Modernization of electric infrastructure as a foundation for renewable resources transformation

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Abstract— The article addresses the urgent need for modernizing electric infrastructure as a foundation for integrating renewable energy sources (RES) in Europe. As the continent transitions toward decarbonization and RES, this shift poses significant challenges due to the diversity of national energy systems and unequal access to renewable resources. The study places the European energy transition in a broad policy context, particularly within the framework of the EU's climate objectives. It aims to identify key strategic directions in energy sector development, with a focus on selected European countries, especially Poland. The article employs comparative analysis to assess infrastructure readiness, country-specific challenges, and technological needs. Special attention is given to how disparities in infrastructure affect the capacity of each country to effectively utilize RES. The study outlines current modernization trends and critical requirements for integrating RES, emphasizing the necessity of aligning infrastructure with policy goals. Findings suggest that targeted modernization of infrastructure is essential not only for energy transformation but also for broader economic and environmental sustainability. The conclusions support the development of long-term strategies for achieving climate neutrality in line with EU targets.

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Keywords— Energy transition, renewable energy integration, electric infrastructure, European energy policy, climate neutrality, Poland energy sector.

I. INTRODUCTION

The energy transition, characterized by the decarbonization of the energy sector and a progressive shift toward renewable energy sources (RES), presents a considerable challenge for numerous European electricity markets. Central to this transformation is the modernization of energy infrastructure, which serves as a critical enabler for effectively integrating RES into national energy systems. The diversity of European electricity markets—reflected in the variation of natural conditions and differential access to renewable resources—significantly influences the energy profiles of individual countries. These disparities, in turn, affect the capacity of each country to efficiently generate and utilize energy derived from renewable sources.

This article seeks to identify key directions in the development of the energy sector in response to major shifts in the European Union's energy policy. An analysis of energy infrastructure in selected European countries has been conducted, with particular emphasis on the specific characteristics of the Polish energy market. Furthermore, the study highlights the principal requirements and challenges involved in modernizing energy infrastructure to facilitate the integration of renewable sources. This article examines current trends and developmental pathways within the European energy industry that may inform projections of future changes within the broader European economy.

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II. The importance of energy infrastructure modernization in the face of energy policy

In November 2019, the European Parliament declared a climate and environmental emergency through a series of resolutions, recognizing the urgency of addressing the escalating ecological crisis. Following that, the European Commission was mandated to align all legislative proposals to limit global warming to below 1.5°C. In another resolution concerning the United Nations (UN) Climate Change Conference, the European Parliament urged the European Union to formulate a comprehensive strategy aimed at achieving climate neutrality by 2050 at the latest. In response, the European Commission, in a communication dated 11 December 2019, announced the European Green Deal, which aims to achieve climate neutrality for European Union countries by 2050.

A central regulatory initiative supporting the implementation of the European Green Deal is the Fit for 55 package, a comprehensive set of legislative proposals introduced on 14 July 2021. The name of the package refers to the stated goal of reducing the European Union's greenhouse gas emissions by 55% by 2030 compared to 1990 levels, with the overarching objective of achieving climate neutrality by 2050. The package consists of 13 legislative measures, which are both amendments to existing directives and new regulations. Its primary aim is to align the EU's legislative environment with the emission reduction targets established under the European Green Deal.

Achieving the target of climate neutrality necessitates the comprehensive modernization of energy infrastructure, which has become a critical component of the broader transformation of the energy sector. Such modernization efforts are expected to significantly contribute to the reduction of greenhouse gas emissions and the mitigation of the energy sector's environmental impact. These developments are essential to fulfilling the European Union's commitments to sustainable development and climate protection.

Over the past decade, renewable energy technologies—often referred to in the literature as variable and weather-dependent sources—have rapidly expanded globally, as noted by Sirin and Sevindik (2022). According to Saha et al. (2023), this is primarily due to environmental concerns, including global warming and climate change, as well as the depletion of fossil fuel reserves. Within the European context, cross-border interconnections between electricity markets provide the opportunity to share RES reserve capacity across multiple countries, thereby enhancing energy security and improving the reliability of supply (Macedo et al., 2021). As energy demand continues to rise across Europe, while reliance on conventional energy sources is being reduced, the further development of renewable energy sources and cross-border infrastructure becomes increasingly imperative.

The transformation of energy infrastructure toward low- and zero-carbon sources has been the subject of scholarly analysis for several years. For instance, de Menezes and Houllier (2015) examined the implications of Germany's energy policy—particularly the expansion of renewable energy sources (RES) and the decommissioning of eight nuclear power plants—for neighboring countries such as France and the Netherlands. Their findings suggest that a reduction in baseload capacity in the electricity system (associated with the nuclear plant shutdowns) and the increasing share of RES could lead to increased fluctuations in electricity prices in Germany and neighboring interconnected markets. Similarly, Phan and Roques (2015) analyzed the impact of RES growth in Germany on price volatility in France, concluding that RES tend to lower average energy prices and contribute to increased volatility not only at home but also abroad. In addition, Pinto et al. (2015) examined the adequacy of existing European transmission networks in facilitating the development of a unified European electricity market amidst rising RES development. Their analysis revealed that the current level of interconnection capacity remains insufficient, posing a challenge to the continued integration of RES across the continent.

III. Analysis of the current state of energy infrastructure in Europe—an overview of the energy mix

To meet its energy needs, each country utilizes diverse types and proportions of energy sources, resulting in distinct energy mixes. The availability of specific energy sources within a country largely shapes its electricity generation profile. However, a long-term trend has emerged toward reducing reliance on conventional energy sources, driven by increasingly ambitious climate objectives that necessitate a reconfiguration of national energy portfolios. The simultaneous rise in energy demand and the limitation of fossil fuel extraction underscore the urgency of accelerating the development of renewable energy sources to mitigate dependency on energy imports and ensure long-term energy security.

According to data from the European Commission (2023), European countries are increasingly using RES for electricity generation every year. Between 2007 and 2021, the share of RES in the structure of energy consumption in the European Union more than doubled, rising from 17.7% to 38%. Thus, nearly two-fifths of the European Union's electricity comes from renewable sources, as all member states have increased their use compared to 2007. Furthermore, non-EU countries such as Switzerland, Norway and the UK also see a strong trend toward renewable energy development.

Three European groups of electricity markets can be distinguished based on the degree of RES utilization. The first group comprises countries where RES account for more than 60% of total electricity production. These include Norway, Austria, Denmark, Croatia, Lithuania, Sweden, Switzerland, Portugal and Latvia. The second group includes markets for which RES account for an average share of electricity production, ranging from 30% to 59%. These include Finland, Spain, Romania, Greece, Italy, Germany, Estonia, the United Kingdom, Slovenia and the Netherlands. The third group includes the remaining electricity markets, where the share of renewable electricity in total generation is below 30%.

However, the increase in RES expansion is associated with greater volatility in the electricity market (RES has priority access to the grid due to the merit order effect, which dictates the order in which power plants are placed in the electricity trading market) (Würzburg et al., 2013; Antweiler and Muesgens, 2021).

Nuclear power remains a significant source of electricity in Europe, although its share of total electricity generation has been gradually declining, from 29.2% in 2007 to 25.2% in 2021. This is primarily due to the gradual phasing out of nuclear reactors, particularly in Germany and France. The largest shares of nuclear power in the national energy mix in 2021 were observed in France (68%), Slovakia (52%), Belgium (50%) and Hungary (45.5%). There are also countries in Europe that do not have nuclear power plants, including Poland, Croatia, Denmark, Estonia, Lithuania and Latvia.

It is important to note that in 1974 Poland inaugurated the MARIA nuclear research reactor, with a nominal thermal power of 30 MW. Although this reactor does not generate electricity for external consumers, it plays a vital role in research applications, particularly in neuron-based studies. In addition, according to the Polish energy policy, there are plans for the construction of six units of a nuclear power plant, where the first unit is expected to be put into operation in 2033, and others at intervals of 2-3 years (Poland's Energy…). Moreover, the largest share in the energy mix of European countries is natural gas, the consumption of which has fluctuated in recent years reaching 19.9% in 2021. The countries with the largest share of natural gas in the national energy mix are Italy (50.5%) and the Netherlands (49%). Italy is one of the leading net importers of natural gas in Europe (Ministry…, 2023), while the Netherlands has the largest natural gas deposits in Europe. On the other hand, countries such as Norway and Sweden almost entirely exclude natural gas from their electricity generation portfolios.

The Russian invasion of Ukraine has significantly impacted the energy landscape in Europe, prompting a reduction in natural gas consumption by EU member states over the coming years. In response to this crisis, the European Union adopted a regulation in August 2022 aimed at reducing member states' natural gas demand by 15% compared to their average consumption during the period from 1 August 2022, to 31 March 2023. This reduction target was subsequently extended in April 2023 for the period from 1 April 2023, to 31 March 2024, with the benchmark being the average gas consumption between 1 April 2017, and 31 March 2022.

An important aspect of the European Union's energy strategy is its steadfast commitment to decarbonization, which has led to a significant reduction in fossil fuel consumption across member states. This transition away from conventional energy sources has been further accelerated by rising carbon prices and the decreasing costs associated with the installation of renewable energy technologies. Between 2007 and 2021, the share of fossil fuels in the energy consumption mix of European countries saw a marked decline. For instance, in the European Union, the proportion of fossil fuels in electricity generation decreased by nearly half, from 28.5% to 14.6%. Estonia serves as a notable example of this trend, having reduced its reliance on oil shale for electricity generation by more than 45% over 13 years. Despite these advancements, fossil fuels still comprised the majority of the energy mix in 2021 in countries like Poland and Estonia, where they accounted for 71% and 48%, respectively.

Oil represents the smallest share in Europe's energy mix, consistently accounting for less than 1% of total energy consumption since 2007. However, it maintains a more significant presence in the national energy mixes of certain countries, such as Greece (8%) and Spain (4%). A detailed breakdown of the energy mixes across European electricity markets in 2021 is presented in Table 1, which categorizes countries into seven distinct regions: Central Western Europe (CWE), Central and Eastern Europe (CEE), Southeastern Europe (SEE), Apennine Peninsula (AP), Northern European Plain (NP), British Isles (BI), and the Iberian Peninsula (Iberian)

IV. Development and transformation of energy infrastructure in Poland

Between 1970 and 1990, the Polish power sector faced several negative phenomena related to a highly energy-intensive economy compared to Western European countries, a heavy dependency on coal, significant environmental degradation largely attributed to the energy sector, and an inefficient fuel and electricity pricing system. The socio-political changes that followed the 1989 elections began a systemic transformation linked to the marketization of the economy. This period heralded the liberalization of the electricity sector, alongside efforts to restructure the industry, aimed at demonopolization and privatization of energy companies (Motowidlak, 2019). Consequently, the restructuring of the electricity sector in Poland commenced with the dissolution of the Energy and Coal Community in 1990.

Following the dissolution of the Energy and Coal Community, smaller state-owned companies were established, leading to the segmentation of Poland's electricity sector into three primary components: generation, transmission, and distribution. The generation sector consisted of 17 power plants and 14 thermal power plants, while the transmission sector was represented by a one-person joint stock company established by the State Treasury, Polskie Sieci Elektroenergetyczne (PSE). The distribution sector is comprised of 33 power plants (Żebryk, 2018). In addition, coal and lignite mines remained state-owned and operated independently. Reforms after 1989 meant that existing regulations were not adapted to changes in the electricity economy. Ongoing work on legislation for the electricity sector led to the establishment of Energy Law in 1997, which marked the beginning of the process of liberalizing Poland's electricity market.

The European Union's current climate policy is exerting a significant influence on the transformation of Poland's energy sector. This transition primarily entails a shift from traditional, high-carbon energy sources, such as coal and oil, towards more

sustainable energy infrastructure, including wind and solar power. A central objective of this process in Poland is to reduce greenhouse gas emissions, improve environmental quality and mitigate the adverse impact of the energy sector on the climate.

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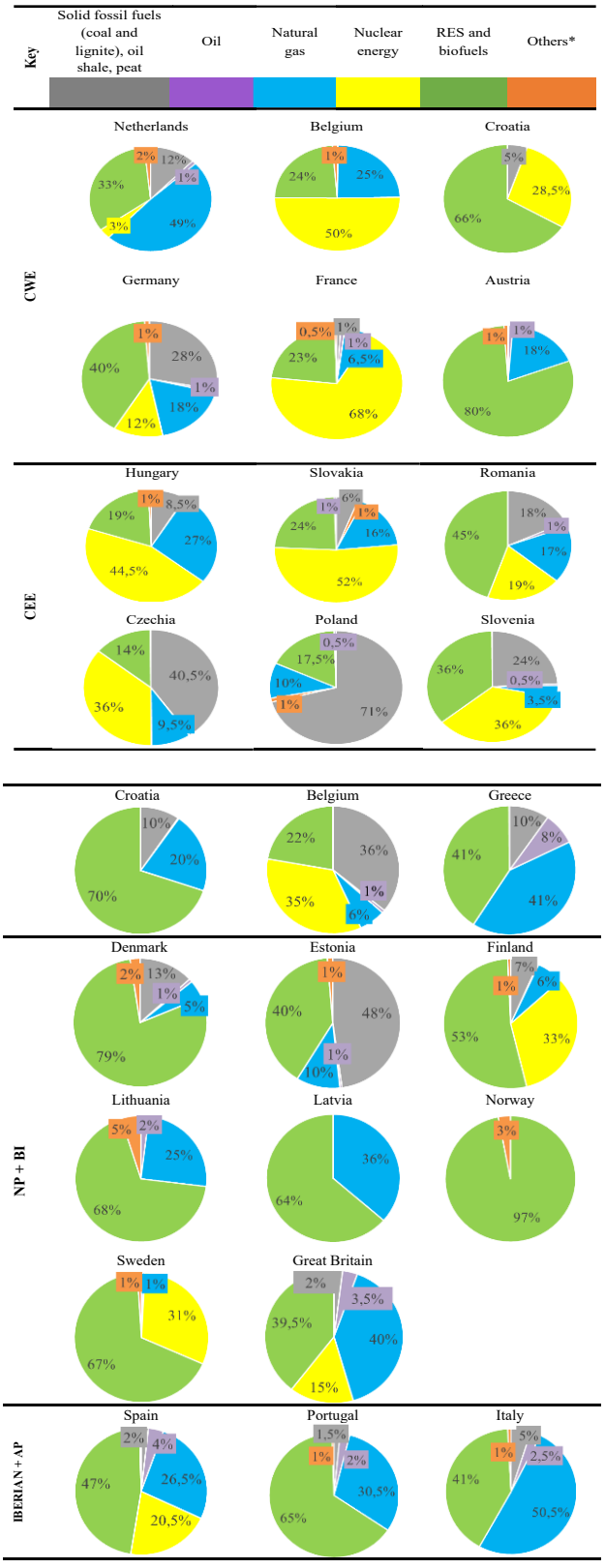
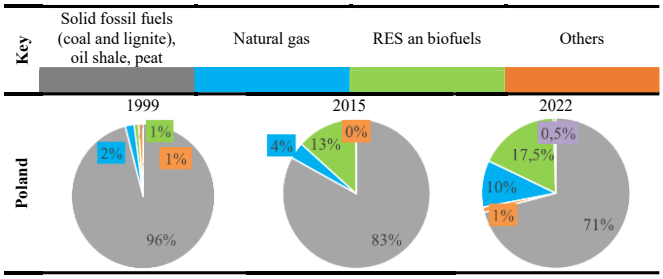
CHART 1. STRUCTURE OF ENERGY PRODUCTION AND CONSUMPTION BY CRITERIA OF ENERGY CARRIERS (SO-CALLED ENERGY MIX) OF EUROPEAN ENERGY MARKETS FOR 2021.



Source: own compilations based on: EU energy statistical pocketbook and country datasheets (updated 2023) and www.statista.com.

Compared to other EU countries, Poland's energy mix remains the most dependent on fossil fuels. However, recent years have seen a clear trend toward diversification of energy sources, with increased investment in renewable sources and a gradual reduction in the reliance on coal within the electricity system. This shift aligns with the European Union's climate neutrality policy. Evidence of this is illustrated in Table 2, which compares Poland's energy mix in 1999, 2015 and 2022. The data presented, clearly show a substantial decline in the share of lignite and hard coal alongside a notable increase in the importance of renewable sources.

CHART 2. STRUCTURE OF ENERGY PRODUCTION AND CONSUMPTION BY ENERGY CARRIERS (ENERGY MIX) IN POLAND IN 1999, 2015 AND 2022.



Source: own compilation based on: EU energy statistical pocketbook and country datasheets (data update 2023) and www.statista.com.

In February 2022, Russia's invasion of Ukraine severely disrupted the European energy system, highlighting the European Union's over-reliance on imports of gas, coal, and oil from Russia. In response, the European Commission issued its communication on 8 March 2022, titled "REPowerEU: joint European action for more affordable, secure and sustainable energy," which called for rapid independence from fossil fuels from Russia and accelerated implementation of the European Green Deal objectives. Subsequently, on 18 May 2022, the European Commission published the REPowerEU plan with a package of supporting documents. Based on the Fit for 55 package of proposals, the REPowerEU plan outlines additional measures for :

- electricity savings – changing the target for reducing Energy consumption by 2030 to 13% compared to the projections presented in the 2020 baseline scenario,
- replacing fossil fuels with renewable energy – changing the target for the level of electricity generation from RES from 40% to 45% (from the proposal in the Fit for 55 package),
- diversification of energy supplies from Russia to Europe.

As part of the REPowerEU plan, substantial funding has been allocated for the development of new energy infrastructure and the energy system. The plan provides both grants and repayable forms of support, which can be utilized to address internal and cross-border bottlenecks in electricity transmission and distribution, as well as to build energy storage facilities .

Following the introduction of the REPowerEU plan by the European Commission, European Union member states, including Poland, have updated their National Recovery Plans (NRP) to include objectives and actions related to energy transition and energy security. Under Poland's NRP, the REPowerEU chapter outlines 10 key investments and seven new reforms aimed at strengthening the country's energy security, accelerating the energy transition and diversifying energy sources. The investments focus on developing renewable energy sources, modernizing existing energy infrastructure, expanding transmission networks, and supporting technological innovation in the energy sector.

V. REQUIREMENTS AND CHALLENGES OF ENERGY INFRASTRUCTURE MODERNIZATION

Fossil fuel resources are finite, and thus, a gradual shift towards increasing the share of renewable energy sources in electricity generation is essential for ensuring long-term energy sustainability. The main problem hindering the development of technological systems is the unpredictability of energy production. The amount of energy generated in the systems depends on atmospheric conditions, which are variable and difficult to predict. Renewable energy also does not correlate with periods of highest power demand during the day.

Currently, the European electricity market is struggling with, among other things, the absence of large-scale energy storage solutions, which could enhance the integration of energy produced by RES installations. Currently, surplus energy cannot be freely stored and used beyond the time of generation. The primary objectives of the development of energy storage technologies are to improve the efficiency of energy generation, optimizing the management of production and transmission systems, improving the security of energy supply and maximizing the utilization of renewable energy sources. The selection of the most suitable energy storage technology is based on a range of technical and economic criteria, such as energy and power density, cost-effectiveness, economies of scale and operational lifespan. Presently, countries that are leaders in renewable energy development also tend to have the most advanced energy storage infrastructure. In Europe, the United Kingdom and Germany are at the forefront of energy storage deployment. The expansion of energy storage capacity is also closely linked to the availability and quality of raw materials used in the production of batteries. Ideally, an energy storage solution would combine high performance with the use of inexpensive and widely available materials.

One of the key challenges associated with the growing share of renewable energy sources in the electricity mix is price cannibalization. This occurs as renewable generation capacity increases, leading to lower wholesale electricity prices due to the near-zero marginal costs of RES and the merit order mechanism, which sets market prices based on the cost of the most expensive generating unit needed to meet demand. The resulting decline in electricity prices can undermine the profitability of renewable investments themselves—a dynamic often referred to as the cannibalization effect. This issue has been extensively examined in the literature (Mills & Wiser, 2012; Hirth, 2013; Prola et al., 2020; Peña, 2022; Liebensteiner & Naumann, 2022). Additionally, the rapid development of renewables—facilitated by subsidies and priority grid access—has negatively impacted the profitability of conventional power plants (Rintamäki et al., 2017). This poses a significant

challenge in markets that still rely heavily on lignite and hard coal for electricity generation, such as Poland.

Another challenge lies in the modernization and expansion of networks, with a focus on transforming both the transmission and distribution systems into smart grids. The challenges arise from the need for a new electricity system, which necessitates the integration of renewable energy sources and a flexible response to fluctuating electricity demand. The transmission system operator, Polskie Sieci Elektroenergetyczne, expects to spend more than PLN 64 billion by 2034 on the development of the transmission network. The investments include the construction of 4,700 kilometers of new 400 kV lines, 28 new substations and the modernization of 110 existing substations to increase network capacity and integrate new energy sources .Prosumer power generation, in which consumers simultaneously act as energy producers, poses a significant challenge to traditional energy infrastructure. This model of decentralized energy production introduced several complexities, including:

- dispersion of energy sources, mainly in the form of photovoltaic panels, small wind installations or heat pumps,
- intermittent power generation and grid balancing problems,
- the need to enable two-way energy transmission - from the prosumer to the grid and vice versa,
- the need to introduce smart grid technologies.

These challenges highlight the need for a modernization of the energy infrastructure that ensures flexibility, facilitates integration of renewable energy sources and enables the efficient management of variable demand.

VI. Conclusion

The modernization of energy infrastructure is a critical cornerstone for the transition toward a sustainable economy based on renewable energy sources. The evolving market conditions, increasing energy demand and the dynamic development of RES technologies necessitate the implementation of advanced solutions to effectively integrate distributed energy sources, increase system flexibility and ensure the stability of energy supply.

As the analysis of the energy infrastructure in Europe used for electricity generation has demonstrated, some energy markets, owing to favorable natural conditions and the availability of renewable resources, have greater opportunities for energy production from renewable sources (e.g., Norway, Austria, Denmark, Croatia, Lithuania, Sweden, Switzerland, Portugal and Latvia). Conversely, countries such as Poland and Estonia face greater challenges in achieving energy transition goals, due to the limited availability of renewable resources, high dependence on traditional energy sources, as well as the need to adapt energy infrastructure to accommodate new, more diverse and variable energy sources.

However, regardless of the specifics of each country's energy sector, all EU member states are committed to ambitious climate policy goals. In this context, the modernization of energy infrastructure is integral to the transition process, ensuring the integration of an increasing share of renewables and the growing number of prosumers. In addition, given the volatility and instability of RES generation, it becomes necessary to further develop large-scale energy storage systems to meet demand during periods of low production. Consequently, the energy infrastructure must not only be more flexible, but also smarter, so that it can respond effectively to changing demand, which requires the implementation of modern technologies such as smart grids and mechanisms that optimize the balance between supply and demand.

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