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The Evolution of Renewable Energy Sources in the Visegrad Four Countries: A Comparative Study of Trends and Policies

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Abstract

This article examines the current state of renewable energy sources (RES) in the Visegrad Four (V4) countries in the context of historical developments and the influence of national policies. The primary aim of this study is to compare progress, challenges, and opportunities in RES development across the V4 countries between 2014 and 2022, using standardised per capita indicators and combining political and technical analyses. Our methodology involves analysing statistical data from Eurostat and the IEA, conducting a qualitative assessment of RES support policies, and performing ANOVA to verify the statistical significance of differences between countries. The findings suggest that countries such as the Czech Republic and Hungary have made significant progress in decarbonising their energy sectors. At the same time, Poland and Slovakia face greater challenges—Slovakia, in particular, due to its greater reliance on biomass and political turbulence. Poland has long lagged in developing RES, mainly due to its strong dependence on coal, but it is now becoming a leader in implementing RES within the V4. The main obstacles to the development of RES include insufficient political and legislative support and administrative barriers that hinder the adoption of new technologies. Another critical factor is public concern about the potential negative impacts of RES on quality of life, which may stem from a lack of information and education in this area, as well as from political intentions. To improve the situation, it is necessary to increase transparency, provide relevant education, and involve local communities in decision-making processes. Ensuring a stable political and legislative framework and adequate financing are key to achieving ambitious renewable energy targets in the region.

Keywords: renewable energy sources (RES); Visegrad Group; decarbonization; political support; legislation; public opinion; administrative barriers



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1. Introduction

The development of renewable energy sources (RES) and related energy policies is a key area of interest in the Visegrad Four (V4) countries: the Czech Republic, Hungary, Poland, and Slovakia. Although these countries share a common history and geographical proximity, their approaches to RES implementation vary significantly, influenced by factors such as the availability of natural resources, political priorities, and the legislative

framework. In the broader EU energy transition framework, it is essential to emphasise that the V4 countries are part of the European effort to achieve climate neutrality by 2050, as set out in the European Green Deal. This initiative includes extensive goals in the areas of greenhouse gas emission reduction, increased energy efficiency and the development of RES. The European Union supports the development of RES through various policies and instruments, including RES directives (e.g., Directive (EU) 2018/2001), the Emissions Trading Scheme (ETS), and financial mechanisms such as the Recovery and Resilience Facility. These policies and instruments directly affect the national policies and strategies of the V4 countries in the field of RES.

Over the past two decades, the European Union (EU) has emerged as a global leader in the energy transition, consistently pursuing the goal of climate neutrality by 2050 [1,2]. The EU's climate and energy policy, initiated by the so-called 20-20-20 package, has gradually evolved toward increasingly ambitious objectives—from the Clean Energy for All Europeans strategy (2018) [3], through the European Green Deal (2019), to the Fit for 55 (2021) and REPowerEU (2022) [1,3–5]. These initiatives aim to raise the share of renewable energy sources (RES) in final energy consumption to at least 42.5% by 2030 [6,7], as well as to transform the EU into a resource-efficient, modern and competitive economy [8,9]. These changes are part of a broader global economic decarbonization process. Their goal is to diversify supply and accelerate the green transformation, with renewable energy serving as a key pillar of the low-emission transition, to increase energy security [10–17]. In the current era of an unstable geopolitical situation, energy security has become a priority in the energy policies of all countries, especially the European Union [18,19].

Against this background, the Visegrad Group (V4—Poland, Czechia, Slovakia, and Hungary) represents a particularly compelling case for comparative analysis [20–22]. Despite their shared post-socialist transformation after 1989, these countries display substantial heterogeneity in their energy mix and in the pace of implementing EU-level policies [23,24]. While Poland and Czechia have long been heavily reliant on coal, Slovakia and Hungary have relied more on nuclear energy and imported fuels [25,26]. A common feature across the region, however, has been the relatively late start in developing modern renewable energy sectors, limited flexibility of national energy systems, and persistent challenges in grid modernisation and market integration [27–30].

Compared with Western Europe, the V4 countries entered the energy transition process with a noticeable delay—both legislatively and technologically [20,22]. The transposition of the first Renewable Energy Directive (RED I, 2009/28/EC) required adapting national regulatory frameworks to the principles of competitiveness and investment predictability. In practice, this took different forms—from feed-in tariffs in Czechia and Slovakia, to green certificate and auction systems in Poland, and feed-in premiums under the METÁR scheme in Hungary [24–26]. These differences reflect not only diverse political and economic contexts but also varied interpretations of EU frameworks in light of national energy-security priorities [27,28,31].

Although all four V4 countries formally achieved or even exceeded their 2020 renewable-energy targets, their development paths show marked differences in dynamics, technological structure, and the effectiveness of policy instruments [20,21,32,33]. In Poland, biomass and wind power growth dominated; Czechia experienced a rapid photovoltaic boom between 2010 and 2012; Hungary saw an acceleration of PV capacity additions after 2017 through the METÁR reform; while Slovakia observed a more moderate expansion of prosumer initiatives after 2020 [23–26,34,35]. As a result, the region constitutes a unique laboratory of post-coal transformation and regional adaptation to EU climate and energy policy [28,29].

Previous research on renewable energy policy in Central Europe has focused primarily on individual case studies or technical aspects of the transition [20,21,23]. However, comprehensive comparative analyses covering the long-term evolution of support mechanisms and their effectiveness in achieving EU objectives remain relatively scarce [22,24,27,29,36]. This article aims to fill that gap by providing a holistic assessment of renewable-energy policy developments in the Visegrad Four between 2000 and 2025, with special attention to the efficiency of economic and regulatory support mechanisms [20,21,27,36].

This article aims to provide a comprehensive analysis of RES development in the V4 countries between 2014 and 2022, with an emphasis on comparing their performance, identifying key political and economic factors, and evaluating their future growth potential. This study focuses on analysing trends, assessing the impacts of regulatory measures, identifying challenges and obstacles, and examining the sectoral and technological aspects of RES in these countries. Our contribution lies in using standardised per capita indicators to compare V4 countries and in combining political and technical analyses when assessing RES development. This combination provides a more comprehensive view of the obstacles and opportunities for RES development in the region. It also aims to contribute to the discussion on harmonising EU energy policies and preserving national sovereignty, both of which are crucial to ensuring an effective and sustainable energy transformation.

The study addresses two research questions:

- i. How do RES support policies differ in the V4 countries, and what impact do these differences have on their effectiveness in achieving RES targets?
- ii. What are the main obstacles to RES development in the V4 countries, and how can these obstacles be overcome?

2. Literature Review

The literature review focuses on existing knowledge and findings on energy policy and RES development in the V4 countries. The aim is to identify key themes, methodological approaches, and main conclusions of previous studies to provide a comprehensive context for further analysis.

2.1. Trends in Energy Consumption and Factors of RES Development

Analyses of energy consumption trends in the V4 countries highlight the crucial role of RES in reducing dependence on fossil fuels and minimising environmental impacts. Bozsik and Magda (2018) [37] emphasised the unique character of energy transformation in each of these countries. Marques, Fuinhas, and Manso (2010) [38] identified key factors in the development of RES in Europe, finding that the main drivers are reducing energy dependence and CO₂ emissions, which supports the importance of strategic policy measures. Muweis and Łamasz (2019) [39] analysed the aviation fuel market in Poland and changes in civil passenger transport, identifying a growing trend in passenger numbers and traffic at Polish airports, highlighting the interconnection between energy policy and the transport sector. In the context of CO₂ emissions and energy consumption, Supron and Łacka (2023) [40] analysed the relationship between these factors in the V4 countries, finding that fuel consumption in road transport and economic growth are cointegrated in the long term in the Czech Republic and Slovakia, indicating their interdependence.

2.2. Impact of Regulations and Policies on RES Development

A significant aspect of RES development is the impact of regulations and policies. Godawska and Wyrobek (2021) [41] examined the effect of environmental regulations on RES production in the V4 countries, finding that stricter regulations have a positive impact, though effectiveness varies across countries. Solorio and Jörgens (2020) [42] addressed the

EU's transition to RES and highlighted jurisdictional disputes between the EU and member states, implying that a re-evaluation of powers accompanies RES policy. BloombergNEF (2023) [43] summarised climate and energy policies in the Czech Republic, stating the goal of achieving zero greenhouse gas emissions by 2050. On the other hand, Bart, Csernus, and Sáfián (2021) [44] identified serious problems with the transition to RES and reducing dependence on fossil fuels in Hungary. Adamczyk and Graczyk (2020) [45] analysed the support system for RES production through green certificates in Poland, identifying its strengths and limitations. To improve energy efficiency, Jonek-Kowalska and Rupacz (2024) [46] emphasised the importance of coordinating energy transformation plans among the V4 countries, highlighting the need for a stable regulatory environment and government financial support.

2.3. Challenges and Obstacles in RES Development

Despite progress, the V4 countries face several challenges and obstacles in RES development. Kacperska et al. (2021) [47] identified the Visegrad Group as countries with higher RES use and better environmental characteristics, but also noted that they lag behind the EU average. Tucki et al. (2021) [48] assessed the V4 countries' ability to achieve the goals of the Paris Agreement, highlighting the obstacles faced by some, particularly Poland. Kochanek (2021) [20] focused on the perspectives and challenges of RES development, emphasising existing barriers such as funding constraints and an unstable political environment. Afsharzade et al. (2016) [49] examined RES development in rural Iran and identified challenges and opportunities for sustainable development. Svobodová and Hedvičáková (2015) [50] analysed the business environment in the Visegrad Group economies, focusing on the determinants of starting a business and paying taxes.

2.4. Sectoral and Technological Aspects of RES

The energy transformation in the V4 countries is reflected across various sectors and technologies. Jonek-Kowalska and Rupacz (2024) [46] found that Poland and Slovakia are actively seeking to reduce their dependence on non-renewable sources, while Hungary and the Czech Republic have made significant progress in decarbonising their energy sectors. Piwowar et al. (2017) [51] focused on the structure of RES use. They found that although biomass is the dominant source across all V4 countries, there are significant differences in the use of solar, wind, and hydro energy. Gostkowski et al. (2021) [52] conducted a cluster analysis of energy consumption in the V4 countries, finding differences in energy intensity and productivity between sectors. Taušová et al. (2025) [53], in their comparison of RES use across industries in the EU, identified differences and trends in their integration in transport, heating, cooling, and electricity generation. Ellabban et al. (2014) [54] discussed the key role of RES in ensuring the security of electricity supply and addressing problems associated with the cost and availability of fossil fuels. Pous de la Flor et al. (2024) [55] explored the potential of converting abandoned coal mines into sustainable energy hubs using innovative technologies. Mikušová et al. (2018) [56] compare the technological and economic aspects of RES and non-renewable energy in electromobility and highlight the advantages and disadvantages of both approaches in the context of Slovakia and Hungary. Brożyna et al. (2020) [57] demonstrated that the increasing share of RES in Slovakia is closely linked to improving energy efficiency. Taušová et al. (2024) [58] examined energy poverty in the EU, with a particular focus on Slovakia, and confirmed that it is a significant social problem. Hajdukiewicz and Pera (2017) [59] examined international trade disputes in the field of RES and identified the leading causes and nature of these disputes, particularly in the solar photovoltaic sector. Findings show that companies PGE Energia Odnawialna (Warszawa, Poland) in Poland and Slovenské Elektrárne (Bratislava, Slovakia) actively

invest in RES, which contributes to reducing CO₂ emissions and increasing the energy security of the countries in which they operate [60,61]. Gökgöz and Güvercin (2019) [62], in their research on renewable energy systems for heating, cooling, and electricity generation, emphasised the growing importance of thermal energy storage. Pham and Hrdý (2023) [63] examined the determinants of the capital structure of small and medium-sized enterprises in the Visegrad Group countries. They found that access to finance and the regulatory environment have a significant impact on SME decision-making regarding RES investments. Pavolová et al. (2012) [64] analysed the increase in the use of alternative and renewable energy sources in Slovakia and compared it with developments in other selected EU countries. Kochanek (2021) [20] analysed the energy transformation in the economies of the Visegrad Group and concluded that increased use of biomass for energy and heat production is the most significant driver of RES development. Jonek-Kowalska and Rupacz (2023) [65] examined innovative ways to replace Polish energy sources with RES and found that advanced solar and wind technologies can significantly increase the efficiency of RES. Rokicki and Perkowska (2020) [66] analysed changes in the energy source structure in the V4 countries and identified a shift towards RES technologies, particularly solar and wind energy. In the context of these sectoral and technological shifts, Andrejovska et al. (2024) [67] underscore the impact of effective tax rates (ETR) on the banking sector in the V4 countries, which, in turn, affects capital and asset financing for RES investments. Similarly, Suliková et al. (2024) [68] caution that excessive quantitative easing could hinder economic growth in the EMU, a critical factor for sustaining investment in renewable energy sources. Additionally, Dancaková and Glova (2024) [69] emphasise that the value added by intellectual capital significantly boosts corporate performance, which is vital for promoting innovation and competitiveness, particularly in the renewable energy sector.

In summary, this literature review highlights existing gaps in the comprehensive assessment of the political, economic, and social impacts of the transition to RES in the V4 countries. There is a lack of deeper analysis of the interrelationships among individual factors and of the relationship between harmonised EU-level policies and national sovereignty. The aim of this study is therefore to fill these gaps and provide a comprehensive analysis of energy policy and RES development in the V4 countries, contributing to the formulation of policies that will not only be effective in reducing emissions, but also fair and sustainable for social and economic development.

3. Materials and Methods

This study's methodological basis was the analysis of the development of renewable energy sources (RES) in the Visegrad Four (V4) countries from 2014 to 2022 (Figure 1). The aim was to compare the structures and efficiencies of RES use in these countries and identify areas for improvement. Emphasis was placed on analysing the share of RES in the transport, electricity generation, and heating and cooling sectors. The period 2014–2022 was chosen for two main reasons: (1) limited data availability for some indicators for 2023 at the time of writing the study, and (2) the desire to minimise data distortion caused by the extensive changes in the energy mix that occurred as a result of the war in Ukraine. The year 2023 was excluded because data for many relevant indicators were either unavailable or incomplete. The impact of the war in Ukraine on EU energy markets was significant, leading to sharp changes in energy consumption and production that could distort the analysis of long-term trends in RES development. By analysing the period preceding this conflict, we sought to provide a more accurate picture of the underlying trends in RES development across the V4 countries, free from the influence of these extraordinary events. This study also focused on analysing RES support policies and differences across V4 countries to evaluate their impact on RES development and identify the most effective approaches for future RES

development in the region. The study also considered bureaucratic, political, and cultural barriers that influence the adoption of RES in the analysed countries.

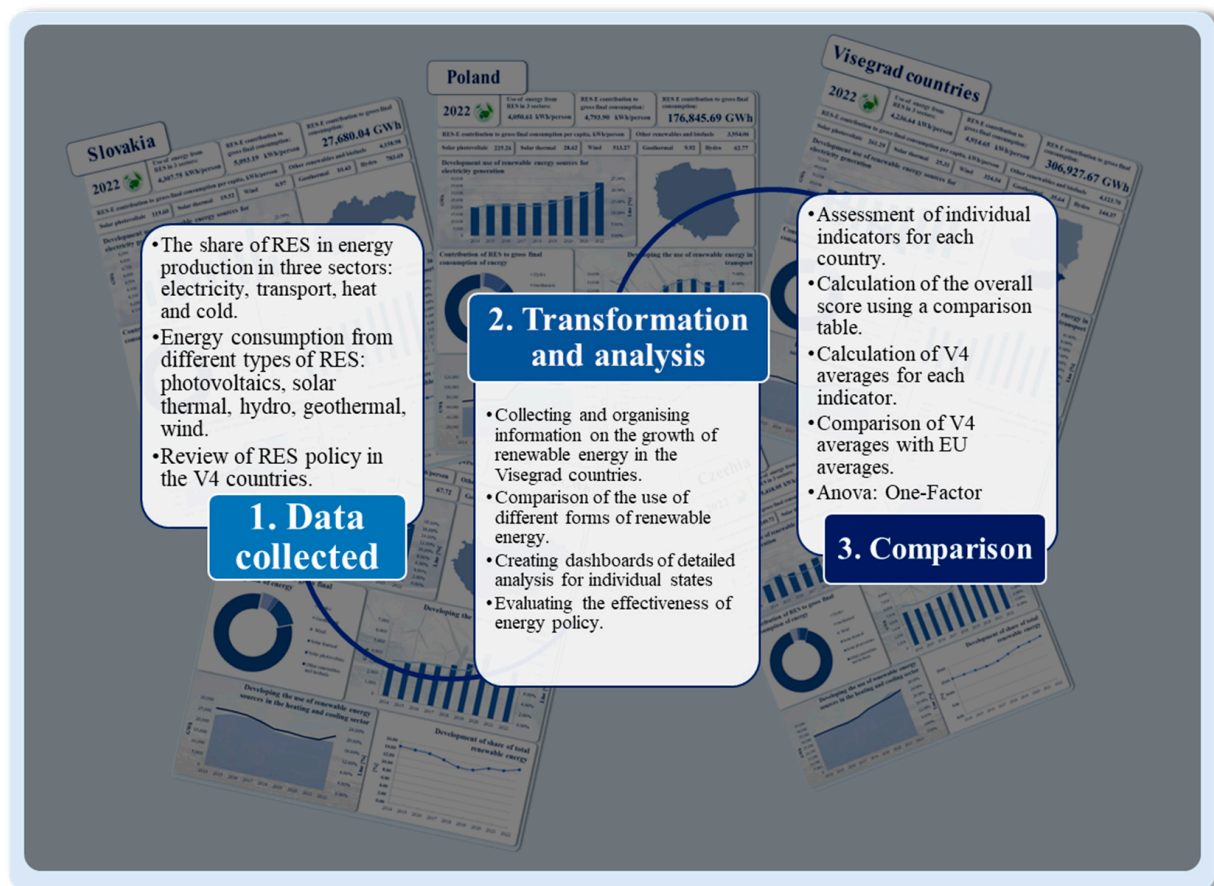


Figure 1. Scheme of methodology.

Data collection and transformation for this analysis were based on Eurostat, the national energy agencies of the Visegrad Four (V4) countries, and the International Energy Agency (IEA). To enable meaningful comparisons between countries with different populations, the original data were categorised by consumption type, focusing on final consumption from renewable energy sources (RES) in the transport, electricity generation, and heating/cooling sectors.

Some indicators, initially presented in thousands of tons of oil equivalent (toe), were converted to gigawatt-hours (GWh) to improve comparability. The transformation of units from thousands of tons of oil equivalent (toe) to gigawatt-hours (GWh) was performed to improve data comparability and consistency. The GWh unit is a standard unit for measuring electricity production and consumption, allowing better comparisons between different energy sources and sectors. The conversion was performed using a conversion factor of 1000 tons of oil equivalent = 11.63 GWh. This conversion factor is commonly used in energy studies and ensures accurate conversion. Specifically, 1000 tons of oil equivalent were converted to 11.63 GWh. After this transformation, the values were further converted to kilowatt-hours per person (kWh/person) by dividing the GWh by the population for the last year of the study period, 2022. The conversion to kilowatt-hours per person (kWh/person) was performed to normalise the data and enable comparison across countries with different population sizes. Using 2022 population data, we ensured that all indicators were expressed per capita, enabling fairer comparisons of RES consumption across V4 countries. This step is crucial for identifying relative differences and trends in

RES consumption that would otherwise be hidden in absolute numbers. This approach enabled a standardised analysis across countries, with all indicators ultimately expressed in kWh/person or as percentages. Values for V4 were calculated as the average of the percentages for the four states, and values in kWh/person were calculated by dividing the total gross final consumption of all V4 states by their population. Such processing not only improved data clarity but also enabled a more detailed comparison of renewable energy consumption patterns across the V4 nations. All data were rigorously sourced from Eurostat and the IEA, ensuring the accuracy and reliability of the analysis.

The statistical analysis focused on examining trends in the use of renewable energy sources (RES) in the Visegrad Four (V4) countries. As part of this, the annual increase in the share of RES (chain index) was calculated for each V4 country from 2015 to 2022 to determine growth dynamics. Subsequently, a one-factor ANOVA was performed to determine whether differences between countries are statistically significant. The qualitative study focused on RES support policies, examining feed-in tariff systems, subsidy programs, and tax incentives. In addition, external factors such as changes in EU legislation, technological advances, and investment trends were considered. Public influence also plays a key role, as perceptions, acceptance, and attitudes toward technologies directly impact the development of RES in these countries.

It is important to note that the legislation, support mechanisms, and financing related to RES were last updated in 2015, as reflected in the analyses of data availability on renewable energy sources in the RES LEGAL EU system. This information was combined with data on RES trends and developments during the period under review (2014–2022), which enabled an assessment of whether political measures and support had a beneficial impact on the development of renewable energy sources. The interpretation of the results also addressed the limitations of the analysis, including the timeframe and potential biases resulting from current geopolitical events, such as the war in Ukraine, which may affect energy markets and political decision-making in the region.

To verify the differences in RES development, the following hypothesis was established:

Hypothesis 1. *There is no statistically significant difference in the year-on-year increase in the share of energy from RES (chain index) between the V4 countries in the period 2015–2022.*

The study also identified key barriers and proposed solutions to increase the efficiency of RES utilisation in the V4 countries. The study provided a more unambiguous indication of the direct connection between the literature findings and the results of specific analyses. The aim was to provide a comprehensive overview of the obstacles and opportunities for RES development in the V4 region, with an emphasis on integrating theoretical knowledge with practical experience.

4. Results

4.1. Comprehensive Analysis of Renewable Energy Sources and Their Development in Poland

Poland is making efforts to transform its energy sector towards renewable energy sources (RES), but the pace of this transition is relatively slow and it faces significant challenges. While the increase in the share of RES in electricity generation and the growing adoption of heat pumps and solar technologies indicate some progress, the overall picture is more complex and requires critical evaluation. The contribution of energy from RES to gross final energy consumption is indeed diversified, but biofuels play a dominant role, the sustainability of which is debatable. Hydro energy (2315.46 GWh, 62.77 kWh/person), geothermal energy (365.98 GWh, 9.92 kWh/person), wind energy (18,934.52 GWh,

513.27 kWh/person), solar thermal energy (1055.76 GWh, 28.62 kWh/person), and solar photovoltaics (8309.67 GWh, 225.26 kWh/person) contribute to varying degrees. Still, the largest share is in the “other renewable sources and biofuels” category, with a value of 145,864.29 GWh (3954.06 kWh/person). The total contribution of RES reaches 176,845.69 GWh (4793.90 kWh/person). However, it is essential to emphasise that the high share of biofuels may mask the actual progress in the field of RES, as some biofuels do not meet sustainability criteria and their production may hurt the environment (Figure 2).

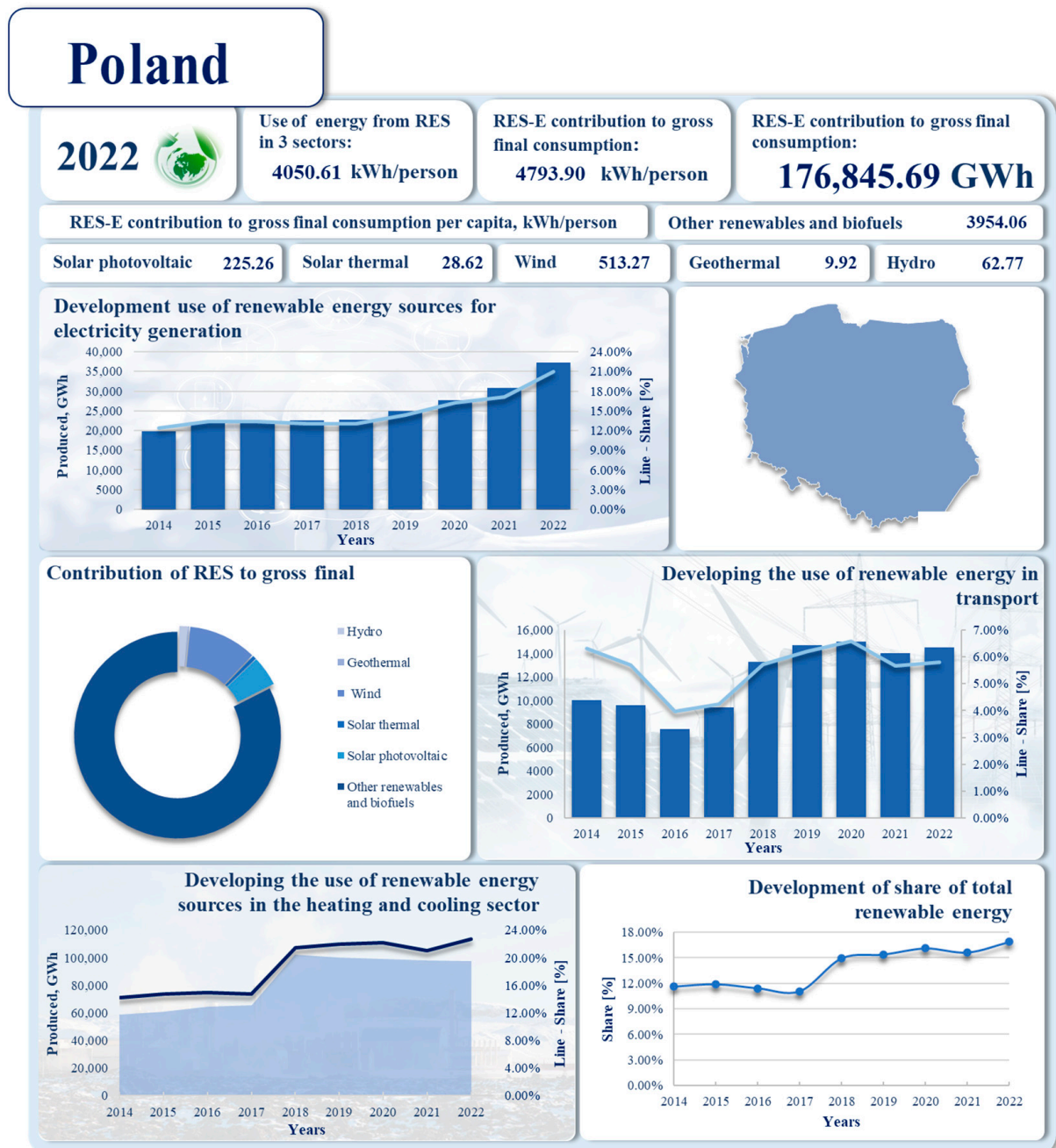


Figure 2. Complex Analysis of Renewable Energy Sources in Poland. Source: own processing according to Eurostat [70–75].

The share of RES in electricity generation reached 21.01% in 2022, a relatively low figure compared to the European Union average. The overall share of RES in Poland’s energy mix is 16.86%, signalling a shift towards decarbonization, but this is insufficient and requires significant acceleration. At the per capita level, key indicators include wind

energy and solar photovoltaic systems, but their share remains relatively low. In transport, the share of RES in 2022 reached 5.79%, a very low figure that underscores the need for radical measures to support biofuels and the electrification of transport. The total energy from RES used across the three sectors (transport, electricity, and heating) in Poland is 4050.61 kWh/person. While the heating and cooling sector shows significant growth potential through biomass, heat pumps, and solar systems for heat storage, most households still use outdated coal-fired boilers, which contribute significantly to air pollution.

In Poland, RES are supported through a quota system, tax relief, and subsidy and loan schemes. Access to the grid for electricity from RES is to be ensured as a priority, with transmission system operators required to prioritise its transmission. Support for heat generated from RES is provided through three subsidy schemes and a loan scheme. Specifically, the National Fund for Environmental Protection and Water Management offers low-interest loans to support the purchase and installation of RES equipment. Programs include “BOCIAN—Dispersed, Renewable Energy Sources,” “Prosument—Financing for the Purchase and Installation of Micro-installations of Renewable Energy Sources,” and “Rys—Thermal Modernisation of Single-Family Buildings.” The “Mój Prąd” program is a subsidy for households to install photovoltaic panels. In addition, there is a “Czyste Powietrze” program aimed at improving the energy efficiency of existing buildings and replacing old solid-fuel boilers with more modern, environmentally friendly heating sources, including heat pumps. However, it is questionable whether these programs are sufficiently practical and accessible to all population groups.

Other relevant funds and programs include Regional Operational Programs (ROPs) at the level of individual voivodeships, funded by the European Regional Development Fund (ERDF). These programs allow regional governments to support RES and energy-efficiency projects aligned with regional priorities. Under the Infrastructure and Environment Operational Program (OPIŚ), funds are also available for RES projects, particularly for the construction of new or the modernisation of existing facilities for generating energy from RES, as well as for the development of infrastructure for the transmission and distribution of energy from RES. However, it is necessary to ensure that these funds are used effectively and that RES projects are implemented in line with sustainability principles.

In transport, RES is supported through mandatory biofuel quotas. Producers, importers, and suppliers of fuels are required to meet an annual biofuels quota as a percentage of the total volume of liquid fuels they produce, supply, or import. This obligation is established in the Act on Biocomponents and Liquid Biofuels. Additionally, there are tax reliefs for biofuels and support programs for the development of biogas plants and biomethane production. However, as already mentioned, the sustainability of biofuel use is questionable and requires stricter regulation.

The legislative framework for RES in Poland is primarily defined by the Act on Renewable Energy Sources, which sets out the rules for RES support, grid connection, and the issuance of energy origin certificates. Other relevant legislation includes the Energy Law and the Act on Energy Efficiency. These laws and regulations implement EU directives on RES and energy efficiency into the Polish legal order. However, it is necessary to ensure that the legislative framework is stable, predictable, and transparent to encourage investment in RES without hindering the development of innovative technologies.

Poland has introduced a system of green certificates, which confirm the production of electricity from RES. Energy companies that sell electricity to end consumers are required to obtain these certificates or pay a so-called replacement fee. The amount of the replacement fee is set annually and serves as an incentive for energy companies to purchase green certificates and support electricity generation from RES. In addition, there are support systems for high-efficiency combined heat and power (cogeneration) that are based on

principles similar to those of the green certificate system. However, it is necessary to ensure that the green certificate system is effective, transparent, and not abused.

In the field of heat pumps, Poland implements various programs to support their installation in households and businesses. The “Moje Ciepło” program provides subsidies for the purchase and installation of heat pumps. In contrast, the “Czyste Powietrze” program allows you to obtain a subsidy for replacing an old solid-fuel boiler with a heat pump. Additionally, regional programs are available to support the installation of heat pumps, which ERDF supports. Support for solar systems with heat storage is provided through programs such as “Prosument”, which offers a subsidy for the purchase and installation of solar collectors and heat storage tanks. The trend of energy production from heat pumps that capture ambient heat has increased significantly in Poland since 2014. In 2014, production was 1271.35 GWh, and by 2022, it had risen to 6043.72 GWh. This growing trend highlights the increasing importance of heat pumps in Poland’s energy mix and their potential for lower-emission heating. However, it is necessary to ensure that heat pump installations are combined with comprehensive building energy renovations to achieve maximum energy efficiency.

Overall, Poland faces significant challenges in transforming its energy sector towards RES. It is necessary to review existing policies and support mechanisms, ensure the sustainable use of biofuels, support the development of innovative technologies, simplify administrative procedures, and strengthen public awareness of the benefits of RES.

4.2. Comprehensive Analysis of Renewable Energy Sources and Their Development in Slovakia

Slovakia, despite its declared efforts to transition to a climate-neutral economy, has made only moderate progress in renewable energy sources (RES). The increase in the share of RES in electricity generation, accompanied by the growing popularity of heat pumps and solar systems, indicates some progress. Still, its dynamics are insufficient to meet the ambitious targets set in the National Energy and Climate Plan (NECP) and in accordance with the recommendations of the International Energy Agency (IEA). The structure of RES’s contribution to final energy consumption reflects the continued dominance of traditional sources, while innovative technologies do not yet play an adequate role. Hydropower, with a production of 4259.14 GWh (783.69 kWh/person), represents a stable but significantly depleted potential, the further development of which is limited not only by environmental constraints but also by legislative barriers and a lack of strategic planning. According to Eurostat analyses, the potential of wind and geothermal energy remains significantly underutilised in Slovakia, underscoring the need for targeted measures to improve the investment climate, simplify permitting processes, and build the necessary infrastructure. Solar thermal energy (106.11 GWh, 19.52 kWh/person) and solar photovoltaics (650.00 GWh, 119.60 kWh/person) are growing. Still, their development is heavily dependent on subsidy schemes and market externalities, which do not guarantee long-term sustainability. The category “other renewable sources and biofuels” (22,602.86 GWh, 4158.98 kWh/person) is also problematic, as it accounts for the dominant share of total RES consumption. Most of this energy is biomass—mainly wood and wood chips—used for household heating and, to a lesser extent, for electricity generation. However, the sustainability of biomass use is questionable, as burning wood emits pollutants and contributes to deforestation. It is therefore essential to introduce stricter criteria for the use of biomass, support the transition to more modern and efficient technologies, and stimulate the use of alternative biofuels that meet the sustainability criteria defined in the RES Legal EU directive. Total gross final energy consumption from RES reaches 5093.19 kWh/person (Figure 3).

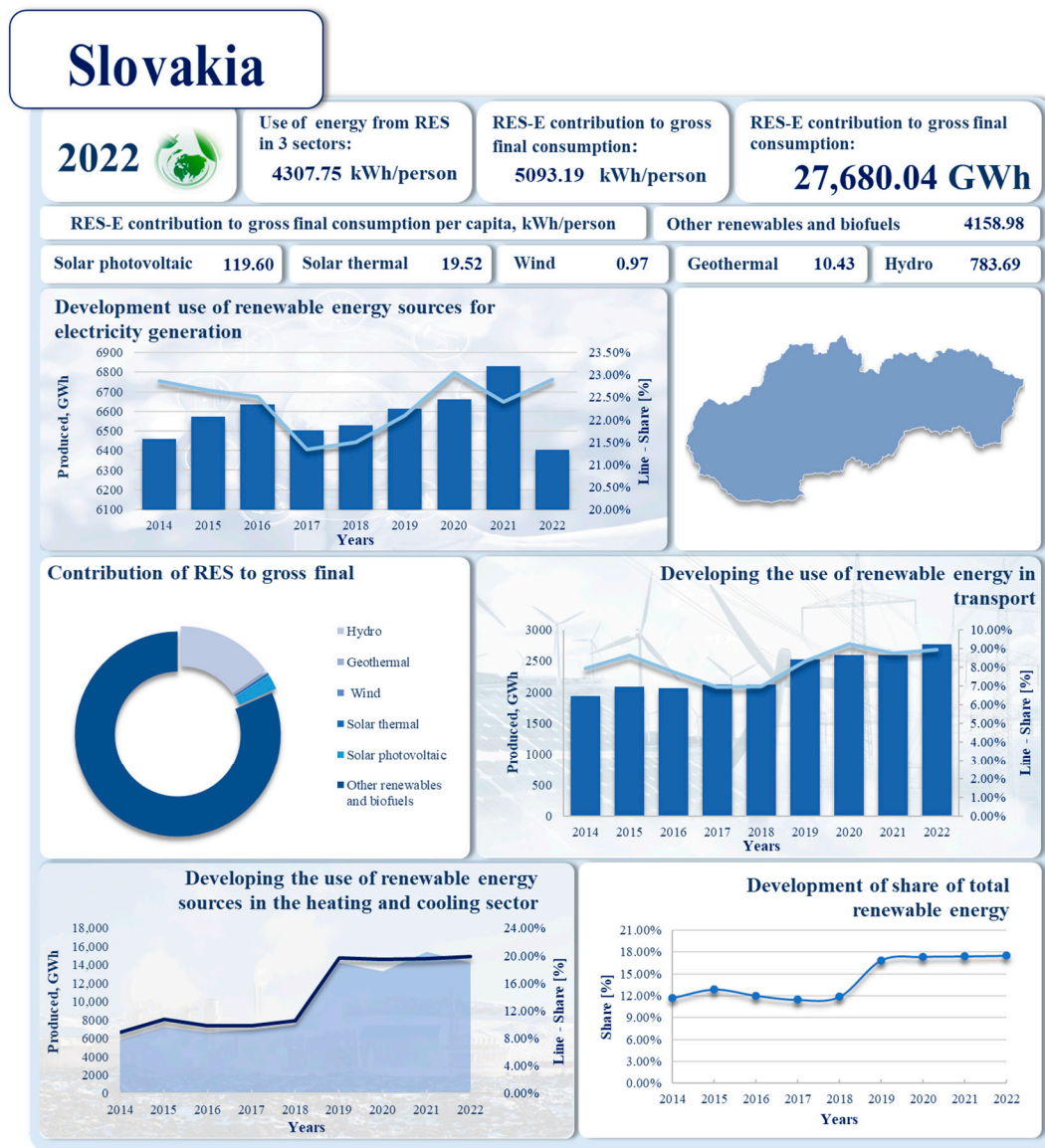


Figure 3. Complex analysis of renewable energy sources in Slovakia. Source: own processing according to Eurostat [70–75].

The share of RES in electricity generation reached 22.90% in 2022, compared to 22.87% in 2014, indicating stagnation and raising questions about the effectiveness of the support mechanisms in place. Findings from the Annual Report of the Slovak Photovoltaic Industry Association (SAPI) indicate persistent administrative barriers and insufficient support for the development of small- and medium-sized solar system installations, hindering their wider application in the energy mix. The overall 17.50% share of RES in Slovakia's energy mix signals some progress, but given the country's potential and commitments to the EU, this share is insufficient. An analysis of RES per capita contributions confirms hydropower's dominance and the inadequate share of solar photovoltaic systems, underscoring the need to diversify sources and support innovative technologies. The share of RES in transport reached 8.93% in 2022, which is de facto the same value as in 2014 (7.95%) and reflects the failure of existing policies to support biofuels and the electrification of transport. The total energy use from RES in the transport, electricity, and heating sectors in Slovakia amounts to 4307.75 kWh/person.

The potential of the heating and cooling sector remains untapped in Slovakia due to legislative barriers, insufficient investment, and low public awareness of the benefits of RES.

Outdated biomass combustion technologies contribute to environmental problems, while heat pumps, despite their growing popularity (from 458.44 GWh in 2019 to 1003.67 GWh in 2022), remain financially unaffordable for many households. Support for RES in Slovakia is provided through feed-in premiums and mandatory electricity purchases, but their effectiveness is questionable. Programs such as the Recovery and Resilience Plan of the Slovak Republic and the Quality of the Environment Operational Program face bureaucratic obstacles. The legislative framework, although complex, is poorly implemented and unstable, which reduces investment attractiveness. To achieve more ambitious RES targets, a reform of the energy sector, revisions to support mechanisms, improvements to legislation, increased investment, and heightened awareness of the benefits of RES are necessary.

4.3. Comprehensive Analysis of Renewable Energy Sources and Their Development in Czechia

The Czech Republic, although declaring ambitions in the field of emission reduction and the transition to a low-carbon economy, faces significant challenges in meeting its targets for renewable energy sources (RES). The growth in the share of RES in electricity generation is slow and uneven. At the same time, the structure of RES's contribution to final energy consumption is heavily reliant on a single source, raising questions about diversification and long-term sustainability. The total contribution of RES to final energy consumption reaches 61,552.02 GWh (5852.78 kWh/person), with the dominant share in the "other renewable sources and biofuels" category at 55,825.43 GWh (5308.26 kWh/person). While the use of biomass has a long tradition in the Czech Republic, it is essential to ensure that its extraction and processing are carried out sustainably, with a focus on protecting forests and maintaining air quality. Hydropower (2202.21 GWh, 209.40 kWh/person), wind energy (665.22 GWh, 63.25 kWh/person), solar thermal energy (232.88 GWh, 22.14 kWh/person), and solar photovoltaics (2626.27 GWh, 249.72 kWh/person) contribute to a lesser extent, suggesting room for their further development. It is alarming that geothermal energy, which has the potential for heating and electricity generation, is almost entirely untapped in the Czech Republic (0.00 GWh) (Figure 4).

The share of RES in electricity generation reached 15.50% in 2022. Although this is an increase from 13.89% in 2014, the gradual pace is insufficient to meet the set targets. The situation is even worse in the transport sector, as the share of RES in 2022 reached only 7.20%, practically the same as in 2014 (7.00%). This points to the urgent need to implement measures to support second-generation biofuels and the electrification of transport. The total energy use from RES in the transport, electricity, and heating sectors in the Czech Republic is 5418.95 kWh/person.

The heating and cooling sector in the Czech Republic is heavily dependent on RES, particularly biomass. The transition to more modern, efficient biomass combustion equipment, along with support for installing heat pumps, can significantly reduce emissions and improve air quality. Energy production from heat pumps has recorded dynamic growth in recent years, increasing from 1098.97 GWh in 2014 to 4492.76 GWh in 2022. However, installing heat pumps must be accompanied by comprehensive building energy renovations to achieve maximum energy efficiency and reduce operating costs.

To achieve more ambitious RES targets, a key element is the legislative framework, primarily defined by Act No. 165/2012 Coll. on supported energy sources. This law sets out the basic rules for supporting the production of electricity, heat, and biomethane from RES; regulates the conditions for connecting RES equipment to the electricity system, issuing guarantees of origin of energy; and defines support mechanisms such as the purchase price and green bonus. In addition to this law, the legislative framework also includes the Energy Act (Act No. 458/2000 Coll.) and the Energy Management Act (Act No. 406/2000 Coll.), which regulate the conditions for doing business in the energy sector, access to the grid,

and requirements for energy efficiency. Support for RES is financed from various sources, including the state budget, European Structural and Investment Funds (ESIF), and funds from the sale of emission allowances. The main funds and programs to support RES are the Operational Program Environment (OPŽP) and the New Green Savings program, which provide subsidies for the construction of new RES facilities, the modernisation of existing facilities, and measures to increase energy efficiency. Under the National Recovery and Resilience Plan, funds are allocated to support RES and energy efficiency, to strengthen energy security and reduce greenhouse gas emissions. Many regions and municipalities also provide regional and local initiatives to support RES. However, the RES support system in the Czech Republic has undergone several changes in recent years and has faced criticism for its inefficiency and complexity; therefore, reform is needed to ensure long-term sustainability and effectiveness.

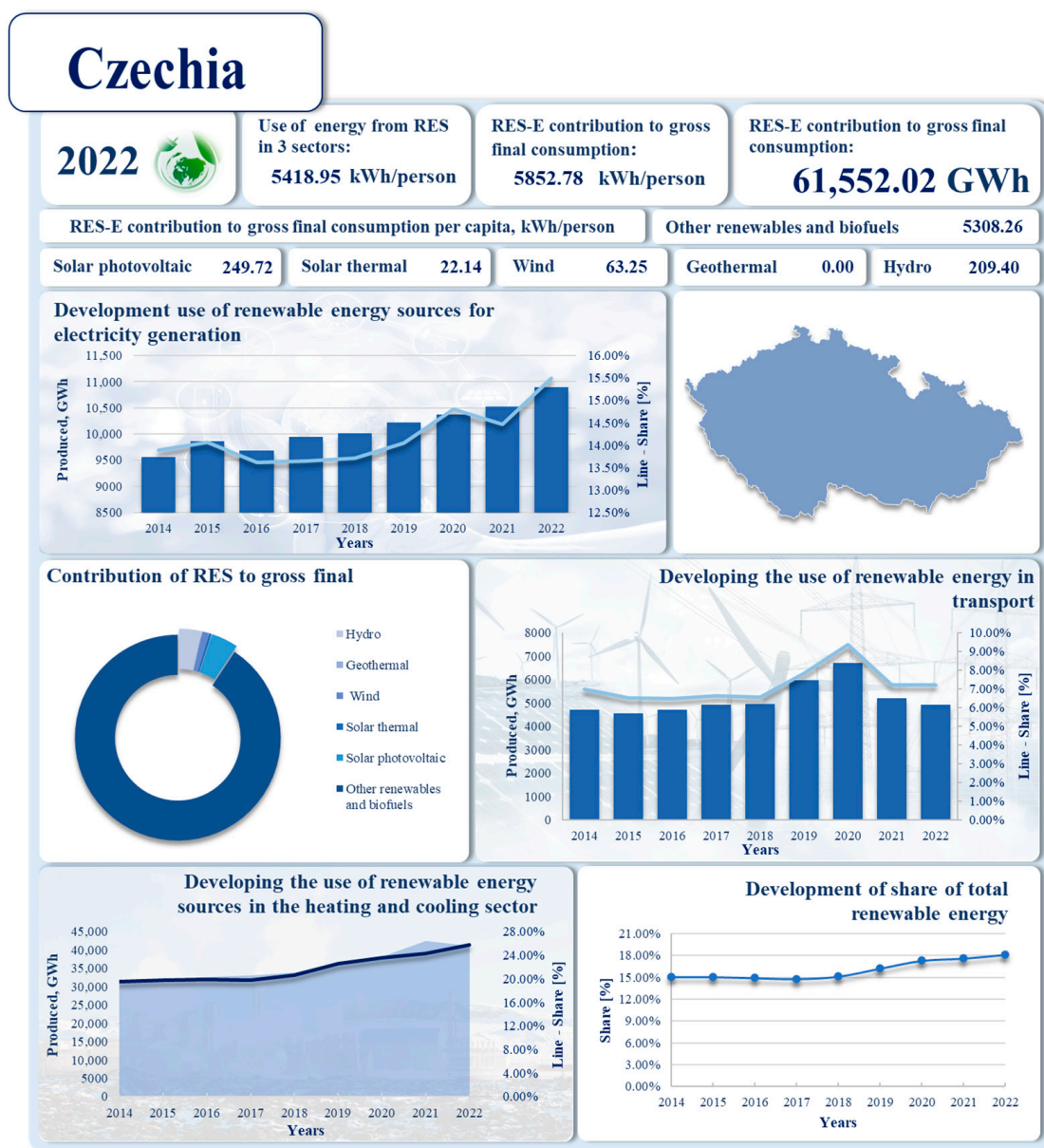


Figure 4. Complex Analysis of Renewable Energy Sources in the Czech Republic. Source: own processing according to Eurostat [70–75].

In conclusion, the Czech Republic needs to adopt a comprehensive strategy for the development of RES that takes into account the country's specific conditions, minimises

environmental impacts, and promotes innovation. It is necessary to diversify RES, improve the efficiency of support mechanisms, simplify administrative procedures, and strengthen public awareness of the benefits of RES.

4.4. Comprehensive Analysis of Renewable Energy Sources and Their Development in Hungary

Hungary is striving to transform its energy sector towards increasing the share of renewable energy sources (RES) and reducing dependence on fossil fuels. Evaluating this development requires considering specific conditions and challenges. In 2022, the share of RES in gross final energy consumption reached 15.19%. Analysis of the structure of this share and the rate of growth is key to assessing the fulfilment of the targets set in the National Energy and Climate Plan (NECP) and in accordance with the recommendations of the International Energy Agency (IEA).

The total contribution of RES reached 40,849.92 GWh (4250.59 kWh/person) in 2022. The structure of RES in Hungary differs from that of neighbouring countries. While the category “other renewable sources and biofuels” shows the largest share (33,239.23 GWh, 3458.67 kWh/person), geothermal energy is also significant with a production of 1802.894 GWh (187.60 kWh/person). Hydropower (239.17 GWh, 24.89 kWh/person) and wind energy (650.79 GWh, 67.72 kWh/person) contribute to a lesser extent, while solar photovoltaics, with a production of 4732.00 GWh (492.38 kWh/person), is becoming a significant source of electricity. Solar thermal energy currently holds a marginal share (185.84 GWh, 19.34 kWh/person).

In 2022, the share of RES in electricity generation reached 15.34%, up from 7.30% in 2014. However, efforts to further increase the share of RES in the electricity sector need to be continued. In the transport sector, the share of RES reached 7.76% in 2022, which is a value comparable to 2014 (7.00%). This highlights the need for more effective measures to support biofuels and the electrification of transportation to accelerate reductions in emissions. The total energy use from RES in the transport, electricity, and heating sectors in Hungary is 3616.67 kWh/person.

The heating and cooling sector in Hungary primarily uses biomass and geothermal energy. The use of geothermal energy has a long-standing tradition in the country. Installing heat pumps helps reduce dependence on fossil fuels. Energy production from heat pumps increased during the period under review, from 46.24 GWh in 2014 to 786.65 GWh in 2022 (Figure 5).

The legislative framework for RES in Hungary is formed by the Act on Electricity (2007. évi LXXXVI. törvény az villamos energiáról) and other related regulations. Support for RES is ensured through various mechanisms, such as feed-in tariffs, green certificates, and investment subsidies. Information from the RES LEGAL EU database confirms that Hungary is transposing EU RES directives into its legal system.

The financing of RES in Hungary is provided by various sources, including the state budget, European Structural and Investment Funds (ESIF), and proceeds from the sale of emission allowances. Essential programs and funds include Környezeti és Energiahatékonysági Operatív Program (KEHOP), Gazdaságfejlesztési és Innovációs Operatív Program (GINOP), and Program Nová Széchenyiho plán.

In the period under review, the RES support system in Hungary underwent changes that have drawn criticism. The introduction of taxes and fees for electricity producers from RES has hurt the development of some technologies, especially wind energy. This instability in legislation and support creates obstacles for investment in RES.

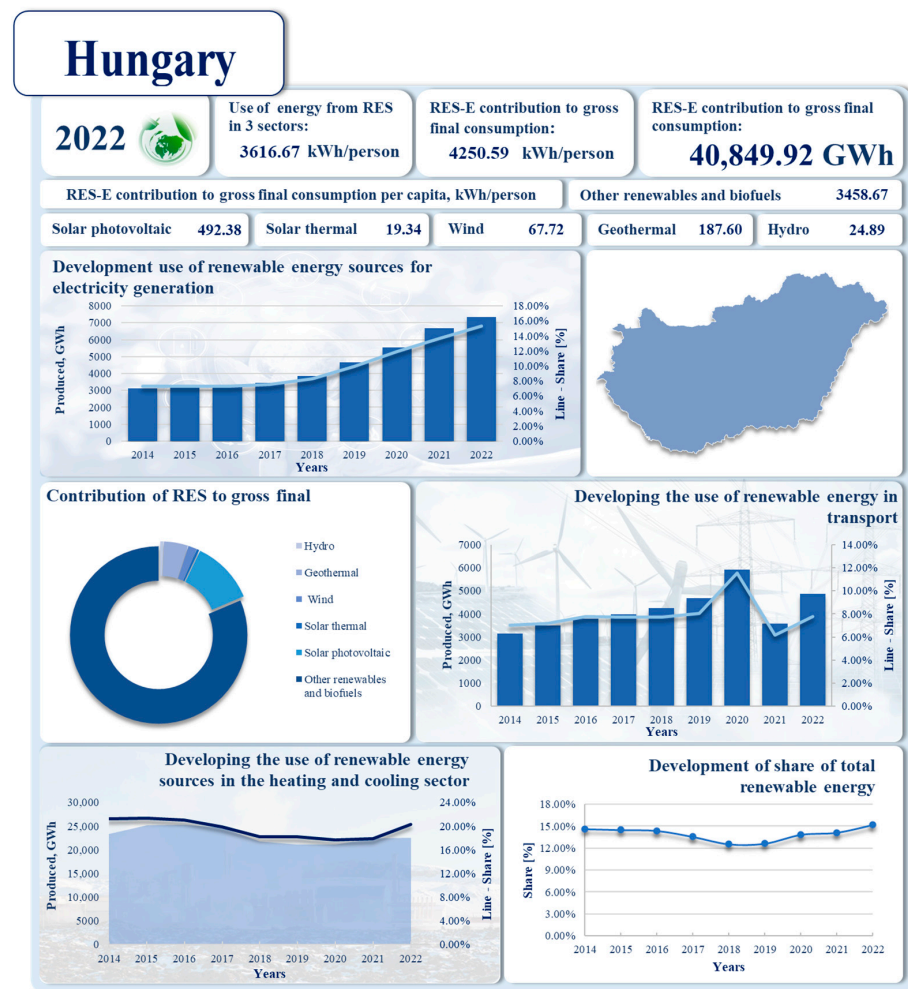


Figure 5. Complex analysis of renewable energy sources in Hungary. Source: own processing according to Eurostat [70–75].

4.5. Comparison of the Visegrad Countries

A comprehensive analysis of the implementation of renewable energy sources (RES) in the V4 countries during the period under review highlights significant differences, influenced by a combination of natural endowments, political priorities, and the specifics of each country's legislative environment. A thorough comparison of these countries and subsequent evaluation relative to the European Union (EU) average requires a detailed analysis of available data and consideration of factors that influence the dynamics of RES development.

Within the V4 countries, Slovakia is dominated by hydropower (783.69 kWh/person), a historical legacy shaped by geographical factors. Nevertheless, the potential for further development is limited by environmental regulations and public opinion, which hinders larger investments. Hungary holds a leading position in geothermal energy (187.6 kWh/person) and solar photovoltaics (492.38 kWh/person). This trend is supported by state subsidies and a long-term strategy aimed at energy self-sufficiency. Support for RES is seen here as a tool to reduce dependence on energy imports. Poland is characterised by a relatively high share of wind energy (513.27 kWh/person), but political support for this sector is unstable and influenced by the changing political situation. Public opinion is polarised, with increasing opposition to wind farms in populated areas. Especially in Slovakia, public opinion is a significant obstacle to the construction of incinerators and wind farms. Residents express concerns that these initiatives will negatively affect their

lives, both aesthetically and through potential noise and impacts on local ecosystems. Such problems may mainly stem from a lack of information and education, leading to unwarranted assumptions about the adverse effects of RES. Without adequate communication and involvement of local communities in the planning processes, it will be difficult to overcome resistance and ensure a smooth transition to renewable energy sources. Interestingly, there is a high share of “other renewable sources and biofuels” (3954.06 kWh/person), which is associated with a political effort to support domestic agriculture but raises questions about sustainability. In the Czech Republic, biomass use has traditionally been important (5308.26 kWh/person), but given its negative impact on air quality, this strategy is being re-evaluated. Political support is linked to regional development and the promotion of rural employment. Other forms of RES, such as hydropower (209.4 kWh/person), wind energy (63.25 kWh/person), and solar energy (249.72 kWh/person), are supported to a lesser extent (Table 1).

Table 1. Comparison of the Visegrad countries, 2022. Source: own processing according to Eurostat [70–75].

Indicator, 2022	Poland	Slovakia	Czechia	Hungary	Average V4	Average EU
Hydro [kWh/person]	62.77	783.69	209.4	24.89	144.37	774.06
Geothermal [kWh/person]	9.92	10.43	0.00	187.6	35.64	39.31
Wind [kWh/person]	513.27	0.97	63.25	67.72	324.34	972.06
Solar thermal [kWh/person]	28.62	19.52	22.14	19.34	25.31	81.4
Solar photovoltaic [kWh/person]	225.26	119.6	249.72	492.38	261.29	462.05
Other renewables and biofuels [kWh/person]	3954.06	4158.98	5308.26	3458.67	4219.99	5946.58
Share of RES energy in transport [%]	5.79%	8.93%	7.20%	7.76%	7.42%	9.62%
Share of RES in the electricity sector [%]	21.01%	22.90%	15.50%	15.35%	18.69%	41.17%
Share of energy from RES in the heating and cooling sector [%]	22.73%	19.92%	25.80%	20.35%	22.20%	24.81%

To better understand the dynamics of RES development in the V4 countries, we analysed the annual increase in each country’s RES share between 2015 and 2022. The results are shown in Figure 6.

The graph shows that the dynamics of RES share growth vary significantly between the V4 countries. Slovakia and Poland show significant jumps in some years, which may be due to one-off investments or legislative changes. On the other hand, the Czech Republic and Hungary show more stable, albeit more moderate, growth. To verify the statistical significance of differences between countries, a one-factor ANOVA was performed. The ANOVA results ($F = 0.463$; $p = 0.710$) indicate that differences in annual increases in the share of RES across the V4 countries are not statistically significant. Based on this, we accept null hypothesis 1, which assumes that there is no statistically significant difference in the year-on-year increase in the share of energy from RES between the V4 countries.

Comparing the V4 countries reveals differences in political priorities and the support mechanisms they implement. Hungary focuses on reducing energy dependence, Poland on supporting domestic agriculture, the Czech Republic on regional development, and Slovakia on maintaining the status quo about environmental constraints. The legislative environment for RES varies across countries and often changes, which creates barriers to investment and long-term planning.

When comparing the V4 average with the EU average, a lag is evident in RES electricity generation (V4 average 18.69% vs. EU average 41.17%) and transport (V4 average 7.42%

vs. EU average 9.62%). The use of solar thermal energy in all V4 countries is significantly below the EU average, indicating untapped potential (Figure 7).

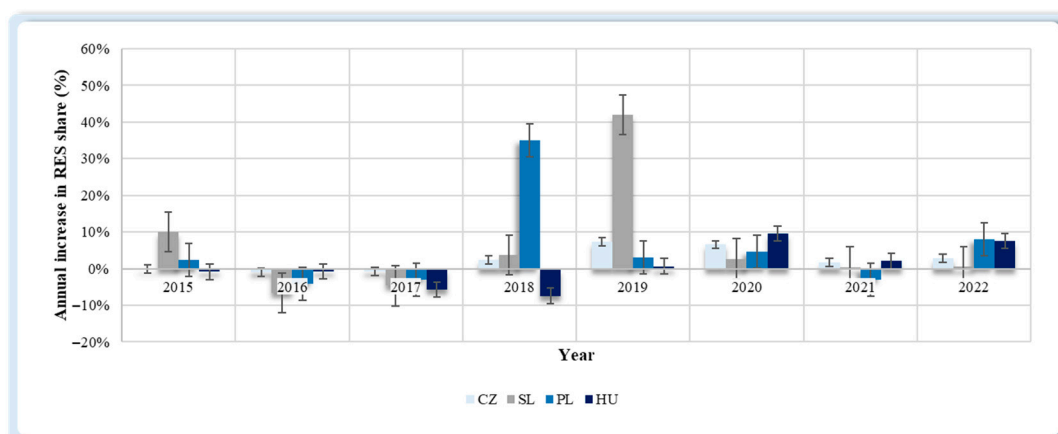


Figure 6. Annual increase in RES share in V4 countries (2015–2022) [70–75].

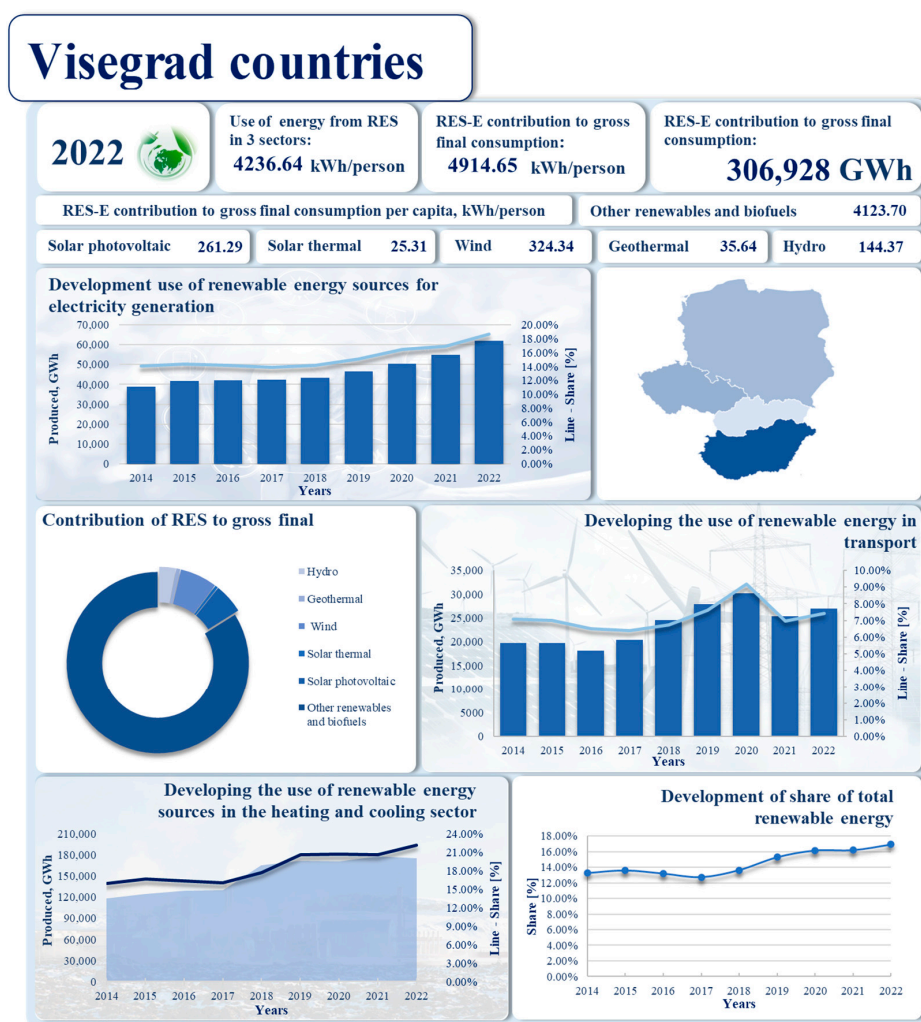


Figure 7. Complex analysis of renewable energy sources in V4. Source: own processing according to Eurostat [70–75].

Comparing the V4 countries reveals differences in political priorities and the support mechanisms they implement. Hungary focuses on reducing energy dependence, Poland on supporting domestic agriculture, the Czech Republic on regional development, and

Slovakia on maintaining the status quo regarding environmental constraints. The legislative environment for RES varies across countries and often changes, creating barriers to investment and long-term planning.

The findings show that low public awareness of the benefits of RES is an obstacle to their development across all V4 countries, and that there is a need to improve communication and involve citizens in decision-making processes.

5. Discussion

Currently, progress in renewable energy sources (RES) varies across the Visegrád Four countries—Poland, Slovakia, the Czech Republic, and Hungary. While the Czech Republic and Hungary have made significant progress in transforming their energy sectors primarily through investments in solar and wind technologies, Poland and Slovakia have faced greater challenges due to a higher dependence on biomass. This observation is consistent with the findings of Jonek-Kowalska and Rupacz (2024) [46], who state that while the Czech Republic and Hungary are leading in the implementation of RES, Poland and Slovakia have faced greater obstacles in achieving their energy goals. Our analysis aligns with the claim by Adamczyk and Graczyk [45] that RES support in Poland is insufficient and requires fundamental adjustments to improve RES performance. Insufficient public awareness and community engagement are barriers to the acceptance of RES projects. There is a need to improve communication and public education about the benefits of RES, and to involve local communities in decision-making processes to address concerns and resistance to these projects, as indicated by the findings.

In the transport sector, progress in implementing RES appears to be slower than in electricity generation and heating and cooling. We agree that the lack of capacity and quality in electricity distribution hinders the development of hydrogen-fuelled transport infrastructure, and that countries such as the Czech Republic and Hungary need to modernise their networks. Similarly, as Svobodová and Hedvičáková (2015) [50] point out, post-communist countries lag behind Western European countries in building the necessary infrastructure, making it impossible to implement transitional steps.

Even though positive political initiatives and regulations are essential to promote the transition to RES, countries that invest in effective policies and incentives can create an environment that supports innovation and reduces administrative barriers. Our analysis shows that functional policy frameworks not only contribute to more stable RES development, but also to the longer-term planning needed to ensure sustainable energy policy. To better understand the impact of policy frameworks on RES development in the V4 countries, we provide a clear summary of the evaluation of support instruments in each country (Table 2).

Our findings, similar to those of Godawska and Wyróbka (2021) [41], highlight the importance of strict environmental regulations for RES production. At the same time, our findings suggest that while biomass is currently the dominant source of RES, the growing competition from solar and wind energy indicates that diversification of the energy mix is necessary to reduce dependence on biomass and minimise environmental impacts, which supports Kochanek's conclusions (2021) [20] on the need for a comprehensive approach to RES development.

In the areas of heating and cooling, innovations such as integrating phase change materials with solar systems are increasingly being discussed. Our findings show that the use of advanced technologies can optimise energy use and increase the potential to reduce greenhouse gas emissions, opening new opportunities to reduce the carbon footprint in these sectors. Similarly, Gökğöz and Güvercin (2019) [62], in their research on renewable energy systems for heating, cooling, and electricity generation, highlighted the growing importance of thermal energy storage, which directly supports the use of phase

change materials. Although structural innovations and technologies offer many benefits, administrative challenges also pose obstacles that reduce the region's ability to adapt to new technologies.

Table 2. Qualitative Assessment of the Effectiveness of Support Instruments for RES in the V4 Countries (2022) [76].

Support Instrument	Czech Republic	Hungary	Poland	Slovakia
Financial Subsidies and Grants	Effective	Effective	Effective	Effective
Green Certificates	Inadequate	Inadequate	Moderate	Inadequate
Feed-in Tariffs	Moderate	Moderate	Moderate	Moderate
Feed-in Premiums	Moderate	Moderate	Moderate	Inadequate
Tax Breaks and Incentives	Effective	Inadequate	Effective	Effective
Tenders and Auctions	Inadequate	Effective	Effective	Inadequate
Research and Development	Inadequate	Effective	Inadequate	Inadequate
Support for Biofuels	Effective	Effective	Effective	Effective
Support for Electric Vehicles	Effective	Inadequate	Inadequate	Inadequate
Support for Hydrogen Fuel Cells	Effective	Effective	Effective	Inadequate
Support for Heat Pumps	Effective	Effective	Effective	Effective
Support for Solar Thermal Systems	Effective	Effective	Effective	Effective
Support for Biomass	Effective	Effective	Effective	Effective

In contrast to the study by Kacperska et al. (2021) [47], which identified the Visegrád Group as countries with relatively high RES use and good environmental characteristics, our more detailed analyses show that there are significant differences between the individual V4 countries and that the environmental impacts of biomass use, which dominates in some countries, may not always be positive. This points to the complexity of assessing the effects of RES and the need to consider specific contexts and technologies.

At the same time, monitoring the use of RES across sectors is crucial for countries' transition to sustainability and for the more efficient achievement of climate goals. The use of new renewable sources and the maintenance of investments in older RES must be part of each state's strategy to reduce the electricity grid's vulnerability to climate change. Similarly to Tucki et al. (2021) [48], highlighting the need to meet the goals of the Paris Agreement, we also state that without a strong political commitment and an adequate legislative framework, it will be a significant challenge for the Visegrád Four countries to achieve their set ambitions in the sphere of renewable sources and energy transformations.

From a political perspective, our findings point to several key implications for each V4 country. In the Czech Republic and Hungary, where significant progress in RES has been noted, these results may encourage further investments in solar and wind technologies and strengthen support for more ambitious RES targets. In Poland and Slovakia, where progress is slower and dependence on biomass is higher, our findings may prompt a re-consideration of policy strategies and consideration of more effective support mechanisms, as well as diversification of the energy mix. These findings also highlight the need for better communication with the public and for the involvement of local communities in decision-making processes, which can help minimise resistance to RES projects. At the European level, our findings contribute to the discussion on policy harmonisation and the

preservation of national sovereignty in energy, which is crucial to ensuring an effective and sustainable energy transition across the region.

6. Conclusions

Currently, the Visegrád Four countries are at a critical crossroads in the development of renewable energy sources (RES), with findings indicating that while progress has been made, significant obstacles remain. Our analyses suggest that investments in solar and wind technologies are yielding more essential results in decarbonising energy sectors in the Czech Republic and Hungary. At the same time, Poland and Slovakia lag, primarily due to greater reliance on biomass. Support systems have proven inadequate, particularly in Poland, where legislative approaches need to be re-evaluated and administrative processes streamlined to increase the attractiveness of RES for investors and entrepreneurs.

Effective policies and legislation have a fundamental impact on the development of RES, but our analysis emphasises that political frameworks alone are not enough. The absence of investment, as well as insufficient support for innovation and technology in the field of RES in the region, contributes to stagnation. This is particularly evident in the transport sector, where clear priorities and strategic plans oriented towards gradual transitions to renewable sources are needed. To ensure real progress in RES, not only is legislative support necessary, but also a stable financial base that would motivate entities to invest in sustainable projects. For policymakers, the study highlights the need to stabilise the legislative environment and establish more effective support mechanisms. At the same time, we recommend that investors diversify their RES and invest in innovative technologies.

At the same time, local communities and the public play a key role in the transformation process towards sustainable energy. Our findings show that low awareness of the possibilities and benefits of RES often leads to resistance to new projects, hindering their implementation. It is essential to ensure transparency, education, and citizen involvement in the decision-making process. Only in this way can we gain their support and mitigate concerns about the potential negative impacts of RES on quality of life. Currently, the V4 countries face a clear challenge: strengthening education about RES and promoting information exchange to ensure a positive, engaged public approach to renewable energy sources. The findings show that low public awareness of the benefits of RES is an obstacle to their development across all V4 countries, and that there is a need to improve communication and involve citizens in decision-making processes.

This study focuses on analysing data from 2014 to 2022 and does not include econometric modelling that would allow quantifying the impact of individual factors on the development of renewable energy sources. Future research should focus on this area. In addition, future research should focus on the effects of global events, such as the war in Ukraine, on the diversification of the energy mix and the development of RES in the V4 countries. The crisis may accelerate the transition to RES, but it is necessary to examine in detail how it affects investments, political priorities, and resource availability. Furthermore, a deeper analysis of the impact of public and local communities on the development of RES is key to understanding how to effectively involve citizens in decision-making and alleviate concerns that may hinder the implementation of RES projects. Future research could explore practical strategies for building trust and public support for renewable energy sources. It is essential to strengthen education about RES and promote information exchange to ensure a positive, engaged public attitude towards renewable energy sources.

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supervision, P.T.; project administration, M.T.; funding acquisition, M.M. All authors have read and agreed to the published version of the manuscript.

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