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REGULATION OF THE DEVELOPMENT OF DISTRIBUTED ENERGY GENERATION

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An essential component of supporting sustainable development is the expansion of distributed renewable energy source generation. The purpose of this work is to identify the key areas of influence of state authorities in support of the formation of distributed energy generation. The example of Ukraine revealed the potential of their use in conditions of military threats. The methodological basis of the study encompasses tools of institutional, historical, genetic, structural, comparative, and complementary analysis. Instruments of state regulation of the development of decentralized power generation are presented. The potential for regulating the development of renewable energy generation through artificial intelligence is shown. Attention is focused on the contradictory influence of scaling effects on the stimulation of its development.

Keywords: *artificial intelligence, digital technologies, distributed energy generation, energy policy, regulation, renewable energy*

1. Introduction

The purpose of this article is to identify the key areas of influence of state authorities in support of the formation of distributed generation. The example of Ukraine revealed the potential of their use in the face of military threats.

The development of renewable energy has led to a return to the historical origins of energy systems as they evolve into microgrids. The first electrical system in history was created in 1882—the Pearl Street Microgrid in Manhattan, New York. A coal-fired generator supplies electricity to power a hundred lamps (Monaco 2011).

Accounting for 40% of CO_2 emissions, the energy sector's heavy reliance on fossil fuels is the result of a lack of social responsibility. Traditionally, energy production has been concentrated in large power plants, which are combined into centralized energy systems. This increases the efficiency of carbon resource use. Simultaneously, the rapid growth of consumption in developing countries, high dynamism, and periodic crises of the world economy are accompanied by significant fluctuations in the supply, demand, and price of carbon resources in global markets. Energy systems face challenges such as deficits, low efficiency of use, and the need to update distribution systems. Additional problems arise from the aggravation of confrontations between leading players in the global economy. The war in Ukraine has demonstrated the vulnerability of centralized energy generation systems. By targeting thermal and hydroelectric power plants, distribution centers, and energy networks, the aggressor hopes to destroy the country's ability to organize and resist.

The importance of ensuring the development of distributed generation (Soshinskaya et al. 2014) and the formation of a hybrid energy system capable of combining the advantages of centralized and decentralized energy supply is growing. Reliance on digital technologies and the exploitation of artificial intelligence (AI) potential pave the way for integrating power generation microgrids and accumulating energy from multiple dispersed participants (IEA 2025). It provides microgrid stability, automatic monitoring of energy flows, and two-way communication between participants. Systems can be implemented to respond to fluctuations in demand. The list of services and products provided in the electricity market is growing significantly every year. Zhang et al. (2017) emphasize that the number of end-user participants has increased in the energy market. Digital platforms are forming full-fledged value chains (networks) within renewable energy microgrids. They provide the ability to combine distributed generation, redistribution, accumulation, consumption, monitoring, control, energy flow balancing, and microgrid management, as well as ensure mutual settlements between its participants. The development of distributed generation becomes relevant in conditions of hostilities. The emergence of threats to energy state security has resulted in targeted attacks on centralized generation objects and the distribution of energy flows (Lypov 2024).

Various factors complicate the development of distributed generation systems. First, we discuss the need for a radical restructuring of the national energy system. This involves the technological and resource components in the energy supply organization. The institutional environment is critical in the energy generation process. Effective utilization of natural resources and climate change are key components of sustainable environmental management (Nosova 2024). And effective state management of transformation processes in the energy sector is also crucial.

2. Literature Review

Platformization and technology for producing renewable energy are essential components of the Third Industrial Revolution, as they create opportunities for a radical restructuring of the energy sector (Nosova 2024). Among the models of the transition from centralized to distributed power generation, researchers have singled out microgrids (Soshinskaya et al. 2014; Hirsch et al. 2018), smart grids (Zhang et al. 2017; Dawn et al. 2024), and virtual power plants (Abdelkader et al. 2014). Grytsenko and Lypov (2024) highlighted a strategy of combining independent energy producers through the entire ecosystem cooperation or creating a commercial intermediary platform. Simultaneously, significant gains in renewable grid formation are obtained despite challenges. The regulation of distributed generation is a component of renewable energy development policy (IREA 2018). The need for a targeted multi-vector policy to support its development by government agencies is recognized as a necessary condition (Good et al. 2017). The need for AI usage in energy policy is studied (IEA 2025). Distributed generation is relevant in countries with limited development resources (Kona et al. 2018; Lytvyn and Levitsky 2023). The study of the possibilities of stimulating the association of owners of renewable energy stations in federal structures focuses on T. T. Morstin and coauthors (2018). The involvement of equipment owners in the renewable energy microgrids is recognized as a crucial element in the formation of "energy citizenship" (Ryghaug et al. 2018). Scientists have concentrated on the essence, role, and importance of energy democracy (Fairchild and Weinrub 2016), energy inclusion (Lypov 2024), communitarian principles of energy market formation (Moret and Pinson 2018), and ways to enhance the involvement of local authorities in strengthening the energy sustainability of territorial communities (Bauwens and Eyre 2017). Grytsenko and Lypov (2025) asserted that the complementarity of the state and the market is a tool for ensuring the development of renewable generation. Highlights the development of distributed generation (Kloppenburg and Boekelo 2019), the creation of a regulatory framework (Schneiders and Shipworth 2018; De Almeida et al. 2021), the study of problematic issues in the following scientific works, and energy policy (Zame et al. 2018)

A distinct avenue of research involves examining the advancement of technical and technological developments in distributed generation (Cavus 2024).

Organizational and economic aspects of the use of accumulation systems are the focus of the research team led by Xia et al. (2022). A cost assessment of the distributed generation intermediary of microgrids is the research theme for scientists (Lee and Cho 2020). A stimulating mechanism for renewable energy microgrids applies the scale effect in distributed generation (Bauwens et al. 2020).

A distinct area of research involves examining the factors that promote the development of technical, technological, and economic aspects of ensuring the effectiveness of distributed energy generation.

3. Methodology

The methodological basis of this study includes tools of institutional, historical, genetic, structural, comparative, and complementary analysis. We use the institutional approach to studying the regulatory framework and organizational forms of distributed generation. A historical, genetic approach analyzes the evolution of renewable energy generation. Structural and comparative analysis determines and analyzes the construction of options for controlling and stimulating the development of distributed generation. Complementary analysis highlights the institutional unity, interconnection, and interdependence of the elements of the distributed generation development regulation system. A multidisciplinary approach provides specific tools for distributed energy generation. It estimates technical, technological, and socioeconomic components in energy production. Developers, market participants, and renewable energy suppliers are among the stakeholders. The last includes enterprises and households, system operators, and consumers. These economic agents are interested in technological advancements in the energy sector.

4. Results

Transformation of energy markets as a foundation for developing policies to stimulate distributed generation

The necessity for a substantial transformation of energy sector management systems arises from a radical restructuring of the energy market (Good et al. 2017). This transformation involves creating a multi-level structure. The first level consists of prosumers (Morstyn et al. 2018)—households and small to medium-sized enterprises that own energy generation equipment and view this ownership as a distinct avenue for business activity. The second level includes traditional entities involved in centralized energy generation and distribution (Grytsenko and Lypov 2024). There is an opportunity to create energy islands and peninsulas in local communities. Local markets become the first link in the trading of electricity. Real examples include the blockchain-based microgrid energy market in Brooklyn (USA), the Piclo platform in the United Kingdom, and the De Ceuvel project in the Netherlands (Shan et al. 2023). The introduction of accumulation and digital control systems provides the following functions. These systems stipulate exchange flows. It maintains the stability of energy supply and performs calculations between participants at the microgrid level (Zame et al. 2018). With the establishment of the Institute of Aggregators, producers can now actively participate in activities across a range of renewable energy sectors at the regional level. Their presence makes it possible to use flexible generation as a market product. In turn, energy distribution network managers ensure that the entire energy system is stable. To maintain grid operation in the event of an energy imbalance, small power producers can engage in the retail market.

Commercial power generators enter wholesale markets and offer their energy resources to distribution network operators. The latter, in both retail and wholesale energy markets, is responsible for balancing energy production and consumption. The transition from centralized to distributed generation systems is associated with the emergence of significant challenges and necessitates the restructuring and strengthening of the energy system management system.

The controversial nature of transition effects on microgrids' distributed generation

The reliance on digital technologies and the virtual nature of energy contribute to the emergence of scaling effects in distributed generation networks. A crucial factor is the contradictory consequences of decentralization on certain components of maintaining energy supply stability. The possibility of obtaining the inherent centralized generation of economies of scale of production is lost. Simultaneously, decentralized generation creates opportunities for the network effects, and how the placement of other organizations reinforces imprinting (Bauwens et al. 2020). At the same time, dispatching and energy flow management systems have become more complicated. This, in turn, complicates the task of minimizing the use of fossil energy sources. The potentially achievable volumes of generation and income of owners are lost due to various factors, one of which is the need to develop accumulation systems. The use of dynamic pricing systems increases the costs of balancing energy flows in the network.

Data work is controversially organized. Continuous automatic data exchange is the key to the success of this network. Increasing their volume does not incur additional margin costs. The more network members there are, the more valuable the data acquired. Their openness is a prerequisite for the mutual trust of participants, the necessary component in the formation of the territorial community unity. Simultaneously, the importance of preserving their confidentiality and security is growing. Threats of data loss and external unauthorized interference in the network increase costs for ensuring cybersecurity.

The growth of the number of energy generation entities affects consumer protection from interruptions in the energy supply. The infrastructure required for interregional energy flow redistribution and the direct costs of transportation are lessened when production is located closer to consumers. Simultaneously, the mechanisms for ensuring the coherence of their functioning in a single system are significantly complicated (Cavus 2024).

The self-sufficiency of renewable generation station proprietors reduces the demand on the network for consumers. However, from the perspective of the offer, there is a request for the transfer of excess generation. Moreover, there are significant fluctuations in the supply and demand. The owners of generating stations are acting as either producers or consumers of extra energy due to changes in the environment. This creates additional problems for system operators (Young and Brans 2017). The approximation of generation and the growth of the spectrum of techniques for accumulating excess generation have a contentious impact on the cost of energy to consumers. Finally, the expanding importance of the regulator in organizing the development of dispersed generation is determined by the paradoxical influence of its development.

Leveraging AI's potential to facilitate the advancement of distributed generation

In the context of decentralized supply networks, energy flow management is a complex task. System implementation can provide significant support for its artificial intelligence solution.

The efficiency of its application of asset utilization, operational management, technical assistance, and microgrid development is illustrated in Figure 1. It should be noted that all other AI functions are applicable in the context of micro networks. The Report on Energy and AI claims that "AI can help optimize the available capacity in the system—balancing generation, consumption, and grid utilization more efficiently in an increasingly variable environment. This approach delivers faster and potentially more cost-effective improvements without requiring new infrastructure investment. For long-term planning, AI helps navigate the substantial uncertainties in future electricity demand driven by widespread electrification, as well as the unpredictable evolution of power system technologies—from sophisticated grid solutions to emerging generation options—all while accounting for interactions with broader energy system developments" (IEA 2025, 130).

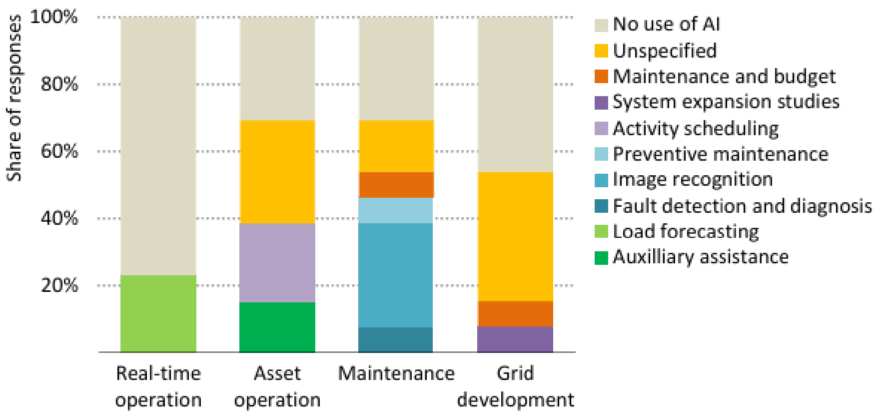

Figure 1. Utilities using AI applications by category, 2024

Source: IEA (2025, 12)

Table 1 shows the potential of using AI for operational optimization of energy flows in microgrids.

Table 1. Potential applications of AI in the real-time operations of electricity networks

Application	Description		Impact on energy	Example
Operational optimization				
Dynamic operating envelope	A framework that sets real-time, adjustable operating limits for grid-connected devices based on current network conditions to maximize available capacity while maintaining security; includes a dynamic security assessment		High: Reduces congestion costs, increases renewable integration, defers grid reinforcement investment, and optimizes existing infrastructure utilization without breaching security limits	A grid operator increases line capacity by 15–30% during cooler weather conditions, safely accommodating additional renewable generation
Fault detection and localization	Uses sensors and AI algorithms to quickly identify and pinpoint grid faults, reducing outage duration and improving response times		High: Reduces outage duration by 30–50%, improves system reliability metrics (SAIDI/SAIFI), lowers restoration costs, and enhances customer satisfaction	A distribution system operator detects a fault within seconds and precisely locates it within a 100-meter section, immediately dispatching repair crews to the exact location
State estimation and automation	Employs advanced algorithms to monitor distribution grid conditions in real time by inferring from measured points the electrical parameters at points without direct observability, enabling automated responses to maintain stability and optimize performance		High: Improves grid stability during variable renewable generation, reduces operating margins, enables higher distributed renewables integration, and decreases manual intervention requirements	An AI system continuously monitors voltage levels across the distribution network, automatically adjusting transformer tap settings to maintain optimal voltage profiles

Source: constructed on data of IEA (2025, 129)

Identifying the challenges of managing distributed generation

Distributed generation is a logical continuation and the deepening of understanding and improvement of tools to stimulate the development of renewable energy. It is based on the support toolkit accumulated by many countries over the past decades. "The Renewable Energy Policies in a Time of Transition" report summarizes administrative, price, and non-regulatory (including financial, tax, and non-financial) methods (IREA 2018). Researchers propose a classification of actively applied renewable energy support policies (see Figure 2). The criterion for classification is the size of the control object.

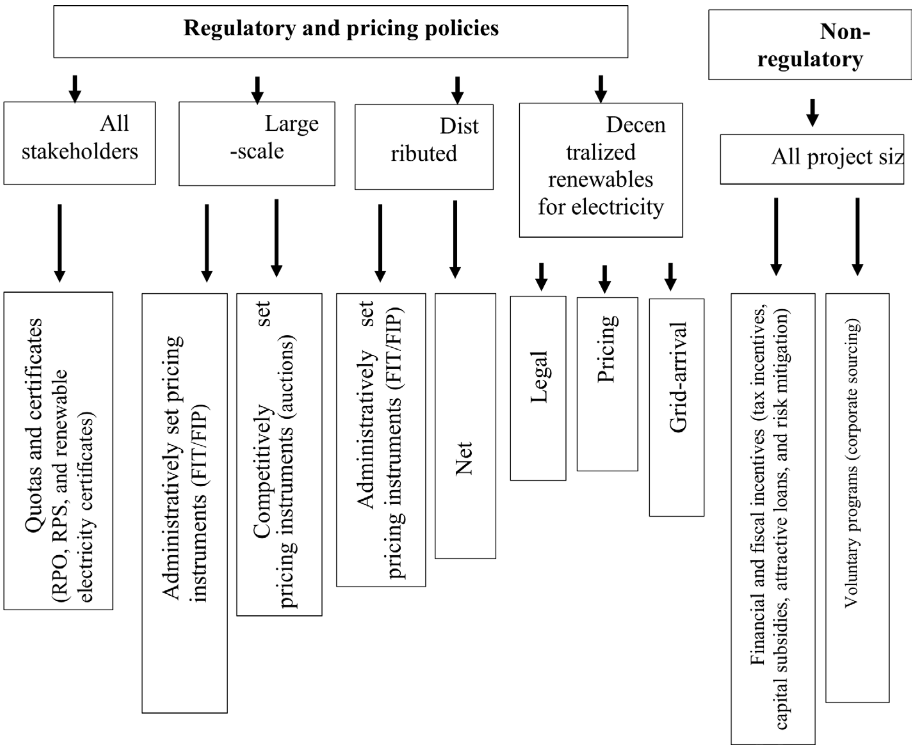

Figure 2. Classification of policies in the energy sector
Source: constructed on data of IREA (2018, 60)

The policy related to supporting the development of distributed generation entities is defined in a separate place. It provides for the use of feed-in tariffs, feed-in premiums, and systems of net metering/net billing. At the same time, one could mention that stimulating the development of distributed generation is not limited only to the use of these tools. An important incentive was the reduction in prices for renewable energy equipment. The possibility of implementing excess generation accelerates its payback period. Market pricing instruments are updated. Regulatory importance increases. In particular, the problems of microgrid function and the usage of centralized and distributed generation can be solved through regulatory and pricing policies. The toolkit of non-regulatory support for the development of distributed generation is expanding both at the national and local levels. The researchers consider that maintaining the incentive impact of taxes and emission allowance systems on CO_2.

All the defined regulatory, pricing, and non-regulatory policies can be applied in the process of ensuring the formation of local microgrids of distributed generation. The decentralization of electricity production and the emergence of a wide range of diverse sources and goals determine multiple approaches. The scale of the energy generation subjects does not exclude the provision of coordination of their activities. Such interaction is an effective tool for the efficiency of the equipment used, accelerating its payback and ensuring the reliability of energy supply not only to owners but also to residents of local communities.

At the same time, the organization into a single microgrid of independent energy producers implies the need to solve technical, regulatory, economic, and social problems. Motivation involves the use of specific instruments for distributed energy generation, organization, and functioning (Bauwens and Eyre 2017).

The first set of tasks involved in controlling the creation and maintenance of stable operations for distributed generation pertains to technical and technological support. This includes addressing purely technical limitations and challenges that hinder the coordinated operation of the network system. The second set of tasks focuses on establishing institutional foundations to ensure the coordinated functioning of distributed generation networks. This encompasses efforts to secure social recognition and public support for the development of distributed generation, as well as overcoming sociopolitical, economic, and regulatory barriers to its advancement.

5. Discussion

The policy of forming social support for the development of distributed generation

The policy of forming social recognition and supporting the development of distributed generation involves participation in a wide range of public structures. It combines sociopolitical movements, volunteer organizations, state structures, potential energy producers on a commercial basis, small and medium-sized enterprises, and households (prosumers and ordinary energy consumers). It creates opportunities for access to energy markets. The installation of distributed generation stations by individual enterprises and households contributes to the diversification of the energy supply. The key subjects of the flow are business structures, local territorial communities, small and medium-sized enterprises, and households. A separate consideration deserves a set of tasks related to the sociopolitical, economic, and regulatory aspects of supporting the development of distributed generation. Overcoming the problem of monopoly in the generation and distribution markets implies the need to develop a system of interaction in which the prompt coordination of the interests of various independent entities is ensured. Table 2 shows the dynamic growth of renewable generation in global energy consumption.

Table 2. Share of types of renewable generation in global electricity production, 2024

Renewable generations	Total (TWh)	Share in energy production (%)	Generation per capita (kWh)	Growth in 2024 (TWh)
Hydro	4413,13	14,31	540,85	179,39
Wind	2498,3	8,1	306,14	186,17
Solar	2128,49	6,9	260,82	471,77
Biogeneration	710,61	2,3	87,08	19,54
Other	88,76	0,29	10,88	-0,16

Source: constructed on data from the Electricity Data Explorer (https://ember-energy.org/data/electricity-data-explorer/?fuel=res&metric=absolute&chart=trend#datasets)

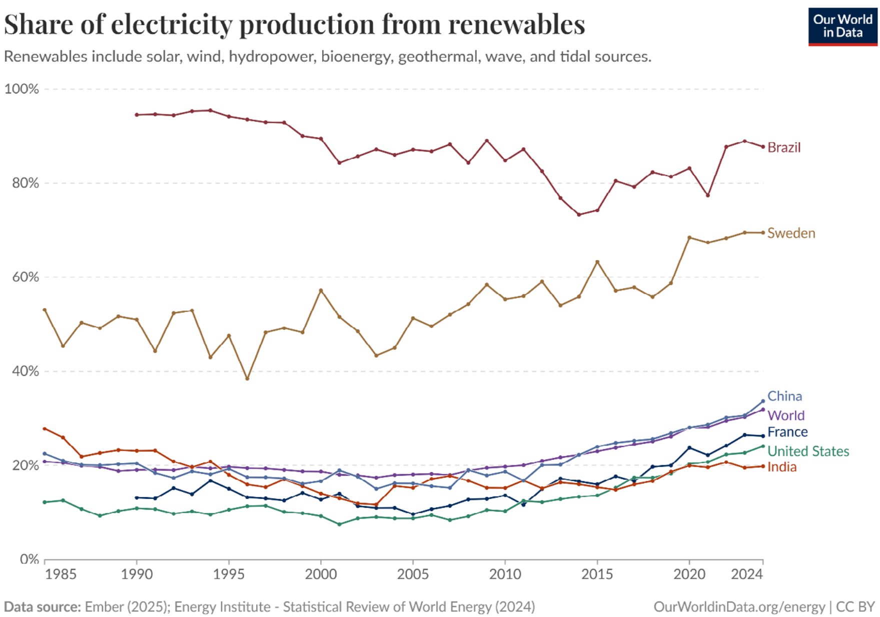

Figure 3. Dynamics of the share of renewable generation in selected countries

Source: *constructed on the data of Ember 2025; Energy Institute; Statistical Review of World Energy 2024; and OurWorldinData.org/renewable-energy*

Figure 3 illustrates the significant impact that variations in resource potential have on a country's role and position in national energy production. Brazil stands out as a leader in this area, while developed nations such as the USA and France fall below the global average for the share of renewable energy generation. This highlights the importance of establishing a focused national policy to support the development of distributed generation.

Managing the distributed generation: Ukrainian experience

Since October 2022, more than 50% of Ukraine's energy facilities have sustained considerable damage due to Russian attacks. By 2025, it was reported that 42.8% of the energy generation capacity had been destroyed. The largest occupied facility is the nuclear power plant in Zaporizhzhia (6 GW). Heat generation suffered the most significant losses (87% of coal-fired thermal power plants are irretrievably lost). A total of 2.3 thousand MW of hydro generation capacity was destroyed and damaged. This situation has exposed the vulnerabilities of an energy system based on centralized production and distribution, which heavily relies on large nuclear, thermal, and hydroelectric power plants. In response, both businesses and households have intensified their efforts to ensure their energy security. In 2024, about 1 GW of distributed generation capacity was built in Ukraine. The first half of 2025 saw the implementation of the same number (In the first half of 2025, 2025).

The distributed generation system should be incorporated into Ukraine's unified energy system. Wind, solar, and bioenergy plants and small hydroelectric power plants are examples of renewable energy sources. Various entities may be involved in distributed generation systems, including:

- Business entities specializing exclusively in the production of electricity
- Entities focused on the storage of electricity
- Companies engaged in the sale of electricity
- Entities involved in the purchasing and selling of electricity across all market segments
- Providers of balancing services
- Providers of ancillary services

Additionally, both individuals and legal entities may participate as consumers in this system.

Conclusions

1. The necessary component of the functioning of the economy under external threats and support of sustainable development is the functioning of distributed generation. The state plays a decisive role in ensuring active development.
2. Renewable generation microgrids form the second circuit in the national energy system. The state's efforts are aimed at supporting the restructuring of energy markets.
3. The transition from centralized to distributed generation systems requires the restructuring and strengthening of energy management. This process is complicated by the contradictory nature of the effects of forming distributed generation

microgrids. The state is designed to maximize the influence of the favorable and minimize the role of the negative.

4. The significant potential for ensuring the efficiency and stability of distributed generation is proposed using artificial intelligence.
5. Significant differences in the sources, conditions, and natural and institutional environments of the implementation of renewable generation determine the differentiation of tools and methods for regulating its development. Researching and creatively applying other countries' experiences, considering national specifics, will contribute to strengthening the energy sustainability of the economy.

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We hereby confirm that we don't have any conflict of interest related to the manuscript.

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