

Distributed energy in management sciences: a regional perspective

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Funding information:

The study was co-financed by the Minister of Science under the "Regional Excellence Initiative".

Acknowledgement:

This work was performed within the framework of state budget research No 0124U000544 "Cybersecurity and digital transformations of the country's wartime economy: the fight against cybercrime, corruption and the shadow sector". The authors (M. Rabe and Y. Bilan) express their gratitude to the project titled "Cluster for innovative energy" in the frame of the program "HORIZON-MSCA-2022-SE-01" under the Grant agreement number 101129820

How to cite this article:

Rabe, M., Gawlik, A., Norek, T., Wajer, E. and Bilan, Y. (2026), Distributed energy in management sciences: a regional perspective. *Acta Montanistica Slovaca*, Volume 31 (2), 638-648

DOI:

<https://doi.org/10.46544/AMS.v31i2.24>

Abstract

Distributed energy systems, treated as complex and flexible structures, form the foundation of modern energy transition strategies that adapt the energy sector to changing economic, technological, and environmental requirements. Implementing these strategies requires a multifaceted approach that considers local conditions as well as global trends in technology and energy policy development. This research aimed to analyse definitions and key aspects of distributed energy as a decentralised electricity generation system encompassing various sources and technologies. The study focused particularly on considering the multifaceted criteria for defining the concept of distributed energy, including parameters such as the installed capacity of systems, the location of generation units, the technologies used, and their impact on the natural environment. To achieve this objective, the study employed literature analysis, a review of reports from research institutions, and an examination of legal regulations related to distributed energy, which allowed identification of key elements of the field. Both traditional text analysis methods and advanced textual data mining techniques using computational tools such as IRaMuTeQ software were applied in the analysis. The primary data source was the Web of Science Core Collection (WoS), one of the most reliable and prestigious sources of scientific information in the energy field. The comparative analysis of approaches to defining distributed energy at the global level considered criteria such as installation capacity, location, energy-production technologies, and the market and regulatory context. The results reveal significant difficulties stemming from the lack of a uniform definition of distributed energy in management sciences, driven by regional and technological differences. Key factors shaping this sector include the decentralised structure of the energy system, local energy production and consumption, technological flexibility, and potential environmental benefits, which form the foundation for further development of distributed energy.

Keywords

Distributed energy, decentralisation of energy systems, renewable energy sources



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Introduction

Distributed energy, also called distributed generation, refers to decentralised electricity production systems located in various places, often close to end-use consumption. A key characteristic of these systems is local energy production, which reduces the need for long-distance transmission and minimises transmission losses. Distributed generation is closely linked to the concept of energy flexibility, enabling more efficient resource management and the integration of renewable energy sources (RES) into the power system. Despite the growing importance of this concept in the global energy transition, the scientific literature lacks a single, unified definition of “distributed generation,” resulting in terminological and interpretative discrepancies (Nadeem et al., 2023).

The dynamic development of decentralised energy systems is reflected in the growing number of scientific publications on energy-related issues, particularly renewable energy sources and new models of energy system management. At the same time, an analysis of the existing literature reveals significant imbalances between technology-oriented research and studies that adopt a management science perspective, including issues related to planning, organisation, coordination, and process optimisation within decentralised energy systems. The management of distributed energy is increasingly influenced by the digital capacity of public institutions and system operators. Lyeonov et al. (2025) show that government AI readiness is positively associated with installed renewable electricity capacity across countries, but not significantly with actual renewable electricity generation. This distinction is relevant to distributed energy because digital governance may facilitate the deployment of decentralised renewable infrastructure, while effective operation also requires grid integration, storage, market coordination, and demand-management capabilities. A broader European perspective also indicates that progress in renewable-energy deployment does not automatically translate into an equally rapid reduction in carbon emissions. Lyulyov et al. (2026) find that convergence in renewable-energy development across European countries occurs faster than convergence in carbon-emission outcomes. This finding supports the need to analyse distributed energy not only through installed capacity, but also through its institutional, technological, and operational contribution to effective decarbonisation.

The geopolitical dimension of this shift has intensified since 2022: Vasylieva et al. (2025) showed that the war in Ukraine significantly accelerated distributed renewable energy deployment across 34 European countries as part of a broader shift from energy dependency to energy security.

Economic resilience provides a further rationale for decentralisation. Vasylieva et al. (2026) show that electricity-price shocks during the European energy crisis weakened macroeconomic stability, whereas higher renewable-energy penetration mitigated this adverse effect in the short run. Consequently, distributed renewable generation should be considered not only as a low-carbon option but also as a means of reducing exposure to external electricity-market volatility.

The transition toward distributed renewable energy should also be understood within the wider economic consequences of climate change. Stankevičienė and Borisova (2022) show that EU countries' climate-change vulnerability is closely linked to the structure of their economic activity. Consequently, decentralised energy strategies should be evaluated not only by technical performance but also by their capacity to reduce environmental exposure and support structurally sustainable development.

In response to the identified research gaps, this study addresses distributed energy from a management perspective, focusing on processes related to the generation, distribution, and use of electricity from local and renewable energy sources. To ensure a high level of reliability and comprehensiveness, methodological triangulation was applied, integrating both qualitative and quantitative approaches, including advanced literature content analysis methods (Cheng et al., 2025).

The primary objective of this article is to systematically identify and analyse the main research directions related to decentralised energy systems, with particular emphasis on management-related issues, as well as to indicate existing research gaps and areas requiring further investigation. From this perspective, expanding distributed energy requires an analytical framework that incorporates technological, organisational, financial, and social conditions. Urbaniec (2015) demonstrated that eco-innovation diffusion is constrained by institutional and financial barriers, particularly in economies that lag behind Western European innovation leaders. This reinforces the need to examine distributed energy as a management challenge involving the mobilisation of local capabilities and investment resources, rather than as a purely technical configuration of generation assets. The financial dimension is especially important because decentralised projects are often implemented by municipalities, households, small firms, and energy communities with limited access to capital. Streimikiene et al. (2024) identify a strong relationship between the implementation of the European Green Deal and sustainable-finance allocations supporting renewable-energy resource use across EU Member States. Therefore, the management analysis of distributed energy should also address the financial mechanisms that link local investment decisions with wider green-transition policies. An additional objective is to determine the dynamics of scientific research development in the field of distributed energy and to assess the extent to which this topic has been integrated into management science research.

These objectives are achieved through an analysis of the literature indexed in the Web of Science Core Collection (WoS), regarded as one of the most reliable sources of scientific information. The results obtained enable the identification of dominant research trends, key concepts, and the evolution of approaches to distributed energy issues in the context of energy management and the optimisation of energy system performance. The relevance of this management perspective is reinforced by the continuing interaction between energy use and economic development. Kasperowicz (2014) identifies a long-run relationship between energy consumption and economic growth in European countries, demonstrating that energy-system transformation has wider macroeconomic implications. Therefore, distributed energy development should be assessed not only as a technical change in electricity generation but also as an element of sustainable economic development and energy-security policy.

Literature review

Distributed energy is a key research area in contemporary energy systems. However, despite the growing interest in this topic, the literature has not yet developed a single, universally accepted definition of distributed energy. Definitional differences arise from diverse regional and technological conditions, as well as from varying criteria used to define the generating capacity of individual units. As a result, the concept of distributed energy is often interpreted and applied inconsistently, which hinders the comparability of research results and the development of coherent analytical frameworks (Ackermann et al., 2001).

In the Anglo-Saxon literature, clear terminological differences can be observed depending on the geographical context. In the United Kingdom, the term *embedded generation* is commonly used, emphasising the functional integration of generating units within local distribution networks. In North America, the concept of *distributed generation* prevails, highlighting the decentralised nature of energy production within the power system. In contrast, Europe and Asia frequently use the term decentralised generation, indicating a departure from the traditional centralised model of electricity generation (Ackermann et al., 2001). This terminological diversity reflects different models of energy system development and varying energy policy priorities.

An important criterion differentiating definitions of distributed energy is the generating capacity of individual units. Research institutions and industry organisations propose diverse approaches in this respect. The Electric Power Research Institute (EPRI) adopts a broad definition, encompassing generating units from a few kilowatts to 50 MW, including both prosumer micro-installations and larger industrial systems (Electric Power Research Institute, 1998). In contrast, the Gas Research Institute (GRI) proposes a narrower definition, classifying distributed energy as units with capacities between 25 kW and 25 MW, with a primary focus on gas-based technologies and cogeneration systems, which are particularly relevant for improving energy efficiency in industrial applications (Gas Research Institute, 1998).

The International Council on Large Electric Systems (CIGRE) defines distributed energy as generating units with capacities below 50–100 MW, clearly distinguishing them from large, centralised power plants (CIGRE, 1998). This approach emphasises the role of smaller units in enhancing the power system's flexibility and resilience, especially in the context of integrating renewable energy sources. This perspective is further refined by CIRED, which highlights the operational independence of distributed units from central planning and dispatch mechanisms (CIRED, 1999).

An increasing number of studies also emphasise the functional and organisational dimensions of distributed energy. The International Renewable Energy Agency (IRENA) defines distributed energy as installations located within distribution networks or at consumer sites, encompassing a wide range of actors—from prosumers and energy cooperatives to municipal power plants (IRENA, 2019). This approach shifts the focus from purely technical criteria toward market structure and the participation of local stakeholders in energy generation processes.

From a technical perspective, distributed energy refers to electricity generation by units significantly smaller than traditional centralised power plants, allowing integration into power systems at various points and contributing to greater system flexibility and resilience (Dondi et al., 2002). At the same time, the literature highlights the important role of distributed systems in the electrification of sparsely populated and remote areas, particularly regions lacking access to national grids. In this context, Colombo, Bologna, and Masera emphasise Distributed Renewable Energy (DRE) as a tool that supports sustainable development and access to clean energy (Colombo et al., 2014).

More restrictive definitional approaches can also be found in the literature. Cardell and Tabors limit distributed energy to units with capacities between 500 kW and 1 MW, focusing on localised energy systems designed for specific applications (Cardell & Tabors, 1998). Conversely, Sharma and Bartels propose a broader definition, covering units from a few kilowatts to over 100 MW, positioning distributed energy as an integral component of the transition toward low-emission energy systems (Sharma & Bartels, 1998). Chambers, in turn, defines distributed energy as relatively small generating units with capacities not exceeding 30 MW, typically located near end-users and supporting local energy demand and distribution-network operations (Chambers, 2001).

An important strand of the literature addresses the socio-organisational dimension of distributed energy. Popczyk introduces the concept of prosumerism, emphasising the active role of energy consumers as both producers and users of energy, which supports the decentralisation of energy systems and the increased deployment of renewable energy sources (Popczyk, 2012). Households' participation in prosumer-oriented energy systems depends substantially on whether the transition is socially and financially inclusive. Streimikiene (2022) argues that targeted support for household micro-generation technologies contributes more effectively to a just low-carbon transition than ex post compensation for energy costs. Accordingly, policies supporting distributed energy should combine incentives for local generation with measures that enable vulnerable households to participate actively in decentralised energy production. This concept is further developed within the framework of citizen energy, as described by Dyka, Kassenberg, and Szymalski, who highlight the involvement of local communities in energy generation, management, and distribution as an alternative to centralised energy models historically dominated by large corporations (Dyka et al., 2019).

Mukhtarov et al. (2023) empirically confirmed the link between decentralised, renewable-based generation and institutional quality in Poland, finding that stronger institutional quality significantly supports the renewable energy transition.

Drożdż et al. (2023) conducted a parallel multi-criteria sustainability assessment of European energy-generation systems, highlighting the divergent challenges Eastern and Northern European countries face in transitioning to decentralised, renewable-based generation.

Regional case studies further illustrate this variation: Streimikienė (2024) documented strong renewable penetration achievements in Nordic and Baltic EU member states, while Kharlamova et al. (2016) framed renewable energy development in Ukraine as both a security imperative and a strategic opportunity.

In summary, the literature review indicates that the diversity of definitions of distributed energy results from differing technical, institutional, and social conditions, as well as from various strategies for energy system development. While some authors focus on small-scale, decentralised generating units, others extend the concept to include larger systems integrating advanced technologies such as photovoltaics, wind turbines, fuel cells, and micro- or small-scale hydropower plants (Watson, 1999). The lack of a unified definition of distributed energy highlights the need for further research, particularly in integrating technical perspectives with management and institutional approaches.

Material and Methods

This study's methodology is based on a systematic review of scientific literature and an analysis of applicable legal and regulatory frameworks related to distributed energy. Because no clear, universally accepted definition exists, a key methodological objective was to organise existing approaches and identify common characteristics recurring in the literature.

The first stage of the research involved a comprehensive search of scientific publications in international databases, including peer-reviewed journals, scientific monographs, and conference proceedings. The search was conducted using keywords such as “distributed energy,” “distributed generation,” “distributed renewable energy,” “microgrids,” and “decentralised energy systems.” As a result of this stage, a total of 2,154 literature items were identified.

In the subsequent step, an initial screening of publications was performed based on the analysis of titles and abstracts, which reduced the dataset to 532 articles considered potentially relevant to the research objectives. Detailed exclusion criteria were then applied, including lack of thematic relevance, publications in languages other than English, and the absence of abstracts. As a result, 189 items were excluded, leaving 343 articles for further analysis.

The second stage of the selection process consisted of an in-depth content analysis of the remaining publications, with particular emphasis on the occurrence of key terms and issues related to distributed energy. For this purpose, a cross-keyword searching methodology was employed, enabling the identification of additional relevant literature sources. Given the increasing use of computational and data-driven tools in energy management research, the analytical process should also account for the governance of data and algorithms. Memarian and Doleck (2024) emphasise that responsible AI requires transparency, accountability, fairness, privacy protection, and attention to implementation risks in addition to technical performance. These principles are relevant to literature-based studies of distributed energy because data-driven analytical methods increasingly influence how research priorities, energy-management options, and technology pathways are identified and evaluated. Moreover, the use of artificial intelligence in distributed-energy management should complement rather than replace accountable human decision-making. Balcerzak et al. (2026) show that users generally prefer hybrid human–AI arrangements when decisions have significant consequences. For distributed-energy systems, this implies that digital tools may support forecasting, optimisation, and monitoring, while strategic decisions concerning regulation, public investment, energy access, and risk allocation should remain subject to human oversight. This process included 46 new publications, primarily focusing on distributed renewable energy between 2008 and 2024.

Based on the collected literature, a comparative analysis of definitions of distributed energy was conducted, identifying key criteria used by different authors, such as the purpose of energy generation, the location and connection of generating units, installed capacity, the area of energy delivery, applied technologies, environmental impact, operational mode, ownership structure, and the level of penetration within the power system. These criteria were then evaluated for their relevance to the definition. Based on the literature review results and applicable regulatory standards, particular emphasis was placed on the key aspects needed to analyse and develop energy systems based on a decentralised model. Beyond technical and regulatory criteria, organisations' and local stakeholders' ability to adopt and operate new technologies should be recognised as a relevant management criterion. Thus, a comprehensive management-science interpretation of distributed energy should incorporate the institutional and human capabilities necessary to implement decentralised generation technologies effectively.

In addition to technical and regulatory criteria, the availability of financial resources should be recognised as a relevant condition for distributed-energy development. Streimikiene et al. (2024) identify a strong relationship between the implementation of the European Green Deal and sustainable-finance allocations supporting renewable-energy resource use across EU Member States. Therefore, a management-science approach to distributed energy should account for the financial mechanisms that link household, municipal, and business investments to broader decarbonisation objectives.

A key aspect of power system operation is the purpose of generation units, which determines whether they focus on meeting industrial energy demand or local consumption. A crucial factor shaping system efficiency is the location of power units, as it affects the minimisation of transmission losses and the optimisation of energy distribution. Equally important is the capacity of generation units within distributed energy systems, as national regulations define their classification and integration possibilities within the power system.

Distributed energy systems are a fundamental component of the modern transformation of the power sector, encompassing microgrids, decentralised generation units, energy storage systems, and renewable energy sources such as photovoltaic technologies and wind power plants. Microgrids play a key role in ensuring electricity availability in areas with limited power infrastructure, enabling autonomous or hybrid operation. In urbanised regions and the industrial sector, decentralising energy generation increases system resilience to disruptions and reduces transmission losses, improving operational efficiency and system stability.

The resilience value of decentralised generation is also evident during periods of electricity-price volatility. Vasylieva et al. (2026) show that electricity-price shocks during the European energy crisis weakened macroeconomic stability, whereas higher renewable-energy penetration mitigated this adverse relationship in the short run. This evidence suggests that distributed renewable energy, particularly when combined with storage and flexible demand, can reduce local and national energy systems' vulnerability to external market shocks.

In the context of decentralised storage solutions, Boutouil et al. (2025) demonstrated the potential of photo-redox flow batteries as a sustainable energy-storage pathway, with case studies specifically addressing the Polish energy market.

Distributed photovoltaic technologies constitute another essential component of decentralised energy systems, particularly where local generation must be combined with affordability and material efficiency. Akhlidej et al. (2026) show that optimising absorber-layer thickness in CdTe/CdS/ZnO thin-film solar cells can improve power-conversion efficiency while reducing material requirements. These results are relevant to distributed energy because the scalability of local photovoltaic generation depends on the cost, efficiency, and environmental performance of available solar technologies.

In the marine environment, distributed energy systems play a crucial role in stabilising energy supply for floating units, extraction platforms, and coastal infrastructure. Technologies such as offshore wind farms, floating photovoltaic installations, and shore-to-ship power systems (cold ironing) are key solutions for reducing greenhouse gas emissions and optimising the energy balance. Furthermore, the dynamic development of autonomous underwater systems and remotely operated research platforms drives innovation in power supply technologies for extreme environmental conditions.

Implementing modern distributed energy solutions is a key element in developing integrated and sustainable power systems, both on land and at sea. Energy supply spans a wide geographic scale, from local microgrids to national power systems. In this context, energy generation technologies, including solar, wind, cogeneration, and small-scale hydropower, play a significant role in defining the nature and structure of distributed power installations.

From an environmental standpoint, it is crucial to evaluate the impact of distributed energy, particularly in terms of reducing CO₂ emissions and increasing the share of renewable energy in the overall energy mix. Additionally, the operational modes of distributed energy units, whether functioning as autonomous systems, grid-connected elements, or backup units, affect their integration and functionality.

Ownership of distributed energy systems is another key factor, which can take various forms, including private enterprises, local communities, or public institutions. The extent to which distributed generation is

integrated into the national grid, referred to as its penetration, highlights its role in the overall energy system and its contribution to national energy production (Ackermann et al., 2001).

Assumption 1: Active Power Supply as the Primary Objective of Distributed Energy

According to the adopted assumptions, distributed energy systems are primarily designed to supply active power rather than reactive power. This distinction underscores their role in meeting active-power demand and facilitating the integration of renewable energy sources for small-scale active-power generation.

Assumption 2: The Location and Connectivity of Distributed Energy Units

Distributed energy is characterised by the installation and operation of generating units that are directly connected to the distribution network or located on the customer side, beyond the meter (Sharma, Bartels, 1998). In competitive electricity markets, only legal definitions of transmission and distribution systems provide a clear distinction between these two frameworks (Klopfer et al., 1996).

The proposed definition of distributed energy aligns with the traditional model, in which generating units connect to the transmission network through industrial sectors. A key attribute of distributed energy is its decentralised nature, which situates production closer to consumers, typically within the distribution network or at the consumer's premises. To differentiate transmission and distribution networks effectively, additional criteria are needed beyond voltage levels. For example, while 220 kV is typically classified as transmission voltage, some distribution companies operate 220 kV lines, and transmission operators manage 110 kV lines.

In the absence of international voltage standards for clear differentiation, a legal framework-based approach is suggested. In competitive markets, law regulates the transmission system, and independent entities manage it without involvement in generation, distribution, or energy sales. In jurisdictions lacking such legal clarity, further delineation between transmission and distribution networks is necessary, as these networks are often treated as part of the distribution system.

The classification of small generating units, such as wind farms or combined heat and power (CHP) systems, connected to the transmission network raises questions. Two scenarios are commonly considered:

- A CHP unit located on industrial premises and connected to the transmission network on the consumer side may qualify as distributed energy.
- A wind farm connected directly to the transmission network due to capacity constraints in the local distribution network does not fit the definition of distributed energy.

In countries like Sweden, legal definitions may also include regional networks that serve as intermediaries between the national transmission grid and local distribution systems.

Assumption 3: Generating Capacity is Not a Determining Criterion for Distributed Energy

This approach rests on two foundational assumptions: generating capacity is not a defining characteristic of distributed energy, and the maximum capacity that can connect to the distribution network depends on the network's transmission capabilities and voltage levels. Because distribution networks vary technically, establishing a universal maximum capacity for distributed energy is impractical.

According to Klopfer's research, units with capacities exceeding 100–150 MW cannot technically be connected to 110 kV networks. Because 110 kV is the highest voltage level in many distribution systems, the maximum capacity for distributed generation is typically considered 100–150 MW (Klopfer et al., 1996).

An exception is the CCGT power plant in Berlin, which, despite its 300 MW capacity, supplies local distribution lines.

Distributed energy encompasses generating units ranging from a few kilowatts to 300 MW, with technical requirements varying by capacity. A proposed classification includes:

- Microgeneration: 1 W–5 kW
- Small generation: 5 kW–5 MW
- Medium generation: 5 MW–50 MW
- Large generation: 50 MW–300 MW

Some authors define distributed generation within a narrower range of 1 kW–1 MW; however, this classification is not widely adopted.

Assumption 4: The Area of Energy Delivery is Not Significant in the Definition of Distributed Energy

Some researchers define the area of energy delivery as the distribution network where distributed systems supply energy. However, this approach can be suboptimal, as restricting the energy delivery area to distribution networks may exclude certain typical distributed energy projects. Furthermore, such limitations would require complex power flow analyses within the distribution system.

The term "embedded distributed generation" more precisely describes scenarios where energy is used locally. However, this term is not widely employed in scientific literature. Distributed generation is often associated with specific technologies, such as renewable energy sources, but this definition does not impose restrictions on the choice of technologies (Hammond & Kendrew, 1997).

Assumption 5: The Technology Used in Distributed Energy is Irrelevant

The term "distributed energy" is frequently linked to specific technologies, such as renewable energy sources. According to the International Energy Agency (IEA), renewable energy resources are inexhaustible sources that include solar, wind, biomass, hydropower, oceanic, and geothermal energy. Although these resources are globally available, their potential and the effectiveness of the technologies that utilise them vary by region (IEA, 1997).

Distributed generation technologies, including micro-hydropower plants, photovoltaic systems, wind turbines, fuel cells, and energy storage systems, are characterised by modular design. This allows for quick installation and commissioning, as well as expansion or relocation as needed. Moreover, the failure of a single module does not affect the operation of the others, enhancing the reliability of these systems (Hoff & Merig, 1997).

An important aspect of distributed generation is combined heat and power (CHP) production, which is highly efficient, particularly when the heat is consumed locally. CHP technologies, such as gas turbines, internal combustion engines, and biomass gasification, are already widely used (Diethelm, 1999).

Assumption 6: Environmental Impact of Distributed Energy is Not Critical

Distributed energy technologies are often regarded as more environmentally friendly compared to centralised energy generation systems. However, some definitions do not treat environmental impact as a key criterion because fully assessing these effects is complex. For example, energy storage systems and fuel cells do not produce direct emissions, but indirect emissions must be considered, such as those resulting from manufacturing processes or the energy mix used to produce stored energy (Lewin, 1993).

For fuel cells, additional emissions arise from hydrogen production processes. Environmental benefits may also result from reducing transmission losses through optimal placement of distributed energy units. However, too many such units could reduce the efficiency of large power plants, increasing emissions per unit of energy produced (kWh) (Kaltschmitt & Fischechick, 1995).

Environmental comparisons are further complicated by differing perceptions of risks, such as those associated with nuclear energy, and by factors like visual impact, noise emissions, and land use, as observed with wind turbines. While distributed energy technologies are not always unequivocally environmentally friendly, they generally have significantly lower greenhouse gas emissions than coal-based technologies.

Assumption 7: Operational Mode and Ownership of Distributed Energy Units are Not Defining Criteria

The diversity of international energy network regulations supports an approach in which the operational mode of distributed energy is not a defining criterion. For instance, in England and Wales, generating units exceeding 100 MW are classified as central generation, while smaller units are subject to less stringent regulations. Consequently, distributed energy does not always operate independently of system-wide rules (Watson, 1999).

Similarly, ownership is not a decisive factor in defining distributed energy. International examples, such as Sweden, show that both independent and traditional producers are involved in developing distributed energy. While large energy corporations may be less flexible in advancing small systems, regionally supported local projects tend to garner greater social acceptance (Grubb, 1995).

Although ownership is not critical for defining distributed energy, it may influence its development. In some cases, this aspect is worth considering, particularly for units owned by independent entities.

Assumption 8: The Penetration Level of Distributed Energy is Not a Key Criterion

The literature presents varying perspectives on the penetration level of distributed energy within energy systems. Some researchers argue that distributed energy represents a fully decentralised energy production system that can function without relying on traditional transmission lines and large power plants. In this view, distributed energy includes independent sources such as photovoltaic panels, micro-wind turbines, and small gas power plants that can operate locally and autonomously, eliminating the need for centralised transmission networks.

On the other hand, some researchers suggest that distributed energy can meet only a portion of a region's energy demand, making full decentralisation unattainable. From this perspective, distributed energy complements traditional energy sources and remains connected to national or regional energy networks. This linkage ensures stable energy supplies, particularly during sudden increases in demand (Milborrow, 1998).

Results and discussion

The main challenge in research on distributed energy systems is determining their penetration level, which is defined as the extent to which these systems can replace traditional energy sources. The penetration level of distributed energy systems depends on many factors, including the scope of the area in which they are implemented. For example, distributed systems assessed in the context of a local distribution network can achieve a higher penetration level than assessments conducted at the national energy network level, where stability and supply-security requirements are more stringent. Differences in scale and definitions across analyses significantly affect results on the efficiency and sustainability of distributed energy systems.

Assumptions about distributed energy, although scientifically justified, require further analysis. In particular:

- **Active Power Supply:** The main role of distributed energy is to supply active power, which facilitates integrating renewable energy sources on a small scale. **Location and Connectivity:** Distributed energy units connect to the distribution network or are located on the customer side, which requires a clear definition of legal frameworks.
- **Generation Capacity:** The maximum power connected to the network depends on its transmission capacity, and the classification of distributed energy includes units with varying generation capacities.
- **Energy Delivery Area:** The definition of distributed energy should not be limited to distribution networks; it should also account for the diversity of projects.
- **Technology:** The technologies used in distributed energy, including renewable energy sources (RES) and cogeneration, are highly diverse, and their efficiency depends on the region's specifics.
- **Environmental Impact:** While distributed energy generally generates fewer emissions than centralised systems, it requires a comprehensive environmental impact assessment that accounts for both direct and indirect emissions.
- **Operating Mode and Ownership:** Ownership and operating mode are not key criteria for defining distributed energy, but regulations may influence the development of these systems.
- **Penetration Level:** Distributed energy does not require full decentralisation but can operate in parallel with traditional energy sources, collaborating with national and regional energy networks.

A review of existing research indicates significant discrepancies in the definition of distributed energy systems, arising from criteria such as generation capacities, technologies used, and the location of production units. Based on these differences, a comprehensive definition can be formulated that reflects the diversity of approaches in the literature.

Distributed energy can be defined as a decentralised model of energy generation, characterised by production units located in various parts of the power system. These units operate both on the consumer side and within distribution networks. A distinguishing feature of distributed energy is its independence from the direct control of transmission system operators. It involves localised generation of electricity or heat, often relying on renewable energy sources (RES), and can operate autonomously or complement centralised energy systems.

Based on an extensive literature review, encompassing 2154 bibliographic entries from the Web of Science database, several key aspects related to distributed energy can be identified:

- **Decentralised structure:** Colombo, Bologna, and Masera (2014) showed that distributed energy systems can function independently of centralised management. This independence enables faster responses to localised energy demands, enhancing the power system's overall flexibility. By reducing reliance on large, centralised power plants, distributed energy systems contribute to improved stability and adaptability in response to evolving operational conditions (Colombo et al., 2014).
- **Local production and consumption:** Research by Meskin, Domijan, and Grinberg (2020) underscores that localised energy generation and consumption significantly reduce transmission losses, improving overall energy efficiency. This localised approach reduces the need for long-distance energy transmission, optimising local distribution networks (Meskin et al., 2020).
- **Technological flexibility:** As Popczyk (2011) notes, distributed energy systems leverage a wide range of technologies, including photovoltaics, wind energy, cogeneration, and energy storage. The modular design of these technologies supports scalability and facilitates seamless integration with existing power systems, thereby enhancing the overall flexibility and efficiency of the energy infrastructure (Popczyk, 2011).
- **Environmental benefits:** According to IRENA (2019), distributed energy systems play a critical role in reducing CO₂ emissions and increasing the proportion of renewable energy sources in the global energy mix. Although they do not always eliminate emissions entirely, distributed energy systems are integral to lowering the carbon footprint of power systems, advancing the energy transition, and supporting the decarbonisation of the energy sector (IRENA, 2019).
- **Scalability and integration:** Studies conducted by Cardella and Tabors (1998) reveal that distributed energy systems are highly scalable. They can be implemented as small, localised installations or as advanced hybrid systems integrated with centralised power systems. This scalability enhances the resilience and stability of the energy infrastructure, enabling it to adapt more effectively to fluctuating operational conditions and dynamic energy demands (Cardell & Tabors, 1998).

This structured perspective on distributed energy systems, incorporating both theoretical insights and empirical findings, provides a robust framework for evaluating their role in transforming contemporary energy systems.

Conclusions

The examination of existing studies and literature demonstrates that distributed energy is a multifaceted and complex concept, defying encapsulation in a single, universal definition. Its diverse nature stems from its decentralised structure and the wide range of technologies applicable within its framework. Distributed energy refers to generating energy through small, dispersed units that operate independently of traditional centralised systems. These units are typically located near end users and include technologies such as residential photovoltaic systems, micro wind turbines, and combined heat and power (CHP) systems.

The complexity of distributed energy can be analysed through several critical dimensions:

- **Technological** – The evolution of distributed energy systems is intrinsically linked to advancements in technology. Innovations in renewable energy production, energy storage, and energy management systems (e.g., smart grids) enhance the efficiency and flexibility of energy generation and distribution. These advancements reduce energy losses, optimise energy consumption, and facilitate the integration of various energy sources within a cohesive ecosystem.
- **Economic** – Distributed energy significantly influences the restructuring of business models in the energy sector. The expansion of localised installations contributes to the diversification of revenue streams and reduces reliance on large-scale energy suppliers. Additionally, it enables consumers and small enterprises to actively engage in energy markets, stimulating competition and fostering innovation.
- **Environmental** – A pivotal advantage of distributed energy is its contribution to reducing environmental impacts. The growing adoption of renewable energy technologies such as solar, wind, and biomass helps decrease greenhouse gas emissions and reliance on fossil fuels. These outcomes align with global strategies to mitigate climate change and conserve natural resources.
- **Social and Local** – Distributed energy enhances local energy autonomy by decentralising energy production and giving communities greater control over their resources. This decentralisation strengthens resilience to energy crises and creates opportunities for ecological education and the advancement of civic engagement.

In summary, the flexibility required to define distributed energy arises from its capacity to adapt to diverse technological, economic, and social contexts. Furthermore, its role in shaping local and global energy systems highlights its significance as a transformative force in the energy landscape.

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