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Time to Rethink Energy: An Initiative towards Renewable and Smart Energy. A Comparative Analysis of Poland and Germany and Conclusions for Cross-Border Cooperation and Improving Resilience

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Abstract

By analyzing the regional disparities in energy production and consumption between Poland and Germany, and precisely defining the concept of smart energy (SE), we contribute to the discussion on the challenges related to "territorially oriented energy management" policy. On the basis of our research, we take the position that cooperation between border communes in terms of energy challenges is becoming extremely relevant. This study draws on quantitative and qualitative data. We undertook a comparative study of energy production and consumption in Poland and Germany, thus presenting a regional and local perspective. The main research outcomes are conclusions resulting from the comparison of different strategies in the energy areas of Poland and Germany, a definition of the term SE, and solutions concerning interregional, and especially cross-border, cooperation. One of the key conclusions of this study is that in practice regional asymmetry in the Polish-German borderland may stimulate wider cross-border cooperation based on the SE concept.

Keywords: energy economy, energy cooperation, energy resilience, war in Ukraine, asymmetry, border regions

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Introduction

As a civilization, we find ourselves in a developmental phase, in which the significance of so-called natural capital is diminishing, while so-called anthropogenic capital — i.e., capital generated by human activity, is gaining traction. Education is the factor that enables natural capital to be replaced by anthropogenic capital (if only to a limited extent) (Szwarczyński and Gorynia 2022). When it

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comes to **renewable energy technologies** (RET), most countries in the world follow their own development policies, setting goals to be achieved within a certain period of time. Depending on the region, these goals are to quite a large extent diverse (Gnatowska and Moryń-Kucharczyk 2019; Igliński et al. 2013; Jankowska, Staliński, and Trąpczyński 2021; Sokołowski 2017). A particular exception in this regard is the legal framework adopted in the EU, in which one consequence of decisions made at the group level is their implementation into the legal systems of the member states forming the group. In the context of RET in the energy sector, this is exemplified by Directive 2009/28/EC of the European Parliament and of the Council, establishing goals for the share of energy from renewable sources in the gross final consumption of energy in the EU27 Member States in 2020.[1]

However, not all countries are able to invest in new technological solutions to the same degree, nor do they all have comparable access to renewable sources. Attempts made by regions located close to each other to cooperate are natural, particularly when they are in the same country. However, in the case of border and cross-border regions, such cooperation is still at an immature stage, and it is rarely established in communes or regions. This is influenced by different legalities, lack of coordinating institutions, varying objectives, diversity in economic structure, lack of common financial instruments, and others. In the case of interregional cooperation, it is important to identify the actors according to their level of involvement and then develop ways to organize and manage their cooperation (= collaborative efforts) (Sedlacek, Tötzer, and Lund-Durlacher 2020). In the case of adjacent and cross-border communes, these processes are more complex because there are different legal and cultural circumstances, varying levels of infrastructure, technological advancement, and others.

A literature review on the topic of energy management revealed **two empirical research gaps**. The first is related to the poorly explored area of comparative research in terms of macroeconomics (in this case, Poland and Germany) and regional economics in border regions, where proximity is a natural element conducive to such cooperation, if only for social, technological or economic reasons (van Dijk, Wieczorek, and Ligtvoet 2022). However, the existing limitations in the form of asymmetry pose an obstacle. Key actors must be selected for the process of cross-border cooperation, who will pioneer certain solutions and initiate cross-border energy cooperation related to locally oriented energy management thanks to their knowledge of the local environment. On the one hand, cross-border cooperation in terms of energy (Jankowska, Staliński, and Trąpczyński 2021) fills an essential gap in various essential areas of cooperation; on the other hand, such cooperation raises the question of the local potential to initiate it and the ability of decision-makers to indicate the economic and social benefits that should accompany this process.

The second gap concerns research on renewable energy in a regional dimension. Most of the studies on how to help develop renewable energy focus on the analysis of exports and imports between countries rather than on issues related to regions or smaller units (Späth and Rohracher 2010). In the case of regions, administration can be observed on many levels, including top-down incentives resulting from climate and energy policy (especially under the European Green Deal and the “Fit for 55” legislative package), as well as bottom-up actions initiated in the area of energy. These multiple levels of administration need to be taken into account when identifying significant characteristics and challenges to energy regions. In this context, it is worth mentioning the goals set by Poland in the Europe 2020 Strategy[2] regarding the share of energy from renewable sources in gross final consumption of energy, aiming for a level of 15% by the year 2020. Additionally, these objectives were pursued within the framework of the Regional Operational Programs 2014–2020 (ROPs),[3] especially under the priority axis of Low-Emission Economy in all regions of Polish cross-border areas.

1. See: Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC (Text with EEA relevance). OJ L 140, 5.6.2009, p. 16-62.

2. See: EUROPE 2020. A strategy for smart, sustainable and inclusive growth. Brussels, 3.3.2010, COM/2010/2020 final.

3. See: “ROP 1 Regional Operational Programme for Dolnośląskie Voivodeship 2014-2020,” available at https://

Issues related to the share of renewable sources in energy production are subject to ongoing reporting to international organizations: the International Energy Agency (IEA)[4] and the International Renewable Energy Agency (IRENA)[5]. This study examines energy management in Poland and Germany in 1990–2020 and also indicates the similarities between European countries in energy management. Regional disparities in energy production and consumption are illustrated along with "good practices" when it comes to initiating cooperation in SE along the Polish-German border.

In Section 2 of the article the overall concept of the research on the issue is discussed and research hypotheses are formulated. The next section presents the research methods and their quantitative and qualitative results, providing a new concept of smart energy (SE) management and discussing the results that might constitute a basis for formulating policy recommendations. In addition, a SWOT table is introduced, summarizing the internal and external qualitative factors affecting the positive verification/of the research hypothesis. Finally, some conclusions are drawn regarding the topic, and our future plans to extend our research are mentioned.

1 Conceptual background and development of hypotheses

The research topics presented here fall into several areas of theoretical consideration regarding regional disparities, place-based policy, the Technological Innovation System (TIS), resilience, and Green Smart Energy (GSE). In the 1970s, attention started to be paid to the effectiveness of a bottom-up approach, which resulted in looking for new, more effective models of growth and development during the great oil crisis (Churski 2018). Place-based policy enables the use of resources as well as relational and functional elements that create networks of interpersonal and inter-institutional connections, putting development in a given place (Churski 2018; Churski et al. 2017). Interference in the process of territorial development must take place in accordance with a new paradigm of regional policy, based on comprehensive and dedicated intervention tailored to the individual specificity of territorial capitals.

In this article, the conceptual framework for the literature review also focuses on several other theoretical approaches to sustainable development that bring together researchers from diverse backgrounds, such as economics, sociology, history, socio-economic geography, and engineering. It is TIS that stands out among these approaches (Bergek et al. 2008; Jacobsson and Johnson 2000; Soe et al. 2022). Aspects related to the role of actors and the institutional environment are strongly emphasized in the literature.

Well-respected authors in regionalist circles consider it highly advisable to eliminate "institutional bottlenecks" (Pike, Dawley, and Tomaney 2010). Institutions are arenas where social, economic, cultural and political values are promoted, and as such they may become subjects of political dispute as well as consensus. A key area of future research and regional action is the role played by political institutions due to their fundamental function in creating frameworks and conditions for the development of local and regional innovations and transformations (Pike, Rodríguez-Pose, and Tomaney 2017). This area is particularly unrecognized when it comes to relatively weak territorial systems. New technologies require assistance in their development before they can compete on an equal footing with current technologies in practice (or perhaps replace them). Focusing on territorial institutions and actors is crucial for the processes of cooperation, coopetition, synergy, and complementarity of action.

ec.europa.eu/regional_policy/in-your-country/programmes/2014-2020/pl/2014pl16m2op001_en; "ROP 4 Regional Operational Programme for Lubuskie Voivodeship 2014-2020," available at https://ec.europa.eu/regional_policy/in-your-country/programmes/2014-2020/pl/2014pl16m2op004_en; "ROP 16 Regional Operational Programme for Zachodniopomorskie Voivodeship," available at https://ec.europa.eu/regional_policy/in-your-country/programmes/2014-2020/pl/2014pl16m2op016_en.

4. See: International Energy Agency website. https://www.iea.org/.

5. See: International Renewable Energy Agency website. https://www.irena.org/.

In the light of the above discussion, the following research hypothesis may be proposed:

> **H$_1$: Cross-border cooperation between countries, regions and communes in energy management is positively influenced by processes whereby local government strategies are adapted, thus facilitating social and economic relations, the use of new technologies, and the introduction of a new style of life and consumption.**

The popularity of research on resilience is associated with numerous crisis situations encountered at macroeconomic, mesoeconomic or microeconomic levels (Haggag et al. 2022; Korhonen et al. 2021; Meerow and Newell 2019). The financial crisis that began in 2008, the COVID-19 pandemic, and, more recently, Russia's aggression against Ukraine are the main reasons why the resilience of economies, regions and enterprises has been discussed over the last decade (Bristow and Healy 2015; Drobniak et al. 2021; Fröhlich and Hassink 2018; Martin 2011). The subsequent shock and prolonged pressure in recent months is exemplified by the Polish government's introduction of an embargo on coal imports from Russia as part of the sanctions imposed in response to the Russian invasion of Ukraine in February 2022. Another example is Russia's gas blackmail in reaction to the restrictions introduced by Poland (until April 2022, 46% of gas imports to Poland had come from Russia). This resulted in a change in the supply of energy resources to domestic and regional markets in the short and medium term, a search for alternatives, a subsequent destabilization, and a rise in electricity and heating prices, which had a knock-on effect on production and service costs. According to the report of the Institute for Structural Research (IBS), it is the service sector that is especially exposed to the harm caused by the present situation, as exemplified by the poorest households, relying on previously cheap, imported energy sources, which have been hit the hardest.[6]

The concept of resilience can generally refer to four main areas of know-how:

- the ability to absorb economic, environmental or social shock or tension and mitigate its effects while maintaining the capability to perform basic functions without transferring them to other entities;
- the system's capacity to adapt to change or adapt structure and to transform under certain circumstances;
- the ability to change outcomes when faced with the challenge of creating a completely new system so that the shock no longer has any effect; and
- the ability to 'learn' and to plan ahead to anticipate future shock (Borsekova, Koróny, and Nijkamp 2022).

According to the World Economic Forum, the greatest challenges facing the future of energy[7] include transformations in energy systems, management of energy supply and demand, new technologies for energy, and building resilience of energy systems. This is strictly related to creating the adaptive capacity of social and ecological systems, including cities and regions. The pressures in question may be local or global, and might occur suddenly or develop gradually (Drobniak et al. 2021; Martin and Gardiner 2019; Martin and Sunley 2020; Martin et al. 2016; Simmie and Martin 2010; Walker et al. 2006).

The World Energy Council (WEC) distinguishes 4 areas to consider when assessing the resilience of national energy systems: energy security (including security of supply and demand as well as energy system resilience), energy capital, environmental balance, and the national context. In 2021, Germany was ranked seventh among the countries of the world (with the highest AAAa rating), maintaining its position compared to the previous year, while Poland came in at number 30 among the 101 countries included in the analysis (with a BBCb rating), compared to its 41st

6. See: "The Economic Effects of Stopping Russian Energy Import in Poland." IBS Research Report 01/2022 by Jakub Sokołowski, Marek Antosiewicz, and Piotr Lewandowski, Instytut Badań Strukturalnych, May 2022, available at https://ibs.org.pl/wp-content/uploads/2022/12/The-economic-effects-of-stopping-Russian-energy-imports-in-Poland-1.pdf.

7. See chart elaborated by MIT, published at World Economic Forum website, https://intelligence.weforum.org/topics/a1Gb00000038oN6EAI?tab=publications (accessed 2023-01-12).

place in 2020.[8] In view of the current situation, this evaluation seems highly debatable with regard to the German economy, which has been much more severely affected by the consequences of being linked to Russia's energy resources. In a joint speech on September 29, 2022, Chancellor Olaf Scholz, Minister of Economy Robert Habeck and Minister of Finance Christian Lindner announced the creation of a financial "umbrella" of up to EUR 200 billion for intervention in the energy market (Kędzierski and Płóciennik 2022). First and foremost, this decision is aimed at financing the natural gas price freeze mechanism and supplementing the financing of the electricity price freeze mechanism. The government's decision is a reaction to the drastic leap in energy prices in Germany in recent months, as well as inflation, which in September 2022 reached 10%—the highest rate since the early 1950s. The situation on the gas market is particularly precarious due to Germany's major dependence on supplies from Russia. Germany is not yet able to fully compensate for the deficit of this raw material by, for example, importing liquefied natural gas (LNG) due to lack of the necessary infrastructure, which increases price pressure and the uncertainty of market participants. The first terminals for receiving liquefied gas in Germany are to be commissioned at the turn of 2022 (Kędzierski and Płóciennik 2022).

Poland, on the other hand, is coping better with the current energy crisis by diversifying its approach and fostering investment based on stable energy relations.[9] Thanks to decisions taken long before Russia's war against Ukraine, Poland's gas requirements can be met by the recently launched Baltic Pipe and the previously built LNG terminal. In addition, the WEC has indicated some key priorities for the development of Europe's energy systems: Renewable Energies (RES), Digitalization, Energy Efficiency, Demographic Patterns, and Quality Energy Access. One challenge to Europe's development in this respect is to maintain the security and availability of energy. At the same time, the development of nuclear energy is considered as an opportunity while determining the significance of gas and nuclear energy in the European energy mix in the long term (Kędzierski and Płóciennik 2022).

The initiative to build the first reactor in the civil nuclear energy sector, based on a Polish-American agreement signed in November 2022, is intended to diversify generation sources and stabilize the Polish energy system (Górzyński 2022; Jarco 2022). Ultimately, the government plans to build several nuclear reactors in Poland (Jarco 2022), including a private nuclear power plant in Pątnów, on the basis of a letter of intent on trilateral cooperation between state-owned companies PGE and ZE PAK and the Korean company Korea Hydro & Nuclear Power (KHNP) (the contract is planned to be signed in 2023).[10] The current version of the Polish nuclear energy program envisages 6–9 GW of nuclear energy by 2043.[11] The private sector is also considering including small and micro reactors (SMR and MMR) in the construction process in the vicinity of production plants, as well as the creation of energy storage facilities and hydrogen production in Poland (Oksińska 2021). Furthermore, the goals outlined in the Energy Policy of Poland until 2040 (PEP2040) include the development of smart power grids for the conscious utilization of energy, efficient management, minimizing losses while maintaining high-quality supply, the use of digital communication and smart sensors, the establishment of an energy market information operator, and increased deployment of RES (Renewable Energy Sources) due to technological progress.[12]

In the study of resilience, an important element is the scale and duration of disruption. The literature describes the so-called resilience triangle, with time on the X axis and changes in the economy or environment on the Y axis. Consequently, the longer the crisis and the deeper the changes, the

8. See: "World Energy Trilemma Index 2021," pages 13-14, available at https://www.worldenergy.org/assets/downloads/WE_Trilemma_Index_2021.pdf?v=1649317554.

9. See: "World Energy Trilemma Index 2021," op. cit.

10. See: "ZE PAK, PGE and KHNP signed a letter of intent, 2022-10-31." https://www.zepak.com.pl/en/about-us/press-office/news/14036-ze-pak-pge-and-khnp-signed-a-letter-of-intent.html (accessed 2023-11-12).

11. See: "Polish Nuclear Power Programme (PPEJ)." Ministry of Climate, Warsaw 2020, available at https://www.gov.pl/web/polski-atom/program-polskiej-energetyki-jadrowej-2020-r.

12. See: "Energy Policy of Poland until 2040 (PEP2040)." Warsaw 2021, available at https://www.gov.pl/web/klimat/polityka-energetyczna-polski; see also Obwieszczenie Ministra Klimatu i Środowiska z dnia 2 marca 2021 r. w sprawie polityki energetycznej państwa do 2040 r. [Announcement of the Minister of Climate and Environment of March 2, 2021 on the state energy policy until 2040], Monitor Polski z 2021 r. poz. 264.

lower the resilience (Falasca, Zobel, and Cook 2008). From the point of view of duration, there is a sudden shock (e.g., as a result of the war in Ukraine or the influx of refugees), and cumulative, smoldering pressure (e.g., due to climate change) (Drobniak et al. 2021). Sustainable development related to green infrastructure strengthens the resilience of a given region. By contrast, a lack of transformation tools available to local economic initiatives, which translates into deterioration of the environment even throughout the entire region, weakens this resilience (Korhonen et al. 2021; Rizzi, Graziano, and Dallara 2018; Szabó, Csete, and Pálvölgyi 2018). Various types of institutions play an important role in building a region's resilience.

In the light of the above, the following research hypothesis can be proposed:

> **H_2. Regional resilience depends on the education, science, economy, and economic strategies of individual countries as well as the involvement of their residents in SE**

A GSE system consists of a conventional energy system (1) and several segments in the green economy (2), including energy generation, energy efficiency, energy storage, energy infrastructure, and energy transmission (Grose 2013). A conventional (national/regional/municipal) energy system is therefore developed with the following main elements:

- RES technologies and devices (solar, wind, geothermal, biomass, hydro, sea and tidal waves, and hydrogen) and cogeneration in energy production
- monitoring technology and equipment, management software, and measurement systems and devices
- alternative applications of various devices: solar heating, lighting, etc.
- advanced batteries and production of their components, accessories, and fuel cells
- transmission system, cabling (local systems), and equipment

In addition, an SE system is supplemented by the following elements that stimulate the economy: researching and testing "green" solutions, engineering and consulting services in RES and energy consumption reduction, research on energy efficiency, energy-efficient products and services, and management.

Economically speaking, the justification for using RES technology in the energy sector stems from at least five economic and social premises: (1) enhanced efficiency of resource use, (2) potential for growth in the long-term competitiveness of the economy by using resources available for free (along with investment in the creation of solar and wind technology), (3) stimulation of the economy and GDP growth (high-tech industries and industries generating high added value) in developed economies that implement intervention strategies to stimulate the economy in periods of crisis, (4) increased independence of the energy sector and the entire economy from foreign trade in energy resources to mitigate the impact of demand/supply crises and shocks (bolstering economic resilience), and (5) less negative impact on ecosystems and human health along with mitigation of long-term costs in this regard (Arias-Gaviria, Carvajal-Quintero, and Arango-Aramburo 2019; Boomsma, Meade, and Fleten 2012; Couture and Gagnon 2010; Gnatowska and Moryń-Kucharczyk 2019; Maulidia et al. 2019; Njoh et al. 2019; Xu et al. 2019).

It is worth noting that our research is not related to a precise comparison of the energy markets (and the related economic parameters) in Poland and Germany, and especially issues related to "green" energy production and usage. Indeed, such research could be very interesting and valuable. Unfortunately, this domain needs much more comparative research and much more space to present; thus, it is beyond the scope of this article. However, we plan to extend our research in the future so that it includes such a comparison.

As research on the Polish RES energy sector shows, some of its areas may be conducive to improving the resilience of energy systems not only locally or regionally but also nationally. In this respect, hydropower can contribute to a stable power system, in particular thanks to the emergence of small run-of-river power plants with a capacity of less than 10 MW, which constitute a majority of 761 out of 771 run-of-river power plants in Poland, without generating significant environmental costs. The total operating capacity of river hydroelectric plants amounts to 937 MW, and hydropower plants can act as energy storage for RES system regulators due to the disadvantages of other energy generation technologies, in particular the long-time required need to change the level of the power supplied to the system (Piwowar, Dzikuć, and Adamczyk 2016).

A similar regulatory potential, increasing the level of resilience of energy systems associated with RES technologies, is offered by technologies based on biofuels. The Polish economy, due to its big area of agricultural land and well-developed agri-food industry with a large pig and cattle population, has considerable local and regional potential to produce RES from agricultural biomass and is characterized by considerable growth dynamics. The total capacity of installations for the production of agricultural biogas in Poland in 2014 was estimated at 244,156,466 m^3/year, and the increase in its production between 2011–2014 amounted to 137.29 million m^3 (Piwowar, Dzikuć, and Adamczyk 2016). However, due to the unfavorable regulatory environment, the prospects for developing these systems in Poland are frowned upon by potential biogas suppliers (Jankowska, Staliński, and Trąpczyński 2021). According to the authors, assistance in this regard should start by simplifying procedures for constructing biogas plants and providing subsidies for construction purposes, as well as eliminating tax breaks and limiting support for coal-based energy. Also, the development of a transmission network is crucial so that long and expensive connections with biogas stations are not required. Research on the potential of biomass conducted in 2020 for the Baltic Sea region indicates that Germany and Poland represent the greatest technical potential for agricultural biomass, manure and slurry. However, one should also consider the overall impact and potential of the country's economy. For example, Germany is the leading producer of pellets as well as the largest producer of biogas (92% of all the biogas plants in the area under analysis). Furthermore, Germany has the highest final bioheat energy consumption in all sectors (Stolarski et al. 2020). Nevertheless, it is worth comparing the effects and ways of introducing green-energy solutions in the two countries.

The resilience of energy systems is also affected by natural factors, including climate change and, consequently, changes in air circulation across the European continent. According to the latest CMIP6 future climate scenarios, by the end of this century wind trends in some areas will have changed (an increase or decrease in wind resource potential). Studies indicate that, according to the SSP2-4.5 projection, apart from eastern Ukraine and Turkey (where there will be an increase of about 15%–30%), most of the continent will see a significant decrease (5%–15%) in wind potential, which by the end of the current century will have dropped most significantly (by around 10%–20%) throughout the British Isles, Poland, western Ukraine, and northern Norway. Another projection (SSP5-8.5) for the same period predicts a reduction in future wind energy resources practically throughout Europe (by 10%–20%), especially in northern Norway, Poland, and western Ukraine (by 25%–30%). At the same time, there is a great uncertainty as to the inter-year and mid-year changes in wind resources in the future (Carvalho et al. 2021).

Taking into account the above discussion, the following research hypothesis may be formulated:

H_3. SE has a positive impact on the extent of adaptation during the energy crisis, assuming that the technology is widely available to residents.

External factors in the form of economic policy determine the competitiveness of RES sub-sectors in emerging markets, as confirmed by research (Jankowska, Staliński, and Trąpczyński 2021). In the case of markets at an early stage of RET development (such as Poland), state intervention can effectively stimulate their development, especially by applying hard instruments, direct aid and assistance in the investment phase. The simplification of administrative procedures is also relevant — reducing bureaucracy can provide beneficiary sectors with returns comparable to direct funding. A well thought-out and responsible cost-effect policy is also important, including cost reduction and accelerated allocation of funds (Jankowska, Staliński, and Trąpczyński 2021).

Pollutants and greenhouse gases (GHG) emitted during manufacturing processes and resulting from excessive consumption are cross-border in nature. This applies in particular to the energy sector based on fossil fuels, whose combustion generates significant amounts of gaseous pollutants including carbon dioxide (CO2) and water vapor, emitted directly into the atmosphere. In terms of climate, historically, over the central part of the European continent, the dominant wind direction has been west or north-west (the average direction in the period 1991–2020 in June was 301 degrees, which means a warm/cool polar-marine air mass on average, depending on the season, and the average from 1991–2020 is 251 degrees (i.e., west direction).[13] The natural conditions related to air circulation are therefore conducive to a greater frequency of cross-border advection of air masses, GHG and pollutants from the eastern area of Germany to the western regions of Poland, which in turn burdens ecosystems on the Polish side. However, there is no precise data on the balance of GHG flows on the Polish-German border in terms of nominal units, which may vary over the years due to the volatility of circulation.

Therefore, the following hypothesis can be formulated:

> **H_4. The short-term and long-term effects of energy transition are cross-border in nature, but their impact on technologically and economically diverse areas on both sides of the border varies.**

2 Materials and methodology

The authors triangulated data sources to verify their research hypotheses (Saunders, Lewis, and Thornhill 2012) and research methods. The combination of different methods and sources facilitates a broader analysis (Fusch, Fusch, and Ness 2018). The quantitative analysis was supplemented with a qualitative element, conducted in the form of individual and direct in-depth interviews. Since qualitative research does not have a priority of representativeness, it tends to be aimed at acquiring a broader understanding of the problem from fewer cases (Glinka and Czakon 2021). Interviews were conducted with representatives of local governments. The survey was conducted via the Computer-Assisted Web Interview (CAWI) method. Raw data were also collected from the following sources:

- European Statistical System (ESS), Statistical Office of the European Union (EUROSTAT)
- Federal and State Statistical Offices of Germany (DESTATIS)
- Central Statistical Office of Poland (Statistics Poland), Local Data Bank
- International Renewable Energy Agency (IRENA)
- Polish Energy Market Agency S.A. Annual Reports
- the authors' own research

The resilience of the Polish energy sector during the crisis can be measured through various indicators, including the following:

- monitoring the trends and fluctuations in energy prices, particularly electricity and gas, can provide insights into the impact of the crisis on the energy sector; high energy prices may indicate challenges, while stable or lower prices may reflect resilience
- assessing the energy production and consumption levels can indicate the sector's ability to maintain a stable energy supply and demand during the crisis
- tracking investments in renewable energy sources, energy efficiency measures, and technological innovations can demonstrate the sector's adaptability and resilience in response to the crisis
- evaluating the performance of energy companies, market dynamics, and regulatory responses can provide an overview of the sector's ability to withstand the crisis and adapt to changing conditions
- assessing the effectiveness of policy responses, regulatory frameworks, and government interventions in stabilizing the energy sector during the crisis can indicate the sector's resilience

Due to the very wide range of possible areas for resilience analysis, the article is limited to analyzing the costs of mitigating the energy crisis in Poland compared to other economies in Europe in 2022. The conclusions from these observations are as follows:

13. See: "Monthly Climate Monitoring Bulletin. June 2022." Institute of Meteorology and Water Management—National Research Institute, available at https://klimat.imgw.pl/pl/biuletyn-monitoring/#2022/06.

- European countries allocated a total of EUR 674 billion (including the EU — EUR 573 billion) for protection against the crisis. The most significant support packages were prepared in Germany, Great Britain, France, Italy, and the Netherlands. Of these, only France recorded lower increases in electricity and gas prices than the European average.
- 90% of the analyzed countries (EU, Great Britain, and Norway) reduced VAT/energy taxes and directed cash transfers to those most likely to be affected by the energy crisis. Only four countries regulated wholesale prices.
- There was a +67% y/y increase in average electricity prices between January and October, 2022 in the Northern countries (Denmark, Sweden, and Finland), which was clearly above the European average (+45%). These countries allocated the most minor funds in Europe to fight the crisis.
- There was a +6% y/y increase in the average prices of electricity and gas in Poland between January and October, 2022. This is the third lowest result in the EU, despite the government's aid of EUR 12.4 billion — i.e., 2.2% of GDP (the EU average was 2.9% of GDP.) In Germany, the support amounted to EUR 264.2 billion — i.e., 7.4% of GDP.[14]

In relation to smart energy, a survey, literature studies, and statistical research were used. With regard to resilience, the method of its assessment is mainly based on comparative studies in the area of expenditure on not mitigating the effects of the energy crisis in relation to the GDP of economies.

Thirty communes located on the Polish-German border were invited to participate in the study, nine of which answered the questionnaire.[15] In the case of border towns with a direct German partner across the border, in-depth interviews were conducted, which yielded some promising results regarding the cross-border energy projects that had been implemented. The article describes some interesting solutions from three cities on the Polish-German border: Słubice, Zgorzelec and Bogatynia.

In order to observe the configuration of the regions, regardless of the cluster analysis, principal component analysis (PCA) (Krzyśko et al. 2008) was initially performed to visualize the regions on a map. PCA, also known as singular value decomposition or spectral decomposition, is a popular technique used to reduce the dimensionality of data (the number of features). Since it is a non-parametric method, it does not require any assumptions about the distribution of the analyzed data. Via this method, we aim to replace the set of correlated features (if the variables are not correlated, PCA does not offer any data reduction) with a small number of uncorrelated so-called principal components, which together can explain almost all of the variability in the data. The first component explains the variation the most (the components are linear combinations of the input variables). The second component is chosen in such a way that it is not correlated with the first one and explains the remaining variability as far as possible.

The values of the first and second components are presented on the map. In addition, for the first two components, the regions are represented on a plane in a scatter plot. This kind of graph can say a lot about regional similarities. If they are close on the graph, they are similar. Likewise, similar colors on the map indicate similar regions. Similarity is understood as the degree to which the regions differ from each other, and PCA identifies these patterns to provide a more compact representation of the data.

3 Results and discussion

In order to confirm H1, and in accordance with the concept adopted in the article, the energy economy analysis is based on the **spatial criterion** (in Nomenclature of Units for Territorial Statistics of the European Union, NUTS: NUTS1, NUTS2, NUTS5 communes along the Polish-German borderland), the **quantitative criterion** of energy production and consumption, and the **qualitative criterion** in relation to border regions and communes in Poland. First of all, the problem was

14. See: "Scenariusze polskiego miksu energetycznego 2040" [Scenarios of the Polish energy mix 2040]. Policy Paper No. 4 by Maciej Miniszewski and Marcelina Pilszyk, Polski Instytut Ekonomiczny, Warszawa, 2023, available at https://pie.net.pl/wp-content/uploads/2023/11/PP-4-2023.pdf.

15. The questionnaire [in Polish — Ed.] is available as an appendix to this paper, in the form of supplementary material on page 66.

examined from a broader perspective than a mere comparison of the Polish and German economies, i.e. from a European Union (EU) point of view. A cluster analysis based on the principal components in 2020 makes it possible to distinguish five clusters among European Union countries (taking into account the 60.83% variability of the model input data) — groups of countries characterized by similar electricity generation and consumption systems (in size and structure), as distinct from countries belonging to other clusters:

1. Scandinavian countries (excluding Denmark) and Iceland
2. Belgium and the Netherlands
3. Germany
4. France, Spain, and Italy
5. countries in the Visegrád Group, South-Eastern Europe, the Baltic States, Austria, Denmark, Finland, Ireland, Luxembourg, and Portugal

In accordance with the adopted methodology, data from the period 1990–2020 were included in the analysis (cf. figure 1). One ought to note in particular the variation in the studied economies and the degree of economic maturity for energy transformation, which is much easier in economically mature economies with large GDP and energy strategies that have been pursued for many years. In the case of Poland and other countries in the EEC region, this low maturity results from their economic backwardness dating back to the period of communism and from insufficient financial resources for their subsequent profound transformations. The obtained grouping reflects the diversity of Gross Domestic Product per capita in purchasing power standards (GDP per capita in PPS) in EU countries. The results of our research do not confirm the results of analyzing the share of RES in production capacity structures in EU countries (Puertas and Marti 2022) — for example, countries at the top of the ranking of installed RES capacity, which may provide a model for Eastern Europe to follow, i.e. Sweden, Austria and the Netherlands, were classified into three separate groups by the cluster analysis. By examining what determined RES consumption in 30 European countries in the period 2010–2019, the following factors were identified as conducive to the use of RES: RES production capacity, lower emissions, and country size (Puertas and Marti 2022).

It is worth noting that the basic methods of energy production in a given country are usually related to its specific features, such as geography and climate (e.g., water electricity plants in Norway, solar panels and hot-water generators in southern countries, methane generators in agricultural regions, etc.), history and politics (e.g., coil mines in Poland, Germany, and the Czech Republic, nuclear plants in France, etc.) as well as recent trends in society (Germany's closure of nuclear plants). However, these differences are beyond the scope of this article.

The presented changes were related to the integration of the Polish electricity transmission system and energy market with European markets (Market Coupling), which has been taking place since the beginning of Poland's accession to the EU in the first decade of the 21st century. This integration includes the establishment and development of Single Day-Ahead Coupling (SDAC), Single Intraday Coupling (SIDC), the merging of balancing markets, and Bidding Zone Review.[16]

In order to verify the hypotheses, it is also important to relate the issue of energy management to energy exports and imports in Poland and Germany against the background of the EU27 economies. Synthetic conclusions from this analysis are listed below and detailed conclusions are included in the Supplementary Information section (part 4. Detailed conclusions — results and discussion).

Throughout the EU, over the last 3 decades there has been an increase in the amount of electricity consumed, while the volume of energy export in relation to production has increased by 5.2%, with a 4.1% increase in import compared to production in the same period. On the German market, export has considerably exceed import (in 2017, export amounted to 288% of import). In relation to domestic production, import gradually fell in Germany after 2011, while in Poland an increase of nearly 10% was recorded during the study period, and in 2020 three times as much energy was imported as exported. Detailed conclusions are presented in the Supplementary Information section (part 4, figure 2). Even if these figures are not crucial for our research, they suggest that exports,

16. See: "Integracja polskiego rynku z rynkami europejskimi" [Integration of the Polish market with European markets]. Chapter of the 6th report published by Polskie Sieci Elektroenergetyczne S.A., available at https://raport.pse.pl/wplyw-na-gospodarke-i-rynek/integracja-polskiego-rynku-z-rynkami-europejskimi.

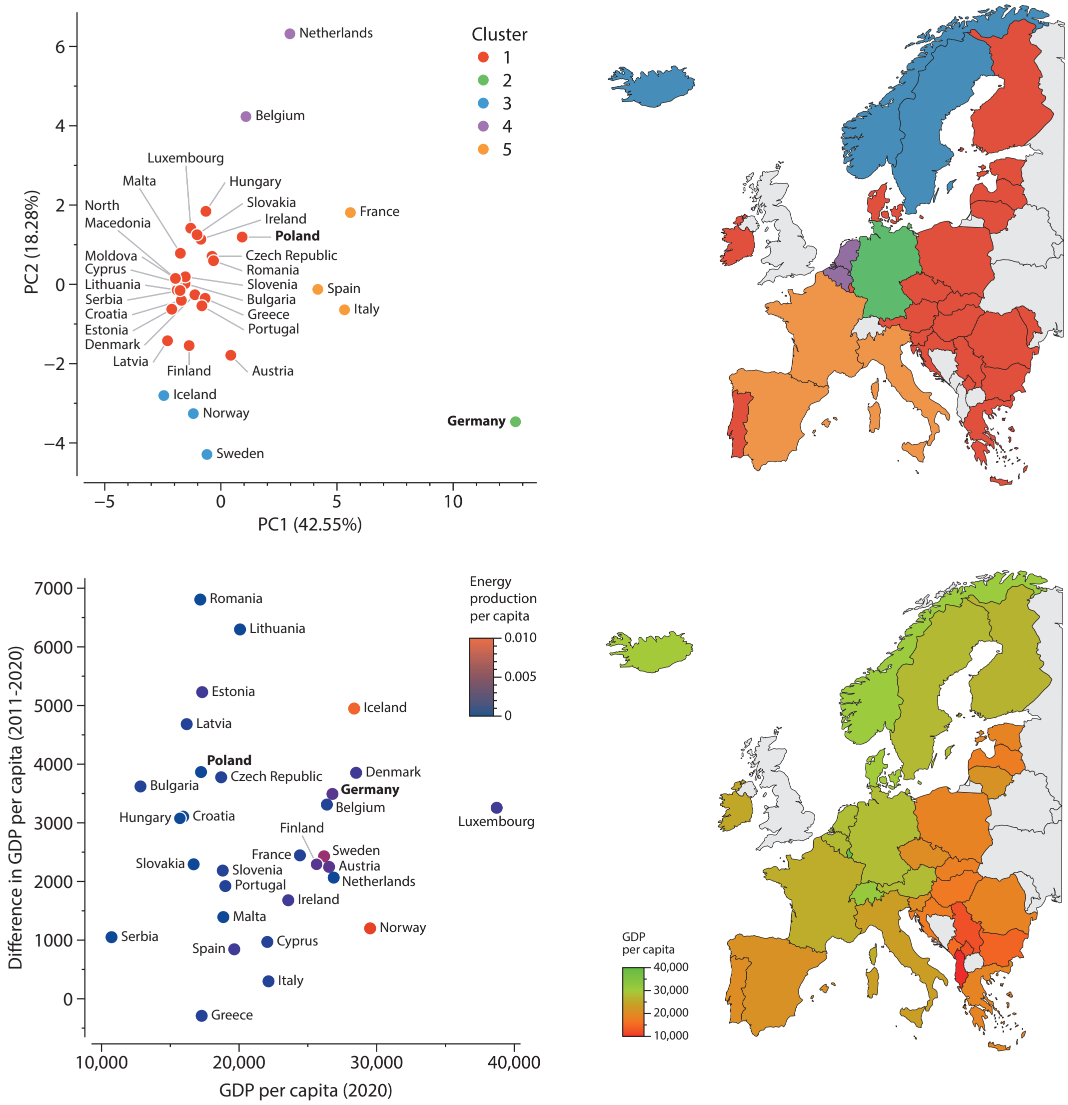

Figure 1. Cluster analysis on PCA plane—energy production and consumption, 2020 (top left); Cluster analysis—energy production and consumption, 2020 (top right); Gross Domestic Product per capita (GDP per capita) in PPS vs difference in GDP per capita between 2020 and 2011 and energy production per capita, 2020 (bottom left); GDP per capita (in PPS), 2020 (bottom right)

Source: Own study based on data published by European Statistical System (ESS), and Statistical Office of the European Union (EUROSTAT), as on 2022-06-19.

which are an expression of the increasing openness of power systems, already impact regional cooperation. In the future, further growth is expected, providing additional justification for including this element in the study.

Germany's main trading partners in terms of electricity imports are France, the Netherlands, Austria, and the Czech Republic (in total, 64.5%—i.e., 30.9 thousand GWh, was imported in 2020.) This country exports energy mainly to Austria, Poland, the Czech Republic, and the Netherlands (65.4%—i.e., 43.7 thousand GWh). After 2013, partners from outside the EU became increasingly significant in the case of exports to Central Europe. Poland has fewer trading partners: 99.7% of its exported energy goes to the Czech Republic, Slovakia, and Lithuania (7.3 thousand GWh in 2020); in the case of energy imports, in 2020 19.1 thousand GWh came from Germany (54.5%), Sweden (18.4%), Lithuania (10.5%), the Czech Republic (9.0%), and Ukraine (7.2%). Detailed conclusions are presented in the Supplementary Information section (part 4, figure 3).

In the case of Germany, in 2018 34.7% of its electricity came from RES, and electricity production amounted to 640,175 GWh. The largest amount of electricity was produced in Nordrhein-Westfalen (150,851 GWh—i.e., 23.6% of German energy). In the Polish-German borderland region, the

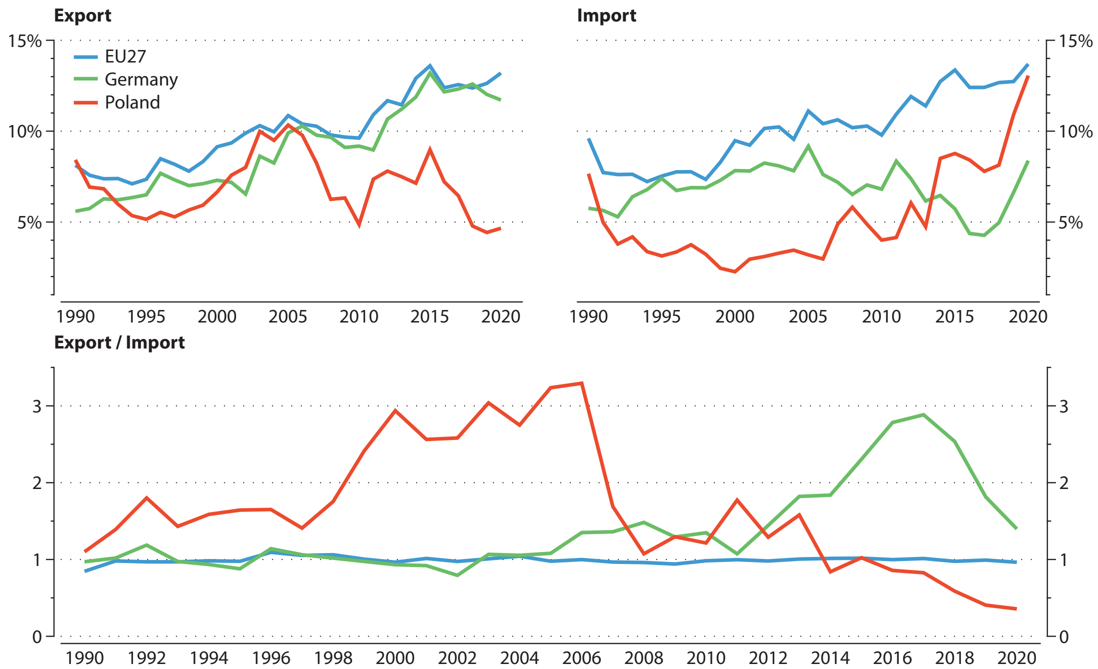

Figure 2. Exports vs imports in Poland and Germany in the period from 1990 to 2020

Source: Own study based on data published by ESS and EUROSTAT, as on 2022-06-19.

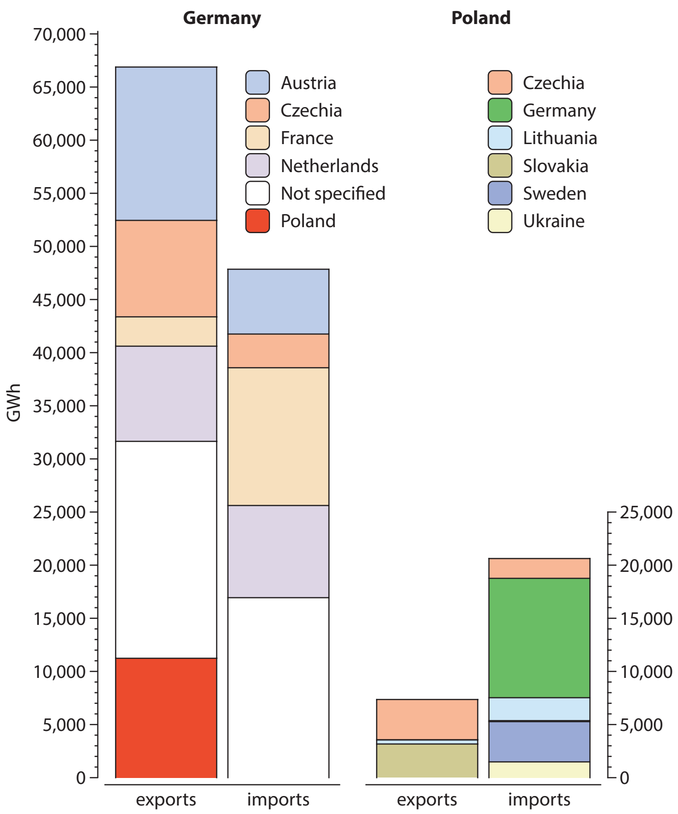

Figure 3. Spatial diversification of trading partners regarding electricity imports and exports in Germany (A) and Poland (B) in 2020

Source: Own study based on data published by ESS and EUROSTAT, as on 2022-06-19.

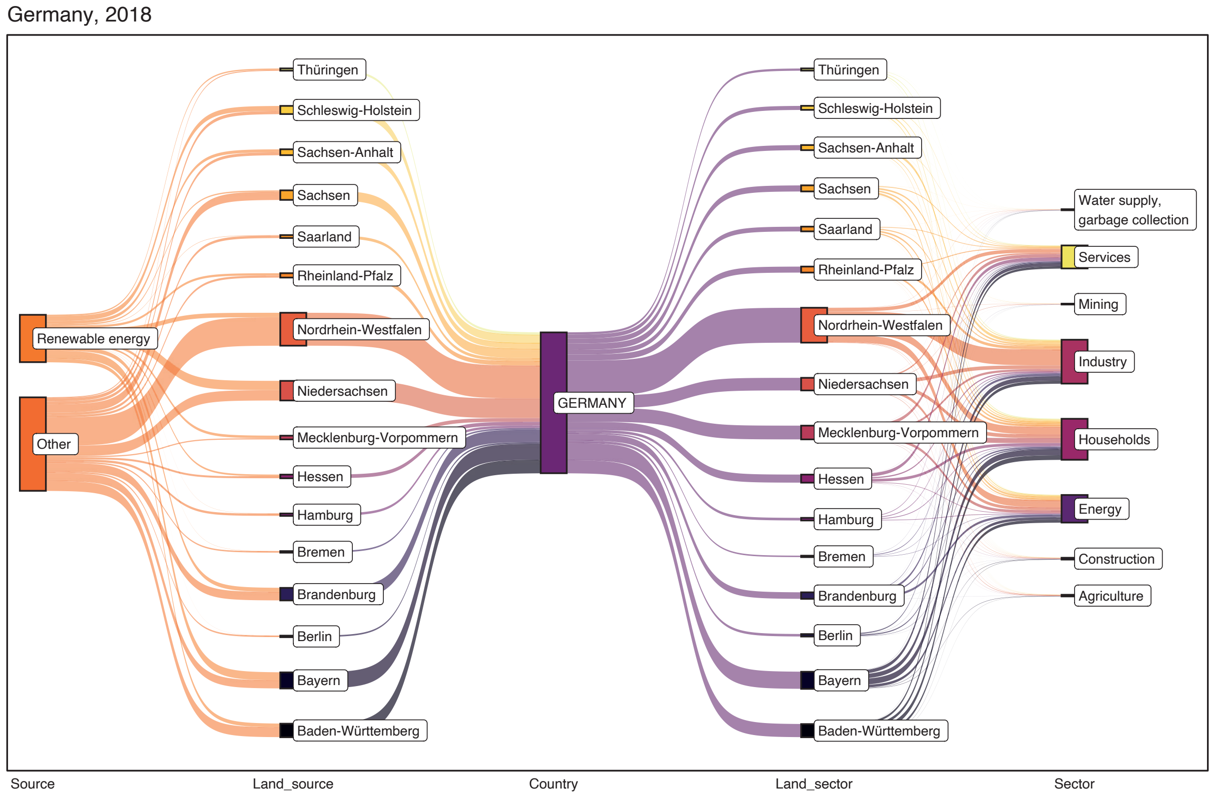

Figure 4. Structure of electricity production and consumption by sources, federal states and economic sectors — Germany, 2018

Source: Own study based on data published by Federal and State Statistical Offices of Germany (DESTATIS), as on 2022-08-03.

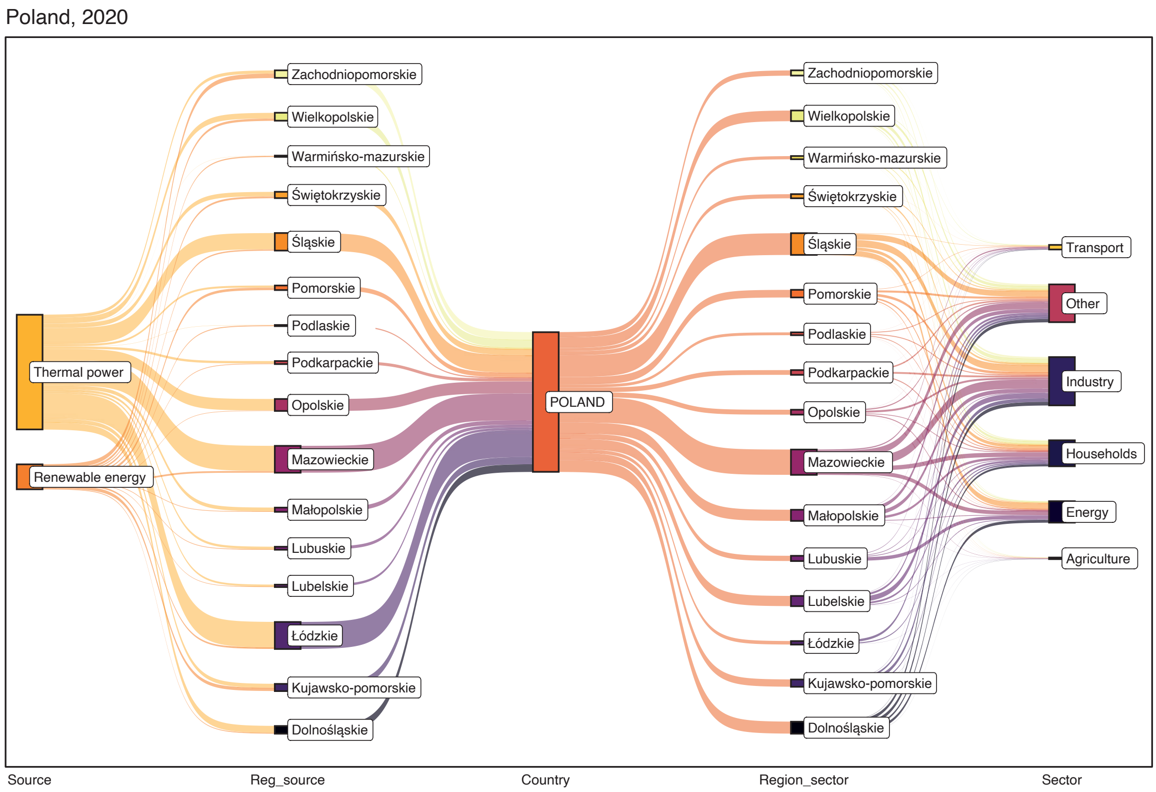

Figure 5. Structure of electricity production and consumption by source, voivodships and sectors of the economy — Poland, 2020

Source: Own study based on data published by the Statistics Poland (Central Statistical Office of Poland), as on 2021-10-20.

main electricity producers were Brandenburg with 57,633 GWh (including 32% from RES), Sachsen with 43,730 GWh (including 13.4% from RES), and Mecklenburg-Vorpommern with 17,073 GWh (including 68.8% from RES). About 50% was consumed by industry, followed by households. Detailed conclusions are presented in the Supplementary Information section (part 4, figure 4).

The structure of electricity generation in Poland in 2020 was dominated by conventional sources (out of 158,042.7 GWh of the electricity generated, 17.9% came from RES), and the decrease in total production between 2011–2020 was accompanied by a 9.8% increase in RES. In 2020, a similar volume of energy was produced in the Łódzkie Voivodship (30,563 GWh—i.e., 19.34% of national production) and Mazowieckie Voivodship (30,365.5 GWh—i.e., 19.21%). The production of electricity from RES is dispersed and markedly higher in the regions of offshore wind and land farms in Northern Poland (Zachodniopomorskie, Kujawsko-Pomorskie, and Pomorskie) and in the Wielkopolskie Voivodship. As in Germany, the structure of consumption is dominated by industry (34.6%), followed by households. The structure of energy use in the western part of the country differs from the national sectoral structure. Detailed conclusions are presented in the Supplementary Information section (part 4, figure 5). The computations and data analysis were performed within the R framework.[17]

A comparison of total production and total consumption of electricity in 2020 shows that disparities exist on a regional scale, which is particularly visible on the German side of the Polish-German borderland. Detailed conclusions are presented in the Supplementary Information section (part 4, figure 6).

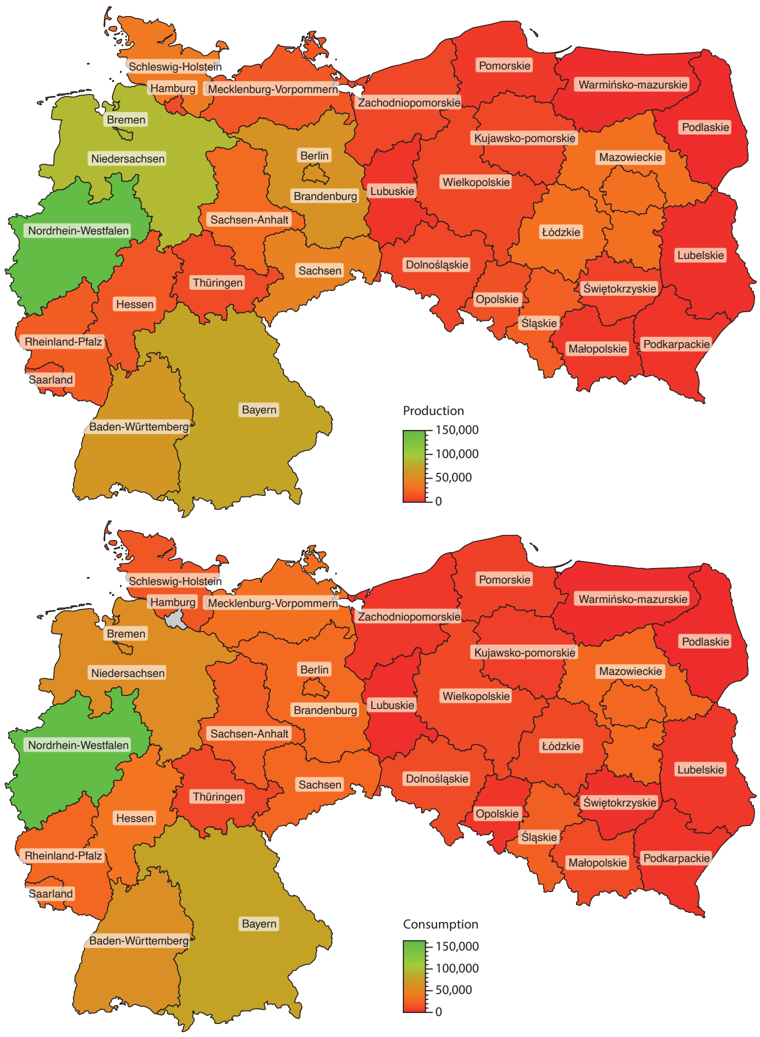

Figure 6. Total production and total consumption of electricity in Poland and Germany (NUTS2), 2020.

Source: Own study based on data published by Statistics Poland, as on 2021-10-20, as well as the Federal and State Statistical Offices of Germany (DESTATIS), as on 2022-08-03.

17. R Core Team (2022). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

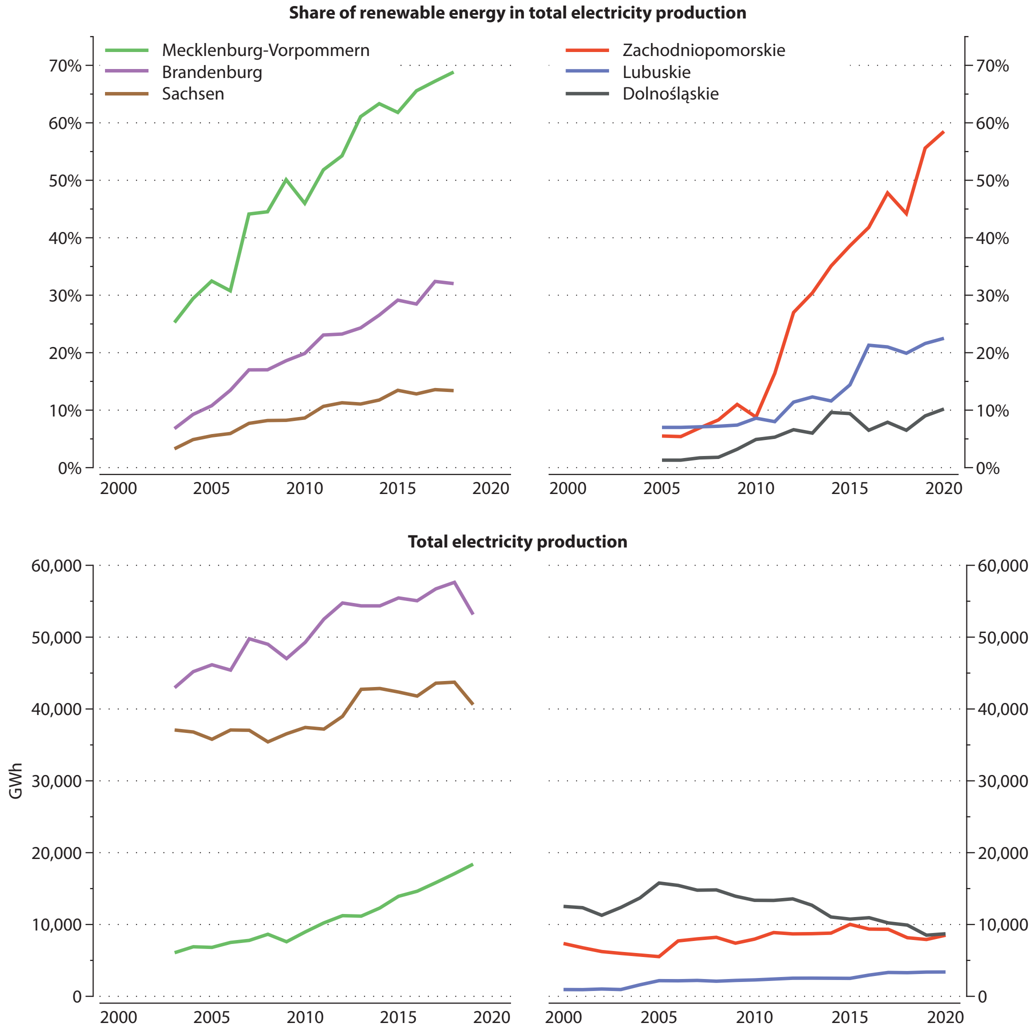

Figure 7. Share of renewable energy in total electricity production (in%) and total electricity production (in GWh) in Polish-German border regions in 2003–2019 in Germany (A) and 2000–2020 in Poland (B)

Source: Own study based on data published by Statistics Poland, as on 2021-10-20, and DESTATIS, as on 2022-08-03.

The amount of energy produced in the German borderland is at least five times higher than the scale of production on the Polish side. In all border regions, with the exception of Dolnośląskie, over the last 15-20 years, a steady increase in electricity production has been observed, which to a large extent may result from the continuous development of distributed RES technologies. RES technologies in the Polish-German borderland are more developed towards the north of the region (due to the use of wind technologies in the Baltic Sea coastal strip), which is especially visible in the Zachodniopomorskie Voivodship and Macklenburg-Vorpommern. On the German side, trends in RES development in the electricity sector have been uniform (with an increasing share in total electricity production). The indices of RES development dynamics in Polish regions from 2011-2020 may indicate that the Lubuskie (399) and Zachodniopomorskie (343) voivodships are catching up with Brandenburg (203) and Sachsen (191). Detailed conclusions are presented in the Supplementary Information section (part 4, figure 7).[18]

The Polish leader in RES electricity generation is the Zachodniopomorskie region (17.6% of domestic RES production and 58.5% of regional production). In other Polish borderland regions, 22.5% was produced in the Lubuskie Voivodeshp and 10.2% in the fossil fuel-dependent Dolnośląskie Voivodship. Detailed conclusions are presented in the Supplementary Information section (part 4, figure 8).

18. See: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Renewable_energy_statistics (accessed 2022-01-03).

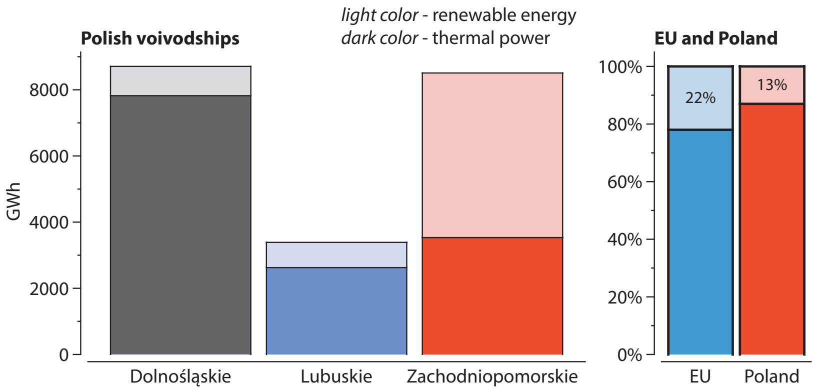

Figure 8. Structure of electricity production by source (in GWh) in selected Polish voivodships along the Polish-German border (NUTS2) and share of electricity production by source in Poland and the European Union (in %), 2020

Source: Own study based on data published by Statistics Poland, as on 2021-10-20, ESS, EUROSTAT, "Sytuacja w Elektroenergetyce [Bulletin of Power Industry] Nr 4(117). IV kwartały 2021 [After Fourth Quarter of 2021]." Ministerstwo Klimatu i Środowiska, Agencja Rynku Energii S.A., Warsaw 2022, available at https://www.are.waw.pl/wydawnictwa#2021-rok-3, and "Renewable Energy Statistics 2023." Datasets on renewable energy statistics for the last decade (2012-2022) published by International Renewable Energy Agency (IRENA), Abu Dhabi, available at https://mc-cd8320d4-36a1-40ac-83cc-3389-cdn-endpoint.azureedge.net/-/media/Files/IRENA/Agency/Publication/2023/Jul/IRENA_Renewable_energy_statistics_2023.pdf?rev=7b2f44c294b84cad9a27fc24949d2134.

It is worth noting that the abovementioned three sources do not provide regional data (NUTS2). Thus, the IRENA report has been taken into consideration, as presented in the above figure.[19]

A clearly higher share of RES may be observed in the northern federal states and voivodships as a result of better conditions for wind farms as well as a delay in the development of RES in most transformation regions, such as coal regions on the German and Polish sides with a very low share of RES—i.e., Dolnośląskie, Śląskie, and Łódzkie voivodships (as well as Małopolskie, Wielkopolskie, and Lubelskie voivodships) in Poland, and the Ruhr Basin (Ruhrgebiet), Nordrhein-Westfalen, Saar Basin (Saargebiet), the Saarland and Lusatian lignite mining area (Lausitzer Braunkohlerevier), and Sachsen/Brandenburg (Sachsen-Anhalt) in Germany.

It is a common opinion that the low share of RES in the highlighted regions is mainly due to the high share of conventional energy and not necessarily to delays in RES development. This is only partially true. The need for investments in RES-based solutions depends on three essential

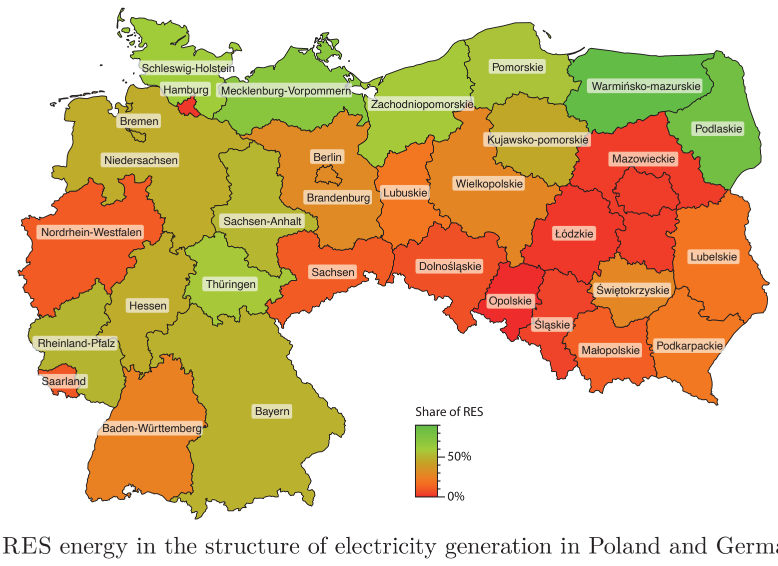

Figure 9. Share of RES energy in the structure of electricity generation in Poland and Germany (NUTS2), 2020

Source: Own study based on data from Statistics Poland, as on 2021.10-20, and DESTATIS, as on 2022-08-03.

19. See: "Sytuacja w Elektroenergetyce [Bulletin of Power Industry] Nr 4(117)...", op. cit.; "Renewable Energy Statistics 2023." op. cit.

factors: technical and organizational obstacles, economic analysis, and society-related aspects, such as tradition, the local level of urbanization and industry, and others. For example, it is hard to install solar panels in large numbers in city centers (high buildings limit the luminance and effectiveness of the solar panels, there is not enough space on the roof to install them, etc.); there are some traditions in the organization of the city area (such as big housing estates in Poland vs single-family houses in the suburbs in Germany); the ownership is sometimes not clear (such as perpetual usufruct and inheritance matters in Poland); the law is fluctuating (recent changes in "prosumer" acts in Poland and a significant change in solar-energy billing in Germany a few years ago), and many more. It is beyond the scope of this paper to discuss all the abovementioned aspects. Such an analysis is, however, planned as the authors' future work.

During our study, in-depth interviews were conducted in Polish and German border communes. The local solutions are diverse. Three examples have been selected and described below.

- The Słubice Commune and the city of Frankurt/O are cooperating on the basis of strategic assumptions until 2030 to adopt intelligent SE solutions.[20] These include restrictions on vehicular traffic, a common "green" transport concept involving urban transport, park-and-ride systems, electric bikes, scooters, car sharing, more greenery in city centers, elimination of cars from city centers in the future, and complementing the concept of cross-border, joint urban development with appropriate computer assistance. Implementation of these ideas requires close and sustained cooperation between public and private partners at the municipal, regional, national and European level, as well as obtaining support funding from various sources.
- The second interesting example is the Bogatynia Commune, located at the tripoint of Poland, Germany and the Czech Republic. In recent decades, the commune's peripheral location has not been conducive to building infrastructure and creating an alternative to the Turów mine currently operating there or other prospects for energy generation and a bigger labor market for the residents. Currently, the situation is changing — alongside the operation of the mine, the local governments are working fast to come up with joint plans for the development of the tripoint area although such projects are quite difficult to finance. Strategic ideas include replacing mining with more modern technologies focused around RES, establishing a cross-border university in Zgorzelec, developing cooperation-based tourism, and others. One of the top developing clusters in Poland is the Zgorzelec Cluster for the Development of Renewable Energy Sources and Energy Efficiency (ZKlaster), which operates in the Zgorzelec County (PL). In the transformation process, the role of local governments is very important (issuing permits and localizing investments).
- The third example is the city and Zgorzelec Commune[21]– the leader of cross-border energy projects in the border region. The Zgorzelec Commune (Dolnośląskie) has a twin administrative unit on the German side — Goerlitz. The main projects run together with Germany are the modernization of the heating plant and preparation for the transformation of the region in cooperation with Saxony. Within the scope of municipal initiatives, a Science and Industry Centre is to be built to attract start-ups in the energy sector. An important aspect of cross-border cooperation for the region was the air filter replacement project. In the Zgorzelec County, a feasibility study is being conducted for a pumped storage hydropower plant, which is to be built on the site of an open lignite pit. The Renewable Energy Cluster is also very active in the region, producing energy for the Zgorzelec County, obtained, *inter alia*, from solar energy.

The results of the survey reflect a trend emerging from the activities of small communes and do not apply to the twin towns where in-depth interviews were conducted, which gives a fuller picture of the positive adaptation strategies developed by the communes with reference to the new energy situation over the last decade. Such strategies include, among others, the following:

- using passive technologies such as phased materials, effective building insulation, and renewable technologies to improve the energy efficiency of buildings

20. The interview was conducted with Dr. Joanna Pyrgiel — Head of the Office of Projects and International Cooperation and Sören Bollmann — Head of the Frankfurt-Słubice Cooperation Center (in the year 2021).

21. The interview was conducted with the Mayor of Zgorzelec and the Zgorzelec Commune, Marek Wolanin (in the year 2021).

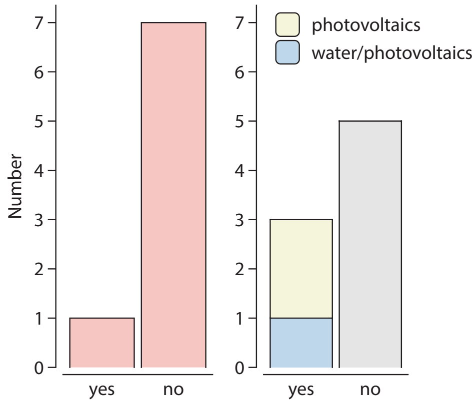

Figure 10. Results of surveys on the Polish-German border: Does the commune cooperate with German partners in terms of energy solutions? (left); Does the commune obtain energy from unconventional sources and, if so, from which? (right)

- using energy management systems and changing user behavior to improve energy efficiency and manage energy consumption
- applying technologies such as artificial intelligence, evolutionary algorithms, and hybrid models to optimize the energy efficiency of buildings
- improving HVAC (ventilation, heating, and air conditioning) and lighting systems to increase energy efficiency
- using renewable energy sources such as solar and wind energy to power buildings
- analyzing the impact of climatic and geographical variables on building design and taking advantage of favorable conditions to ensure sustainable energy efficiency
- implementing "green" building rating systems, policies, and regulations to incentivize and enforce energy efficiency measures in buildings

These strategies aim to reduce energy consumption, mitigate environmental impacts, and improve the overall sustainability of buildings. They require a combination of technological advancements, policy interventions, and behavioral changes to achieve significant energy savings and climate adaptation.

Hypothesis H1 is supported by the example of a project to connect the heating systems of the neighboring areas of Poland and Germany, which is the third investment of this kind in Europe. An agreement between the SEC Słubice, owned by Szczecińska Energetyka Cieplna (SEC), and Stadtwerke Frankfurt (Oder) heat and power plants for the mutual sale of heat and the provision of transmission services was concluded in April 2013. The parties foresee that approx. 15.833 GWh will be generated during the 15-year term of the agreement. Another project in this area is the modernization of the heating plant in Zgorzelec together with a German partner. Thanks to these investments, new opportunities for cross-border cooperation between the regions and communes have opened up in the pursuit of creating a clean environment and, above all, making the border area a more attractive place to live.

Hypothesis H2 can be supported by action taken by the communes and regions to initiate institutions in the area of scientific cooperation that may foster regional resilience (and thus their competitiveness), such as Collegium Polonicum in Słubice (a branch of Adam Mickiewicz University) or CASUS (the Center for Advanced Systems Understanding) research institute established in Goerlitz in 2019. The founding partners of this center include the University of Wrocław, the Helmholtz Center Dresden-Rossendorf (HZDR), the Helmholtz Center for Environmental Research in Leipzig (UFZ), the Max Planck Institute for Molecular Biology and Genetics in Dresden (MPI-CBG), and the Dresden University of Technology (TUD). Other initiatives include the construction of a branch of the University of Zielona Góra and the Brandenburg University of Technology in Cottbus. These are just a few examples of the whole catalogue of the initiatives undertaken in this respect. In order to strengthen resilience in the area of cross-border cooperation, the establishment of bilingual schools, kindergartens, and other institutins has also been supported.

As a contribution to the discussion, we recommend that the communes take a broader approach to energy management (hypothesis H3). The term SE should be associated with methods of obtaining, transmitting, sharing, and accounting for energy.[22] Purely technical aspects, such as the availability and cost of the technology, should be taken into consideration, along with socio-economic and organizational concerns (Soliński et al. 2017), such as convincing the people of the benefits of new methods of producing and consuming energy (in particular, energy saving and local distribution), and the necessary cost of introducing the changes. The term *smart* is often associated with the term *green*, which implies care for the natural environment, ecology and climate change.[23] In the context of energy, the common understanding is that these two concepts are very closely related — care for the environment includes saving and preventing energy wastage as well as its effective distribution and mindful use.

On the one hand, the main research question relating to SE concerns the technologies along with the organizational and social solutions that are widely available today to supply smart energy. On the other hand, the term also touches on residents' lifestyles and their acceptance of these technologies. While such research is indeed conducted among large-scale producers and recipients (such as manufacturing companies and cities), especially in the context of emerging technologies,[24] the subject has not yet been exhaustively studied among households (the so-called prosumer market). Nor has there been any investigation regarding the use of SE to provide public services in generally accessible places, such as city streets, tram stops, elements of road and tourist infrastructure, and others. Research is being conducted on the popularity of new solutions in rural (Chodkowska-Miszczuk et al. 2021) and urban areas (Lewandowska et al. 2020), as well as on the use of certain specific environmental or climatic conditions, such as the Bernoulli effect for energy generation using micro wind turbines in highly urbanized areas (Stelmach 2018). Some initial analyses have been made of energy networks operating in isolation — e.g., on a sea island (Barrera-Santana and Sioshansi 2023; Liu and Wu 2010) or an isolated region of the country. A great deal of research is also being conducted on cogeneration,[25] trigeneration, and the use of waste heat (e.g., generated by server rooms and used for heating) or heat derived from sewage.[26] However, the prosumer market is not so much guided by the results of scientific research as by marketing and fashion as well as the possibility of recouping part of the investment costs through funding national and local programs. Nor are there any national or supra-national initiatives for local development of installations to produce and store "green" energy. The existing studies either refer to the circumstances and state of knowledge from a few years ago (Łyp, Dąsal, and Popławski 2009; Wasilewski and Baczyński 2011) or are limited to investigations of very small areas (when viewed nationally), for example communes or counties (Popławski 2018), or just one selected technology.[27] There is also a lack of comparative studies on the use of similar technologies and solutions in several countries, with different economic and social circumstances. Even though there are some research results on predicting energy supply from renewable sources (Dutka 2020; Raza et al. 2019), they are either short-term (e.g., forecasts for a 24-hour period) or refer to global data on an annual or monthly basis, which makes them practically useless for day-to-day management of the energy market (Koltsaklis, Liu,

22. See: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Renewable_energy_statistics (accessed 2022-01-03).

23. See: "Shaping the Future of Energy in Europe: Clean, Smart and Renewable." EEA Report No 11/2017 published by European Environment Agency, Luxembourg, 2017, available at https://www.eea.europa.eu/publications/signals-2017.

24. See: "Inteligentne oświetlenie dla Krakowa 2018. Pilotażowa modernizacja oświetlenia ulicznego Miasta Krakowa wraz z rozbudową warstwy telemetrycznej oraz stworzeniem systemu sterowania" [Intelligent lighting for Krakow 2018. Pilot modernization of street lighting in the City of Krakow along with the expansion of the telemetry layer and the creation of a control system]. http://oswietlenie.krakow.pl (accessed 2022-01-02).

25. See: Ciepłownictwo — Gazownictwo — Elektroenergetyka. Zeszyt Naukowo-Techniczny CGE nr 01/14, available at https://www.cire.pl/pliki/2/cge.pdf.

26. See: "Wrocław będzie pozyskiwał ciepło ze ścieków. Pomoże olbrzymia pompa ciepła." Last updated 2022-11–14, https://globenergia.pl/wroclaw-bedzie-pozyskiwal-cieplo-ze-sciekow-pomoze-olbrzymia-pompa-ciepla/ (accessed 2022-11-15).

27. See: "Rynek Fotowoltaiki w Polsce 2020" [Photovoltaics market in Poland 2020]. Report published by Instytut Energetyki Odnawialnej, available at https://ieo.pl/pl/raporty.

and Georgiadis 2015; Nahmmacher et al. 2016). Unfortunately, such studies cover only one specific technology or region of a given country — no comparative cross-border studies exist.

In Poland and Germany, over the last few decades, two systems have been developed to help households save energy on a micro-scale — dual tariffs and the installation of "green" energy generators. Due to the availability of the new technology, the population's higher purchasing power, and installation costs, as well as a significantly better quality of the transmission system, Germany is far ahead of Poland in terms of pro-saving solutions, such as subsidizing solar panels (both in terms of partial reimbursement of installation costs and subsequent billing by energy companies).

It should also be noted that Germany was the first to introduce restrictions on the abovementioned subsidization of prosumers, and recently began to introduce the obligation to install solar panels on the roofs of new buildings. In Poland, there are no plans to introduce such solutions, especially in view of the need to modernize transmission lines for heat and electricity. Heat transmission lines do not allow for the possibility of "giving back" thermal energy to the grid, and power lines seriously limit this possibility due to the capacity of local connections and the one-way nature of transformer stations, often not replaced for many decades. High-performance connections are also lacking, especially in larger cities, where points with high peak energy consumption (such as charging stations for electric cars) also pose a problem. As a result, lately there has been a considerable slowdown in the process of installing new solar energy systems in Poland. Not without significance is also the decreasing profitability of energy resale in the "prosumer" program, caused by recently adopted legal regulations.[28]

In addition, unlike in Germany, supervision over the correct operation of prosumer installations is not efficient in Poland, which, combined with old energy distribution infrastructure, practically prevents a large concentration of local prosumers (e.g., one street, a line of row houses or a micro-housing estate). Such concentration causes "energy overload" problems in the local distribution system, increases grid voltage, and in extreme cases, after exceeding the critical voltage, disconnection of an entire branch from the operator's system and power outages. Since individual solar panel installations are not certified before being connected to the grid, a practice of unfair competition in access to the transmission grid has emerged, consisting in increasing the threshold voltage for disconnecting an installation when energy is overproduced. Similar problems are uncommon in the German network, which is subject to much stricter supervision. It is worth noting that the abovementioned observation contrasts with the installation of a large number of new SE sources (mainly photovoltaic panels and small wind generators) in Poland by both private investors and companies. These problems are visible only after the installation, and the investors cannot wholly control SE production and get full profits. Thus, even if, nominally, the installations are huge, in reality, in some regions of Poland, their nominal production is very restricted, especially when the local infrastructure is old and underestimated for its total power, has a high concentration of the prosumers in a given area, etc. These limitations cannot be measured by the grid operators (in the case of prosumers); thus, it is hard to estimate the actual level of SE production, especially during "rush hours" (in sunny and windy weather or around high noon).

In Poland, at present, the most common smart solution for saving household energy costs is the dual tariff system. Recently, a number of solutions have been suggested, mainly theoretical and unproven in practice, that might make energy exchange possible not only for large players but also for individual consumers. One idea is to create energy islands enabling two mechanisms: micro-energy exchange and synchronization of equipment operation. For the former, the consumer can sign a contract with a specific local producer and pay for energy directly or take part in an auction where many producers compete for customers, for example by price, or, vice versa, auction their current energy capacity out to the highest bidder although probably still below the costs of obtaining energy from a grid run by a large operator. The second mechanism that would significantly boost the "smartness" of the island is the synchronization of equipment operation. Instead of competing on price, the demand for energy can be spread over time, which could level out the

28. See: "Koniec opustów od 2022 roku. W zamian — sprzedaż energii" [End of discounts from 2022. In return — energy sales]. Last updated 2021-06-02, https://globenergia.pl/koniec-opustow-od-2022-roku-w-zamian-sprzedaz-energii/ (accessed 202-01-23).

operating conditions of the island. For example, neighbors' washing machines may turn on sequentially rather than simultaneously, thus spreading the load on the network over time. Synchronization requires all devices powered by "island" energy to be connected to a control network (which does not require special investment if, for example, home WiFi networks are used). However, the above methods are scientific experiments rather than real practical solutions, both in Germany and in Poland. The authors of this article are not aware of any cross-border initiatives in this area.

Finally, one should also bear in mind EU recommendations and directives that enforce energy saving by automatically switching off unnecessary devices, limiting power consumption in standby mode, replacing "energy-consuming" technologies with energy-saving ones (e.g., light emitting diode lighting, LED), and limiting the maximum power consumed by devices (vacuum cleaners, cookers, fans, etc.). According to some recent calculations by econometricians, energy storage reduces costs by up to 23% and may be conducive to increasing the capacity to generate energy from renewable sources, whose supply may grow in the long term by up to 40% due to rising CO_2 emission prices. In addition, transmission connections help reduce the operating costs of systems. In turn, combining technologies can contribute to a 25% reduction in costs and a 50% decrease in power demand (Barrera-Santana and Sioshansi 2023). However, this lies beyond the control of the average citizen, who has little influence and must adapt to legal regulations in this area. In the field of energy consumption, state and large energy companies are gradually losing their monopoly on supplying energy to small consumers as technology progresses and the way energy is produced and stored changes. Local solutions may gain traction, but new legal regulations will be slow to catch up and, for example, allow the possibility to use alternative (private) energy transmission lines, making them available on the basis of free competition. At present, "small" users are just left with the installation of "clever" micro-energy sources such as solar panels and energy storage facilities. However, such solutions are expensive and without state aid it is hard to count on a return on investment within a dozen or so years, which makes these options unattractive for the majority of residents. On the other hand, excessive state aid may lead to overinvestment from users, which the infrastructure (in particular, the energy transmission network) will not be able to cope with, as currently witnessed in Poland in the case of solar panels.

Clearly, beyond areas regulated by the EU, solutions adopted on a micro-scale for prosumer energy production do not facilitate cross-border cooperation. While the energy networks of Poland and Germany are interconnected nationally, the local connections (common heating and electricity networks) tend not to be widely used. This is not only due to different methods of billing customers for energy consumption but also to different needs on both sides, and above all to the general state (quality) of the transmission grid in both countries and their asymmetric saturation with prosumer installations. New initiatives in this area (e.g., energy "islands" and prosumer clusters) are yet to leave the experimental stage in both countries. Since energy from renewable sources is still not fully available locally, it is impossible to positively assess the results of cross-border cooperation in this area. However, what is indisputable is that the popularity and profitability of solar solutions on both sides of the border will increase, even if joint initiatives in this area are still lacking.

In support of H4 in terms of communes, the example of the dispute over the operation of the Turów mine in Bogatynia may be cited, which has grown to the rank of an international conflict, whereas, according to the authors, it should be resolved at the local level. Energy transformation is a long-term process and requires extensive investment to systematically replace the existing business paradigm in accordance with today's climate trends. It is essential to communicate such action to raise residents' awareness and to quell their doubts about it. It is also important to consider new technologies that might substantially mitigate damage to the natural environment. One can and should ask oneself if, and to what extent, the proximity of the power plant in Bogatynia guarantees a safe and fair space for the development of the Polish-German borderland. The answer to this question is problematic because the unstable geopolitical situation unveils new factors that may affect evaluation.

H_1 SWOT analysis

Strengths	**Opportunities**
• Awareness of the need to introduce changes in the energy systems in EU countries • Social approval for “green” change in the energy sector, no clear opposition to the hitherto unfavorable perception of nuclear energy in Poland • Joint heating initiatives agreement: SEC Słubice — Stadtwerke Frankfurt (Oder) • Modernization of the heating plant in Zgorzelec, together with a German partner	• Changing energy production models • Development of a model of multi-level international cooperation in the area of energy • Developing a community development strategy • New technologies for energy, environmental climate, development of energy storage technologies • Development of RES and nuclear energy in the long and medium term; small and micro nuclear reactors (SMR and MMR) • The prospect of private sector investment in the energy sector • Development of energy clusters and new forms of energy management within the cluster
Weaknesses	**Threats**
• The ongoing economic crisis which may worsen, differences in political positions between authorities at various levels in Poland	• Growing tension in the international arena re-garding the war in Ukraine, which affects energy security in Europe • Deterioration of bilateral relations between Poland and Germany • Growth of negative public sentiment (Polish-German relations, nuclear energy, green trans-formation, and the EU) • Political instability and the 2023 elections in Po-land • The prospect of private sector investment in the energy sector • Current bilateral relations (e.g., financial repara-tion claims regarding World War II from the Polish side)

H_2 SWOT analysis

Strengths	**Opportunities**
• Developed technologies for the use of biofuels — the greatest technical potential of biomass in Poland and Germany • Germany's experience in the production of biogas and the use of bioheat • A significant pool of EU funds for the creation of prosumer RES installations • First initiatives in the field of PL-DE scientific cooperation: CASUS, Collegium Polonicum in Słubice, creation of a branch of the University of Zielona Góra and the Brandenburg University of Technology in Cottbus • Bilingual schools and kindergartens	• The ongoing crisis on the fuel markets • Potential for the development of hydropower plants in the borderland • Constantly higher levels of education; RES and SE specializations at universities • Research and implementation of RES and SE projects • Increasing the efficiency of solar panels as a result of global warming and related weather changes (e.g., lower cloud cover and long-term precipitation) • An increase in the cost of obtaining energy from traditional sources
Weaknesses	**Threats**
• Differences in the efficiency of energy networks on either side of the border, especially in terms of connecting “green” and small energy sources such as solar panels • Differences in the bi-directional capacity and the capacity of energy networks • Differences in methods of billing customers for energy production and consumption costs • Lack of joint research on renewable energy	• Change in wind potential due to changes in the circulation of air masses in Europe (an average decrease of about 10%–20%) • Development of micro-energy sources (solar panels and small wind generators) mainly for local consumption and personal use, not shared with the grid due to unattractive financing and lack of effective energy storage methods

H_3 SWOT analysis

Strengths	Opportunities
• Dissemination of SE and RES technologies • Declared demand for RES technologies • RES and SE funding programs • A developed standard for the introduction of RES and SE technologies in new buildings in Germany	• A new perception of SE — combining savings with care for the environment • The potential of SE in the public sector • Economic crisis — growth in the scale of intervention • New technologies/opportunities (microturbines, Bernoulli effect) and their dissemination • Fashion and the growing popularity of "green" technologies • Development of technologies and databases according to the network management standard in GIS Utility Network Analysis • Development of energy exchange; energy islands, technologies and software for synchronizing the operation of electrical devices • Immediate reaction of energy storages to temporary energy shortages in the network (compensating work) • The EU and national regulatory environment
Weaknesses	**Threats**
• Lack of national and supra-national initiatives to anticipate the local development of installations to produce and store "green" energy • No analytical supra-local studies • A significant disproportion in the development of the transmission network on either side of the border; the need to modernize infrastructure (including transformer networks) on the Polish side • Doubtful financial profitability of prosumer RES in the new regulatory environment in Poland	• Lack of a long-term strategy for the development of the energy sector / major volatility in the availability of raw materials • Dependence of RES technology supplies on the Chinese market, the political situation along the East-West line • Lack of efficient energy storage technology, both locally and regionally (such as cross-border pumped storage and thermal or kinetic energy storage)

H_4 SWOT analysis

Strengths	Opportunities
• "Seeds" of cooperation being sown • Shared climate problems and similar methods and technologies to solve them	• Diffusion of solutions and technologies • The existence of cross-border environmental needs (e.g., poisoning of the Oder river) and awareness of the need to improve information flow between the two sides
Weaknesses	**Threats**
• No local agreement; excessive centralization of power and sources of financing on the Polish side • Systematic destruction of the natural environment in areas where raw materials are extracted • The two sides blaming each other for the devastation of the cross-border environment	• Significant costs involved in the transformation; • Political instability • Cross-border transfer of pollutants and other costs • Lack of coordination of cross-border action aimed at shifting emphasis to "green" energy — the apparent compatibility of these activities results from similar methods of solving problems rather than joint strategic decision-making

Conclusion

Our quantitative and qualitative research reveals significant regional disparities in energy production and consumption in Germany and Poland. This state of affairs is affected by exogenous factors, such as EU policy, as well as endogenous factors, including historical events related to war losses, which impact today's level of economic development in Poland, the dependence of the post-1945 Polish economy on that of Russia, the postponement of difficult reforms in regions with energy resources, and low financial outlays in the energy sector following 1989. Furthermore, Germany finds itself in a much better financial situation from a long-term perspective. It should also be added that the historical division of Germany has affected its economy, which to this day translates into a lower level of economic development in the eastern federal states on the one hand, and the high industrialization and energy intensity of the western federal states on the other.

A comparative assessment of the energy economy of Poland and Germany is also influenced by circumstances arising from the location of their regions, some of which can be clearly distinguished as having similar production and consumption characteristics (for example, the use of wind energy) or as having a lower GDP and less energy production and consumption as well as fewer RES. Diversity can also be assessed from the point of view of local politics, which to a large extent depends on such factors as historical conditions, communes' links with other local partners, local government policies, and the degree to which residents are involved in micro-scale action. In the case of border communes, the opportunities are greater because in this particular case assymetry, assuming that formal and technological obstacles are overcome, may provide an impetus to share energy on a larger scale. However, it should be borne in mind that economic as well as cultural and technological asymmetry is not conducive to combining energy solutions, and extensive action related to raising public awareness etc. is also necessary. This is theoretically possible in the case of twin cities. It has been noted that the micro-scale is of key relevance in the context of energy generation, but there are still many technological barriers that hinder the diffusion of this approach. A holistic approach to the problem in the context of SE may undoubtedly produce far-reaching effects, related to the lifestyle of residents, means of transport, micro-scale production of energy, and others.

This study also contributes to current knowledge on asymmetry in production and consumption of energy due to the various needs of the Polish and German economies. These disparities are reflected not only in territorial sections but also in the context of conventional energy and RES. Renewable energy is undoubtedly in its early stages of development, but the production volume and share of this energy in Poland is also lower. Territorial circumstances are considered to be similar in terms of wind and solar power, but in other areas they may differ. Furthermore, on a micro scale, a relatively higher household income may have a positive impact on investing in RES. The availability of all kinds of means of financial assistance that definitely affect the resulting picture has not been examined, but, drawing on other studies, we conclude that there is also significant variation in this aspect. In the case of border regions, the asymmetry is also strong, which does not encourage action towards cross-border cooperation, and this also includes legal, formal and organizational obstacles. Our overall conclusion is that cross-border flows are limited and numerous obstacles exist, such as lack of information, local community participation, and financial resources available to Polish and German partners.

We have also contributed added value to knowledge on energy resilience considered on different levels of regional circumstances. The research clearly shows that modern resilience rankings do not take into account strong external factors, such as Russia's aggression against Ukraine and its consequences for energy policy on a global scale. Resilience should be built on the basis of a multi-level strategy, starting from the smallest unit (an individual resident) and then moving to economic policy at the macroeconomic level. Current endeavors in many countries, including Poland, focus on energy independence from Russia. In the context of these considerations, the processes of supra-regional institutional cooperation are relevant. SE plays an important role in such a concept of operation.

Various types of asymmetry (economic, social, environmental, institutional, infrastructural, and social) in regional development are a natural process strongly related to endogenous factors, the location of regions, the historical shaping of economic policy towards these regions, energy resources, and others. The same applies to energy management. The research provides practical recommendations for regional and municipal governments in terms of increasing energy resilience through action taken regionally or locally with respect to educating residents about how to reduce energy consumption in households, prosumer action, and changes in lifestyle and consumption. A very important element of regional or municipal endeavors should be territorial marketing that communicates the achievements of the communes and other actors influencing the environment.

Regional policy aimed at strengthening competitiveness by building energy resilience was not very high-profile until the energy crisis. Polish regions clearly differ in their approach to diversifying energy sources, as evidenced by the structure of the energy mix, the activity of prosumers, or the wealth of consumers. In the medium term, an increase in the resilience of the energy economy in Poland may occur thanks to the growing use of RES (a greater diversification of sources) and greater energy efficiency, while in the long-term, a step towards increasing energy security and stabilizing the energy system, as recommended by national experts, may be made when nuclear energy is introduced to the energy mix (Borsekova, Koróny, and Nijkamp 2022). Currently, communes are also actively involved in energy management in a broader sense, paying attention to energy sharing, safeguarding against energy losses, monitoring energy processes, and others. Building resilience also takes place by implementing transformation programs in areas associated with mining.

The diverse sources of data and research methods used in this study have yielded a number of results regarding the overall comparative analysis of Poland and Germany. The resilience of Poland's energy sector during the crisis has been assessed through various means, including monitoring trends in energy prices, evaluating production and consumption levels, tracking investments in renewable energy sources, assessing the performance of energy companies, and evaluating policy responses and regulatory frameworks. These indicators provide insights into the sector's ability to withstand and adapt to crisis situations.

The analysis shows that Poland and Germany face several challenges related to the energy transformation process. The German strategy aims to increase the share of energy from renewable sources in its energy mix up to 80% by 2030, which is a key step towards sustainable transformation. In 2023, the share of renewable energy in German electricity consumption rose to 50.3%. At the same time, Germany decided to abandon nuclear energy and gradually reduce its use of coal. In the case of Poland, the share of renewable energy in the energy mix dropped to approximately 17%, despite record production from these sources. Poland remains heavily dependent on coal, which accounts for over 72% of its electricity production. Poland plans to invest approximately USD 250 billion for the energy transformation and to gradually reduce the share of coal to at least 56% by 2030 while increasing the share of renewable energy to at least 23%.

The analysis shows significant differences between Poland and Germany in the production and consumption of electricity in the border area. The German side of the border is characterized by higher electricity production, especially noticeable in border regions, which may be due to the level of development of renewable energy technology and to specific features resulting from the possibility of using specific energy production methods. These technologies are more developed in the north of the region, especially in the West Pomeranian and Mecklenburg-Pomeranian regions. The German side of the border presents uniform trends in the development of renewable energy sources in the electricity sector, which translates into a growing share in its total electricity production. Looking at the development of renewable energy sources in Polish regions in 2011–2020, the Lubuskie and Zachodniopomorskie voivodships seem to be catching up with Brandenburg and Saxony. Significant differences in the production of electricity from renewable energy sources in the Polish-German area emphasize the need to further develop renewable energy technologies in this region. Additional investments in renewable energy and international cooperation can contribute to sustainable energy development.

Notably, in 2021, Poland hit record electricity production: 179.4 TWh, which was 14% more than the previous year. However, 72% of this energy came from coal, and the share of renewable energy fell to around 17%, despite record production from these sources, too. In the Polish-German region, it is the Zachodniopomorskie Voivodship that plays a leading role in the production of energy from renewable energy sources. The analysis also shows diverse energy management approaches in Poland and Germany's border regions. Examples include cooperation between Słubice and Frankfurt (Oder) in terms of smart energy solutions and plans to develop the tributary in Bogatynia, including replacing coal mines with more modern technologies based on renewable energy. Energy projects in Zgorzelec are also of value, including the modernization of a combined heat and power plant and the construction of a scientific and industrial center. This emphasizes the need to further develop renewable energy technologies in Poland and to reduce greenhouse gas emissions by gradually phasing out coal and increasing the share of renewable energy sources in electricity production. International cooperation and further investments in renewable energy are crucial to achieving sustainable energy development in the Polish-German region.

We recommend the following for further research: examining to what extent residents, including those in rural areas, would accept energy production technologies, identifying opportunities for cooperation in various legal aspects, and testing various dimensions of energy resilience of regions and other territorial systems. From the point of view of border communes, an interesting point of research may be residents' willingness to participate in energy projects, to contribute to the planning stage of projects for new technologies, in particular those related to "green" solutions, and others.

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Questionnaire Form

Smart energy

Aktywność gmin pogranicza polsko-niemieckiego w obszarze energetycznym (7 min – to przewidywany czas wypełnienia ankiety)

Projekt finansowany przez Fundację Współpracy Polsko-Niemieckiej
Miejsce realizacji projektu: Uniwersytet Ekonomiczny w Poznaniu

* Wskazuje wymagane pytanie

Adres e-mail * . . . .

Proszę o podanie adresu mailowego do kontaktu

Imię i nazwisko * . . . .

Ankieta
Szanowny Respondencie! Dziękuję za wzięcie udziału w badaniu. Jego celem jest ocena aktywności gmin w zakresie energetycznym. Będziemy bardzo wdzięczni jako autorzy ankiety za przesłanie nam zdjęć potwierdzających ciekawe rozwiązania związane z wprowadzeniem nowych technologii pozwalających na pozyskiwanie energii z nowych źródeł oraz zmniejszenie zużycia energii. Zdjęcia można przesłać na adres: ewa.lazniewska@gmail.com

Czy gmina pozyskuje energię z niekonwencjonalnych źródeł, a jeśli tak, to z jakich? *

- biogaz
- woda
- biomasa
- wiatr
- fotowoltaika
- nie pozyskuje
- inne: . . . .

Czy gmina wdraża rozwiązania prowadzące do zmniejszenia zużycia energii lub zastosowania niekonwencjonalnych źródeł energii w następujących obszarach. Proszę napisać przykłady.

- zarządzanie gminą
- transport
- biznes i przedsiębiorstwa
- kultura
- turystyka
- ochrona środowiska
- nauka i edukacja
- gospodarka wodna i odpadami
- ochrona zdrowia
- inne: . . . .

Czy gmina wdraża rozwiązania prowadzące do zmniejszenia zużycia energii lub zastosowania niekonwencjonalnych źródeł energii w następujących obszarach. Proszę napisać przykłady.

. . . .

Czy gmina stosuje inteligentne rozwiązania prowadzące do monitorowania zużycia energii? Np. aplikacje, systemy inteligentnego sterowania oświetleniem na ulicach itd.

- tak
- nie
- inne: . . . .

Czy gmina współpracuje z partnerami niemieckimi w zakresie rozwiązań energetycznych?

- tak
- nie

Z jakich źródeł gmina korzysta przy finansowaniu projektów energetycznych?

Twoja odpowiedź: . . . .

Supplementary Information

I. Data and matadata

Table A1. Set of control variables used in the analysis and the PCA model — quantitative data sources. Units of measurement: size — GWh, structure — % (except GDP per capita, which was measured in PPS); reference period — annual

Variable	Period	Number of units	Unit accessibility	Data source
Energy production and consumption (size and structure)	2020	32	NUTS 0, countries	ESS, EUROSTAT (accessed: 19.06.2022)
Import/export	1990–2020	3	EU27, NUTS 0 — countries: Poland, Germany	ESS, EUROSTAT (accessed: 19.06.2022)
Trade partners (electricity import/export)	2020	2	NUTS 0 — countries: Poland, Germany	ESS, EUROSTAT (accessed: 19.06.2022)
Structure of electricity production by sources	2020	1 16	country (NUTS 0) and regions (NUTS 2), voivodships	Local Data Bank of Statistics Poland (BDL GUS) (accessed: 20.10.2021)
Structure of electricity consumption by sectors of the economy	2020	1 16	country (NUTS 0) and regions (NUTS 2), voivodships	Local Data Bank of Statistics Poland (BDL GUS) (accessed: 20.10.2021)
Structure of electricity production by sources	2018	1 16	country (NUTS 0) and regions (NUTS 2), regionsn	Federal and State Statistical Offices of Germany (DESTATIS); (accessed: 03.08.2022)
Structure of electricity consumption by sectors of the economy	2018	1 16	country (NUTS 0) and regions (NUTS 2), regionsn	Federal and State Statistical Offices of Germany (DESTATIS); (accessed: 02.08.2022)
GDP per capita	2020; 2011	1	country (NUTS 0)	–
Share of renewable energy in total electricity production	2000–2020	3	cross-border regions: Poland — regions (NUTS 2), voivodships	Local Data Bank of Statistics Poland (BDL GUS) (accessed: 20.10.2021)
total electricity production	2003–2019	3	Germany — regions (NUTS 2), regionsn	Federal and State Statistical Offices of Germany (DESTATIS) (accessed: 03.08.2022)

II. Cluster analysis and PCA plan method

In order to observe the configuration of the regions, regardless of the cluster analysis, principal component analysis (PCA) was initially performed to visualise the regions on the map. Principal component analysis, also known as singular value decomposition or spectral decomposition, is a popular technique used to reduce the dimensionality of data (the number of features). It is a non-parametric method, and so does not require any assumptions about the distribution of the analysed data. Via this method, we aim to replace the set of correlated features (if the variables are not correlated, PCA does not offer any data reduction) with a small number of uncorrelated so-called principal components, which together can explain almost all of the variability in the data. The first component explains variation the most (the components are linear combinations of the input variables). The second component is chosen in such a way that it is not correlated with the first and explains the remaining variability as far as possible. The PC1 component accounts for 42.55% of the variance in the data (main component), while the PC2 component accounts for 18.28% of the data variability (orthogonal component).

The values of the first and second components are presented on the map. In addition, for the first two components, the regions are represented on a plane in a scatter plot. This kind of graph can say a lot about regional similarities. If they are close on the graph, then they are similar. Likewise, similar colours on the map indicate similar regions.

Table A2. Matrix of charges for the first 4 components

Variable	PC1	PC2	PC3	PC4
EP_total_main	0.3072	−0.1086	0.0190	−0.0688
EP_total_auto	0.2802	0.1554	0.1517	0.1096
EP_solar_main	0.2868	−0.1382	−0.1576	0.0525
EP_solar_auto	0.0847	0.3682	0.2919	0.2588
Share_of_energy_all	−0.0811	−0.3378	0.3648	0.1511
Share_of_energy_electricity	−0.0053	−0.3059	0.3651	0.1807
Share_of_energy_heating	−0.1491	−0.3131	0.1811	0.0838
Solar_collectors_surface	0.2752	−0.1415	−0.1724	0.1649
Primary_energy_consumption	0.3062	−0.0308	0.0410	−0.0603
Final_energy_consumption	0.3114	−0.0421	0.0146	−0.0297
Energy_cons_solid_fossil	−0.0170	0.0466	−0.2385	0.0358
Energy_cons_gas	0.1737	0.2834	−0.0304	−0.0592
Energy_cons_biofuels	−0.0970	−0.2102	0.0119	−0.1241
GEP_gas	0.2760	0.0434	0.0232	−0.0704
GEP_total_hydro	0.0906	−0.2326	0.3779	−0.1213
GEP_total_wind	0.2898	−0.1232	−0.0754	0.1367
GEP_total_solar	0.3006	−0.0845	−0.1002	0.0193
GEP_auto_hydro	0.1191	−0.0321	0.1163	−0.5746
GEP_auto_wind	0.1212	0.2581	0.3638	−0.0273
GEP_auto_solar	0.0865	0.3634	0.3060	0.2335
Heat_pumps_aero	0.1668	−0.0063	0.1435	−0.5318
Heat_pumps_geo	0.1467	−0.2202	0.1180	0.1501
Heat_pumps_hydro	0.2411	−0.1665	−0.2113	0.2637

Source: Own study based on data published by ESS and EUROSTAT, as on 2022-06-19.

Explanation for abbreviations in tables A2 and A3

EP_total_main — total energy production, EP_total_auto — total energy production (autoproducers), EP_solar_main — solar energy production (in GWh), EP_solar_auto — solar energy production (autoproducers, in GWh), Share_of_energy_all — share of energy from renewable sources (total, in %), Share_of_energy_electricity — share of energy from renewable sources (electricity, in %), Share_of_energy_heating — share of energy from renewable sources (heating, in %), Solar_collectors_surface — solar thermal collectors' surface (in GWh), Primary_energy_consumption (in GWh), Final_energy_consumption (in GWh), Energy_cons_solid_fossil (in GWh), Energy_cons_gas — consumption of energy from gas (in GWh), Energy_cons_biofuels — consumption of biofuels energy (in GWh), GEP_gas — general energy production form gas (in GWh), GEP_total_hydro — general hydro energy production (in GWh), GEP_total_wind — general energy production form wind (in GWh), GEP_total_solar — general solar energy production (in GWh), GEP_auto_hydro — general hydro energy production (autoproducers, in GWh), GEP_auto_wind — general energy production form wind (autoproducers, in GWh), GEP_auto_solar — general solar energy production (autoproducers, in GWh), Heat_pumps_aero — air source heat pumps energy production (in GWh), Heat_pumps_geo — geothermal Heat Pumps energy production (in GWh), Heat_pumps_hydro — hydro Heat Pump energy production (in GWh).

Country symbols in table A3 according to ISO 3166-1, Alpha-3 codes

III. Input data — see table 3 on next page

Table A3. Input data—Cluster analysis on PCA plane PCA (in 2020)

Country code	EP_total_main	EP_total_auto	EP_solar_main	EP_solar_auto	Share_of_energy_all	Share_of_energy_electricity	Share_of_energy_heating	Solar_collectors_surface	Primary_energy_consumption	Final_energy_consumption	Energy_cons_solid_fossil	Energy_cons_gas	Energy_cons_biofuels	GEP_gas	GEP_total_hydro	GEP_total_wind	GEP_total_solar	GEP_auto_hydro	GEP_auto_wind	GEP_auto_solar	Heat_pumps_aero	Heat_pumps_geo	Heat_pumps_hydro
BEL	17,639.80	6,285.70	4.60	4,632.00	13.00	25.12	8.45	724.20	43.88	33.29	1.20	29.28	6.85	7,059.60	1,181.20	9,750.20	4,251.60	0.00	68.70	4,247.10	0.00	0.00	0.00
BGR	11,071.88	160.77	1,047.95	0.00	23.32	23.59	37.18	425.48	17.19	9.54	3.07	12.37	16.30	165.17	3,382.75	1,316.99	1,442.47	0.00	0.00	0.00	0.00	0.00	0.00
CZE	20,086.82	1,925.30	2,086.42	0.00	17.30	14.81	23.54	555.00	37.47	24.48	5.93	21.72	14.23	304.00	3,174.69	700.01	2,311.57	574.59	0.00	0.00	1,979.46	321.58	33.10
DNK	13,467.94	1,667.36	0.00	1,080.00	31.65	65.32	51.07	1,915.12	15.32	13.15	0.81	11.49	12.42	229.71	16.96	16,149.83	963.27	0.00	0.00	963.27	0.00	0.00	0.00
DEU	219,787.00	12,034.00	49,045.00	0.00	19.31	44.70	14.81	19,326.00	262.49	201.66	1.77	26.76	8.94	26,770.00	25,671.00	125,894.00	44,383.00	98.00	0.00	0.00	7,627.96	3,916.33	786.70
EST	2,721.60	24.00	120.60	0.00	30.18	29.20	57.90	0.00	4.31	2.78	0.27	8.99	17.70	18.55	19.00	687.00	73.50	1.00	2.00	0.00	0.00	0.00	0.00
IRL	10,682.16	448.37	0.00	58.31	16.16	39.06	6.26	336.95	13.43	11.18	2.29	18.02	4.44	1,992.19	1,131.90	10,019.49	40.08	0.00	52.01	40.08	0.00	0.00	0.00
GRC	19,910.31	567.79	2,833.79	0.00	21.75	35.86	31.94	4,867.50	19.68	14.33	1.17	6.79	12.03	1,271.79	4,050.90	7,266.35	4,428.51	0.00	0.00	0.00	9,496.00	175.00	0.00
ESP	103,186.82	6,483.24	8,772.01	67.24	21.22	42.94	17.97	4,067.77	105.03	73.76	0.48	19.10	8.95	29,584.00	26,874.00	55,647.00	9,420.00	897.00	134.00	87.00	30,769.68	179.88	1.86
FRA	128,070.14	8,214.14	8,159.47	2,648.40	19.11	24.82	23.37	3,302.19	208.36	130.23	0.65	20.63	10.87	7,380.81	61,572.66	34,787.35	12,227.50	595.23	1,267.11	2,670.05	65,020.85	2,199.97	0.00
HRV	4,547.10	164.70	84.80	0.00	31.02	53.82	36.93	272.20	7.76	6.47	1.63	17.10	18.25	305.70	5,932.60	1,467.30	83.10	5.90	0.00	0.00	0.00	0.00	0.00
ITA	111,003.27	5,431.69	20,865.28	0.00	20.36	38.08	19.95	4,343.77	132.32	102.74	0.40	30.86	10.34	17,827.77	48,153.52	20,202.04	23,688.90	492.04	0.00	0.00	117,522.78	812.23	90.25
CYP	1,726.19	93.02	88.18	63.08	16.88	12.04	37.12	1,084.11	2.20	1.57	0.92	0.00	14.76	0.00	0.00	238.57	218.27	0.00	0.43	86.26	0.00	0.00	0.00
LVA	2,903.81	33.98	0.24	3.07	42.13	53.36	57.09	21.67	4.26	3.86	0.57	8.50	26.35	26.08	2,107.55	154.00	3.14	2.01	2.25	2.91	1.44	2.92	0.18
LTU	3,096.00	282.00	103.00	0.00	26.77	20.17	50.35	0.00	6.23	5.31	2.52	11.03	14.67	455.80	947.70	1,499.40	91.10	0.00	0.00	0.00	56.70	52.10	1.30
LUX	1,559.72	215.00	0.00	159.74	11.70	13.89	12.61	69.89	3.94	3.81	1.18	17.28	5.42	78.58	949.29	281.28	130.39	4.81	0.00	130.39	11.29	7.12	0.00
HUN	8,889.00	1,025.00	699.00	701.00	13.85	11.90	17.72	350.00	23.89	18.01	0.89	32.34	10.92	390.00	219.00	729.00	1,497.00	0.00	0.00	811.00	155.00	29.00	15.00
MLT	590.00	159.82	0.00	155.16	10.71	9.49	23.03	73.49	0.74	0.54	0.00	0.00	7.24	0.00	0.00	0.06	195.36	0.00	0.06	195.36	0.00	0.00	0.00
NLD	24,781.70	12,353.46	848.00	6,378.00	14.00	26.41	8.05	672.00	58.38	45.52	0.41	37.61	4.69	16,803.66	74.18	11,507.93	5,400.57	0.00	1,135.61	4,800.59	0.00	0.00	0.00
AUT	23,682.35	2,219.54	1,702.09	0.00	36.55	78.20	35.00	5,050.40	29.73	26.07	1.39	18.72	16.36	1,592.51	44,204.02	7,450.08	1,702.09	534.63	0.00	0.00	1,643.09	1,323.74	259.95
POL	38,760.47	4,679.95	0.00	1,539.26	16.10	16.24	22.14	2,696.00	96.53	71.00	12.75	13.15	12.87	8,329.83	2,664.88	15,106.76	710.67	3.11	0.00	710.67	1,592.79	979.79	46.61
PRT	19,165.89	2,409.39	381.53	519.91	33.98	58.03	41.55	1,347.96	19.54	15.02	0.06	11.44	19.10	5,140.05	10,242.52	13,666.95	1,342.25	17.69	2.51	659.35	11,058.87	0.00	0.00
ROU	18,637.98	2,260.83	1,030.04	367.67	24.48	43.37	25.33	218.91	30.92	23.53	2.57	24.91	16.39	4,757.21	16,005.70	6,772.81	1,777.62	269.54	256.97	163.63	0.00	0.00	0.00
SVN	3,396.55	435.42	7.34	270.54	25.00	35.10	32.14	224.32	6.13	4.39	0.64	13.14	14.15	139.07	4,682.54	6.15	303.04	212.68	0.00	295.45	0.00	0.00	0.00
SVK	6,523.00	1,201.00	215.00	375.00	17.35	23.07	19.43	0.00	15.15	10.34	3.71	25.25	11.96	291.00	4,571.00	6.00	589.00	120.00	5.00	375.00	0.00	0.00	0.00
FIN	15,010.14	2,462.00	3.00	219.00	43.80	39.56	57.62	73.00	29.80	23.28	0.46	2.99	27.20	462.00	12,412.71	6,024.75	147.25	752.02	0.00	144.35	0.00	0.00	0.00
SWE	41,413.00	1,411.00	714.00	0.00	60.12	74.50	66.38	459.00	41.82	30.93	0.96	1.50	29.39	30.00	65,393.00	19,847.00	679.00	5.00	0.00	0.00	5,233.00	7,017.00	0.00
ISL	2,978.70	0.00	0.00	0.00	83.73	102.71	80.51	0.00	5.80	2.96	0.00	0.00	2.46	0.00	13,461.47	6.57	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NOR	36,268.00	552.00	0.00	0.00	77.36	113.80	36.13	0.00	25.00	18.38	2.75	2.09	11.25	2,055.37	126,404.07	5,536.25	12.84	0.00	0.00	12.84	0.00	0.00	0.00
MKD	1,843.90	0.00	16.71	0.00	19.22	23.53	33.73	0.00	2.55	1.83	3.84	2.41	12.16	0.00	1,163.67	101.81	23.23	0.00	0.00	0.00	0.00	0.00	0.00
SRB	7,744.00	152.09	11.00	0.00	25.98	30.70	34.77	0.00	15.18	9.08	5.92	9.77	18.28	210.63	10,198.24	898.21	13.55	0.00	0.00	0.00	0.00	0.00	0.00
MDA	363.30	123.00	2.00	3.00	25.06	3.12	41.17	0.00	2.69	2.55	3.06	17.36	25.27	18.00	65.00	43.00	3.00	0.00	24.00	2.00	0.00	0.00	0.00

Source: Data published by ESS and EUROSTAT, as on 2022-06-19.

IV. Results and discussions

Part 4. Fig. 2.
Exports vs imports in Poland and Germany in the period from 1990 to 2020 (ESS, EUROSTAT, accessed 2022-06-19)

- The ratio of exports to imports of electricity in the EU is constant, with a relatively stable increase in its scale on the energy market, both in terms of exports and imports (between 1990–2020 in the case of exports from 8.1% to over 13.3% of the production value (5.2 %), while imports rose from 9.6% to 13.7% of the production value (4.1 %).
- The German and Polish ratios of exports to imports of electricity are different. In Germany, after 2010, export of electricity exceeded import, with a clear peak in 2017, when the amount of exported electricity accounted for 288% of the import value. This change was the result of a systematic higher level of energy exports compared to its production in 2010–2019 (maximum increase from 8.7% in 2010 to 13.2% in 2015 (4.5%), stabilising at around 12% of production). This trend after 2011 was accompanied by a reduction in the share of imports in relation to domestic electricity production (from 8.3% in 2011 to 4.3% in 2017) and its upturn in 2019–2020 back to the level from the beginning of this period (8.4% in 2020).
- In the case of Poland, dependence on energy imports increased significantly in this period (by 9.1%, from 4.0% in relation to the production volume in 2015 to 13.1% in 2020), after 2015 exports also exceeded imports, so that in 2020 the volume of electricity import was almost three times export (20,624.0 GWh vs. 7,357.0 GWh). Apart from a clear increase in the volume of imports (in the period 2011–2020 from 6,780.0 GWh to 20,624.1 GWh), Poland, unlike Germany, did not record a long-term trend of export growth.
- After 2017, both in Poland and in Germany, the previous trend towards increasing the scale of electricity production was reversed (in Germany from 653,723.0 GWh in 2017 to 572,666.0 GWh in 2020, in Poland from 170,465.0 GWh to 158,043.0 GWh in the same period).

Part 4. Fig. 3.
Spatial diversification of trading partners regarding electricity import and export in Germany (A) and Poland (B) in 2020 (ESS, EUROSTAT, accessed 2022-06-19)

- In 2020, Germany imported a total of 47,853 GWh of electricity, of which 27.1% came from France, 18.1% from the Netherlands, 12.7% from Austria and 6.6% from the Czech Republic. Eurostat lacks data on the import origin of the remaining 35.4% of energy — i.e., about 6% of the size of the German electricity market (for reasons of statistical confidentiality).
- In the case of exports, amounting to 66,882 GWh in 2020 in Germany, 21.6% went to Austria, 16.8% to Poland, 13.6% to the Czech Republic and 13.4% to the Netherlands. In addition, 4.1% to France, and for the remaining 30.5%, the destination was not indicated in the Eurostat database. In Germany, there was a change in the direction of trade, after 2013 the share of partners from outside the EU began to increase. In the case of exports, the former cooperation with countries of Germanic origin (with the Netherlands and Switzerland especially — about 30% of the export volume each) was replaced with trade partners from Central Europe (Poland, the Czech Republic) and over 30% to countries outside the EU and aspiring join.
- In 2020, Poland exported 7,357 GWh of electricity and imported 20,624 GWh. Compared to Germany, the number of trading partners was smaller. In terms of exports, Poland traded with the countries in Central Europe — i.e., the Czech Republic (51.6%), Slovakia (42.9%) and Lithuania (5.2%). The list of countries from which energy was imported included Germany (54.5%), Sweden (18.4%), Lithuania (10.5%), the Czech Republic (9.0%) and Ukraine (7.2%). This means that the Polish economy was largely dependent on imports from Germany.

Part 4. Fig. 4.
Structure of electricity production and consumption by sources, federal states and economic sectors — Germany, 2018 (Federal and State Statistical Offices of Germany DESTATIS, accessed: 2022-08-03)

- In the case of Germany, in 2018, 34.7% of electricity came from RES, and electricity production amounted to 640,175 GWh. The largest electricity generators were Nordrhein-Westfalen (150,851 GWh — i.e., 23.6% of electricity produced in Germany), where only 13.6% of electricity came from RES. Among the regions producing significant amounts of electricity, there are also some with a significant share of energy from RES: Niedersachsen (89,843 GWh — i.e., 14% of national production, including 47.5% from RES), and Bayern (73,796 GWh — i.e., 11.5% of domestic production, including 49.6% from RES).
- In the regions studied, the level of electricity production was as follows: Brandenburg 57,633 GWh (including 32% from RES), Sachsen 43,730 GWh (including 13.4% from RES) and Mecklenburg-Vorpommern 17,073 GWh (including 68.8 % from RES).
- The structure of electricity consumption in Germany shows that about half of the consumption is for the industrial sector, followed by household consumption.

Part 4. Fig. 5.
Structure of electricity production and consumption by sources, voivodships and economic sectors — Poland, 2020 (Statistics Poland, accessed 2021-10-20)

- The structure of electricity generation by source in Poland in 2020 was dominated by conventional sources. On a national scale, 158,042.7 GWh of electricity was produced, of which 86.5% was from conventional thermal power plants and 17.9% from RES.
- The volume of electricity production in Poland during 2011–2020 decreased by 5,505.2 GWh, with an increase in the share of energy from RES by 9.8% (from 8.0% to 17.9%) — i.e., by 15,089.7 GWh (from 13,136.9 GWh in 2011 to 28,226.6 GWh in 2020).
- The volume of electricity production in Polish voivodships varies — in 2020, a similar volume of electricity was produced in the Łódzkie Voivodship (30,563 GWh — i.e., 19.34% of the national production) and Mazowieckie Voivodship (30,365.5 GWh — i.e., 19.21%) — regions with the highest production rates in the country. Significant energy producers also included the Śląskie Voivodship (19,856.7 GWh — i.e., 12.56%) and the Opolskie Voivodship (13,532.7 GWh — i.e., 8.56%). The indicated regions are dominated by solid fuels burnt in conventional power plants.
- Although the RES electricity production is dispersed, in 2020 it was clearly higher in areas with offshore and land wind farms in Northern Poland (West Pomerania — 4,973.7 GWh — i.e., 17.6% of the national production of energy from RES; Kujawsko-Pomorskie — 3,694.0 GWh — i.e., 13.1%, Pomorskie — 2,928.8 GWh — i.e., 10.4%) and in Western Poland (Wielkopolskie — 2,619.6 GWh — i.e., 9.3%).
- In the case of Poland, the following voivodships have the highest energy consumption: Mazowieckie (18.1% of national consumption), followed by Śląskie (15.6%). Western regions are characterised by average (Dolnośląskie — 8.6%) or low levels of electricity consumption: Zachodniopomorskie — 3.8% and Lubuskie — 2.5%.
- The structure of consumption by sectors in 2020, as in Germany, was dominated by industry (34.6% of domestic electricity consumption; 55,777 GWh), followed by households (18.6%; i.e., 30,027 GWh) and the energy sector (15.3% — i.e., 24,740 GWh).
- The structure of energy use in the western regions of the country differs from the national sectoral structure. In the case of the Dolnośląskie Voivodship, in 2020 there was a clearly higher consumption by the energy sector (23.2 GWh) and a lower share of electricity used in industrial processes (29.8%). In the Lubuskie and Zachodniopomorskie voivodships, consumption in the energy sector was clearly lower (7% and 9.3%, respectively), with a higher share of consumption in the industrial sector (43.1% and 33.7%), as well as a slightly higher share of consumption by households (23.3% and 20.2%). The average electricity consumption per capita was also highly diverse: Dolnośląskie (4,791.6 kWh), Zachodniopomorskie (3,586.4 kWh) and Lubuskie (2,882.7 kWh).

Part 4. Fig. 6.

Total production (A) and total consumption of electricity (B) in Poland and Germany (NUTS2), 2020 (Statistics Poland, accessed 2021-10-20; DESTATIS, accessed 2022-08-03)

- Comparing the picture of total production and total consumption of electricity in 2020 according to NUTS2 shows differences on a regional scale, particularly visible in the Polish-German borderland on the German side (this applies in particular to the following regions: Maclemburg-Vorpommern, Brandenburg and Berlin) and Schleswig-Holstein or Niedersachsen. They are less visible on the Polish side.

Part 4. Fig. 7.

Share of renewable energy in total electricity production (in%) and total electricity production (in GWh) in Polish-German border regions between 2003–2019 in Germany (A) and 2000–2020 in Poland (B) (Statistics Poland, accessed 2021-10-20; DESTATIS, accessed 2022-08-03)

- The amount of energy produced in German borderland regions is at least five times higher than the scale of production in voivodships on the Polish side. The dynamics of change in energy production in Polish regions manifested greater volatility than German regions — in the Dolnośląskie Voivodship (where production is largely based on conventional sources) over the 2000–2020 period, the volume of production decreased by 30.5% (from 12 519.2 GWh to 8,706.2 GWh). In two Polish border regions (Lubuskie and Zachodniopomorskie) and in all German regions surveyed (Brandenburg, Macklenburg-Vorpommern, Sachsen), the general trend in the volume of electricity production in the last 15–20 years has been increasing. Also noteworthy is the systematic nature of the increase in production in the Lubuskie Voivodship and the Brandenburg, Macklenburg-Vorpommern regions, which coincides with the observed consistent increase in the share of RES in these regions. This may be the result of the constant development of distributed RES technologies — the multiplicity of projects and/or the multi-stage nature of investment processes within RES.
- RES technologies in the Polish-German borderland are more developed towards the north of the region (due to the use of wind technologies in the Baltic Sea coastal strip), which is especially visible in the Zachodniopomorskie Voivodship and Macklenburg-Vorpommern.
- In the case of German regions, despite existing differences in terms of dynamics, trends in the development of RES in the electricity sector have been homogeneous (with a growing share in total electricity production). The pace of this process between 2003–2019 was the fastest in Macklenburg-Vorpommern (north-eastern coastal region of Germany) — a 45% increase in RES (from 25.3% to 70.3%). Brandenburg recorded an increase of 30.5% over the period. (from 6.8% to 37.3% — i.e., from 2,917 GWh in 2003 to 19,836 GWh in 2019), while in Sachsen, with the slowest growth of RES in the energy mix, this share only increased by about 12% (from 3.3% to 15.2% — i.e., 1,212 GWh in 2003 to 6,185 GWh).
- In 2019, in the German region with the lowest production of energy from RES — Sachsen (6,185 GWh) — almost 3 times more energy was generated from RES than in the region of Poland with the highest production of energy from these sources — the province of Zachodniopomorskie (2,200 GWh).
- At the same time, the low base value of energy production from RES in the regions of Poland at the beginning of the 21st century contributed to the fast growth dynamics of this sector – over the 2005–2020 period, the dynamics in Polish regions were as follows: Zachodniopomorskie — 1628%, Lubuskie — 502%, Dolnośląskie — 427%. In the German regions studies between 2003–2019 the figures were as follows: Mecklenburg-Vorpommern — about 810%, Brandenburg — 680%, Sachsen — 510%. An analysis of the dynamics over the last 10 years for German regions (2010–2019, 2010 = 100) and Polish voivodships (2011–2020, 2011 = 100) shows the Dolnośląskie Voivodship (index value equal to 126) lagging behind in the development of RES in relation to German regions, the absolute primacy of Mecklenburg-Vorpommern (446), with the voivodship Lubuskie (399) and Zachodniopomorskie (343) catching up with Brandenburg (203) and Sachsen (191).

Part 4. Fig. 8.

Structure of electricity production by source (in GWh) in selected voivodships along the Polish-German border on the Polish side (NUTS2), share of electricity production by source in Poland and European Union (in %), 2020 (Statistics Poland, accessed: 20.10.2021; ESS, EUROSTAT, Polish Energy Market Agency Annual Report (2021) and IRENA Report (2023)

- In 2005, the share of RES in energy generation did not exceed 10% in any of the Polish regions under study. In 2020, in the Zachodniopomorskie Voivodship, which is the national leader in terms of the amount of energy generated by RES (4,973.7 GWh in 2020), it was 58.5% (i.e., 17.6% of national energy production from RES). In the remaining voivodships of Poland, the increase in RES was smaller, with a much slighter increase in the quantity of electricity generated from RES—22.5% (i.e., 502.2 GWh) in the Lubuskie Voivodship and 10.2% (i.e., 427.2 GWh) in the Dolnośląskie region, which is dependent on fossil fuels.