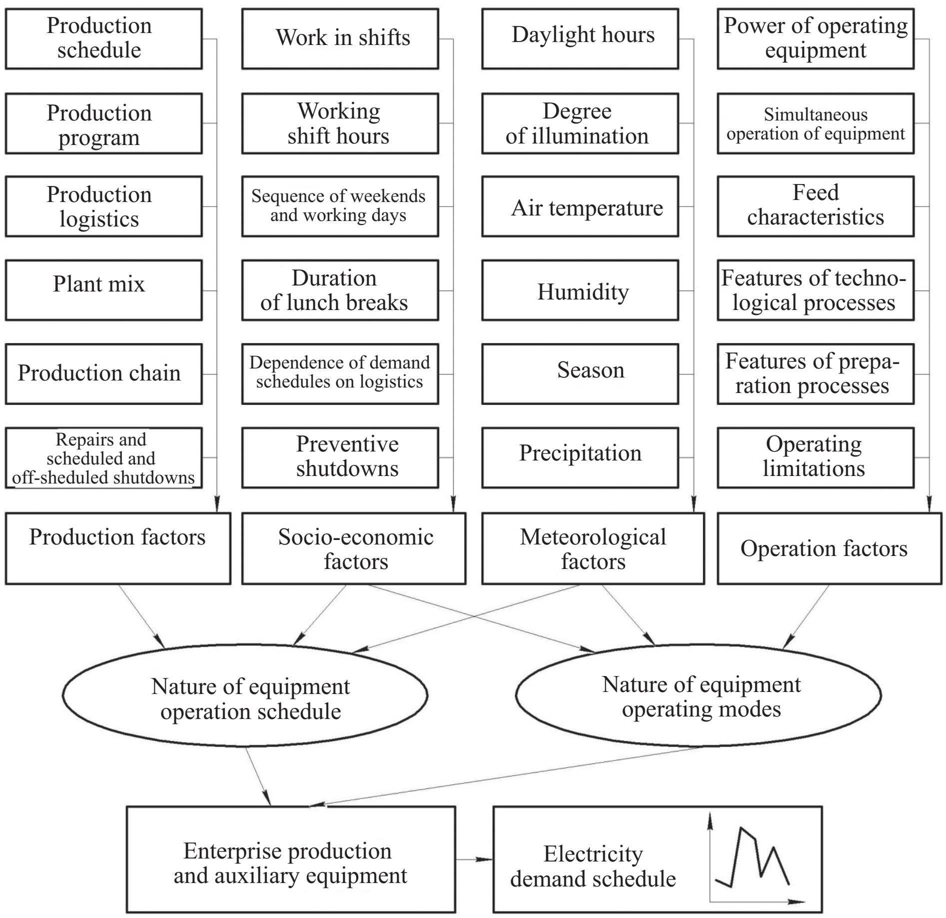
Socio-economic factors are factors influencing the change in the electricity consumption schedules of industrial enterprises associated with the influence of the schedules of

Fig. 9. Electricity consumption schedules and operating schedules of industrial enterprise equipment



Source: [Dzyuba, Semikolenov, 2021b].

Fig. 10. Structure of the influence of different factors on the uneven demand for electricity consumption in an industrial enterprise



Source: compiled by the authors.

the enterprise, its work in shifts, and the sequence of weekends and working days.

Production and regime factors have a direct effect, while meteorological and socio-economic factors have an indirect effect on the working hours of production and auxiliary equipment in industrial enterprises. The structure of the influence of various factors on the uneven demand for electricity consumption at an industrial enterprise is shown schematically in Figure 10.

The existing instruments of the wholesale and retail electricity markets in Russia and in most countries of the world provide, firstly, for the formation of the final cost of electricity based on the cost of its individual components, and secondly, for the formation of each component of the cost for the industrial consumer individually. The peculiarities of the uneven schedule of electricity demand for a particular consumer should be taken into account.

The cost of electric energy purchased by Russian industrial enterprises consists of the cost of electricity, the cost of electric power, and the cost of electricity transmission services [Dzyuba, Solovyeva, 2020a; 2020b].

The ‘Electricity’ component of the cost reflects the payment per unit of electricity generated by the power plants of the electricity system. The ‘Electric power’ component of the cost reflects the payment by the consumer for the possibility of uneven consumption of electricity from the power system and an increase in the schedule of electricity consumption to the maximum permitted values. The ‘electricity transmission service’ component of the cost reflects the cost to the electricity system of transmitting and distributing the electricity generated, taking into account irregular demand.

The electricity cost is calculated according to the formula:

$$S_{e\_c} = \Sigma[W_t \times P_t], \quad (1)$$

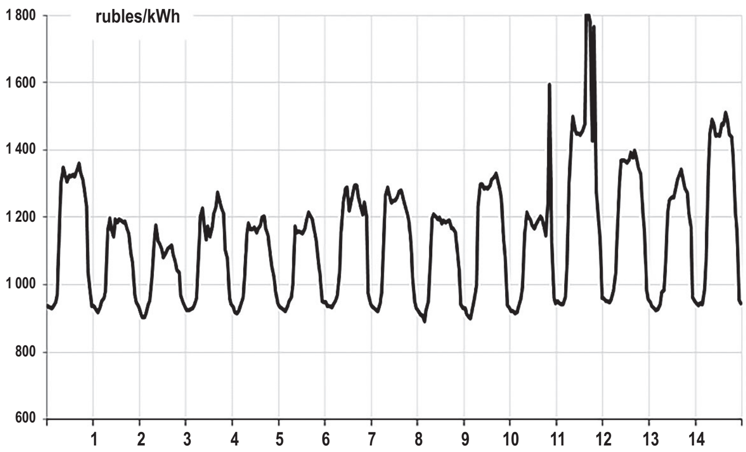
where W_t is hourly electricity consumption of an industrial enterprise during the study period (kWh), P_t is the price for the purchase of the electricity component formed for an industrial enterprise (rubles/ kWh).

Figure 11 shows an example of hourly prices for electricity supply in Tyumen Oblast in November 2021. Taking into account that the prices of sold electricity are characterised by unevenness that repeats the form of volatility of the demand for electricity consumption, the cost of electricity sold on the wholesale and retail electricity markets increases during the day, and, on the contrary, decreases at night. The difference between the day and night prices can reach 55% on some days. Considering that the share of the electricity component in the structure of the total cost of purchasing electric energy by industrial enterprises can reach 40%, the difference between night and daytime peak prices can have a significant impact on the amount of an industrial enterprise’s costs.

Therefore, by managing the daily fluctuations in an electricity in an industrial company’s electricity demand schedule, it is possible to achieve a reduction in the cost of purchased electricity:

$$S_{e\_c} = f(W_t). \quad (2)$$

Fig. 11. Hourly prices for electricity supply in the Tyumen Oblast in November 2021



Source: compiled by the authors.

Such management of the electricity demand schedule is called price-responsive demand for electricity consumption, which is the management of the uneven schedule of hourly demand for an enterprise, consuming electricity from the Unified Energy System, depending on the price signals of the energy market environment according to the minimum cost criteria for purchasing electricity.

Price-dependent electricity consumption by industrial enterprises is a tool for managing the demand for electricity consumption, which is an initiative form of economic interaction between the electric power industry entities and electricity consumers aimed at jointly levelling the volatility of demand schedules for electricity consumption on the scale of the Unified Energy System [Baev et al., 2018].

The implementation of price-responsive electricity consumption mechanisms makes it possible not only to reduce the electricity purchase costs for each individual industrial enterprise, but also to cut down the expenditure of the Unified Energy System for uneven demand in the energy system of the country as a whole.

The electric power cost component is calculated according to the formula:

$$S_{ep\_c} = T_{ep\_c\_m} \times P_{ep\_m}, \quad (3)$$

where $T_{ep\_c\_m}$ is the power value accepted for calculating enterprise obligations for purchasing electric power per month m (kW per month), P_{ep_m} is the price for power that is valid for enterprise obligation payment for purchasing electric power per month m (rubles/kW per month).

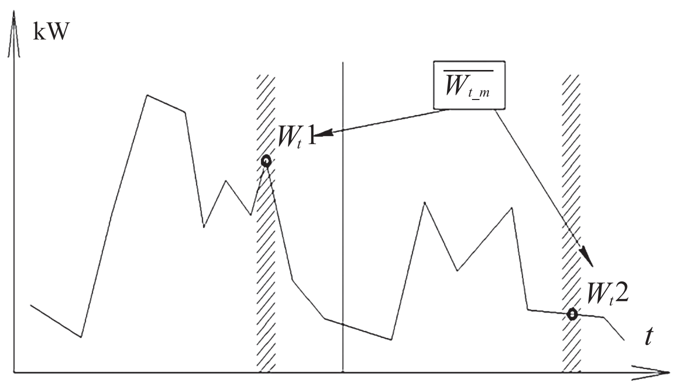
For each billing month, P_{ep_m} is formed based on the market pricing while $T_{ep\_c\_m}$ is formed based on the personal power demand schedule of the industrial enterprise:

$$T_{ep\_c\_m} = \overline{W_{t\_m}} \ni T_{peak\_region\_SO}, \quad (4)$$

where $\overline{W_{t\_m}}$ is the average hourly electricity consumption of an industrial enterprise for a calendar month m(kW), $T_{peak\_region\_SO}$ is the peak hour of the regional electric power system on working days during the periods of planned peak hours determined by JSC ‘System Operator’.

Figure 12 shows an example of the value $\overline{W_{t\_m}}$ formation for an industrial enterprise.

Fig. 12. An example of the value $\overline{W_{t\_m}}$ formation for an industrial enterprise (kW)



Source: compiled by the authors.

The value used to calculate the indicator $\overline{W_{t\_m}}$ per day is taken as the number of hours in which the peak hour of the regional electric power system was formed. The electricity consumption of an industrial enterprise per peak hour of the regional electricity system can be quite different. The consumption in this hour can be either very large or very small, which significantly affects the purchase cost in the electricity cost component.

In this way, it is also possible to reduce the cost of purchased electricity by managing the daily fluctuations in an industrial company's electricity consumption pattern:

$$S_{ep\_c} = f(W_t). \quad (5)$$

Table 1 shows peak hours of electricity systems in some regions of Russia for November 2021.

Despite the fact that the number of peak hours of the electricity systems in different regions is quite different, the number of peak hours in each region does not differ significantly, which allows their prediction with a sufficiently high degree of accuracy.

The electricity transmission cost component is calculated according to the formula below:

$$S_{t\_c} = (\mathrm{T}_{loss\_c} \times \sum W_{t\_m}) + (\mathrm{T}_{care\_c} \times \overline{W_{h\_m}}), \quad (6)$$

where T_{loss_c} is the cost rate of technological consumption (losses) within the two-part tariff for electricity transmission (rubles/kWh), T_{care_c} is the cost rate to maintain electricity networks within the two-part tariff for electricity transmission (rubles/kWh), $\sum W_{t\_m}$ is monthly electricity consumption of an industrial enterprise (kWh), $\overline{W_{h\_m}}$ is the average maximum hourly electricity consumption of an industrial enterprise during the planned peak hours of the power system in working days for a calendar month m(kW).

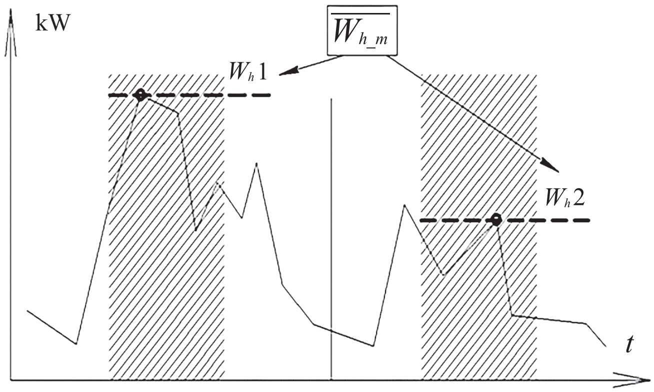
T_{care_c} is the most significant of the two summands of formula (3), and cost management for the T_{care_c} value considerably reduces the cost of purchasing electricity in its transmission

Table 1
Number of peak hours of electric power systems in some Russian regions for November 2021

Data	Kemerovo oblast	Krasnoyarsk oblast	Nizhny Novgorod oblast	Novosibirsk oblast	Perm oblast	Republic of Bashkortostan	Sverdlovsk oblast	Komi Republic	Oryol oblast
01.11.2021	15	15	11	11	17	17	17	18	19
02.11.2021	15	14	11	15	17	17	17	19	19
03.11.2021	15	14	11	7	17	17	17	18	11
04.11.2022									
05.11.2022									
06.11.2023									
07.11.2023									
08.11.2021	15	15	11	8	17	17	17	18	11
09.11.2021	15	15	11	6	17	17	17	18	11
10.11.2021	15	6	10	7	17	17	17	18	11
11.11.2021	15	14	10	15	17	17	17	18	18
12.11.2021	15	15	10	8	17	17	16	10	11
13.11.2021									
14.11.2021									
15.11.2021	15	14	11	8	17	17	16	18	10
16.11.2021	14	15	11	15	17	9	17	19	10
17.11.2021	15	14	11	8	17	17	18	18	11
18.11.2021	15	14	10	8	16	17	17	18	11
19.11.2021	15	14	11	8	11	17	10	18	10
20.11.2021									
21.11.2021									
22.11.2021	15	15	11	8	16	17	16	18	11
23.11.2021	15	15	18	15	17	17	16	19	10
24.11.2021	15	15	10	7	17	17	16	18	11
25.11.2021	15	14	11	7	17	17	16	18	11
26.11.2021	15	14	10	7	16	17	10	18	11
27.11.2021									
28.11.2021									
29.11.2021	15	14	10	8	17	8	17	18	11
30.11.2021	15	14	11	7	16	17	17	18	11

Source: compiled by the authors.

Fig. 13. An example of forming the value $\overline{W_{h\_m}}$ for an industrial enterprise



Source: [Dzyuba, Semikolenov, 2021a].

service component. Depending on the level of the rated voltage, according to which the cost of the transmission service is calculated (LV, MV2, MV1, or HV), the transmission service cost component can reach 50–60% in the tariff structure.

Figure 13 gives an example of forming the value $\overline{W_{h\_m}}$ for an industrial enterprise. It shows that, regardless of external factors, the value $\overline{W_{h\_m}}$ depends only on the value of internal demand for the power consumption of an industrial enterprise, which the enterprise can manage.

Therefore, by managing the daily irregularity of the demand schedule for electricity consumption of an industrial enterprise, it is also possible to reduce the cost of electricity transmission:

$$S_{t\_c} = f(W_t). \quad (7)$$

Table 2 shows the periods of planned peak load hours of a power grid in the areas of the first and second price zones for the first half of 2022.

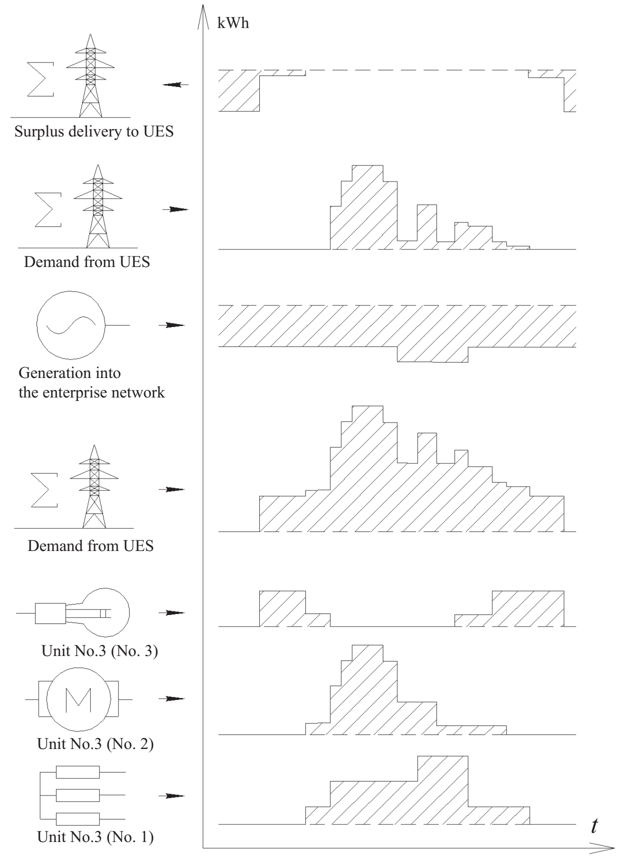
The periods of planned peak hours are approved before the beginning of the calendar year and are known to the industrial enterprises, enabling them to manage their demand schedules according to the cost-minimising indicators of the electricity transmission service.

Thus, all components of the cost of electricity purchased by an industrial enterprise on the retail and wholesale electricity market depend on the value of three components, namely the cost of electricity, electric power and electricity transmission services, the value of which is directly related to the nature of the enterprise's demand schedule:

$$S_c = S_{e\_c} + S_{ep\_c}\, S_{t\_c} = f(W_t), \quad (8)$$

where S_c is the cost of electricity purchased by an industrial enterprise (in roubles).

Fig. 14. Diagram of distributed power generation in the network of an industrial enterprise



Source: compiled by the authors.

A distributed generation system, operating as part of an industrial enterprise, generates electrical energy in the internal network of the industrial enterprise, thereby substituting the enterprise's consumption of electricity from the Unified Energy System with the electricity generated in the enterprise's network. Managing the schedule of electricity generation into the network of an industrial enterprise makes it possible to control the demand schedule of the enterprise for consuming electricity from the Unified Energy System, and thus to manage all cost components of purchasing electricity, namely, the cost of electricity, electric power and transmission service (Figure 14).

Figure 15 shows the influence of external and internal factors on the operation of a distributed generation system in an industrial enterprise. Internal factors include electricity demand characteristics of the enterprise and the operating mode of the

Table 2
Periods of planned peak load hours of a power grid within the territories of the first and second price zones for the first half of 2022

Zones	January	February	March	April	May	June
First pricing zone	From 8th to 21th hours	From 8th to 13th and from 17th to 21th hours	From 8th to 21th hours	From 8th to 15th and from 18th to 21th hours	From 8th to 15th and from 20th to 21th hours	From 8th to 16th and from 20th to 21th hours
Second pricing zone	From 5th to 8th and from 11th to 17th hours	From 5th to 8th and from 12th to 17th hours	From 5th to 8th and from 13th to 17th hours	From 5th to 8th and from 13th to 17th hours	From 5th to 8th and from 13th to 17th hours	From 5th to 11th and from 13th to 17th hours

Source: [Dzyuba, Semikolenov, 2021a].

DG system. External factors include system constraints and the functional capabilities of the enterprise's power grid, including those for feeding electricity into the grid. Indirect factors affecting the operation of a DG system include price factors.

As an internal factor, the electricity demand characteristics of an industrial enterprise influence the operation of a distributed generation system, resulting in the peculiarities of the internal unevenness of the enterprise's electricity demand and determining the limitations and capabilities of the DG system to generate electricity into the industrial enterprise's network and control the production schedule.

External factors such as system constraints and functional capabilities of the enterprise power grid manifest themselves in possible cross-flow limitations, fuel limitations, fuel supply limitations, etc.

The main indirect factors influencing the operation of a distributed generation system are price factors, which are expressed in the prices for the production of electricity by the DG system, the alternative costs of purchasing electricity from the power grid. It is necessary to take into account the dependence on the time period and the nature of the irregular demand schedule, fuel prices, prices for repairing the DG system, etc.

Based on the study of the characteristics of the pricing of electricity supply to enterprises, the perculiarities of DG system operation, and the external and internal factors affecting their work, the authors have developed a model for the control of industrial microgrids, integrated with the technology for the control of electricity demand (Figure 16).

As part of the model implementation, the analysis of the electricity cycle is carried out in two main directions: the analysis of the domestic demand for electricity consumption by an industrial enterprise and the analysis of electricity generation by a distributed generation system. In the domestic demand direction, the industrial enterprise analyses its production schedules, raw material supply schedules, and the equipment operation schedules to project its planned hourly electricity consumption. Based on the planned hourly schedule of electricity consumption schedules, the parameters of the electricity purchase cost in its main components are predicted.

The obtained value of the planned cost of electricity makes it possible to analyse the possibilities of its optimisation on the basis of price-responsive demand schedules and to model various changes in the operating schedules of production equipment on the based on the criteria of minimising energy costs.

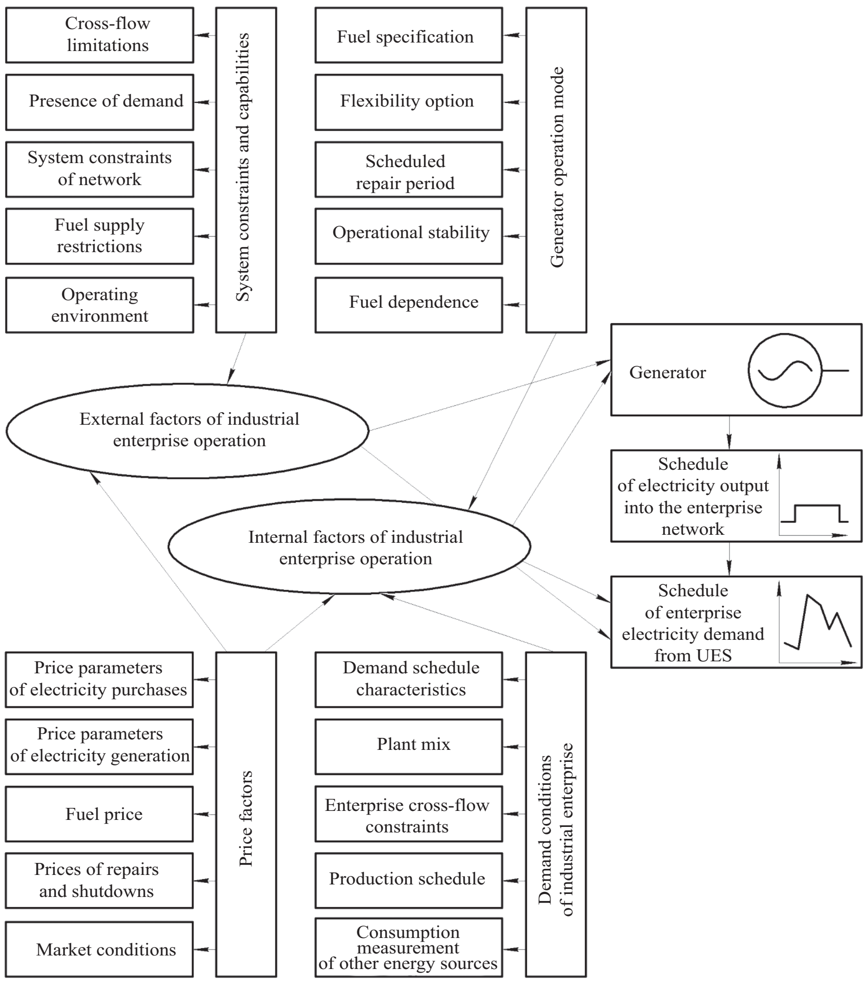
In the direction of DG generation, the planning of a schedule for DG generation into the industrial enterprise's grid is based on an analysis of hourly generation schedules, contractual gas consumption values, and shedules for repairs and equipment shutdowns. On the basis of the planned generation schedules, a forecast is made of the price parameters of the electricity produced by DG for the main cost components. The possibilities of optimising the generation costs and modelling different generation schedules according to the criteria of minimising the production costs of a DG system for an industrial enterprise are analysed.

Based on the results of the analysis of the two main areas, modeling the scenarios for the consumption of electricity by an enterprise and the generation of electricity by a distributed generation system within the framework of an industrial microgrid system are performed.

The modelling takes into account the existing constraints, such as the need to fulfil the production plan of the enterprise and to ensure the system reliability of the enterprise and the technological stability of the equipment of the enterprise and the DG system.

The results obtained are the basis for adjusting the planned hourly schedules for the operation of production and auxiliary equipment at the industrial enterprise, planning hourly schedules for electricity generation by the distributed generation system, and synchronising the planned parameters of the enterprise and

Fig. 15. Factors affecting the power consumption of an industrial microgrid

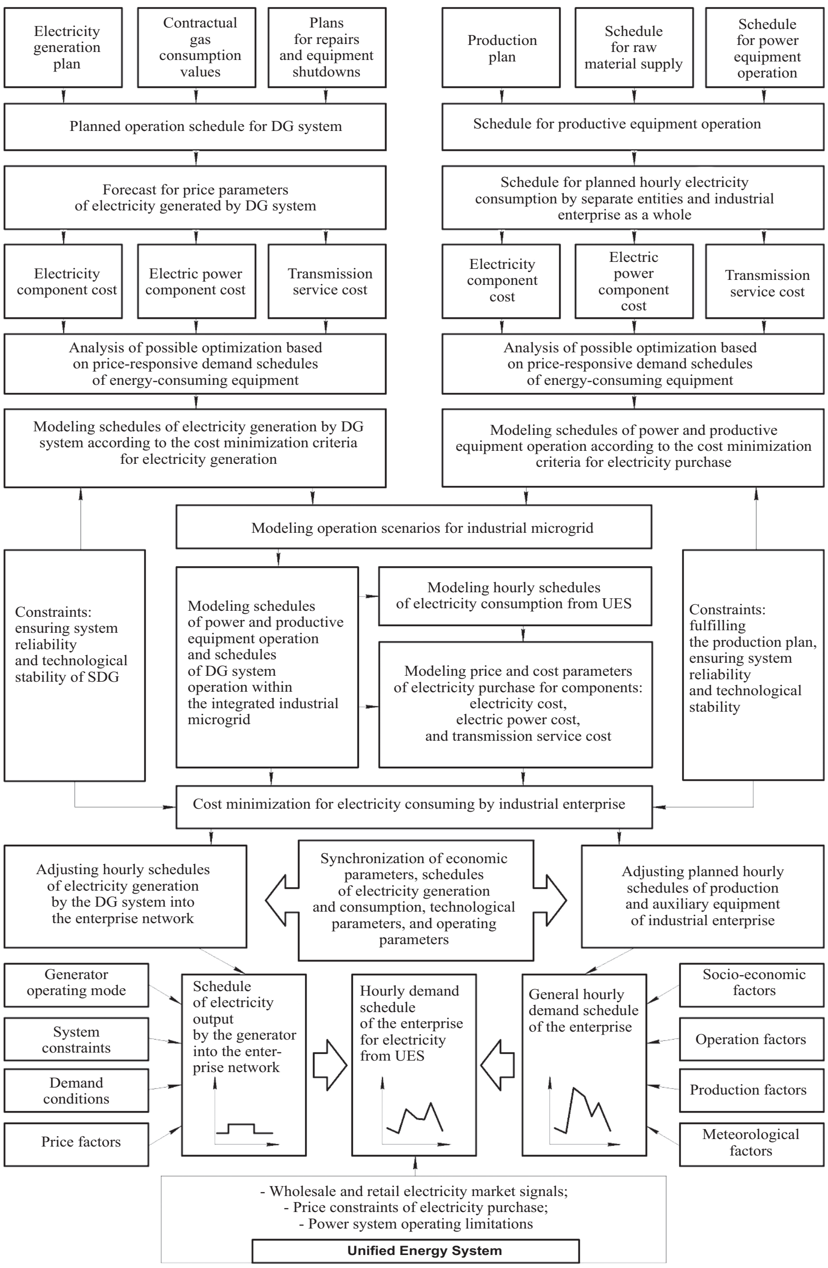


Source: compiled by the authors.

the DG system according to economic parameters, consumption schedules of electricity generation, technological parameters and operating conditions. Electricity consumption not covered by the generation of the distributed generation system is consumed from the Unified Energy System under the conditions of electricity supply from the wholesale or retail electricity markets, which is taken into account when modelling the operation of the industrial microgrid.

Thus, the management of industrial microgrids under their integration with the technology for the control of electricity demand includes the analysis of factors and the internal and external parameters of the enterprise and DG system operation within a unified industrial microgrid system with simultaneous electricity consumption by an industrial enterprise from the Unified Energy System under the conditions of the wholesale and retail electricity market. The functioning of the model includes planning the operation of the industrial enterprise and distributed generation, forecasting the demand for electricity consumption and electricity market parameters, and modelling various scenarios for the operation of individual elements of the system and the industrial microgrid as a whole are carried out.

Fig. 16. Industrial microgrid control model integrated with electricity demand response technology



Source: compiled by the authors.

Despite the fact that the study and development of the industrial microgrid management model integrated with the technology for controlling electricity demand uses the pricing principles of the Russian wholesale electricity market, it is possible to apply the proposed methodological framework to consumers worldwide. In order to implement the developed management model, it is necessary to adapt it taking into account the peculiarities of the energy market functioning and the principles of pricing of electricity, depending on the volatility of the demand for electricity consumption of industrial enterprises.

4. Implementation of the research results in an industrial enterprise

The proposed management model received practical approval on the basis of a machine building plant operating in the Sverdlovsk region of Russia. The industrial enterprise purchased and installed a small distributed generation system powered by natural gas with an installed capacity of 2000 kW. Previously, the enterprise did not use a small distributed generation system as an industrial microgrid and provided electricity generation for its own consumption in order to increase the reliability of the enterprise's energy supply.

The obtained results of testing the developed model controlling the industrial microgrid in the conditions of integration with the technology of electricity demand management on the basis of the industrial enterprise confirmed the effectiveness of the developed solutions (Table 3).

The effect of using the small distributed generation system as part of the industrial microgrid was to reduce the cost of electricity consumption by 19%, i.e. 5,100,000 roubles per month ($ 80,000), which is approximately 1.275 rubles/kWh in terms of the cost of each kilowatt-hour purchased. Thus, for an industrial enterprise with an electric power consumption of 9 MW, the installation of a small distributed generation system within the industrial microgrid with a capacity of 3 MW enables to reduce energy consumption costs by 19%. This

Table 3
Results of the practical validation of the industrial microgrid control model
in conditions of integration with electricity demand management technology

No	Parameter	Units of measurement	Before working in industrial microgrid	After working in industrial microgrid	Difference
1	Total enterprise electricity consumption	MWh	4000	4000	0
2	Enterprise electricity consumption from power system	MWh	4000	2500	-1 500
3	Enterprise electricity consumption from small-scale distributed generation system	MWh	0	1500	1500
4	Electricity generation from small-scale distributed generation system	MWh	0	1500	1500
5	Enterprise electricity consumption from power system	MWh	9	6	-3
6	Electricity transmission services to regional power system operators	MWh	10	7	-3
7	Price of purchasing the electricity component from the power system	rubles/ MWh	2100	2100	0
8	Price of purchasing the electric power component from the power system	rubles/ MWh	800000	800000	0
9	Price of services for electricity transmission to the power system	rubles/ MWh	1100000	1100000	0
10	Price of purchasing the electricity component from small-scale distributed generation system	rubles/ MWh	1500	1500	0
11	Price of purchasing the electric power component from small-scale distributed generation system	rubles/ MWh	500000	500000	0
12	Price of electricity transmission services from small-scale distributed generation system	rubles/ MWh	0	0	0
13	Total cost of purchasing the electricity component by the enterprise	rubles	8400000	7500000	-900000
14	Total cost of purchasing the electric power component by the enterprise	rubles	7200000	6300000	-900000
15	Total cost of transmission service for the enterprise	rubles	11000000	7700000	-3300000
16	Total cost of purchasing electric energy by the enterprise	rubles	26600000	21500000	-5100000
17	Total cost of purchasing electric energy by the enterprise	rubles/ KWh	6.65	5.375	-1.275
18	Total cost of purchasing electric energy by the enterprise	%	100%	81%	-19%

Source: compiled by the authors.

saves more than 60 million roubles per year and covers the cost of purchasing a small-scale distributed generation system, as well as construction and installation work to develop power grid infrastructure and automation systems. The results of the practical approval demonstrate the economic efficiency of using the developed model of industrial microgrid management both in Russia and in other countries of the world.

Conclusion

The research carried out enables us to draw the following conclusions.

1. Despite the development trends in the fuel and energy industry aimed at the gradual replacement of expensive hydrocarbon raw materials by cheaper and cleaner renewable energy sources, in a number of countries, such as Russia, due to the relatively low cost of electricity generation by traditional sources of electricity, the large-scale introduction of RES technologies is not economically justified. Therefore, the vector of power industry development in the countries with a relatively low power generation costs will be different from the global one, and this will continue for the next 20–30 years.

2. Despite the relatively low cost of electricity generation in Russia, there is a significant shortfall in the capacity of the distribution grid infrastructure. The capacity of the distribution grid infrastructure cannot meet the growing electricity consumption of industrial enterprises in the country. In such conditions, the most effective solution is the use of small-scale distributed generation systems powered by natural gas, which makes it possible to meet the demand for electricity and offers many technological and economic advantages.

3. One of the modern directions in the development and use of small distributed generation systems is the use of industrial microgrids. Such microgrids are integrated facilities for the production and consumption of electricity, operating within a unified control system, synchronising the parameters of production and consumption of electrical energy, and allowing industrial enterprises to reduce the costs of final energy consumption.

4. The methodological approach developed by the authors to control industrial microgrids operating on the basis of industrial enterprises takes into account all components of the cost of purchasing energy resources of industrial enterprises, includes the management of production process schedules for the operation

of equipment, schedules for the generation of electricity by a small distributed generation system. It also takes into account the impact of multiple factors acting on the uneven demand for electricity consumption. The methodological approach provides for planning the modes and parameters of synchronous operation of each element of the system under centralised management of the industrial microgrid.

5. The results of the study of price parameters for the purchase of electric energy for industrial enterprises in Russia showed that all components of the cost of electric energy, namely: the component of electric energy, the component of electric capacity, the component of electricity transmission services, are directly related to the type of the volatility of demand for electricity consumption of each industrial enterprise. Price-dependent management of power consumption schedules on industrial enterprises in terms of minimising the cost of electricity can significantly reduce the cost of purchasing electricity from the Unified Energy System.

6. The developed model for managing industrial microgrids integrated with electricity demand management technology is based on the analysis of internal and external operating parameters of an industrial enterprise and a distributed generation system, as well as factors within a unified industrial microgrid system, subject to simultaneous consumption of electricity by an industrial enterprise from the Unified Energy System in the conditions of the wholesale and retail electricity market. The model allows the industrial microgrid system to reduce the complex costs of purchasing electric power.

7. The practical significance of the developments is confirmed by the results of their practical approval at industrial enterprises, which showed a potential saving in the cost of electricity consumption for the enterprise by 20%.

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