Годишник Телекомуникации 2024, том 11, с. 119-129

Yearbook Telecommunications 2024, vol. 11, p. 119-129

eISSN 2534-854X https://telecommunications.nbu.bg/bg/godishnik-telekomunikacii

DOI: https://doi.org/10.33919/YTelecomm.24.11.12

MAIN ASPECTS OF RENEWABLE ENERGY INTEGRATION

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Abstract: The transition in the energy sector is essential for reducing carbon emissions and building a sustainable future. In this process, wind and solar energy play a leading role, offering environmentally friendly solutions. Their effective integration into the power system requires addressing various technical, operational, and regulatory challenges. This study examines long-term strategies for power system planning, which are crucial for maintaining the security of electricity supply. The analysis presents energy transition scenarios applied in Europe, clarifying their significance and timeline for implementation. This review provides an overview of existing studies on the technical, regulatory, and climatic aspects of renewable energy integration, highlighting key findings to support stakeholders in risk assessment and decision-making within the current decarbonization framework.

Keywords: Renewable energy integration, hosting capacity, power system stability, energy transition, Net Zero 2050.

1. INTRODUCTION

The transformation of the energy sector is at the core of the global shift toward carbon neutrality by 2050. Renewable energy sources are the key drivers of this evolution due to their low-carbon nature and continuously decreasing production costs [1–3]. Worldwide, numerous research institutes, universities, and industrial consortia conduct in-depth studies focused on the effective integration of renewable energy sources (RES) into power grids. Despite their clear advantages, the full utilization of these technologies requires overcoming significant technical, operational, and regulatory challenges related to the security and stability of energy supply [4–5]. Within the European Union (EU), the regulatory framework for promoting RES is defined by Directive (EU) 2018/2001 ("RED II") on the promotion of the use of energy from renewable sources. According to Article 3(1) of the directive, member states are required to ensure that the share of RES in gross final energy consumption reaches at least 32% by 2030. Additionally, Regulation (EU) 2019/943 on the internal electricity market and Directive (EU) 2019/944 on common rules for the electricity market establish key principles such as grid access, balancing market mechanisms, and interaction among energy sector participants grid operators, producers, consumers, and prosumers (who are both energy producers and consumers) [6–10].

At the national level, states implement specific laws and regulations that transpose EU requirements, such as Energy Laws and Regulations on connecting new capacity to the electricity distribution and transmission networks. Many existing regulatory documents were developed when the share of RES in the energy mix was insignificant. This creates regulatory gaps, related to: procedures for integrating new RES capacities; lack of sufficient energy storage mechanisms; inadequate incentives for decentralized energy production; limited coordination between the power sector and other industries, such as transport and heating [11]. These challenges highlight the need for a flexible and adaptive regulatory framework that facilitates RES integration while ensuring power system stability and resilience. This requires a comprehensive and multi-faceted analysis of the technical, economic, and regulatory aspects of this transition, emphasizing strategies for the balanced and effective use of renewable energy in modern power grids.

The traditional centralized power grid model, where large power plants with predictable generation and stable operational characteristics play a dominant role, is undergoing a major transformation. As the share of wind and solar energy increases, the limitations of this model become apparent, necessitating greater operational flexibility and the adoption of new management methods. In this context, the successful integration of RES requires not only technological innovations but also effective regulatory mechanisms that ensure power system stability while promoting efficient network resource management and optimal utilization of renewable energy. To prevent undesirable voltage and frequency fluctuations, power system operators must have access to adequate reserve capacity as well as efficient tools for grid stabilization [12]. This necessitates the integration of advanced load management technologies, predictive algorithms, and real-time adaptive response mechanisms.

The expansion of hybrid energy systems, which combine RES with various energy storage technologies including batteries, hydrogen fuel cells, and pumped storage plants—provides additional flexibility to the power system. These systems significantly complicate operational management and control, requiring the integration of new control algorithms and adaptation of balancing market mechanisms. Many of these challenges are not yet adequately addressed within the existing regulatory framework, requiring gradual regulatory improvements. With the acceleration of the energy transition, new business models emerge, such as real-time energy trading, peer-to-peer platforms, and smart contracts, necessitating appropriate regulatory adaptations. While the primary goal is to facilitate decentralization and encourage investments in RES, sudden regulatory changes lead to uncertainty and pose risks for market participants. For this reason, regulatory institutions often apply a phased approach, allowing the gradual introduction of new technologies without compromising power system stability. To achieve successful RES integration into modern power grids, a comprehensive and strategic planning approach is required, covering all technical, economic, and regulatory aspects.

This study examines the key aspects of renewable energy integration into power systems, focusing on existing strategies and highlighting the critical technical challenges associated with grid infrastructure development and adaptation to the dynamic and intermittent nature of RES.

2. TECHNICAL AND OPERATIONAL ASPECTS OF THE ENERGY TRANSITION

Europe has set ambitious strategic goals to achieve carbon neutrality by 2050, which requires a drastic reduction in greenhouse gas emissions and a complete transformation of energy systems. To realize these objectives, it is essential to overcome numerous technical challenges related to both infrastructure and operational aspects. This necessitates an integrated approach that combines strategic planning, the implementation of technological innovations, and the adaptation of the regulatory framework. Such an approach ensures a comprehensive perspective on all key requirements for the successful integration of renewable energy sources (RES) into the power system. Through a systematic and analytical approach, strategic guidelines and practical solutions are formulated for building a sustainable, secure, and highly efficient power grid, aligned with the increasing share of renewable energy. In this context, RES integration into long-term energy planning emerges as a central linking point between three key areas: the development of long-term strategies and technological innovations; ensuring grid stability under extreme operating conditions; assessing hosting capacity for the effective integration of RES (see Fig. 1).

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eISSN 2534-854X https://telecommunications.nbu.bg/bg/godishnik-telekomunikacii

DOI: https://doi.org/10.33919/YTelecomm.24.11.12

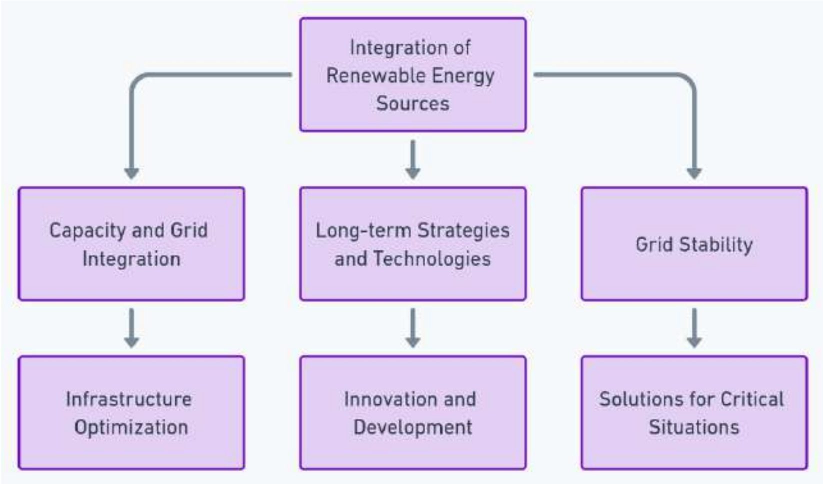

Fig. 1. Integration of Renewable Energy Sources

The graphical representation of the concept aims to highlight the importance of balancing renewable energy source (RES) integration and power grid security, with a central focus on the theme: "Balance between RES Integration and Grid Security." The two fundamental aspects of this balance are: RES integration – Long-term strategies and integration capacity; Grid security Stability under extreme operating conditions. The three key directions that define the sustainable development of the power system include: long-term strategies, technical challenges, and climate goals by 2050; grid stability under extreme operating conditions; evaluation of hosting capacity and grid integration of RES [13-15]. This structure illustrates the interconnections between key factors that determine the successful integration of RES without compromising the security of the energy system (see Fig. 2).

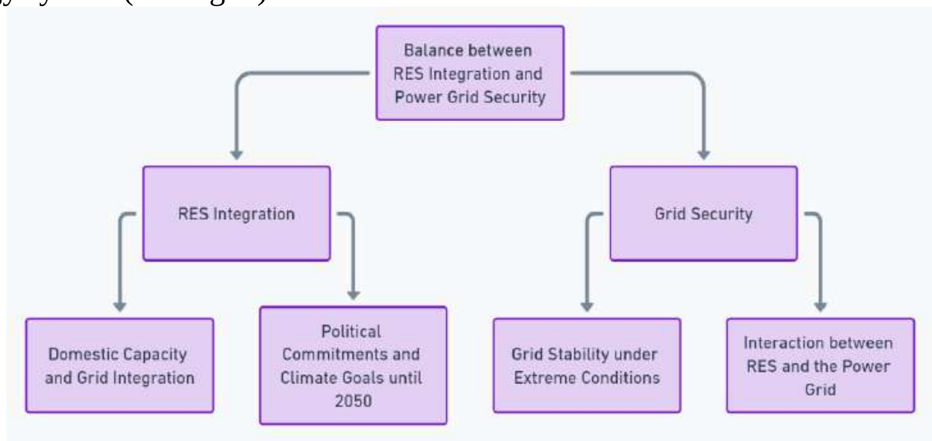

Fig. 2. Balance Between RES Integration and Power Grid Security

From a long-term perspective, the primary issue concerns the adequacy of the power system, i.e., its ability to provide sufficient generating capacity to meet demand under various operating conditions. This requires effective management of peak loads and adverse weather factors, which can significantly affect the availability of RES. Forecasting future electricity generation and consumption is of fundamental importance for maintaining system balance. Insufficient capacity poses a risk of forced supply restrictions, creating the danger of energy shortages and disruptions to the normal operation of the power system. The lack of adequate capacity in certain situations also generates legal risks related to unmet contractual obligations and potential compensation claims, further increasing the financial burden on market participants. To achieve sustainable development, long-term planning must be based on an integrated approach that not only ensures supply security but also minimizes economic and legal consequences arising from the dynamic changes in the energy sector. This includes the development of sustainable risk management strategies and the implementation of innovative technologies for forecasting, storage, and flexible energy resource management.

In the medium-term horizon, covering periods of days, weeks, or months, power system operators must adapt their operational plans based on weather forecasts, scheduled maintenance, and projected loads [17-18]. Optimal distribution of energy resources, effective reserve capacity management, and rational use of grid capacity are crucial for preventing overloads and minimizing the risk of system failures [19].The lack of adequate operational planning and effective coordination poses the danger of depleting available reserves, which significantly increases the risk to electricity supply and seriously threatens the stability of the power system [20-21].

In the short-term timeframe within hours and minutes power system management is characterized by extreme dynamism and increasing complexity. Electricity generation from renewable sources such as wind and photovoltaics can experience sudden fluctuations, requiring rapid and well-coordinated actions by system operators [17, 18]. Balancing the system in real time or through day-ahead markets necessitates the timely activation of reserve capacity to compensate for unexpected variations in generation or consumption [19]. The lack of sufficient operational reserves poses a significant risk of breaching contractual delivery obligations, which could lead to financial losses and legal disputes between grid operators and producers [20]. In this context, successful management of medium and short-term planning requires the integration of advanced forecasting models, enhanced grid flexibility, and innovative mechanisms for demand and supply management [21]. Such an approach not only minimizes operational risks but also significantly contributes to the stability and resilience of the power system, ensuring better adaptability to dynamic market changes and weather conditions [18].

In the most critical timeframe seconds and sub-seconds the integration of RES presents significant challenges to the dynamic stability of the power system and the quality of electricity. Unlike conventional generators with large rotating masses, which provide inertial support and natural frequency stabilization, wind and photovoltaic power plants utilize inverter-based technologies, whose dynamics differ substantially [18, 20]. This means that in the event of a sudden load change or the disconnection of significant capacity, the system response must be exceptionally fast to prevent the risk of large-scale failures or a system blackout [17]. In such situations, the lack of adequate stabilization can lead to severe consequences for supply security. Insufficient mechanisms for frequency and voltage regulation increase the likelihood of system disturbances, placing grid operators under significant technical and legal risks [21]. If operators fail to ensure effective stabilization mechanisms, legal issues may arise concerning liability for damages due to non-compliance with technical standards or contractual obligations [18]. This, in turn, creates the potential for legal disputes and substantial financial penalties.

3. FRAMEWORK FOR THE INTEGRATION OF RENEWABLE ENERGY SOURCES

In addition to technical challenges, the regulatory framework is essential for the sustainable integration of RES into the power system. The analysis of the regulatory framework and RES integration is based on information from ENTSO-E, EURELECTRIC, CIGRE, IRENA, the European Commission, and the IEA. The reports and regulations published by these organizations are widely used by all stakeholders in the sector, including governments, energy operators, and investors. They also play a significant role in the development of policies, technical standards, and strategic forecasts for the energy sector.

eISSN 2534-854X https://telecommunications.nbu.bg/bg/godishnik-telekomunikacii

DOI: https://doi.org/10.33919/YTelecomm.24.11.12

Legislation defines the technical requirements, connection procedures, and operation of new capacities, which must be strictly adhered to in order to ensure the safe and reliable operation of the system [18]. Non-compliance with these standards can result in significant penalties imposed by regulatory authorities, as well as administrative and legal disputes. This, in turn, creates additional risks for investors and operators, increasing legal uncertainty and financial costs [19]. In this context, the sustainable integration of RES requires not only technical innovations but also a precise and adaptive regulatory framework. This framework must ensure safety, reliability, and legal certainty for all stakeholders in the sector. According to the ENTSO-E, harmonizing regulatory standards among member states is critical for the successful integration of RES and the achievement of long-term energy sustainability [18]. The dynamic nature of the sector necessitates that legislative requirements are regularly updated, taking into account both technological advancements and market conditions [23]. The development of more flexible regulatory mechanisms and clearer rules for grid connection can significantly reduce administrative burdens and stimulate further growth in renewable energy. The successful operation of the power system requires the integration of multiple interconnected elements that work in synchrony to ensure reliability and resilience. Long-term planning is crucial for ensuring adequacy and supply security by forecasting the necessary resources to meet future demand [17, 22]. Strategic planning for new generation capacity, energy storage systems, and modernization of grid infrastructure is particularly important [18].

Effective operational management ensures flexibility and stability of the power system by efficiently distributing available resources and responding swiftly to changing conditions. This includes managing operational reserves, real-time monitoring, and maintaining balance between generation and consumption in the face of significant fluctuations in renewable energy supply [20]. Flexible operational strategies minimize the risk of system failures and contribute to better integration of renewable energy sources [22]. A stable and adaptive regulatory framework is also essential for the successful development of the power system. It must account for technological innovations and evolving market realities, while simultaneously creating a predictable and transparent environment for all stakeholders [23]. Updated regulations stimulate innovation, protect investments, and minimize legal and financial risks associated with contractual non-compliance or sudden changes in market conditions [19]. Clear contractual agreements further strengthen sector stability by reducing legal risks and facilitating cooperation between grid operators, producers, and consumers. Well-structured contracts protect the interests of all parties while creating conditions for more efficient electricity trading. The successful transition to a higher share of RES is not merely a result of technological advancements but also depends on the adaptability of legislative and institutional mechanisms to address the challenges of a dynamic energy market. This adaptability is crucial for ensuring the long-term sustainability, security, and reliability of the power system [18-22].

Global warming and its associated climate changes represent one of the most pressing challenges of the 21st century, necessitating coordinated and multi-layered international efforts for its mitigation. In this context, during the 21st Conference of the Parties to the United Nations Framework Convention on Climate Change in 2015, the Paris Agreement was signed—a strategically significant international treaty that establishes a long-term framework for global climate action [25]. The primary goal of the Paris Agreement is to limit global warming to well below 2°C above pre-industrial levels, with efforts to keep temperature increases below 1.5°C. To achieve this ambitious objective, the signatory countries have committed to achieving carbon neutrality in the second half of the 21st century. This commitment entails a drastic reduction in greenhouse gas emissions, a transition to a low-carbon economy, and increased investments in sustainable technologies and renewable energy sources [23]. Achieving carbon neutrality requires an integrated approach that includes emission reductions across key sectors such as energy, transportation, and industry, as well as the development of carbon capture and storage technologies [22]. According to the intergovernmental panel on climate change, timely and coordinated action is essential to limit the catastrophic consequences of climate change and ensure sustainable development.

4. LONG TERM STRATEGIES FOR ENERGY TRANSITION

The path to achieving climate neutrality is multi-layered and requires coordinated efforts from governments, businesses, and society, presenting them with a range of interconnected technical, political, economic, and social challenges [23-24]. In this context, scenario planning has become a foundational tool for developing effective climate neutrality strategies. It allows for the creation of multiple alternative scenarios that reflect different future developments and conditions related to technological innovations, political decisions, and economic factors [22]. The scenario-based approach provides decision-makers with flexibility and a stronger foundation for strategic planning. It enables them to analyze the effectiveness of various policies, technologies, and investments, selecting and combining the most suitable measures depending on the specific context and available resources. This reduces uncertainty and enhances the resilience of decisions, creating a basis for more informed and adaptable energy transition strategies [17, 26]. Scenario planning is particularly useful for assessing the long-term impacts of implementing new technologies and for developing decarbonization policies tailored to regional characteristics and socio-economic realities [24]. This approach ensures better risk management and creates opportunities for sustainable growth, with a focus on integrating renewable energy sources, developing infrastructure, and fostering innovation.

Within the European Union (EU), this process is supported by the ENTSO-E and the ENTSO-G. These organizations play an active role in the development of long-term analyses and strategic plans for the advancement of the energy infrastructure. One of the key instruments in this process is the TYNDP, which serves as a strategic platform for planning and integrating sustainable energy technologies [18]. The TYNDP provides a comprehensive assessment of future infrastructure development needs, taking into account technological advancements, economic trends, and EU political objectives. In this context, scenarios are developed to model different possible pathways toward Europe’s decarbonization. These scenarios are based on both the commitments under the Paris Agreement and the specific climate and energy policies of the EU [23]. These long-term strategies are essential for the transformation of the energy sector, providing scientifically grounded guidelines for achieving a sustainable and low-carbon energy system. The scenarios developed within the TYNDP include an analysis of various technological solutions and investment opportunities, promoting the integration of renewable energy sources and the development of a highly flexible grid infrastructure [26]. They support decision-makers in formulating policies and strategies that align with the EU’s long-term climate neutrality goals. The scenario planning framework within the TYNDP offers an integrated and adaptive approach, aiding in the development of informed and strategic decisions at multiple levels—ranging from policy and regulatory frameworks to investment strategies in the energy sector [18]. This approach involves the creation of scenarios that simulate different pathways to Europe's decarbonization, considering not only the objectives and commitments under the Paris Agreement but also the specific climate and energy policies of the European Union. The scenarios anticipate alternative future developments, based on scientific analyses of energy demand, technological advancements, and socio-economic factors [22-23].

The long-term strategies developed within the TYNDP are primarily aimed at developing energy scenarios to avoid short-term thinking, where decision-makers, due to limited vision and a

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lack of strategic foresight, focus on a single development path, disregarding alternative options. This approach carries significant risks, as the actual course of events often diverges substantially from initial forecasts [18]. Building a strategy based on only one scenario can create a false sense of security, ignoring potential changes in technologies, market conditions, and the political environment. For this reason, the developed scenarios are designed to encompass a wide range of possibilities, providing governments, industry, and investors with the necessary flexibility and adaptability when planning future energy systems [22]. This multifaceted approach enables more informed and strategic decision-making, reducing uncertainty and facilitating the transition to a sustainable and reliable energy infrastructure. By exploring multiple alternative pathways, scenario planning helps identify key risks and opportunities, which is crucial for the long-term sustainability of the energy sector [17]. These scenarios also serve as a key reference for the energy sector, providing a framework for the transition to a sustainable and low-carbon energy system [26]. They assist decision-makers in evaluating different technological and investment opportunities, promoting renewable energy integration, infrastructure development, and increased grid flexibility. This ensures better risk management and supports the achievement of the EU’s long-term climate goals [23]. Two of the most significant energy transition scenarios analyzed within the TYNDP are "Distributed Energy" and "Global Ambition". They explore different pathways to achieving climate neutrality by 2050, presenting two alternative but equally well-founded strategies for decarbonization and sustainable energy development [21].

The "Distributed Energy" scenario emphasizes local governance, consumer engagement, and the expansion of decentralized renewable energy sources, such as photovoltaic systems and battery energy storage at the local level. Its primary goal is to create more resilient and autonomous energy communities, enabling consumers to play an active role in managing energy resources [22]. On the other hand, the "Global Ambition" scenario focuses on large-scale centralized solutions and international cooperation, facilitating the faster integration of innovations and cross-border coordination. This approach prioritizes the development of large-scale infrastructure projects, such as hydrogen transmission networks and extensive offshore wind farms, ensuring sustainable energy supply across the entire continent [23]. Both scenarios provide a comprehensive perspective on the pathways to achieving the EU's long-term decarbonization goals, while also identifying key risks and challenges related to infrastructure, technology, and socio-economic transformations. They offer a strategic framework for making informed decisions about the future development of the energy system.

The "Distributed Energy" scenario envisions achieving climate goals through a high degree of decentralization and active participation of local communities. This approach is based on locally oriented solutions, where communities and households play a key role in integrating distributed renewable energy sources (RES), located in close proximity to consumers [22]. The main idea is to reduce dependence on centralized energy supply and energy imports, thereby stimulating regional autonomy and promoting the use of photovoltaic panels, small wind turbines, and local energy storage facilities [18]. Energy efficiency and sectoral integration are defining elements of this scenario. It encompasses the electrification of heating, transport, and industry, with renewable energy sources serving as the foundation [23]. A high level of energy efficiency reduces primary energy consumption and contributes to the optimization of local energy resources. This model not only enhances the resilience of energy systems but also creates conditions for more flexible energy consumption management, encouraging civic engagement and local innovations. Local communities are given the opportunity to become active participants in the energy transition, promoting the development of energy cooperatives and other forms of shared resource management [22].This, in turn, improves energy security and creates conditions for sustainable economic growth at the regional level. Despite these advantages, its successful implementation requires significant regulatory changes and coordination among multiple small-scale participants.

The "Global Ambition" scenario is based on globally coordinated policies and international exchange of low-carbon resources. A key focus of this scenario is large-scale energy projects aimed at accelerated decarbonization and the widespread deployment of new technologies [18]. Its vision includes the expansion of high-capacity offshore wind farms, production and transmission of green hydrogen, development of nuclear energy, and advancements in carbon capture and storage technologies [23]. This approach requires significant infrastructure investments and enhanced cross-border cooperation to ensure the efficient distribution of energy resources on a global scale and to accelerate the decarbonization process [22]. Large-scale investments in research and development (R&D) are crucial for the successful implementation of this scenario, as they support the deployment of innovative technologies and new decarbonization solutions.

International cooperation and the exchange of innovations are fundamental to and significantly support the successful implementation of the "Global Ambition" scenario. They foster synergy between nations and key energy sector stakeholders, creating conditions for a substantial reduction in greenhouse gas emissions and enhancing the resilience of energy systems. This scenario presents a centralized solution, based on large-scale infrastructure projects and global collaboration, laying the groundwork for faster and more extensive decarbonization. The widespread deployment of green hydrogen and offshore wind farms, combined with carbon capture and storage technologies, not only contributes to reducing the carbon footprint but also strengthens Europe's energy security by reducing reliance on external fossil fuel imports [26]. Despite its potential for rapid decarbonization, this scenario carries risks related to dependency on international energy flows and the requirement for long-term investments.

"Distributed Energy" and "Global Ambition" are not mutually exclusive scenarios but rather represent two poles of the energy transition ranging from highly decentralized solutions to strongly centralized strategies. They offer two distinct approaches to decarbonizing the energy sector, each with its own specific advantages and challenges [18].

The "Distributed Energy" scenario provides greater independence and local control, but it requires significant regulatory changes and coordination among many small-scale participants. On the other hand, the "Global Ambition" scenario relies on large-scale technological solutions and international coordination, yet it carries risks related to dependency and the need for long-term investments. Despite their differences, in most cases, the actual energy mix will be a combination of both approaches. In practice, the real energy transition will incorporate elements from both scenarios, adapted to the strategic priorities of each country or region [26]. The choice between them will depend on: public attitudes and support for renewable energy; the development and cost of key technologies; political decisions and the regulatory framework.

Some countries will see stronger support for local energy production and decentralized energy systems, while others will prefer large-scale infrastructure projects and international energy exchange. Northern Europe is an example of a region that is actively developing offshore wind farms and planning large-scale hydrogen infrastructure, while Southern Europe is focusing on decentralized photovoltaic systems and local energy storage [22].

"Distributed Energy" emphasizes local governance, energy independence, and small-scale innovations, whereas "Global Ambition" focuses on international cooperation, scalable solutions, and cross-border energy infrastructure. In practice, these scenarios are not "chosen" once and for all, but rather serve as dynamic reference frameworks for periodically reassessing the direction of the energy transition process. Depending on technological advancements, market conditions, political will, and international agreements, countries and regions can adapt and adjust their strategies, shifting closer to either a decentralized or centralized energy model [22]. For example, breakthroughs in energy storage technologies could make decentralized energy systems more

eISSN 2534-854X https://telecommunications.nbu.bg/bg/godishnik-telekomunikacii

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efficient, reducing dependence on centralized backup capacities. Conversely, global initiatives for green hydrogen trade or large-scale investments in cross-border energy infrastructure may favor the centralized approach, strengthening integration and international exchange of low-carbon resources [18]. Economic and geopolitical disruptions may also necessitate a reevaluation and adaptation of strategies, requiring a more flexible approach to managing the energy transition [17]. The resilience of power systems depends on their ability to adequately respond to rapidly changing conditions while ensuring supply security and economic efficiency. Flexibility and adaptability in energy systems are critical for achieving a low-carbon future, which requires a diverse set of possible approaches rather than a rigid commitment to a single pathway [26].

A successful energy transition strategy is one that balances economic efficiency, energy security, and sustainable development, integrating long-term vision, adaptability, and technological innovation. In the context of global climate goals and rapidly evolving energy markets, such a strategy must be flexible, pragmatic, and scientifically grounded, taking into account social, economic, and environmental factors [23]. For governments, this means developing policies that encourage investments in low-carbon technologies, ensure energy supply stability, and promote innovation in key sectors such as energy, transport, and industry [22]. For businesses, it involves diversifying energy sources, integrating smart grid solutions, and developing sustainable business models that align with the requirements of a low-carbon economy [27]. Society also plays a crucial role in this process. Consumer engagement and participation models that align individual actions with global decarbonization goals are essential. Changes in consumer behavior and energy efficiency improvements significantly reduce the carbon footprint and support the development of a sustainable energy sector [26]. An effective energy transition is neither one-directional nor universal. It depends on the specific geographical, economic, and social realities of each country or region. Only through a proactive approach, informed decision-making, and coordinated efforts between the public, private, and research sectors can a sustainable, cost-effective, and technologically advanced energy model be achieved. Such a model not only reduces the carbon footprint but also creates economic opportunities for future generations, fostering innovation and sustainable economic growth [24]

5. CONCLUSION

The integration of RES is essential for achieving climate neutrality by 2050, yet it presents significant technical, operational, and regulatory challenges. Ensuring stability in the power system at high RES penetration levels requires reliable balancing mechanisms, the development of advanced management technologies, and the implementation of regulatory measures to facilitate the transition to a low-carbon economy. Different approaches to this transition represent two strategic visions, which can complement each other depending on economic and technological realities. The successful integration of RES depends on joint efforts by governments, grid operators, and the private sector, who must ensure effective grid resource management and a smooth adaptation of existing infrastructure.

The future development of power systems will be determined by their ability to adapt to the dynamic changes in the energy sector, integrating innovation, infrastructure modernization, and effective regulatory policies. Only through a strategic approach and sustainable solutions can a reliable and stable energy system be ensured one that aligns with the long-term decarbonization goals.

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Date of receipt of the manuscript: 01.05.2024
Date of adoption for pubication: 30.09.2024