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Pathways for the Sustainable Development of Distributed Generation Under Key Influencing Factors: Integrating Circular Economy Principles—A Case Study of the Sverdlovsk Oblast

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Abstract

The global energy sector, as the primary anthropogenic source of greenhouse gas emissions, is undergoing a profound eco-modernization driven by the "3D" concept of decarbonization, decentralization, and digitalization. However, fossil fuels still account for a significant share of the energy mix, especially in fossil fuel-exporting countries. The development of decentralized energy could play an important role in mitigation of GHG emissions and comprehensive eco-modernization of the energy sector. This study aims to develop a scientifically grounded scenario-based model for the development of distributed generation in a region with dominance of centralized generation and grid. A distinctive feature of the proposed tool is its systematic consideration of factors and the magnitude of their influence, which allows the model to be more precisely adapted to a specific territory. In addition, the model enables the incorporation of circular economy principles into the formulation of a distributed generation development strategy, creating an additional driver for the energy transition. The methodological approach is tested using the energy complex of the Sverdlovsk oblast, which is part of Russia's Unified Energy System, thereby confirming its viability and operationalizability.

Keywords: circular economy; sustainable development; fuel and energy complex; distributed generation; energy development strategy; factor analysis

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1. Introduction

The global economy is undergoing profound transformations driven by the environmental and climate agenda, structural changes in global supply chains, high volatility in energy markets, digitalization, and the ongoing fourth energy transition [1,2]. The energy sector, alongside the advancement of renewable energy, will play a key role in facilitating a successful transition to a sustainable economic model. Furthermore, as the primary contributor to environmental pollution, the principal emitter of greenhouse gases (GHGs), and the largest consumer of fossil fuels, the energy sector remains central to global decarbonization and green growth efforts [3–6].

The eco-modernization and development of the global energy sector constitute a large-scale comprehensive transformation of the industry. This process encompasses the transition to renewable energy sources (RESs), such as solar, wind, bioenergy and hydroelectric power; the development of energy storage systems and smart grids; and an increase in

energy efficiency. It also involves the integration of circular economy (CE) principles into traditional energy facilities, the electrification of remote and hard-to-reach regions, and the deployment of conceptually new low-carbon technologies [3,7]. However, despite concerted international efforts, the adoption of ambitious climate agreements at both global and regional levels, and substantial investments in green energy initiatives, fossil fuels (coal, oil, and natural gas) continue to prevail within the structure of primary energy consumption. According to [8], in 2025 56.76% of global electricity was generated from fossil fuels. Energy-related CO_2 emissions increased by 55.51% between 2000 and 2025, rising from 24.5 Gt CO_2 in 2000 to 38.1 Gt CO_2 in 2025 [4]. This highlights the structural rigidity of the global energy system and the enduring, foundational reliance of the global economy on natural energy resources.

One of the most promising pathways for the future development of the energy sector is the "3D" concept that includes: decarbonization, primarily achieved through the expansion of RESs and their integration into power grids; decentralization, denoting the transition from centralized energy supply models to more flexible, distributed energy models and infrastructure; and digitalization, which entails the implementation of advanced digital technologies, including artificial intelligence (AI), across all stages of energy generation, distribution, and consumption [9].

Decentralized or distributed energy generation (DG) is a central aspect of the "3D" framework, and represents a long-term strategy for the energy sector's development. It facilitates effective eco-modernization through the integration of RESs and hybrid energy systems, thereby addressing the escalating demand for electricity and advancing global objectives of providing consistent access to heat and electricity, particularly in remote and hard-to-reach regions [10]. DG is conceptualized as an operational paradigm, in which energy for heat and electricity are generated at or near the point of consumption, functioning independently of the large-scale centralized grids designed for long-distance power transmission [11,12]. The operational characteristics of decentralized systems, namely localized power delivery and the relatively modest capacity of generating units, create substantial opportunities for the deployment of renewable energy facilities (e.g., solar, wind, and bioenergy power plants) as well as hybrid energy systems. In such hybrid configurations, RESs are coupled with traditional energy generation facilities to ensure a more resilient and stable energy supply.

The development of DG could play an important role in the greening and modernization of the energy sector in fossil fuel-exporting countries characterized by highly centralized grid infrastructures, such as the Russian Federation. Despite its expansive territorial scale, vast domestic hydrocarbon reserves, and low energy tariffs, the expansion of renewable energy in the Russian Federation is not currently being prioritized within the long-term strategic development of the national energy sector [13]. In 2025, the share of fossil fuels used in primary energy consumption in Russia stood at 89.82% [14]. Achieving a substantial reduction in the sector's adverse environmental footprint and realizing broader economic decarbonization remain unfeasible without the active implementation of alternative energy projects. Moreover, a review of Russia's primary regulatory and legislative frameworks governing energy development reveals that the prevailing strategy is predicated on the further optimization of the centralized grid model. Under this paradigm, the entire fuel and energy complex is administered by a single dominant operator, effectively precluding market entry of independent entities.

Consequently, decentralized energy systems could serve as a driver of the large-scale modernization of the energy sector, facilitating energy provision to remote or hard-to-reach territories [10]. In fossil fuel-exporting countries with established centralized grids, this is often achieved through the deployment of small-scale DG facilities powered by natural gas

or diesel. The construction of such on-site facilities within industrial enterprises located in centralized grid zones has gained momentum, aiming to ensure an uninterrupted power supply or address situations where grid connection is technically unfeasible.

Despite the highly promising prospects for decentralized energy development, its expansion remains constrained by several factors. Existing planning approaches in countries with traditional fossil fuel energy sectors and a highly centralized grid infrastructure are fragmented and rely primarily on the economic viability of a project [15], thereby failing to account for:

- The systemic interrelationship among diverse factors;
- The qualitative impact assessment of each factor on the final outcome, leading to errors in prioritizing investment projects;
- The alignment of interests among various stakeholders within a unified regional energy development strategy, including industrial giants, small businesses, individual households, and grid companies.

A deficit of sound managerial tools for decision-making in the electric power sector, ensuring the transformation of disparate DG projects into coordinated regional systems adapted to the transition to a CE paradigm and regional energy security requirements, is a challenging issue for present research.

The aim of the study is to develop a scientifically grounded model for the development of DG in a region with a traditional fossil fuel energy sector, based on a structural and quantitative assessment of key systemic factors.

To achieve this aim, the following tasks must be addressed:

1. Systematize and classify the factors influencing the development of DG.
2. Determine the degree of influence and priority of the factors within the specific regional context.
3. Develop a scenario-based model for the development of DG in the specific region, based on the matrix of ranked factors.
4. Identify the key actors and technologies that will have a decisive impact on development and describe the set of markers for DG development and the procedure for assessing them.
5. Formulate a set of practical recommendations and tools for regional and state policy to incentivize the adoption of DG.

2. Literature Review

A literature review on the research topic reveals several approaches to the issue. A number of studies acknowledge the significant role of decentralized energy in the ongoing fourth energy transition. The concept of decentralization centers on the geographical localization of energy production and consumption sources, thereby eliminating the energy losses associated with long-distance transmission from large-scale facilities. However, decentralization is not a goal per se; implementing the concept of decentralized energy requires a shift from the traditional vertical "generation → grid → consumer" model to horizontal, flexible, and divergent systems [16–18]. Several key approaches have emerged globally, which are often combined, depending on the market maturity and geographical conditions.

An analysis of contemporary scientific literature on DG reveals two key research vectors that shape the theoretical foundation of this study. The first vector encompasses fundamental approaches to the development of DG. This area examines the technological, socio-environmental, economic, and institutional dimensions of decentralization, ranging from the evolution of the consumer into a "prosumer" and the emergence of local energy markets to the challenges of integrating small-scale power facilities into existing grid infras-

tructure. The second vector focuses on the development and verification of mathematical and simulation models for DG growth. The research in this field centers on the spatial optimization of facility siting, agent-based modeling of participant behavior, and scenario-based forecasting of capacity additions under various tariff and investment conditions. The present study draws upon a synthesis of these two vectors, adapting existing models to address the geospatial assessment of decentralization in industrialized regions.

2.1. Fundamental Approaches to the Development of DG

A technological approach to the development of DG is frequently encountered in the literature; it focuses on the physical transformation of energy infrastructure. In [19], Kabeyi and Olanrewaju study advanced design and energy management strategies to optimize integration of Distributed Energy Resources (DERs) into a traditional grid. Among the integration technologies, the authors highlight the use of smart grids, energy storage direct current (DC) systems, vehicle-to-grid and electrification of transport, optimization tools, alternating current (AC) microgrids, use of virtual power plants (VPPs), and DC microgrids. The investigation by Richter et al. [20] demonstrates that dividing a power system into autonomous "energy cells", characterized by sovereign control and inter-sector connectivity, can significantly improve grid resilience and enhance the efficiency of distributed RESs. A number of articles [21–23] are dedicated to the study of multi-agent control architectures for managing distributed power grids, in which decisions are made by multiple peer-to-peer autonomous agents (software modules) instead of a single central operator.

A distinct group of studies focuses on social and environmental approaches to the development of DG. These entail generating energy close to the point of consumption using renewable and low-carbon resources, with minimal environmental impact, reducing the carbon footprint and transportation losses. These articles prioritize the development of RESs as a zero-emission option. However, DG based on fossil fuels (specifically natural gas) also offers environmental advantages over traditional large-scale power plants. These benefits stem from the higher efficiency of small-scale generation units and reduced energy transmission losses. Furthermore, while large power plants concentrate the environmental impact at a single location, numerous small-scale units produce distributed emissions that are often mitigated by vegetation and effective atmospheric dispersion [24,25].

Studies concerning energy system security and resilience are also gaining increasing popularity, especially when connected with the geopolitical risks, pressing challenges and conflicts of the modern era [26].

It is also worth highlighting another group of studies examining economic and market-based approaches to the development of decentralized energy. This group addresses issues of economic viability; energy costs; the availability of capital and investment instruments; and, ultimately, incentives for implementing DG projects. Several business models for the development of DG can be found in the published literature. The "Energy-as-a-Service" model entails consumers paying for specific energy services rather than purchasing or maintaining the energy systems themselves, thereby fostering the growth of DG [27]. A peer-to-peer energy trading model via a Blockchain Energy Token (ETC) and smart contracts allow consumers and prosumers to exchange energy directly without the need for a central grid company or broker. Transition of the model into multi-energy exchange provides an ecosystem for the trading and integration of multi-energy sources, e.g., power-to-gas and heat-to-power [28,29]. When calculating a project's economics, the Levelized Cost of Energy (LCOE) should be taken into account, which is calculated for specific energy systems over the entire lifecycle of the power plant. It is applied to verify the findings on off-grid systems, to assess where these systems might be deployed and how costs might evolve [30]. Mechanisms for the financial support of projects are also being

developed, including tax incentives, microfinance and special credit programs, interest rate subsidization, crowdfunding, green bonds and certificates, etc. [31,32].

To attract investors into renewable energy projects, the Russian Federation employs a competitive selection mechanism for small-scale generation projects aimed at compensating for losses within grid companies. Grid companies are required to compensate for technical electricity losses in their networks; they have the option to procure electricity to cover their own technological needs (losses) from "green" power plant owners at competitive prices rather than from traditional suppliers. However, this instrument has had a limited impact on the development of RESs, and DG in particular [33,34]. Gitelman et al. [35] propose an authentic approach to the development of DG; the authors consider the implementation of energy projects within a framework of developing unregulated business lines within energy companies, thus involving the key market players.

A group of studies focus on the institutional–legal approaches to the development of decentralized energy. The concept of decentralized energy has gained the most traction in developed countries, with the European Union being one of the leaders in its implementation. EU legislation does not define "decentralized energy" as a single, distinct category; its development encompasses several strategic areas, addressing the environmental agenda, clean energy, energy market development, demand-side management, energy digitalization and CE. The most popular concept for the development of decentralized energy in the EU is based on transforming the passive energy consumer into a "prosumer"—an entity that generates, consumes, and sells energy on-site. Energy communities have emerged as an evolution of the "prosumer" concept; a group of citizens, local authorities, or small businesses form an association to co-invest in and manage distributed energy generation projects. They share the generated energy among themselves and sell any surplus to the grid, while benefiting from incentives and simplified grid access [36–40].

The development of decentralized energy in the Russian Federation is governed by a set of strategic, legislative, and technical–regulatory documents. The core documents defining the general approaches to the functioning and development of the energy sector are Federal Law No. 35-FZ "On the Electric Power Industry" [41] and the Energy Strategy of the Russian Federation for the period up to 2050. Unlike the European approach, which emphasizes decarbonization and energy communities, the Russian regulatory framework for the development of DG focuses primarily on ensuring the energy security of technologically isolated territorial energy systems. The Unified Energy System (UES) remains largely separate from the large-scale development of decentralized energy, with individual projects driven by considerations of economic feasibility for energy consumers. The institutional framework for the development of RESs within the UES of the Russian Federation relies on two mechanisms: a program of RES capacity supply agreements and micro-generation. The first mechanism is designed to attract private investment exclusively in the wholesale energy market. The investor commits to building a new power unit or modernizing an existing one within strictly defined timeframes, while the state and the wholesale market guarantee investment protection and a fixed return on invested capital in exchange. It involves facilities with an installed capacity exceeding 25 MW; consequently, these facilities cannot be directly classified as DG within the scope of the paper. The second mechanism is still in the development stage and currently has no impact on the growth of DG. Furthermore, issues regarding the connection of DG facilities to the general grid are currently unregulated [40–43].

In practice, the most viable models for implementing decentralized energy systems emerge at the intersection of several approaches; for instance, when a technologically mature microgrid-based platform is managed by a local energy cooperative and participates in energy trading within a local market. Associated development strategies, such as the CE concept, serve as an additional stimulus for the development of DG. The transition

towards CE using waste-to-energy techniques, the integration of modular RESs and Power-to-X technologies for carbon dioxide reuse, and shared resource exchange foster a robust symbiotic relationship that mutually drives the development of adjacent sectors [44].

2.2. Development and Verification of Mathematical and Simulation Models for DG Growth

Studies of power system development models incorporating DG can be found in several articles. Modeling the impact of DG on a grid is addressed in the work of Jain and Gupta [45]; the authors examine the optimal placement of DG units using machine learning and neural networks. The research by Ntem [46] focuses on modeling DG not merely as a static source, but as an active control element. The author employs neural networks to control DG inverters in order to mitigate grid disturbances, such as voltage dips and harmonics. Modeling the market implications of DG growth is presented in an article by Galperova [47]; the paper examines economic–mathematical models designed to forecast how the mass adoption of consumer-owned generation will alter a power system's demand profile and affect equilibrium electricity prices. Scenario planning for DG is found in the work of Sifakis et al. [48], in which the authors model integration scenarios involving DG (photovoltaic) and battery energy storage systems (BESSs) at ports to provide shore power to vessels. Another study by Kibungu et al. [49] analyzes the opportunities for the DG potential of the Democratic Republic of the Congo using the Open-Source Energy Modeling System (OSeMOSYS) to assess the technical, economic and environmental impacts of an ambitious energy scenario centered on hydropower. Akpahou et al. [50] propose an energy balance forecasting model for Benin that accounts for the expansion of DG.

2.3. Research Gap

This comprehensive literature review reveals that, while development approaches and policy instruments regarding distributed energy systems have attracted significant attention from the scientific community, a notable gap remains in the literature concerning the methodological approaches to forecasting DG growth within traditionally stable centralized power systems, while accounting for the specific context of the region under consideration. The application of such forecasting models plays a crucial role in formulating national and supranational energy strategies and optimizing investment allocation.

3. Materials and Methods

The methodological framework of the study consists of the following steps:

1. Characterize the case study and define the scope of the research.
2. Identify a set of factors that can influence (either drive or block) the development of DG by conducting a comprehensive literature review.
3. Select expert groups and conduct a survey of them to rank the factors identified in the first step.
4. Analyze the expert feedback and determine the final list of factors.
5. Propose a step-by-step model for the development of DG, using the regional energy system of the Sverdlovsk region (Russian Federation) as a case study.
6. Discuss the results and draw conclusions based on the conducted investigation.

3.1. Case Study and Scope of the Research

The historical development of Russia's electric power industry followed a path of centralizing the generating capacity. In the 1920s, the State Plan for the Electrification of Russia, also known as the GOELRO plan (an acronym in Russian for the State Commission for the Electrification of Russia) was developed and adopted. This document established a sound foundation for the industrialization of Soviet Russia for decades by creating a

reliable and efficient energy complex that met the rapidly growing energy demands of the population and industry [51].

Nowadays, the national electric power sector of Russia consists of UES and five isolated regional power systems located in the northeastern part of the country. The UES comprises 75 regional power systems, which, in turn, are organized into seven Integrated Energy Systems (IESs). The backbone of UES generation consists of large-scale facilities: thermal power plants (65% of total installed capacity), hydroelectric power plants (19.1% of total installed capacity), and nuclear power plants (13.5% of total installed capacity) [52].

The Sverdlovsk oblast is one of Russia's major industrial regions; its economy is driven by metallurgy, mechanical engineering, and the mining industry, resulting in high energy consumption characterized by fluctuating load patterns. The energy sector of Sverdlovsk oblast constitutes one of Russia's most powerful and complex regional power systems, with the installed power plants having a total electricity capacity of 10,683.1 MW, including 1485.0 MW for nuclear power plants, 7.0 MW for hydroelectric power plants, 9153.2 MW for thermal power plants, and 37.9 MW for solar power plants, as of 1 January 2025 [53]. The production of electrical energy at power plants in 2024 amounted to 55,368.0 million kWh, including: 9051.3 million kWh from nuclear power plants, 18.9 million kWh from hydroelectric power plants, 46,290.7 million kWh from thermal power plants and 7.1 million kWh from solar power plants. Energy consumption for the same period amounted to 43,406.0 million kWh. Therefore, regional power generation runs at a surplus; it not only flexibly meets all of Sverdlovsk oblast's needs, but also supplies excess energy to neighboring territories [53,54].

The aforementioned data on the structure of electricity generation indicate that the share of RESs accounts for a negligible share of the region's overall energy balance. It is worth noting that official statistics provide no specific data on the electricity output from DG facilities or their installed capacity, as the development of DG is not explicitly addressed in either federal or regional strategic regulatory documents. Moreover, there is no consensus in domestic or international practice regarding which facilities should be classified as DG. The installed capacity of DG facilities worldwide ranges from 5 kW to 100 MW; however, in a number of cases, power output is not limited at all when the generating facility operates in island mode [55].

A two-tier market for the sale of electric energy and capacity operates in the Russian Federation. The major energy market participants, including generating companies, sales companies, and grid companies (specifically regarding the purchase of electricity to cover transmission losses), and large consumers, purchase energy and capacity on the wholesale market. The wholesale electricity and capacity market operates across regions grouped into price zones and non-price zones. In the price zones, electric energy and capacity are sold at free (unregulated) prices. The retail market represents the "last mile" stage, where the energy reaches the end consumer. Retailers sell energy purchased on the wholesale market, as well as energy from generating facilities with an installed capacity of less than 25 MW [56].

For the purposes of this study, DG facilities are defined as power plants with an installed capacity of up to 25 MW that operate exclusively within the retail electricity market of the UES of Russian Federation, excluding technologically isolated territorial energy systems.

3.2. Selection of Factors Influencing the Development of DG Using a Priori Ranking Method

The development of DG is influenced by a multitude of various factors. Scholars worldwide are attempting to identify the forces acting upon the considered research area, proposing distinct sets of determinants and examining the extent of their influence and interrelationships. The approaches examined in the literature review provide a broad

context for studying the development of DG. The authors synthesized this data, incorporated specialized studies dedicated on the analysis of these factors [57–62], and compiled a list of factors tailored to the specifics of UES of Russian Federation. The factors are framed neutrally; however, they can have positive or negative impacts on the development of DG, depending on the context. The list of factors is presented in Table 1. The tree of factors is showed in Figure 1.

Table 1. A set of factors influencing the development of DG in the Russian Federation (made by the authors).

Factor Code	Name of the Factor	Group
X1	Technical feasibility and duration of connection procedure to centralized power grids	Technological
X2	Technological maturity and operational reliability of DG	Technological
X3	Digitalization and operation of smart grids, microgrids, and energy storage systems	Technological
X4	Strict local environmental requirements and emissions quotas in major industrial centers	Social & Environment
X5	Vulnerability of large, centralized generation facilities to the effects of blackouts, vandalism or external attacks	Social & Environment
X6	Consumer drive for energy autonomy and increased reliability of their own energy supply	Social & Environment
X7	DG import-substituting equipment, components, technologies, and qualified personnel availability in the domestic market	Economic
X8	Economic feasibility and payback periods for DG facility implementation	Economic
X9	Investment attractiveness of the sector, availability and cost of debt capital	Economic
X10	Liberalization of the domestic energy market; preconditions for the emergence of new entities operating DG facilities	Institutional & Political
X11	Geopolitical risks and national stability	Institutional & Political
X12	DG state policy and improvement of the regulatory framework regarding the integration of DG facilities into the UES	Institutional & Political

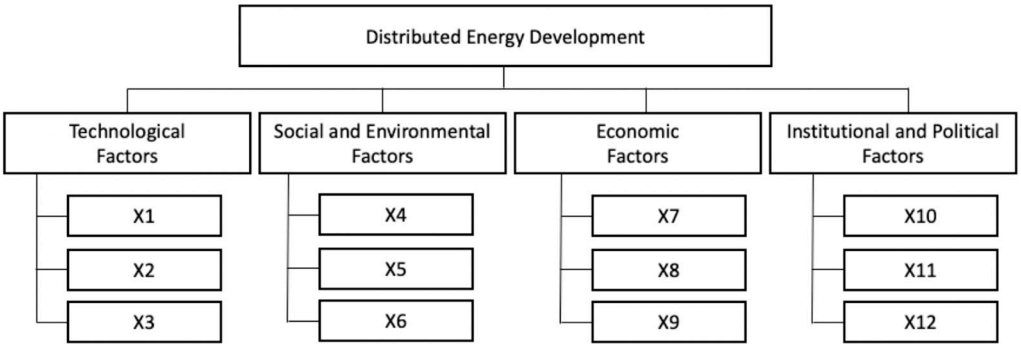


Figure 1. Classification of identified factors influencing DG development in the Russian Federation (made by the authors).

In order to determine the most significant factors, an a priori ranking method based on the individual assessment of factors by a group of experts was applied [63]. The main stages of the a priori ranking method in relation to the research purpose were as follows:

1. Preparation of the questionnaire for the experts.
2. Formation of the expert panel participating in the survey.

The expert panel included 11 experts, 5 of whom were involved in university-based research in the field of energy, while the remaining six were affiliated with state and regional authorities (e.g., Ministry of Energy) and energy enterprises. The experts were required to have at least 10 years of relevant experience in fields related to the operation and/or development of the energy sector of the Russian Federation.

3. Providing instructions to experts for filling out the questionnaire.

The respondents were tasked with assessing the significance of each factor by assigning it a rank from 1 to 12, reflecting the strength of its influence over the medium term (up to 5–10 years). The significance of each factor was assessed based on its rank:

1—The factor has the greatest impact (positive or negative) on the development of DG in UES of Russian Federation.

12—The factor has the least impact (positive or negative) on the development of DG in UES of Russian Federation.

It was also stated that an expert could assign the same rank to different factors (for example, assigning rank 4 to factors X2 and X3) if they considered them to have an equal influence. Additionally, the experts were given the opportunity to propose a factor not included in the table and to specify its impact.

4. Completion of the questionnaire by the expert panel.
5. Processing of the results of the expert survey in accordance with the a priori ranking method: assessment of expert opinion consistency using Kendall's coefficient of concordance (W) and value of the Pearson criterion (χ^2).
6. Selection of the most significant factors and construction of a priori ranking diagram showing the distribution of factors by the sum of ranks.

To increase the objectivity of the research, the expert survey utilizing the a priori ranking method was analyzed (i) for the entire expert panel, (ii) for the group of experts involved in university-based research in the field of energy, and (iii) for the group of experts affiliated with state and municipal authorities and energy enterprises.

3.3. DG Development Model

A DG development model is a complex systemic process that alters the architecture, economics, and management of an entire regional power system. Each regional power system is structurally unique, comprising a specific set of elements, yet it may simultaneously serve as a component of larger integrated systems. Furthermore, the historical evolution of the energy sector, the level of decentralization in the specific area, and the market's commercial and sales infrastructure should be considered. Ultimately, these systems do not operate in a vacuum; they are influenced by a multitude of diverse factors. Creating an objective model under such conditions is a non-trivial task.

Within the framework of the proposed model, the authors focus on forecasting the quantitative industry indicators across three time horizons (steps), culminating in 2050. The model can take into account actual factors influencing the development of DG; in this case, specific measures that cause DG to thrive under the prevailing conditions should be highlighted. The model's objective is to demonstrate how various actions can influence the structure of generating capacities and the share of DG within the installed capacity of a territorial energy system.

The proposed model considers three development scenarios: inertial, independent, and target oriented.

- The inertial scenario relies on a conservative forecast that assumes the ongoing established trends, regulatory methods, and current approaches within the energy sector, without radical shifts in the DG development paradigm.
- The standalone scenario envisions DG growing and addressing key challenges autonomously, thereby minimizing or compensating for the constraints imposed by the centralized power system.
- The target-oriented scenario entails a shift from the ad hoc adoption of DG systems to an integrated strategy in which these systems complement or replace inefficient or obsolete centralized generation assets, e.g., coal-fired power plants.

The scope for DG development covers the most common generation sources: natural gas-fired generation, biogas-fired generation, solar power plants, hydroelectric power plants, and wind power generation. For each step and scenario, the appropriate scale of implementation measures is determined, taking into account the impact of relevant factors specific to the considered case-study territory. The authors deliberately distinguish between biogas- and natural gas-fired generation, as the latter can drive DG development in countries with abundant natural gas resources and extensive gas pipe infrastructure.

Table 2 presents the approaches to estimating the installed capacity by generation source. The authors propose a set of typical project initiators and an assessment procedure that can be adapted to the specific territorial context. Any relevant information with varying planning horizons can serve as input data for the forecast, ranging from prospective project-by-project accounting to general methods for assessing source potential or approximation.

Table 2. Estimated installed capacity by source (made by the authors).

Generation Source	Procedure for Evaluating Key Activities
1. Centralized power plants	Official plans for the development of centralized generation are taken into account. No additional measures are envisaged.
2. DG powered by natural gas	Large industrial enterprises with consumption exceeding 50 MW: Shifting X% of the traditional capacity currently in use to DG. Open data on current consumption is used.
3. DG powered by biogas	Wastewater treatment plant (WWTP) operator: Future projects are considered based on the operator's investment programs OR estimated using statistics from the WWTP or calculated based on the population of the service area. The methodology developed by Kiselev et al. [60] is used to calculate the potential for electricity and heat generation at biogas-powered CHPPs.
4. DG powered by solar energy	Rooftop residential micro-generation: Equipping X% of individual residential houses with rooftop solar panels with installed capacity of 15 kW. Open data on the number of properties is used.
5. DG powered by hydro energy	Future projects are considered based on the operator's investment programs OR an assessment of the generation potential of hydroelectric power plants is used.
6. DG powered by wind energy	Future projects are considered based on the operator's investment programs OR an assessment of the generation potential of wind power plants is used.

To calculate the target value (X%), the assessment procedure employs a matrix-based approach that integrates three key determinants.

- A baseline value for X% is established based on the current level of DG development in the region; this prevents the setting of unrealistic targets for power systems with a low DG baseline.
- This figure is then adjusted according to the results of factor analysis that accounts for various technological, social, economic, and institutional constraints and opportunities.
- The final iteration involves calibrating the indicator based on the readiness of project initiators to implement the planned scope of DG-related initiatives.

The resulting value (X%) represents an economically and technically sound compromise between the theoretical potential for decentralization and the practical feasibility of achieving it within the designated timeframe.

4. Results and Discussions

4.1. A Priori Ranking of Factors

The entire expert panel: The expert analysis demonstrates a sufficient degree of consistency among the interviewed experts: Kendall's Coefficient of concordance (W) is 0.44; the testing of the hypothesis of non-randomness of experts' agreement shows that, with a 5% significance level and degrees of freedom of 11, the calculated value of the Pearson criterion (50.57) is greater than the χ^2 (19.67), which confirms the hypothesis of consistency of experts' opinion and allows the data obtained to be used for further research.

The results of a priori ranking of factors for the entire expert panel are presented in Table 3.

Table 3. The results of a priori ranking of factors for DG development in the Russian Federation for the entire expert panel (made by the authors).

Factor Code	The Sum of Ranks	
	Absolute Value	%
X12	28	3.26
X1	38	4.43
X8	39	4.55
X2	59.5	6.93
X6	68.5	7.98
X5	74.5	8.68
X7	76.5	8.92
X9	77	8.97
X3	92	10.72
X10	100.5	11.71
X11	102	11.89
X4	102.5	11.95

The group of experts involved in university-based research in the field of energy: The expert analysis demonstrates a sufficient degree of consistency among the interviewed experts: W = 0.50; testing of the hypothesis of non-randomness of experts' agreement shows that, with a 5% significance level and degrees of freedom of 11, the calculated value of the Pearson criterion (26.68) is greater than the χ^2 (19.67), which confirms the hypothesis of consistency of experts' opinion and allows the data obtained to be used for further research.

The results of a priori ranking of factors for the group of experts involved in university-based research in the field of energy are presented in Table 4.

Table 4. The results of a priori ranking of factors for DG development in the Russian Federation for the group of experts involved in university-based research in the field of energy.

Factor Code	The Sum of Ranks	
	Absolute Value	%
X12	9.5	2.44
X1	14	3.59
X8	21	5.38
X6	25	6.41
X2	31	7.95
X5	33	8.46
X9	39	10.00
X3	39.5	10.13
X7	41	10.51
X11	43.5	11.15
X4	44	11.28
X10	49.5	12.69

The group of experts affiliated with state and municipal authorities and energy enterprises: The expert analysis demonstrates a sufficient degree of consistency among interviewed experts: W = 0.47; testing of the hypothesis of non-randomness of experts' agreement shows that, with a 5% significance level and degrees of freedom of 11, the calculated value of the Pearson criterion (28.73) is greater than the χ^2 (19.67), which confirms the hypothesis of consistency of experts' opinion and allows the data obtained to be used for further research.

The results of a priori ranking of factors for the group of experts affiliated with state and municipal authorities and energy enterprises are presented in Table 5.

Table 5. The results of a priori ranking of factors for DG development in the Russian Federation for the group of experts affiliated with state and municipal authorities and energy enterprises (made by the authors).

Factor Code	The Sum of Ranks	
	Absolute Value	%
X8	18.0	3.85
X12	18.5	3.95
X1	24.0	5.13
X2	28.5	6.09
X7	35.5	7.59
X9	38.0	8.12
X5	41.5	8.87
X6	43.5	9.29
X10	51.0	10.90
X3	52.5	11.22
X4	58.5	12.50
X11	58.5	12.50

Figure 2 presents the diagrams for the a priori ranking of factors for each considered groups of experts.

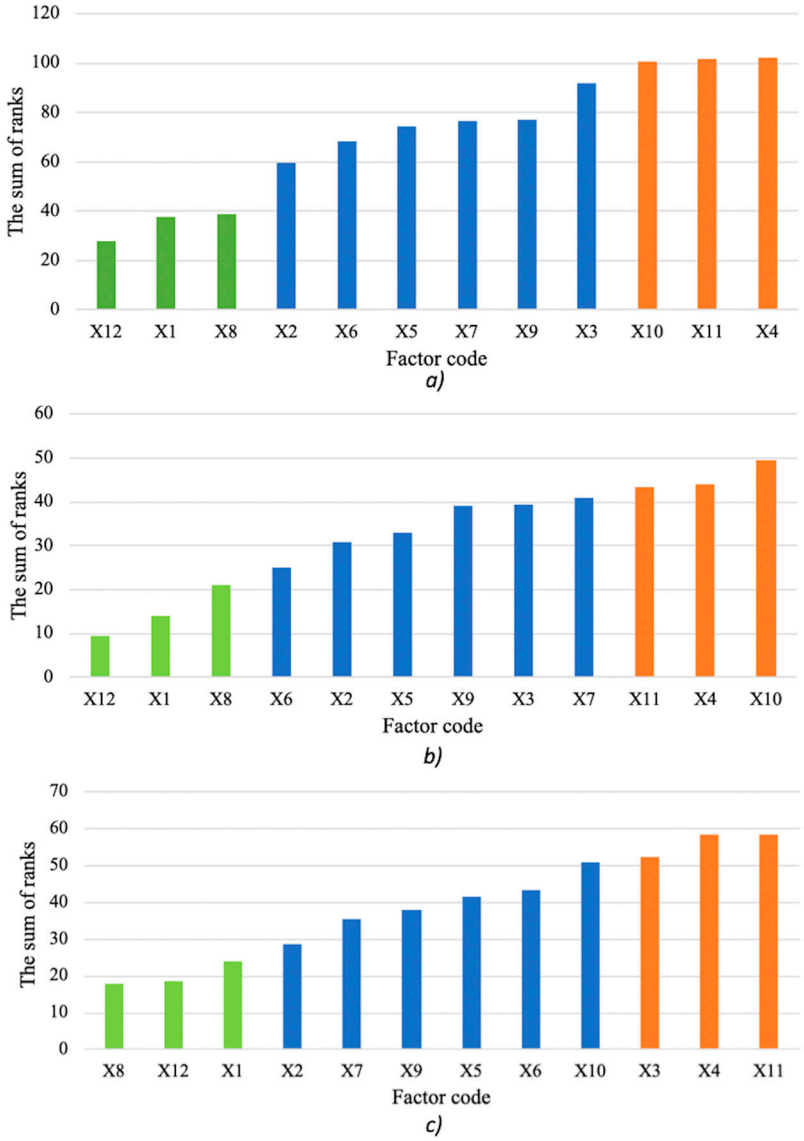


Figure 2. Diagrams of a priori ranking of factors by the considered group of experts: (**a**) the entire expert panel; (**b**) the group of experts involved in university-based research in the field of energy; (**c**) the group of experts affiliated with state and municipal authorities and energy enterprises (green—the most significant factors; orange—the least significant factors) (made by the authors).

Based on the results of experts survey, the authors identify three factors that have the strongest impact on DG development:

1. DG state policy and improvement of the regulatory framework regarding the integration of DG facilities into the UES (X12).
2. Technical feasibility and duration of connection procedure to centralized power grids (X1).
3. Economic feasibility of and payback periods for a DG facility's implementation (X8).

Top #1 Factor (X12): DG state policy and improvement of the regulatory framework regarding the integration of DG facilities into the UES.

The existence of a state policy regarding DG determines the fundamental feasibility of the implementation of an economically viable project within the sector considered. In this

respect, the institutional framework takes precedence over market conditions. The factor primarily acts as a barrier to the development of DG, although certain positive shifts are nonetheless taking place.

In domestic practice, the development of the energy sector is driven primarily by state policy; individual regional or municipal development strategies are formulated in compliance with federal regulations and are virtually unable to pursue independent policies. They can only utilize limited support mechanisms for DG projects or rely on private local initiatives.

Currently, at the federal level, the development of DG is not treated as an independent track. Conversely, the Energy Strategy of the Russian Federation for the period up to 2050 posits that the construction of the country's modern electric power industry is based on principles established during the preparation and implementation of the GOELRO plan (adopted on 22 December 1920), which include:

- The concentration of energy production and distribution based on large-scale power plants;
- The development of high-voltage electrical grids connecting large-scale power plants into the UESs serving major economic regions;
- The construction of large thermal power plants as the basis for the centralized energy supply of major cities and industrial complexes.

Regarding the development of the electric power industry, it is essential to consistently advocate for preserving the sector's existing structure, which is based on large-scale power plants operating within UES of Russian Federation [38].

However, the aforementioned documents outline specific objectives for the development of RESs, but not every renewable energy facility qualifies as a DG asset, and vice versa. The target energy development scenario assumes that, by 2050, the installed capacity of these generation types will increase by more than 40 percent compared to 2023 levels. This includes hydropower, which in the Russian Federation relies on large-scale hydroelectric power plants and accounts for the overwhelming majority of total renewable energy capacity. As of 2023, the installed capacity of RESs, excluding hydropower generation, accounted for just 1.9% of the total capacity mix (or 5 GW in absolute terms). Ultimately, plans for the development of renewable energy, which could theoretically be classified as DG, will account for a relatively insignificant share of the overall energy balance throughout the forecast period.

The preconditions for the development of micro-generation stand out as a positive signal within the institutional framework of the domestic energy sector. Micro-generation refers to small-scale electricity production for self-consumption, primarily aimed at private homeowners. This model allows consumers not only to meet their own energy needs but also to sell surplus electricity to the grid at the retail rates charged to the general public by the "guaranteeing supplier". Amendments to the Law on the Electric Power Industry adopted in the summer of 2026 removed the previously existing 15 kW limit on grid feed-in and opened up micro-generation to multi-apartment buildings. At present, there is no clear understanding regarding the features of micro-generation that will shape the segment's trajectory—e.g., capacity threshold or the settlement procedures between prosumers (consumers, who produce energy) and sales companies, as the government of Russian Federation is still working out the details of this process. In any case, the development and operation of DG facilities that do not qualify as micro-generation currently fall outside the scope of state regulation. It is actually impossible to connect such facilities to the unified grid, while existing tariff regulations and pricing mechanisms do not apply to them [39,64].

Top #2 Factor (X1): Technical feasibility and duration of connection procedure to centralized power grids.

A shortage of available capacity at power supply hubs and lengthy grid connection procedures are driving consumers toward on-site power generation. The commercial data center market, which is already facing a lack of available capacity, serves as a prime example of these constraints. Energy is becoming the primary limiting factor for the development of digital infrastructure. Consequently, domestic companies from the IT and Fin-tech sector have started establishing their own power generation based on DG techniques [65].

Industrial enterprises are also keeping pace with the development of their own power generation capabilities. Energy-deficient regions, e.g., Krasnodar Krai, and industrial sites located far away from existing power supply sources have a strong incentive to build DG facilities. However, this factor may actually hinder the development of DG. The energy sector of Ural macroregion, and Sverdlovsk oblast in particular, is characterized by an energy surplus. This energy surplus is characterized by tremendous energy-generating capabilities, energy consumption volatility throughout the day and week, and the slow decommissioning of physically and technologically obsolete facilities. Affordable, low-cost energy provides no incentive for businesses to invest in complex engineering solutions. Moreover, maintaining on-site generation facilities requires specific expertise: companies must either employ their own engineering staff or outsource the services. Siberia is another macroregion with an energy surplus; it is home to the Angara cascade of hydroelectric power plants, Russia's largest hydropower complex, with a total installed capacity of 11,999.4 MW. Prices in competitive capacity auctions can be zero or even negative; in such cases, there is no economic justification for implementing a DG project, except for the developer's personal convictions [66,67].

Top #3 Factor (X8): Economic feasibility and payback periods for DG facility implementation.

The survey results indicate that economic feasibility is a key factor driving the development of DG, as investment decisions are made by consumers based on a comparison between the cost of self-generated electricity and the final grid price plus grid connection fees. Actually, economic viability serves as the transmission mechanism through which the other eleven factors exert their influence on the development of DG.

The Russian energy sector employs a cross-subsidization mechanism for pricing. Tariffs for residential consumers and equivalent groups are, on average, 30–50% lower than the electricity prices charged to industrial enterprises. Consequently, the industrial sector effectively subsidizes the low electricity costs enjoyed by households. This distorts price signals, undermines the competitiveness of energy-intensive industries, and drives large consumers to develop their own generation capacity. For instance, DG in Sverdlovsk oblast is primarily represented by the combined heat and power (CHP) plants of major industrial facilities, such as the Sredneuralsk Copper Smelter (Revda), the Ural Electrochemical Combine (Novouralsk), Uralelectromed (Kirovgrad), the Nadezhdinsky Metallurgical Plant (Serov), etc. [53,68].

The annual rate of tariff indexation for the industrial sector ranges from 11% to 16%, depending on the region, significantly outpacing the inflation rate (target value for 2026 is 6–7%). While the grid component of the tariff and capacity charges is rising rapidly, the specific capital costs for DG facilities and energy storage systems are falling due to globalization and technological progress. Within this emerging price gap, on-site generation gains a competitive advantage, shortening the payback periods and steadily expanding the pool of consumers for whom the transition is economically rational. Global experience confirms that economic factors are the primary driver [69–71].

4.2. Modelling the DG Development Strategy for This Case Study

Based on the ranking of the strongest and weakest factors influencing the development of DG in the UES, the authors attempted to outline a potential step-by-step development plan for the energy sector of Sverdlovsk oblast and assessed the structure of installed generation capacity across three time periods. The overall planning period was stopped at 2050 to align with current industry strategic documents concerning the development of the domestic fuel and energy sector. The completion date for Step 1 was set for 2031, in accordance with the approved scheme and program for the development of the electric power industry in the Sverdlovsk oblast [53], in order to obtain precise data on the capacity structure, while the deadline for Step 2 was set for 2040. The general concept for the development of DG, broken down by steps and generation sources across three scenarios, is presented in Table 6.

Table 6. Concept for the development of DG in the Sverdlovsk oblast (made by the authors).

Generation Source	Inertial Scenario	Standalone Scenario	Target-Oriented Scenario
Centralized power plants	Step 1: The planned capacity structure from the program in [50] is used. Steps 2, 3: The installed capacity remains unchanged due to a significant capacity surplus.	Equivalent to the inertial scenario.	Step 1: The planned capacity structure from the program in [53] is used. Step 2, 3: A partial decommissioning of coal-fired generation.
DG powered by natural gas	Transfer 0%/1%/2% of installed capacity used by large industrial consumers to the CHP plants in steps 1/2/3, respectively.	Transfer 3%/8%/15% of installed capacity used by large industrial consumers to the CHP plants in steps 1/2/3, respectively.	Equivalent to the standalone scenario.
DG powered by biogas	Steps 1, 3: No measures are being implemented. Step 2: Construction of biogas reactors at WWTP in the regional center—Ekaterinburg.	Construction of biogas reactors at WWTPs in cities with populations exceeding 100,000/50,000/20,000 inhabitants in steps 1/2/3, respectively.	Equivalent to the standalone scenario.
DG powered by solar energy	Construction of rooftop micro-generation for 0.1%/0.5%/1% of all residential houses (excluding multi-apartment buildings) in steps 1/2/3, respectively.	Construction of rooftop micro-generation for 1%/4%/10% of all residential houses (excluding multi-apartment buildings) in steps 1/2/3, respectively.	Equivalent to the standalone scenario.
DG powered by hydro energy	No measures are being implemented.	Step 1: Restoration of 6 abandoned mini-hydroelectric power plants [72]. Steps 2 and 3: Construction of mini-hydroelectric power plants with a total capacity of 20/50 MW, respectively, according to [72].	Equivalent to the standalone scenario.

Table 6. *Cont.*

Generation Source	Inertial Scenario	Standalone Scenario	Target-Oriented Scenario
DG powered by wind energy	No measures are being implemented.	Step 1: No measures are being implemented. Step 2, 3: Construction of new micro-wind turbines with a total capacity of 10/20 MW, respectively, according to [72].	Equivalent to the standalone scenario.

Forecast for centralized generation development

Centralized generation remains the foundation of the entire energy sector throughout the forecast period. The estimate of installed capacity for Step 1 is derived from calculations found in the Scheme and Program for the Development of the Electric Power Industry of the Sverdlovsk region [53,54]. Subsequently, through 2050, the final figure remains unchanged in both the "inertial" and "standalone" scenarios due to the significant capacity surplus in the region. Under the "target-oriented" scenario, the plan proposes decommissioning environmentally unfriendly coal-fired facilities by 2050.

Forecast for the development of DG powered by natural gas

Given the substantial institutional barriers and limited governmental regulation, together with the high energy prices for large consumers and practical impossibility of connecting a local DG facility to the grid, a large number of technologically isolated energy facilities for the support of enterprises, where the cost of electricity will be lower than in a centralized power supply system, are expected to appear. This means that no grid connection approval is required from a system's operator. This stage can be described as individual in nature, as projects emerge through private initiative.

The development of natural gas-based power generation is driven, on the one hand, by the availability of fuel resources in the major industrial centers of the Sverdlovsk oblast and, on the other, by the negligible impact of the environmental factor (X4) identified through the expert ranking. Unlike renewable energy sources, gas-fired power units provide a 24/7 baseload, which is critical for continuous metallurgical production cycles. Incidentally, the use of natural gas is considered the most environmentally friendly option among fossil fuel-based methods. This approach is a distinctive feature of the domestic small-scale power sector, whereas similar systems abroad rely on RESs.

Under the "inertial" scenario, the authors do not anticipate significant involvement of industrial enterprises in the creation of DG facilities. Their primary focus will be on economic feasibility and the payback period; however, the implementation of any form of government support, even at the regional or municipal level, would provide a more compelling basis for pursuing this initiative. The baseline values for shifting a portion of power consumption to distributed generation sources are determined based on the historical data. In turn, the target of meeting 15% of the total power consumption of large industrial enterprises through DG by 2050, under both the standalone and target-oriented scenarios, is based on anticipated shifts in state policy, the high tariff burden on consumers (excluding the residential sector), and the availability of sufficient fuel resources (as the major gas pipelines "Buhara—Ural" and "Urengoy—Chelyabinsk" run through the region). However, a complete transition to DG is not on the agenda, as centralized power generation ensures system stability, regulates frequency and voltage, and covers the base load during peak periods. Abandoning centralized generation would pose risks to the stability of the entire regional energy system.

As individual DG evolves, the operators of these systems will gain greater significance in the energy market. Driven by the digitalization of the energy sector and the growing

number of generation assets, large industrial consumers in the "target-oriented" scenario will eventually move toward establishing microgrids. This bottom-up approach will gradually elevate the issue of DG to an institutional level, thereby creating the prerequisites for integrating DG facilities into the grid. It will be the best moment for removing restrictions and bureaucratic barriers to connecting DG facilities operating in island mode to the unified power grid; however, it will be necessary to develop a unified standard for grid connection and establish mechanisms for the dispatch control of the power system. If this is coupled with a top-down state initiative, a synergistic effect could be achieved, significantly accelerating the development of DG.

Forecast for the development of DG powered by biogas

Municipal wastewater treatment plants (WWTPs) could serve as a driver for the development of biogas-based power generation in the region. A study by Kiselev et al. [73] revealed that, during the modernization of the Northern WWTP in Ekaterinburg (which serves approximately one-fifth of the city's population), anaerobic digesters were installed to produce biogas from sewage sludge. This resource could be utilized in a mini-CHP plant to meet WWTPs' own energy needs in all major cities across the region. Furthermore, the implementation of projects based on the technology of anaerobic digestion of organic waste, with the utilization of biogas for energy production, is one of the best CE practices aimed at reducing GHG emissions: both by capturing GHG from waste and by replacing traditional electricity generation.

Within the second step in the "inertial" development scenario, the creation of biogas plants and generators are considered only in the regional center, Ekaterinburg. The "standalone" and "target-oriented" scenarios envision the creation of similar facilities in all major cities with populations exceeding 100,000, 50,000, and 20,000 residents in steps 1, 2, and 3, respectively [74].

Forecast for the development of DG powered by solar energy

The development of solar power generation in the Sverdlovsk oblast began with the launch of the first industrial-scale facilities in the Arti Urban District in September 2024. Regional authorities are considering increasing the number of renewable energy installations as part of a broader strategy to transition to eco-friendly energy sources [75]. The authors identify micro-generation as the primary driver for the development of this type of power generation. As noted in the discussion of the factor analysis results, the regulatory framework governing rooftop solar panels is currently rapidly evolving. However, it is quite difficult to accurately assess the current and future level of development of the renewable energy-based micro-generation market in Russia, given that all the players in this sector are small companies that do not publish their data, and there are no official state statistics on the commissioning of micro-generation facilities. Nevertheless, under an inertial development scenario, no explosive growth is anticipated, primarily because electricity tariffs are artificially suppressed, and the necessary technological equipment remains quite expensive. In this scenario, the installation of micro-generation systems is of interest only to a small group of enthusiasts. The official statistical data as of April 2026 [76] are used to calculate the number of potential sites for micro-generation installations.

In both the "standalone" and "target-oriented" scenarios, the authors foresee the potential to increase the share of micro-generation installations to 10% of all properties. The proposed target aligns with estimates from the Russian Ministry of Energy, according to which the achievable market potential for solar micro-generation nationwide could reach up to 15 GW [77]. However, this would require a significant reduction in the cost of photovoltaic panels and automation equipment, e.g., by establishing local manufacturing facilities in the region.

Forecast for the development of DG powered by hydro energy

Small hydropower is the most promising area of renewable energy development in Sverdlovsk oblast. Experts estimate the hydropower potential of the Sverdlovsk region at approximately 300 MW of installed capacity [71]. However, this potential is unevenly distributed and possesses specific characteristics determined by the regional geographical features. Despite the existing theoretical potential, its realization faces a number of serious barriers, including economic unviability, the seasonal nature of water inflows, the need for numerous approvals, and strict regulatory oversight of natural resource use by officials. Consequently, the "inertial" development scenario does not consider the development of hydroelectric generation in the region at all.

Under both the "standalone" and "target-oriented" scenarios, it would be possible to restore six abandoned mini-hydropower plants in the first phase and, looking ahead to 2040 and 2050, to construct new hydropower plants with total capacities of 20 MW and 50 MW, respectively.

Forecast for the development of DG powered by wind energy

The wind power generation potential in the Sverdlovsk oblast is poor and localized. The region's primary challenge is insufficient average annual wind speed. This is largely due to geographical factors: the region is predominantly forested, and the Ural Mountains run through its center from north to south. For industrial wind turbines to be economically viable, wind speeds must reach at least 6–7 m per second. Under the "inertial" scenario, no development of wind power generation is envisaged.

Nevertheless, there are specific locations within the region, e.g., Mount Kachkanar, the eastern foothills and ridgelines, industrial sites, open-pit mines, and waste heaps, where wind energy could be effective. Consequently, under the "standalone" and "target-oriented" scenarios, there is the possibility of establishing new wind power generation facilities with a total installed capacity of 10 MW by 2040 and 20 MW by 2050 [71].

Forecast for power consumption

In 2024, the peak power consumption in the region was 6248 MW, while 6546 MW is projected for 2026. During Step 1, the annual growth rate of power consumption is expected to range from 1.92% to 0.9%, reaching 6967 MW by 2031 [53]. For Steps 2 and 3, the authors assume an annual power consumption growth rate of 1%.

Based on the design described, the authors performed calculations for the three scenarios at each step, additionally determining the values for the starting point (2026). The simulation results are presented in Table 7 and visualized in Figure 3.

Table 7. The results of the scenario-based forecast for DG development and power consumption in MW (made by the authors).

Generation Source	Current	Inertial Scenario			Standalone Scenario			Target-Oriented Scenario		
	2026	2031	2040	2050	2031	2040	2050	2031	2040	2050
Central Generation	10,321	10,371	10,371	10,371	10,371	10,371	10,371	10,371	9871	9271
DG Natural Gas	318	318	346	373	401	540	751	401	540	751
DG Biogas	20	20	23	23	24	25	25	24	25	25
DG Solar	38	44	69	100	100	287	660	100	287	660
DG Hydro	7	7	7	7	13	33	63	13	33	63
DG Wind	0	0	0	0	0	10	20	0	10	20

Table 7. *Cont.*

Generation Source	Current	Inertial Scenario			Standalone Scenario			Target-Oriented Scenario		
	2026	2031	2040	2050	2031	2040	2050	2031	2040	2050
Power Consumption	6548	6967	7594	8353	6967	7594	8353	6967	7594	8353

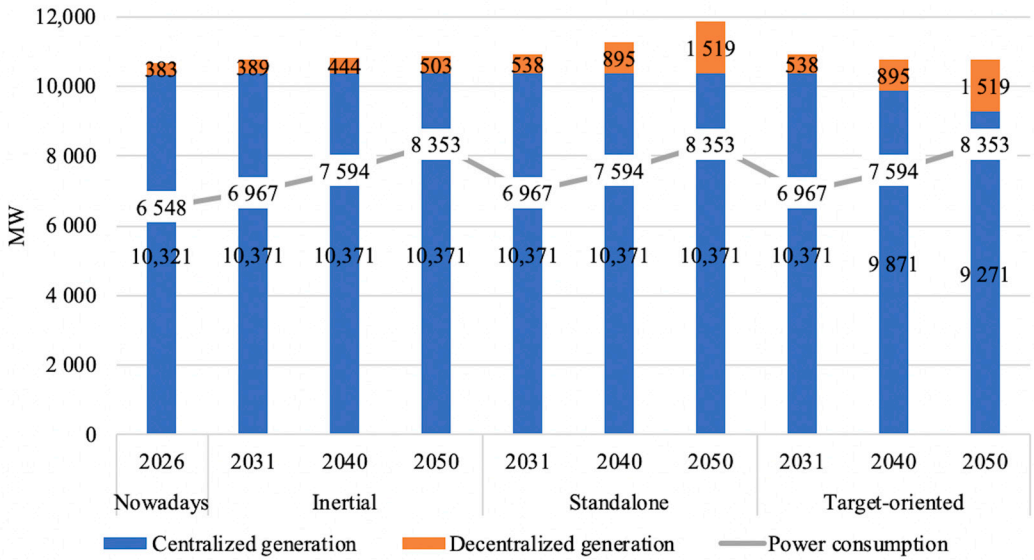


Figure 3. A diagram of the scenario-based forecast for DG development and power consumption (made by the authors).

The "inertial" scenario represents a trajectory in which the industry grows solely under the pressure of fundamental economic factors, without systemic state support, radical regulatory changes, or the large-scale adoption of innovative technologies. Under the current scenario, DG in the region will not emerge as a new economic sector but will instead remain a targeted tool for the internal optimization of large industrial holdings. The authors anticipate that the solar micro-generation sector will expand manifold, yet remain negligible in absolute terms. Its growth will be driven exclusively by enthusiasts and cases of targeted economic viability, without large-scale state support, equipment subsidies, or the introduction of regional "green" premiums. The owner of a micro-generation facility in the Sverdlovsk oblast (First Price Zone) can currently derive benefit not from selling energy at a high price, but from avoiding purchasing it from the grid at the retail tariff. As for surplus electricity fed into the grid, the guaranteeing supplier will purchase it at the wholesale market's weighted average unregulated price, which is several times lower than the retail tariff. Ultimately, under the "inertial" scenario, micro-generation is economically viable only for facilities with high daytime self-consumption. Installing panels to sell electricity to the grid is unprofitable.

The forecasting results under certain activities indicate that the total installed capacity of the regional energy complex will remain unchanged by the end of 2050, with a minor increase in DG. Taking into account the proposed growth in power consumption, the energy system will still maintain a surplus, allowing for the export of excess energy to neighboring regions. Naturally, this situation should be factored into the Russian Federation's electric power system development program to prevent capacity shortages in the UES.

The "standalone" and "target-oriented" development scenarios indicate more robust growth in the installed capacity of DG facilities. The former one would strengthen the

position of DG in the region, while the latter one would form the groundwork for an intelligent regional power system. The installed capacity of DG facilities could increase significantly, rising from 383 MW (in 2026) to 1519 MW (in 2050). This power is comparable to the region's largest centralized generation facility, the Sredneuralskaya GRES. However, the authors believe that priority for replacing centralized generation facilities should be given to the plants with the greatest negative environmental impact.

Under the "target-oriented" scenario, the architecture of DG power would be heterogeneous and segmented by consumer type, with two primary categories predominating. Industrial mini-CHPs would operate in cogeneration mode, meeting the enterprises' own needs while feeding surplus energy into the grid during periods of low demand. Microgeneration units could be aggregated into VPPs, transforming thousands of disparate, low-capacity, intermittent generators into a single, large-scale, controllable asset capable of fully participating in the wholesale electricity market.

The normalized modeling results (Figure 4) and capacity structure charts (Figures 5 and 6) indicate that under the "inertial" scenario, the DG share in the system's total energy balance would be merely 5%, whereas the "standalone" and "target-oriented" scenarios would enable shares of 13% and 14%, respectively. By the standards of developed nations, which have fostered renewable energy and small-scale generation for decades, achieving a 14% share of DG might be considered a modest result. However, for the energy sector of the Sverdlovsk oblast and the UES of the Russian Federation as a whole, this represents a significant threshold, marking the power system's transition to a new level of development and signifying that distributed energy has become an integral part of a robust, well-established industrial cluster. A 14% DG share places the region on par with major industrial economies, albeit with a significant caveat. Globally, DG is synonymous with "green" energy, whereas in the Sverdlovsk oblast, it relies on 50% gas-fired generation. This is a pragmatic industrial approach rather than a "green" one: cost reduction and evading rising grid tariffs take precedence over the environmental agenda. In other words, this is the point where spontaneous decentralization ends, and the era of complex digital coordination begins; an era where industrial giants and private solar panel owners become full-fledged market participants rather than mere consumers.

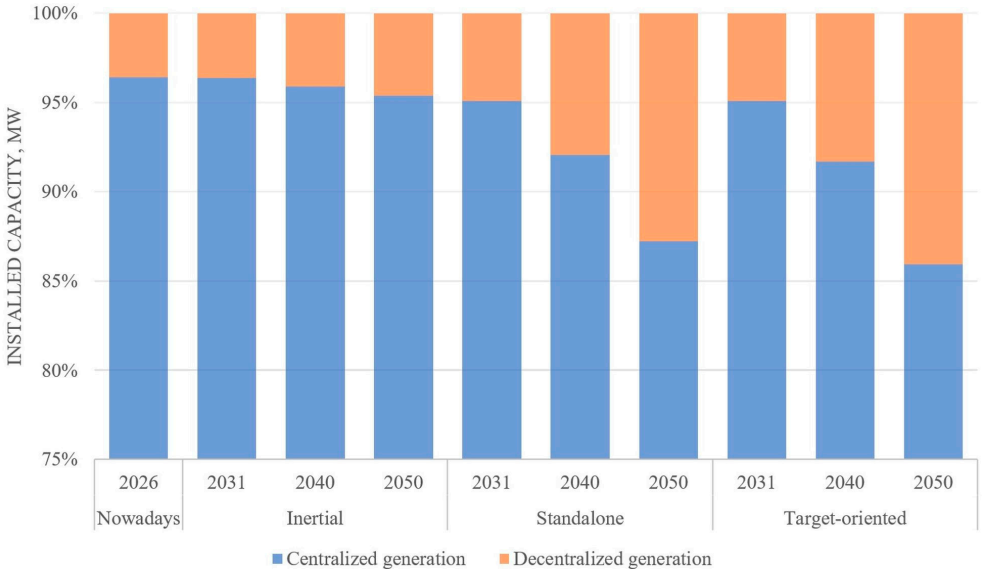


Figure 4. The normalized diagram of the scenario-based forecast for DG development (made by the authors).

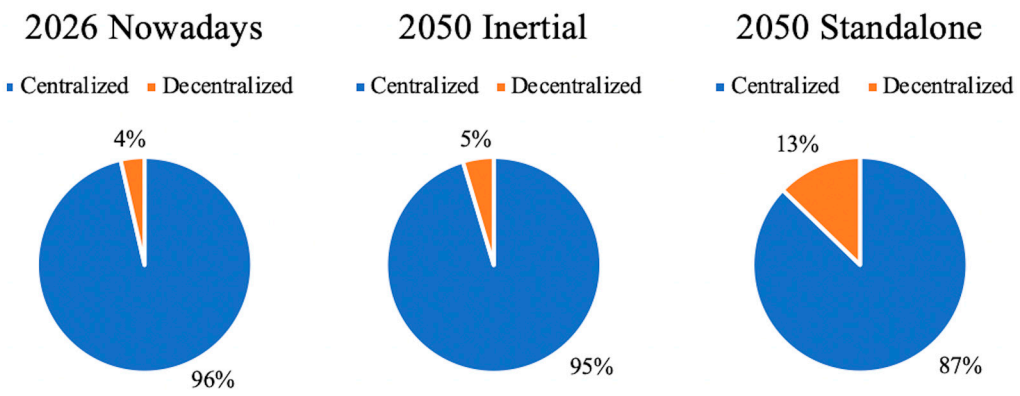


Figure 5. Actual and predicted DG share for 2050 under the inertial and standalone scenarios (made by the authors).

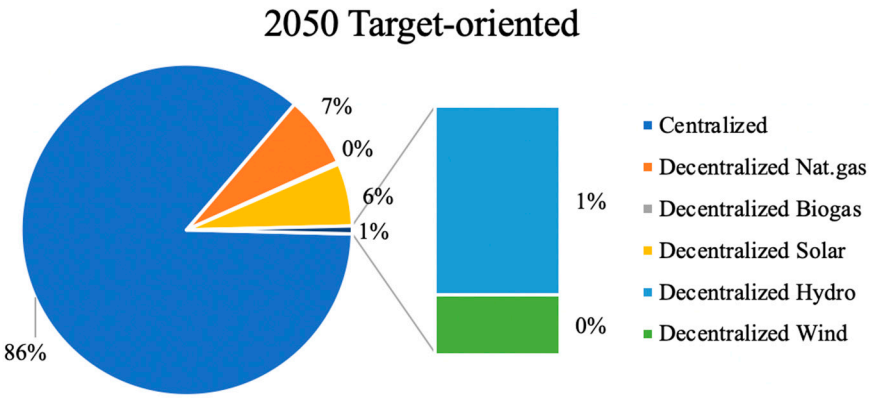


Figure 6. Predicted decomposed DG share by 2050 under the target scenario (made by the authors).

However, the target scenario can only be realized through the implementation of a systemic policy and support for the development of DG.

First and foremost, large-scale changes to the institutional and regulatory environment are required. The priority measures include:

- Market liberalization and the legal recognition of new entities—DG operators;
- The establishment of national regulations and standards for interconnection with the UES;
- The transformation of market commercial and sales infrastructure, along with the development of tariff regulation mechanisms;
- Further simplification of procedures and support for micro-generation.

Attention must also be paid to the economic viability of DG, including reducing the LCOE, ensuring access to financial instruments, providing concessional loans and interest rate subsidies, and utilizing crowdfunding and consumer co-investment models.

The need to ensure national technological sovereignty also deserves special mention. Amidst market constraints and high geopolitical risks, localizing the production of gas piston engines, gas turbines, generators, automation systems, solar panels, and energy storage devices within the region would create a solid foundation for the industry's development. This could be achieved, for instance, through the "Titanium Valley" industrial production special economic zone, which attracts investment in the Sverdlovsk region and fosters high-tech manufacturing.

DG can also be viewed as an element of national security and critical infrastructure protection. Unlike the traditional power system, built on the principle of "maximum efficiency", the DG architecture is based on the principle of "maximum resilience". While

this is not currently a significant factor for the Sverdlovsk oblast due to its geographical location, the digitalization of the energy sector and the rise of cyber threats could drive the development of this area.

Developing DG within a CE paradigm could significantly accelerate its adoption across the region. Under the traditional approach, DG is deployed only when grid tariffs become prohibitively expensive. In the CE framework, power generation arises not as a response to high grid costs, but as a byproduct of industrial process optimization. This shifts the business logic: generation ceases to be a standalone infrastructure investment and becomes part of the production cycle, with its payback period factored into the cost of the primary product. For the Sverdlovsk oblast, characterized by its unique industrial density and high volumes of industrial waste, this approach could fast-track capacity expansion. Growth in generation would be driven not by rising energy prices, but by industry learning to monetize materials previously dismissed as waste. Blast furnace and technological gases, biodegradable waste, sewage sludge, and wood processing residues can serve as energy sources; establishing material and energy recycling systems can boost returns while mitigating environmental impact. In this context, energy sector development is no longer an isolated process; it requires alignment with related economic sectors, specific waste management programs, and the implementation of CE and sustainable development principles.

In summary, the pilot application of the methodological toolkit using a case study demonstrates its viability. By following the methodology's steps—identifying the factors relevant to the territory in the questionnaire, consolidating the experts' opinions on the factors' strengths and impacts, and outlining measures suited to the specific context—the study provides answers to the following questions:

- What factors hinder or foster the development of DG in the specific territory?
- Which stakeholders should be prioritized during the implementation of the action plan?
- How will the planned actions quantitatively affect the capacity structure?
- What should be taken into account to successfully implement the proposed plans?

The proposed methodological tool and the scenario-based modeling of DG development in the case region demonstrate the significant value of this approach for strategic regional energy planning. Shifting from inertial forecasting to active scenario planning, based on the relevant factors affecting the specific territory, opens up fundamentally new opportunities for managing an energy system amidst the energy transition and the adoption of CE practices.

The developed scenario planning model targets a wide range of stakeholders, including:

- Regional executive authorities and energy ministries: Draft the regional programs for the development of the electric power industry, the socio-economic development strategies and justify applications for federal funding.
- Grid companies: Schedule the reconstruction and technical upgrading of distribution networks, as well as assess the feasibility of investments in smart grids.
- Large industrial enterprises and industrial parks: Select the optimal configuration of on-site generation and evaluate the potential to sell surplus capacity on the local market.
- Investors and developers: Assess the risks and potential returns of DG projects across various locations in the region.
- Research organizations: Conduct further research in the fields of energy transition and the integration of new technologies, building upon the existing forecasting methodology.

However, the tool presented in the article has certain limitations. The proposed model provides a generalized forecast of indicators without accounting for the following aspects:

- Wear and tear and the current condition of generating assets and grids;
- Existing grids and transformers operating at various voltage levels;

- Power flows and limits within regional energy systems and between neighboring regions;
- Formation and operation of microgrids and smart grids;
- Development of energy storage systems;
- The geographical mapping of facilities and consumers to the power grid infrastructure.

Detailed planning and forecasting would require the participation of all key stakeholders, including government and local authorities, grid and generation companies, major consumers, the system operator responsible for centralized dispatch control of the UES, the "Market Council" self-regulatory organization, and the commercial market operator. At this stage, the participation of these entities is not feasible.

It is also worth noting that the modeling process lacks a strictly formalized procedural description or mathematical formulas; instead, it relies primarily on reasoning, inferences, cause-and-effect relationships, and conclusions drawn from preceding steps. During the modeling process, it is crucial to identify the DG initiative actors and technologies that will dominate throughout the implementation of the action plan measures. In this regard, the researchers' opinions or attitudes toward the subject matter could influence the modeling results.

The authors envision the following directions for the future development of the proposed methodological framework:

- Inclusion of environmental impact determinants in predictive model scopes;
- Accounting for the thermal capacity of DG facilities;
- Analysis and forecasting of energy losses in the grid;
- Broadening the range of potential project initiators when planning measures for the action plan;
- Assessment of DG investment potential and impact on the regional economy.

Refining the methodology for the scenario modeling of DG opens up broad avenues for studying the subject at the intersection of energy, information technologies, economics, and ecology.

5. Conclusions

The paper presents an original methodological tool for scenario modeling of DG development within a region characterized by established, traditional centralized generation. A strength of the proposed approach is the systematic consideration of factors and the magnitude of their influence, which allows the model to be more precisely adapted to the specific territory. The primary objective of the modeling procedure is to formulate appropriate measures for the action plan to develop the regional energy complex and to quantitatively assess the projected structure of generating capacities. The methodological framework is tested using the Sverdlovsk oblast energy complex, which is part of the UES of the Russian Federation. The main findings are as follows:

- Currently, DG in the region accounts for a negligible share of the energy mix, at 3.58%, with the predominant use of natural gas as an energy source, and its development is proceeding haphazardly, without being reflected in strategic documents.
- Using the method of a priori ranking, the top three factors significantly influencing the development of DG in the region are identified. The primary impediment consists of institutional and political barriers at the federal level, stemming from the rigid hierarchy established within the country's energy sector. A second factor hindering DG development is the capacity surplus in the regional power system, combined with relatively good grid accessibility for consumers. The third key factor is the economic viability of DG projects; the high tariffs for industrial enterprises drive them to establish their own generation facilities.

- The scenario modeling outlines a few potential development paths for DG in the region. Under the "inertial" scenario, growth is limited to cost optimization by industrial enterprises and the modest adoption of rooftop micro-generation units in the residential sector; the increase in DG capacity remains within the margin of statistical error. The "target-oriented" scenario, conversely, envisions the partial decommissioning of coal-fired generation and the creation of a complex architecture in which industrial natural gas-fired mini-CHPs operate in tandem with VPPs comprising household solar panels. In this case, the share of DG in the total capacity mix could reach 14% by 2050. However, the feasibility of the "target-oriented" scenario is contingent upon a set of strict prerequisites that extend beyond the forecasting procedure. Specifically, its implementation relies on favorable institutional and political conditions, including a stable regulatory framework, streamlined permitting procedures, and targeted state incentives for a green energy transition. Furthermore, the scenario critically depends on the proactive initiative of economic entities to create DG facilities in strict accordance with the established plans and assigned capacity targets.
- Shifting to a CE paradigm could serve as the primary driver for breaking away from the business-as-usual scenario. In this model, power generation ceases to be a standalone investment and instead becomes a by-product of waste processing. For the region, this entails utilizing blast furnace and technological gases, biogas from WWTPs, and forestry waste. This reduces the payback period for DG facilities, making their implementation profitable even when electricity prices are low.
- The developed model serves as a decision-support tool for a wide range of users, including government authorities, industrial and grid companies, investors, equipment manufacturers, and research institutes.

Reaching a 15% share of DG by 2050 would be a significant milestone, marking the region's energy system's transition from a rigid, centralized model to an adaptive one. However, such a transition will be impossible without a radical overhaul of the regulatory environment: the target scenario requires the synchronization of federal policy and regional tariff strategies alongside the implementation of CE principles.

The scientific novelty of the research is the development of an original multi-stage assessment tool that integrates several common established methods—identification and analysis of influencing factors, prioritization of these factors through expert assessment, formulation and forecasting of development scenarios, and the incorporation of CE principles—into a unique, sequential algorithmic process specifically tailored to the authentic context of regional industrial energy decentralization, which is manifested in five key contributions:

- Addressing an existing gap in the research devoted to forecasting DG growth within traditionally stable centralized power systems;
- Taking into account the current situation in the region under consideration by identifying the factors and their impact on the development of DG;
- Proposing a specific development pathway typical for a fossil fuel-based national energy system, so called "industrial decentralization", where natural gas-fired generation acts as a driving force for DG, together with the "green" agenda;
- Incorporation of CE principles into the DG development strategy;
- Differentiation of scenarios based on the level of institutional maturity.

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