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An analysis of renewable energy consumption in Visegrád countries

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Abstract

The "Visegrád Group" countries are fundamentally distinct from one another. There is less public backing for green initiatives like climate protection and renewable energy in Western Europe. Since the change began, the region has made substantial efficiency gains. Descriptive statistics and Principal Component Analysis (PCA) were employed to quantify the various energy usage patterns across the V4 countries. Our analysis revealed that in Slovakia, Poland, and the Czech Republic, renewable energy development had accelerated by 149%, 116%, and 87% relative changes, respectively. Hungary has stalled or declined. These results suggest that the V4 countries have made considerable progress in transitioning to renewable energy sources. However, further steps are needed to ensure Hungary can make the same progress as its neighbours. According to the findings of our studies and forecasts, substantial levels of consumption of renewable energy will be observed in the following industries in the year 2022: Electricity usage will rise by 29.78% in Hungary and 22.45% in Slovakia; in the heating and cooling sector, it will rise by 24.60% in Czechia and 16.71% in Poland; and in the transportation sector, it will grow by 8.44% in Hungary and 7.71% in Slovakia. To keep up with expected increases in energy consumption, the V4 countries will need to expand the proportion of their economies that use sustainable and alternative resources. Furthermore, we propose six strategies to tackle increased energy demand and major obstacles to transitioning towards renewable energies. This will ensure energy independence and pave the way to carbon neutrality by 2050. While the EU has high targets for renewable energy, the papers show that the V4 nations each have their own set of ambitious goals.

Keywords: renewable energy; share of renewables; heating and cooling; green transition; visegrád countries

1. Introduction

The European Union directive sets a goal of achieving a 20% share of renewable energy in final energy consumption by 2020 and successfully met its target by consuming 21.3% of energy from renewable sources in 2020. This represents the increased demand for Renewable Energy Sources (RES). But an enormous overhaul in the energy sector will be required to attain the 32% renewable energy target preset for 2030 [1] . Achieving the goal will help Member States build and operate Renewable Energy Sources (RES). Renewable energy sources are playing an increasingly important role in the EU's climate and energy policies. The European Union

reduces its reliance on imported fossil fuels by adopting more renewables to meet its energy demands, resulting in more sustainable energy production. At the end of the 1990s, the European Union, influenced by economic and environmental reasons, committed to boosting the use of renewable energy sources. In 1997, the European Commission published an Energy Policy White Paper that established a single Renewable Energy Strategy and an Action Plan. By 2010, the indicated goal was for renewable energy sources to contribute 12% of the total inland energy consumption in the European Union [2]. The usage of renewable energy has multiple benefits, including lower energy costs, lesser environmental pollution, and less reliance on fossil fuel energy production, as well as a more efficient way of energy production and supply [3], [4].

The EU's energy system must be decarbonized in order to achieve climate neutrality [5]. Three fundamental principles underpin this policy area. First and foremost, put energy efficiency and renewable energy sources at the top of your priority list. Second, a reliable and inexpensive energy supply in the EU, and Third, an EU energy market that is completely integrated, networked, and digitalized [6] are crucial for achieving a sustainable and resilient energy future. These three factors are crucial to ensuring the European Union's energy security and mitigating its reliance on external sources.

Society cannot function without access to reliable heating and cooling, cooking, lighting, transportation, and industrial energy services. Dedicated policies and regulations, along with rapid technological innovation, have resulted in dramatic growth in the production and use of renewable energy across the EU during the past two decades. As a result, the European Union met its 2020 goal of using 20% renewable energy, and greenhouse gas emissions have been continuously decreasing across the EU energy sector since 1990. As a result of this study, more insight has been gained into how the renewable energy industry is currently performing in the electricity, heating and cooling, and transportation sectors in the V4 countries. Hinrichs-Rahlwes [7]discusses the potential for 100% renewable energy in Europe, while Sager-Klauss [8] focuses on planning support for sustainable energy transition in small- and medium-sized communities. Kemfert [9] provides a coordinated expansion planning approach for achieving 100% renewable energy in Germany, while Zhou [10] presents scenarios for China's sustainable energy future. While these papers do not directly address the V4 countries, they provide valuable insights into the potential for renewable energy in different sectors and the importance of coordinated planning and policy support for achieving sustainable energy goals. As a result, the aim of this study is to fill that gap.

The main objective of this paper is to assess the current state and projected future role of renewable energy in the electricity, heating and cooling, and transportation sectors throughout the Visegrad Group (V4) countries. The following research questions must be answered in order to fulfil the expected goal:

1. What is the current state of renewable energy in the electricity, heating and cooling, and transportation sectors in the V4 countries?
2. What are the projected future roles of renewable energy in the electricity, heating and cooling, and transportation sectors in the V4 countries?
3. What are the opportunities for the development of renewable energy in the V4 countries?
4. What are the policies that have been enacted to promote renewable energy in the V4 countries?

Coordination and perception of sharing regarding the execution of the "Clean Energy for all Europeans" package, including the shared electricity energy market, new market services, preparedness to address threats to the electric power system, and electric energy efficiency within the electricity market. Coordination among the V4 nations to share information and build shared perspectives on executing the Clean Energy for All Europeans package and attaining the EU's energy and climate policy goals. The research on this issue has been aided by the various degrees of energy transition implementation in V4 countries.

2. Literature Review

2.1 Renewable Energy Sector in the V4

The V4 country has one of the most dynamic and innovative renewable energy sectors in the area. Wind, solar, biomass, hydropower, and geothermal power are only some of the renewable energy sources that might be used in the V4 nation. The country has set ambitious goals to boost its use of renewable energy, with targets of 20% by 2030 and 50% by 2050 for its ultimate energy consumption. The government has pledged to cut emissions by 40% by 2030 and 80% by 2050 compared to 1990 levels.

Numerous possibilities exist for economic development, employment creation, energy security, and ecological preservation in the renewable energy sector of the V4 country. More than one hundred thousand people are employed in the industry, accounting for around 5% of GDP. Both domestic and international investors have shown a keen interest in the market. A number of incentives and subsidies, as well as a legal and regulatory framework, have been established to encourage the growth of renewable energy sources in the EU.

There are difficulties in the renewable energy industry in this V4 country as well. There are many obstacles to the widespread adoption of renewable energy, including the high

upfront costs of such technologies, the intermittent and variable nature of renewable energy sources, the difficulty of integrating renewable energy into the current grid infrastructure, the lack of public understanding of the benefits and consequences of renewable energy, and the threat posed by fossil fuels and nuclear power. Increasing the country's research and development capabilities, bolstering grid management and storage systems, increasing public communication and education initiatives, and diversifying the energy mix and sources are all necessary to meet these difficulties.

Traditional energy production in Central Europe has relied on nonrenewable energy sources [11] . The V4 energy industry has typically been based on fossil fuels, which are abundant in many countries, including some of the largest coal producers. Poland has the world's 9th greatest coal reserves. In Central Europe, two major fuels play a large role in electrical energy production: hard coal and nuclear energy [12] .

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2.1.1 The Renewable Energy Sector in Czechia. The Czechia, an EU member, aims for carbon neutrality by 2050 through its National Energy and Climate Plan. It aims to reduce emissions by 80% by 2050 and achieve a 22% renewable energy share by 2030. Besides, Czechia is targeting to increase its electric vehicle (EV) market by 220,000 to 500,000 by the end of the current decade as part of its National Energy and Climate Plan, which aims for a 14% share of renewable energy sources in transport by 2030. Furthermore, the government aims to make renewable energy 31% of heating and cooling energy by 2030, with the boiler scrappage project aiming to replace outdated coal boilers starting in 2022 [13].

The Czechia, along with the other Visegrad countries, is a significant producer of solid fuels in Europe. Primarily, they produce hard coal and brown coal. Lignite offers the greatest energy potential for the Czech economy, with estimated resources of 8.8 billion tonnes, of which 2.2 billion tonnes are economically sustainable [14].

Currently, coal contributes 44% of the Czech energy mix. Another key pillar of Czech energy is the atom, which accounts for 34%. And the remaining gas and oil sources are only supplementary to RES so far, accounting for 9% and 12.5% respectively [15]. According to government projections, green sources are expected to be the second-largest source of energy production in the Czech Republic after nuclear energy by 2040, but their share of overall energy output will be lower than in most EU nations. It is worth noting that, in contrast to the vast majority of the population, Czech lawmakers consider the use of coal as an essential comparative advantage of the Czech Republic, maintaining an adequate level of energy security. On the other hand, renewable energy sources are viewed as a hazardous investment that alters the energy sector's status quo [16].

According to CEZ, it intends to close the majority of its coal-fired power facilities by 2030, reducing the share of coal in its energy production mix to 12.5% from 36% last year. They expect to reduce coal-fired energy output to 25% of capacity by 2025 while adding 1.5 GW of renewable capacity by 2025 and 6 GW by 2030 [17]. Furthermore, there is a strategic intention to allocate substantial resources towards the implementation of energy efficiency initiatives, along with a commitment to investigate alternative sources of clean energy, including wind and solar power.

2.1.2 The Renewable Energy Sector in Hungary. The Hungary has the lowest potential for energy resources in the region. Domestic energy production accounts for 45% of the total primary energy supply, making this small country more reliant on imports. Hungary's primary energy sources include natural gas and crude oil, but nuclear power source uses for the majority of electricity generation. Natural gas sources fulfil roughly one-fifth of the country's overall energy demand, and Imports from Russia help to meet the rest of the demand [18]. It's noteworthy to mention that the continual use of coal will be a key aspect of the country's energy strategy until 2030.

In the year 2020, Hungary's utilisation of renewable electricity attained a level of 12%, surpassing its predetermined target of 11% for that year. The utilisation of solar power generation in Hungary experienced a significant surge, growing by a factor of five between the years 2018 and 2021. Consequently, solar power generation accounted for 9% of the total power generation in the country. Hungary has established its renewable electricity and final energy consumption objectives for the year 2030, which have been set at 21%, a figure that falls below the European Union's target of 32%. In the year 2020, the government of Hungary implemented a grant programme amounting to $18 million, specifically designated for the purpose of facilitating the acquisition of electric vehicles. This programme imposed a maximum limit of $7,000 per vehicle in terms of the grant amount that could be obtained. It is anticipated that around 1,300 locally operated buses, which adhere to environmentally sustainable practices, will be deployed by the year 2029, with the assistance of the Green Bus Programme initiated by the government. In 2020, the heating mix in Hungary was predominantly comprised of natural gas, which constituted approximately 65% of the total domestic heat usage. In 2020, around 20% of Hungary's energy consumption in the heating and cooling industries will come from renewable sources [19].

For more than 30 years, Hungary's economy has been reliant on nuclear power. Nuclear power generates over 50% of the country's electricity. According to the National Energy Strategy, Hungary would reduce carbon dioxide emissions along with nuclear power, which is a significant part of the country's energy industry till 2030 in the long run [20], [21].

Renewable energy sources have been steadily increasing in Hungary's energy sector for several years. The most important source of RES growth is biomass. Another source with a lot of potential is geothermal energy. In the European Union, Hungary possesses some of the finest geothermal resources. Solar energy has been the fastest-growing energy source in recent years, despite the fact that energy production from this source is still modest [18].

Wind energy has halted to development as a result of laws passed in 2016, which were impractical for the investors, and the government seems to have little interest in promoting this type of green energy source [22]. Hydropower use has been low for years, and aside from minor installations in limited water basins, the use of big rivers to generate hydropower is improbable.

2.1.3 The Renewable Energy Sector in Poland.

Poland's energy policy emphasizes promoting and developing renewable energy sources in crucial sectors, such as offshore wind and small-scale solar PV systems, to decrease oil demand in the transport sector, support bioenergy and heat pump technologies, and facilitate decarbonization of gas supply. Between 2010 and 2020, Poland's renewable energy proportion increased from 9.5% to 16%, primarily due to wind power and solid biomass for heating. However, Poland's Total Final Energy Consumption ranking stands at 21st place, accounting for only 16% of its gross final energy consumption in 2020. Poland's gross renewable energy consumption accounted for 16% of electricity production, 22% of heating and cooling demand, and 6% of transport demand [23]. The Polish energy mix is exceptional in Europe because it is mainly based on indigenous solid energy resources such as hard coal and lignite[24]. In terms of hard coal mining, Poland is ranked ninth in the world, producing approximately 64 million metric tonnes per year [25]. Poland, like the other V4 countries, has no large oil reserves. Domestic mining is limited, meeting just around 5% of demand; imports from Russia and Saudi Arabia supplement the rest.

In Poland's energy balance, natural gas is becoming increasingly important. The emergence of appropriate investments and the transformation of industrial plants, which are moving away from traditional supply methods, are driving this upward trend. Poland's domestic natural gas production is minimal, at 3.8 billion m3 in 2019, only meeting one-fifth of total demand, entailing imports to make up for the shortfall[26].

Renewable energy sources are also a component of Poland's energy balance. They still aren't widely used and are therefore not cost-competitive with fossil-fuel-derived energy, but their share of Poland's energy mix is steadily increasing, reaching 13.5% at the end of 2017. The RES potential varies by region of the country due to geographical and climate differences. Currently, renewable energy is primarily used in the local power industry to increase local energy security, particularly in areas with underdeveloped energy infrastructure.

Renewable energy source (RES) production continues to soar, with prosumer photovoltaics leading the way. Solar power plants increased by 176 percent (2 TWh), and biomass-coal co-firing increased by 20 percent (to 2.2 TWh), thanks to generous subsidies and the high price of CO2 emission rights. Green power plants such as biogas plants (up 10% to 1.2 TWh) and hydroelectric plants (up 8% to 2.1 TWh) increased output as well. Pumped-storage hydroelectric power plants, Poland's largest energy storage facility, saw a 16% increase in usage (0.8 TWh). This was primarily due to an increase in the share of different energy sources, such as wind and photovoltaic, which the transmission system operator had to balance with stored energy[27].

2.1.4 The Renewable Energy Sector in Slovakia.

Slovakia has set a target to attain climate neutrality by the year 2050, with the objective of reducing greenhouse gas emissions by a minimum of 90% in comparison to the levels recorded in 1990. The nation's objective is to achieve a 19% share of renewable energy in its final energy consumption and a 27% share in the power sector by the year 2030. This target is expected to be attained through the implementation of existing regulations and ongoing efforts. The government's objective is to decrease reliance on imports by implementing an 880 MW expansion of the Mochovce nuclear power station. Slovakia has set a target to attain a 14% share of renewable energy sources in the transport sector by the year 2030. The sales of electric vehicles (EVs) in the nation have experienced substantial growth, as evidenced by the increase in EV sales from 1,674 units in 2020 to 2,341 units in 2021. In order to promote the adoption of electric vehicles (EVs), the motor vehicle tax is waived, and a subsidy programme has been implemented for battery electric vehicles (BEVs) and plug-in hybrid vehicles (PHEVs). Slovakia has set a target of achieving a 30.3% reduction in energy use by the year 2030. As part of this objective, it has been mandated that all newly constructed buildings adhere to near-zero-energy building (NZEB) standards. The nation also endeavours to achieve a 19%

share of renewable energy in the domain of heating and cooling by the year 2030 [28].

The Slovak energy mix includes a balanced contribution of nuclear energy at 23.8%, natural gas at 23.8%, crude oil at 20.4%, fossil fuels at 20%, and renewable energy at 12%. Fossil fuels and nuclear energy are mainly used in electricity consumption [29]. Biofuels and bio-waste production have effectively replaced coal in the generation of heat and energy, enabling the country to maintain a high level of energy security.

The Slovak government has enhanced the share of renewable energy in electricity consumption. Because of hydropower and biomass energy, Slovakia easily met the EU's 14% renewable energy generation target. Their hydropower potential is evenly dispersed across the nation, enabling electricity production from both massive hydropower facilities and small hydroelectric power plants (SHPs). Presently, 70% of the technical hydropower potential is being utilized. Biomass, which has a maximum energy potential of 120 PJ, is another important source of renewable energy in Slovakia [30].

3. Materials and Methods

This study conducted an in-depth analysis by employing descriptive statistics and principal component analysis (PCA) to investigate the dataset on renewable energy obtained from the Eurostat SHARES tool for the period encompassing 2010-2019. The SHARES tool focuses on calculating the share of energy consumption from renewable sources throughout the V4 member states in a consistent manner. This is done in compliance with the RED criteria and is based on Eurostat-reported national energy data. The descriptive statistics offered a comprehensive overview of the dataset, encompassing measures of central tendency and dispersion. Principal Component Analysis (PCA) was subsequently employed to ascertain the latent components that account for the variability in renewable energy generation among various countries and during various time frames. The findings of the study unveiled significant trends and patterns within the dataset, providing insights into the advancement and expansion of renewable energy in Europe across the preceding ten years.

The methodology adopted in this manuscript is congruent with the assumed study objectives. Two quantitative methodologies, principal component analysis and descriptive statistics, were used to investigate the diversity of energy consumption in the V4 countries. Firstly, the research methodologies are considered for the classification of renewable energy sources used based on the transport, energy, and heating and cooling sectors. Secondly, based on three diagnostic sectors, a comparative analysis was utilized to compare the studied phenomenon in the Visegrad Group nations.

Descriptive statisticspart of the study includes the application of statistical measures, including mean, standard deviation, relative percentage change compared to the base year (2010), and the average percentage change compared to the previous year. In order to model the studied factors, linear trends were fitted to the data with the specified explanatory variables.

$$\mathbf{y = a + b*x},$$

where **y** is the source of energy usage (for example, annual heating and cooling, transportation, or electricity), **a** and **b** are parameters, **x** denotes the number of years after 2010 (it varies between 0 and 9). The variable "a" represents the intercept, whereas the variable "b" represents the slope. These parameters were employed in the process of further estimating the data and developing predictions for future outcomes. The forecast of various factors (2020–2022) was derived from predictions generated using a simple ordinary least squares (OLS) regression model. The predictions were based on the coding of variables a, b, and x as 0–9, corresponding to the years 2010–2019. In the coding system, the year 2010 is represented by the variable x with a value of 0, whereas the year 2011 is represented by x with a value of 1. This pattern continues, with the year 2019 being encoded as x = 9. In order to forecast data for the year 2020 using the given equation, it is necessary to utilise the variables a and b. Specifically, the value of x should be set to x =10 for 2020, x =11 for 2021, and x =12 for 2022. Therefore, in order to forecast data for the year 2020 using the given equation, the variables a and b should be used, with a representing the tens digit and b representing the one's digit.

For the estimation, a robust regression [31] was applied, which can leave outliers out of the account and provide a more appropriate estimation of the parameters. An analysis of Principal Components was performed using a range of renewable energy users from Visegrád country categorized as low, medium, and high. The PCA [32] was used to highlight principal components and graphically represent even the countries and the studied factors in a two-dimensional space. For this reason, a so-called biplot was created to study the connections between the counties and factors. The PCA analysis was performed on the correlation matrix and Varimax rotation was used. Robust parameter estimations from the regression coefficients were utilised to forecast the growth of renewable energy use in Visegrád group countries. All calculations were performed using PAST software [33] . The results of the forecast showed a

significant increase in renewable energy use in Visegrád Group countries over the next decade.

4. Results and discussions

Since the European industrial revolution, the usage of energy has increased due to population expansion and growing living standards [34]. To the dynamic enlargement of national economies, the demand for renewable energies is expanding rapidly[35]. Consequently, energy sources that have been used traditionally such as, 'carbon', 'natural gas', and 'oil', are no longer adequate to meet the demands of the global economy[36]. Rapid increases in the consumption of energy across several sectors might lead to their depletion. On the other hand, the European Union pledged to head toward climate neutrality by the year 2050. In order to accomplish this goal, the level of greenhouse gas emissions needs to be considerably reduced; hence, the transformation of power energy in the transportation sector is expected to have an essential role.

Recently, every country in the European Union has come to a consensus over certain national goals that they are capable of accomplishing. For instance, Slovakia and Poland declared to produce 14% and 15% of their energy needs from renewable sources, respectively, while Czechia and Hungary obligated themselves to attain a 13% contribution by 2020[37]. In this regard, all of the Visegrád nations have done rather well in fulfilling their energy goals, even though they are placed behind in the EU. Among the nations that comprise the Visegrád, Slovakia has acquired the maximum percentage of renewable energy in their national energy mix (17%), followed by the Czech Republic, Poland, and Hungary. The 2020 goals were accomplished promptly in Hungary and the Czech Republic. However, after accomplishing its national target in 2014, Czechia's development of renewable energy has remained stable for several years. Additionally, since 2012, Hungary's percentage of renewable energy has even decreased[38].

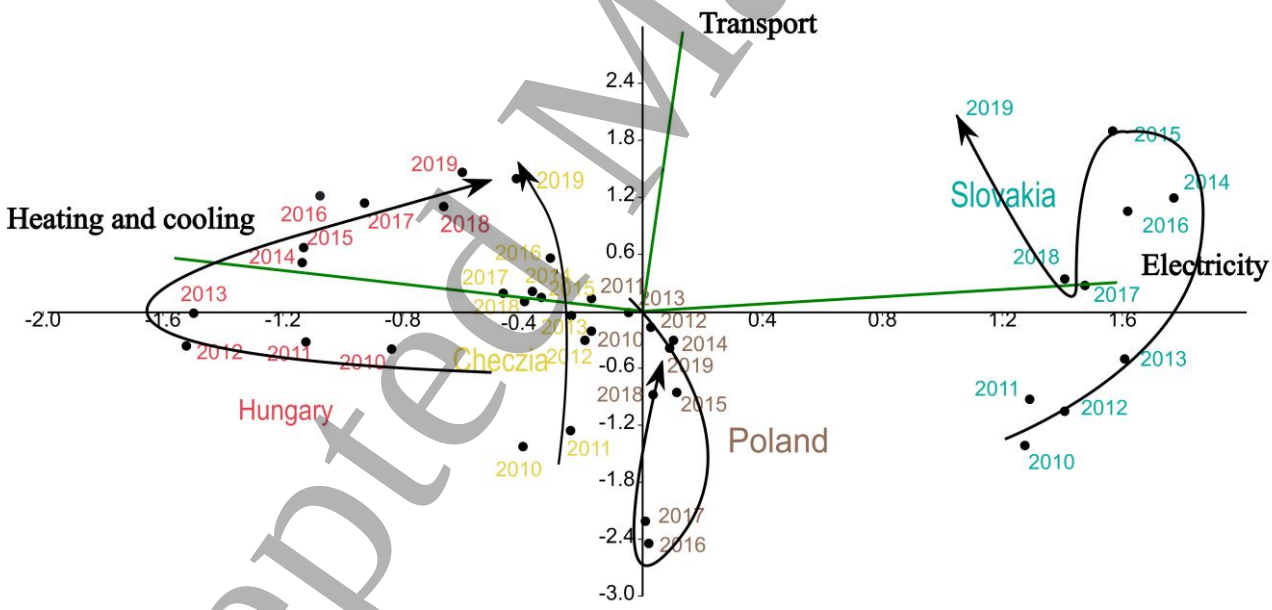

Figure 1. *PCA biplot of the studied countries and factors.* ***Source:*** *Authors' own compilation.*

The first dimension in **Figure 1** differentiates countries concerning heating and cooling and electricity usage. Hungary's and Chechia's energy source use is higher concerning Heating and cooling compared to the other two countries. Slovakia has the lowest heating and cooling usage, but the electricity usage is the largest here, which is why Slovakia is located on the other side of the 1st axis. In the case of Poland, there is a balance between electricity and

heating and cooling usage, so Poland centers around the origin. It can also be seen that Hungary has a U-shaped curve indicating that the peak was in 2012-2013 concerning heating and cooling usage and there was a decline after that. Slovakia's peak electricity usage was between 2014 and 2016. Slovakia's heating and cooling fluctuated the most and relatively increased at a higher extent but from a lower level than in the case of the other countries.

The second-dimension separates countries based on transportation usage. Transportation energy usage was stable in Poland, with a decrease in 2016 and 2017. In all other countries, transportation energy usage was increasing especially in Chechia and Slovakia. The transportation usage of Checzia was steadily increasing while in Slovakia it fluctuated much higher.

The explained variance by the first two Principal Components (PCs) was larger than 70% in all 3 factors (Heating and cooling and electricity (88%), Transportation (97%). The first Principal Component (PC) contributes 55% of the explained variance and the second PC 36%. Altogether the two PCs explained 91% of the total variance which is excellent.

Table 1. *Indicate the average changes in renewable energy usage over time and the parameters of Linear Trends in Visegrád countries based on descriptive statistics.*

Country	Energy source	Minimum	Maximum	Mean	Std. Deviation	Relative % change (base=2010)	Average % change (base=prev. year)	Linear Trend parameters y = a+bx
Checzia	Transport	5.22	7.83	6.42	0.76	+50	+5	a=6.19;b=0.048 R2 = 0.676
	Electricity	7.52	14.07	12.56	2.11	**+87**	+7	a=13.89;b=-0.074; R2=0.657
	Heating and cooling	14.10	22.65	**18.56**	2.64	+61	+5	a=13.49;b=0.926 R2 = 0.919
Hungary	Transport	6.00	8.03	7.01	0.79	+30	+3	a=5.96;b=0.207 R2 = 0.908
	Electricity	6.06	9.99	7.39	1.11	+41	+4	a=6.02;b=1.98; c=0.651
	Heating and cooling	18.08	23.70	**20.49**	2.04	0	0	a=27.48;b=-0.969 R2 = 0.117
Poland	Transport	6.65	14.36	11.59	2.51	**+ 116**	**+9**	a=9.14;b=0.535; R2=0.824
	Electricity	11.81	15.98	14.28	1.18	+35	+3	a=12.52;b=0.349 R2 = 0.884
	Heating and cooling	5.29	**8.63**	6.94	**1.20**	+57	+5	a=5.17;b=0.214 R2 =0.540
Slovakia	Transport	5.29	**8.63**	6.94	**1.20**	+57	+5	a=5.17;b=0.214 R2 =0.540
	Electricity	17.77	22.87	21.08	1.63	+23	+2	a=19.17;b=0.276; R2=0.523
	Heating and cooling	7.88	19.70	10.35	**3.43**	**+149**	**+11**	a=7.63;b=0.306 R2 = 0.473

** The maximum value of changes in Visegrád countries is highlighted in bold.*

Based on a comparison between 2010 and 2019, Checzia utilized 87% more renewable energy in its electricity industry in 2019. Hungary's electricity sector has seen the most noticeable increase of 41%. Poland's transport sector has seen a surge of 116% in the use of renewable energies. Slovakia has seen a 149% increase in renewable energy use in its heating and cooling sectors. On a year-to-year basis, **Table 1.** demonstrates that Slovakia has managed to increase Heating and Cooling usage the most, the average percentage change was 11%. Concerning electricity, Poland managed to increase usage by an average of 9% year to year but in case of the transportation, there was a decrease of 1%. The highest

relative rate of change based on 2010 can be observed in the case of Slovakia (heating and cooling usage increased by 149%), Poland (Electricity increased by 116%) and Checzia (Electricity increased by 87%).

Regarding the robust parameter estimations of the regression coefficients, a is the intercept which expresses the level when x =0 (belongs to 2010), and b expresses the relative change or the slope of the regression. The relative change is the largest in the case of Hungary's electricity usage while Chechia's electricity usage has a negative slope indicating a slightly decreasing trend. Hungary's large negative b parameter indicates a rapidly decreasing trendline in the case of heating and cooling. In the case of Poland's transportation energy usage, only a slight decrease can be observed. The largest slope can be concerning heating and cooling usage in the case of Checzia and transportation usage in Slovakia and Hungary.

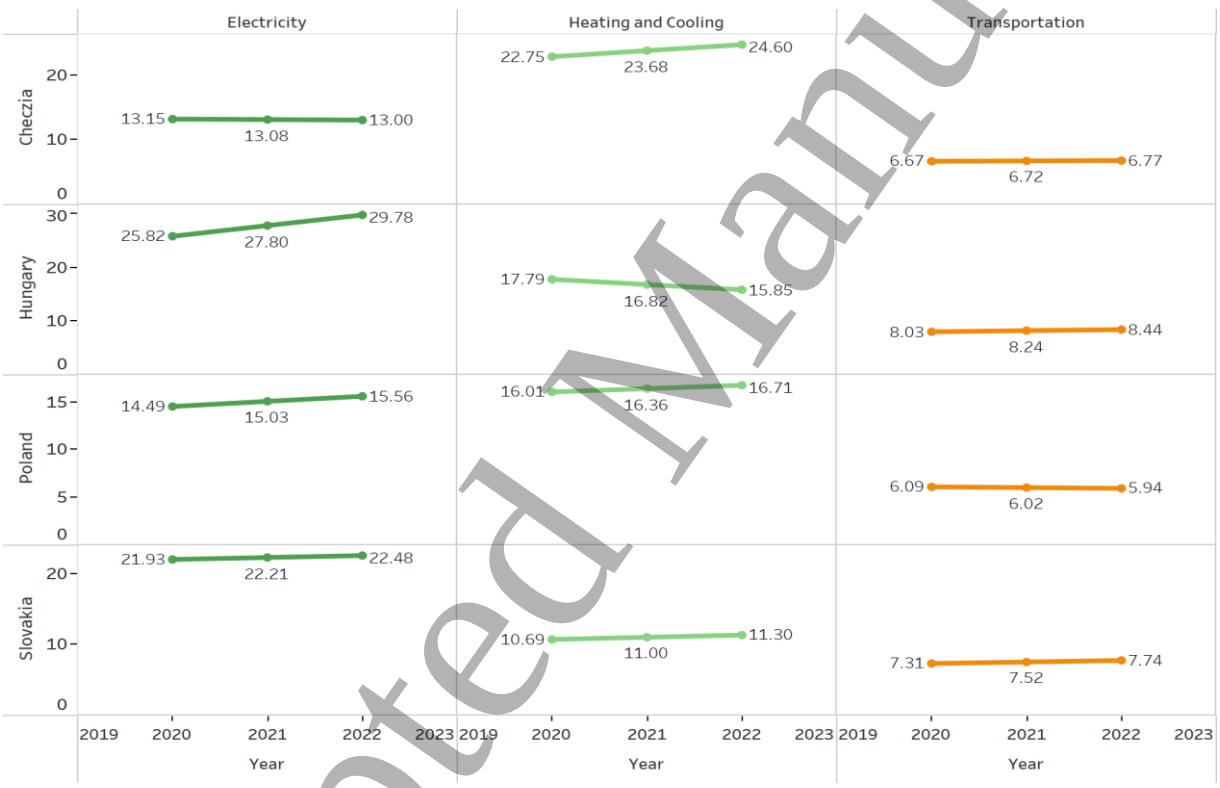

Figure 2. *Forecasts on renewable energy consumption in the transportation, electricity, and heating and cooling sectors from 2020 to 2022. Source: Authors' own compilation.*

Our projections for renewable energy consumption between 2020 and 2022 in **Figure 2** illustrate that transport sectors in Czechia, Hungary, and Slovakia will use, respectively, 6.77%, 8.44%, and 7.74% more renewable energy in 2022. The electricity sectors in Hungary, Poland, and Slovakia will see the most dramatic growth, at 29.78%, 15.56%, and 22.48%, respectively. Renewable energy use in heating and cooling systems is expected to rise by 24.60% in Czechia, 16.71% in Poland, and 11.3% in Slovakia. The projected growth in renewable energy consumption across all energy sectors will help reduce emissions and create a more sustainable energy landscape in these countries. This growth is indicative of a larger trend of increasing renewable energy consumption in Europe.

Box 1. *The European Union (EU) has recently made some significant strides in the realm of renewable energy* [36].

- *The European Union (EU) obtained 22% of its total energy consumption in 2021 from renewable energy sources.*
- *Renewable energy production helped to reduce greenhouse gas (GHG) emissions by 32% in 2020 in the 27 EU Member States.*
- *Renewable energy for the transport sector in the EU rose from under 2% in 2005 to 10.2% in 2020.*
- *The Renewable Energy Directive mandates that by 2030, the European Union's (EU) gross final energy consumption must be comprised of at least 32% renewable energy.*
- *The REPowerEU Plan envisions a more rigorous goal of 45% by 2030 to pave the path for carbon neutrality by 2050.*

Source: European Environment Agency 2023 [39].

However, the European Union (EU) is already in the midst of a transition to renewable energy. It has been more challenging to transition to renewable energy in the transportand heating sectors than in the electrical industry. Increasing reliance on variable energy sources like wind and solar will strain the power infrastructure. In order to meet the revised goals, set for 2030 and 2050, renewable energy sources must expand rapidly across all industries.

4.1 Renewable energy in electricity

According to our Principal Component Analysis, Slovakia's electricity comes from non-conventional, renewable sources. This is largely due to the country's commitment to reducing its carbon footprint and its aim to become a leader in sustainable energy. Renewable sources such as hydroelectric, solar, and geothermal power now account for nearly 30% of Slovakia's electricity production. However, our forecast for 2022 shows that renewable energy sources will account for 29.78% of Hungary's electricity generation. This puts it far ahead of the rest of the V4 countries. This is a significant increase from the 21.01% share in 2020, and it is expected to continue to rise in the coming years. The government has been encouraging investments in renewable energy sources, and this has been paying off. This trend is likely to continue in the future. Poland was unable to meet the EU's 2020 obligation to meet a 20% share of the final energy mix from renewable sources [27].

The Viségrád nations represent an example of a group of states from Central Europe with shared interests that need to branch out beyond national borders for expanding their blooming energy industries[40]. Practically, the traditional energy produced by the fossil fuels industry is still more user-friendly and commercially feasible than renewable energy materials[41]. The present research indicates that international accords have the potential to expedite the development of new technologies relating to a variety of renewable energy sources. However, when examining various energy-related industries in further detail, electricity production is the largest percentage of renewable energy sources among most of the EU member countries. For instance, over 80% of Austria's power energy comes from renewable sources, making the nation a leading position in Europe. If Austria is used as a model for standards, it can be shown that the nation produces over 60 percent of its electrical energy from hydropower, approximately 10 percent from wind energies, and 18 percent from fossil fuel[38]. On the other hand, it is difficult for any of the Visegrád nations to achieve similar proportions of energy from renewable sources in their overall electrical mix.

Nevertheless, there are obvious distinctions among these countries in terms of their energy structure. Despite all four nations utilize fossil fuel and nuclear-based energy to some extent, Poland is not sufficiently well-resourced for a green transformation due to its high percentage (81%) of fossil fuels used to generate electricity. Around 70% of all greenhouse gas emissions come from coal burning. According to Heilmann et al. Poland is the only country that wants to keep using coal until the middle of the century, whereas Slovakia, the Czech Republic, and Hungary have all stated intentions to phase out coal use by 2023, and 2025, respectively [37]. Slovakia has made the greatest progress in decarbonizing its electrical system among the Visegrád group, producing 24% of its electricity from renewable sources despite maximum of it being generated from nuclear energy.

Notably, the use of coal for energy in Slovakia has considerably decreased, accounting for just 7% of all energy used. The two main sources of electrical energy in the Czech Republic are nuclear power (37%) and coal (40%). Nuclear power provides 46% of Hungary's energy, subsequent to coal and natural gas, together accounting for 37% of the country's total energy consumption[38]. In contrast to Austria, the Visegrád nation's attempts to reduce carbon emissions are based on nuclear energy which is a cheap and dependable option to minimize carbon emissions. Building on historical precedent, half of the energy consumed to generate power in Slovakia and Hungary that are derived from nuclear sources, while Czechia aspires to eventually increase its nuclear contribution to a comparable level. In this pertinent, Kochanek [39] stated that presently, Poland refrains from

using nuclear energy, although the country has aspirations to build its very first nuclear energy plant by 2030.

4.2 Renewable energy in heating and cooling

Our PCA shows Hungary and Chechia use more renewable energy sources than the other two countries. Slovakia uses the least renewable energy for heating and cooling. Our analysis predicts a 24.60% rise in renewable heating and cooling energy use in Checzia. Poland is close behind, with a predicted increase of 16.71%. Slovakia is expected to see a much lower increase of 11.30%. These results indicate a shift towards renewable energy usage for heating and cooling in the region.

In 2018, renewable energy contributed 21% of the EU's total heating and cooling energy demand. This percentage has grown consistently since 2004 when it was 12% and data gathering began. The rising demand for renewable energy to heat and cool buildings can be attributed to the expansion of manufacturing, services, and individual households. Sweden's use of renewable energy for heating and cooling in 2018 made it the leader among EU Member States. In Latvia (56%), Finland (55%) and Estonia (55%), renewable energy sources accounted for more than half of the total energy utilised for heating and cooling. By contrast, only 6% of heating and cooling in Ireland and the Netherlands, 8% in Belgium, and 9% in Luxembourg came from renewable sources [42].

Furthermore, the building industry is the second-largest energy user in Europe, consuming nearly half of the energy utilized for heating and cooling in both industrial and residential sectors [38]. According to the report of Eurostat (2023), buildings are able to be heated and cooled using renewable energy sources such as generated heat and energy obtained from the air, the earth, and the water through the use of heat pumps. An analysis of the proportion of renewable energy utilized for heating and cooling in the Visegrád nations, Austria, and the EU27 in the year of 2020 has been highlighted by Riepl & Zavarská [38], demonstrating the contributions made by the preceding heat acquiring technologies. When it comes to the usage of renewable energy for heating and cooling, Austria once again leads the pack with 35%, attributable in large part to the country's adoption of the cutting-edge environmentally conscious technologies of energy-efficient heat pumps and generated heat, which together represent more than 30% of the total energies. On the other hand, in the EU, almost 25% of all the energy utilized for heating and cooling was obtained from renewable sources.

Notably, the Visegrád nations are performing admirably when regard to the environmental enhancement of the construction industry, and by 2020 they will nearly achieve the average level of the EU. National financial programs that accelerate energy-efficient building development and renovation have been accountable for this significant advancement of the building industry. Especially, the "Green Savings Program," which provides residents with access to financial schemes for restoration and also for efficient building, may be related to the recent advancements in Czechia. Similarly, Poland intends to replace boilers heated by coal and insulate buildings with the establishment of a national program. During the last 20 years, Slovakia has achieved enormous accomplishments towards environmentally conscious buildings by boosting energy efficiency as well as enhancing the proportion of renewable energy utilized by communities. Pertinently, Heilmann et al. [34] stated that insulation has been installed in around sixty percent of all apartment buildings at this point; if the current pace of installation remains attained, it is projected that all apartment buildings will be insulated by the year 2030.

Furthermore, the government of Slovak has promoted the generation of heat and electricity from relatively modest in size to domestic renewable energy platforms using the "Greening for Households" initiative [39]. Similarly, Hungary's 'Warmth of Home' campaign encourages homeowners to install energy-efficient technologies in their homes. On the other end of the spectrum, as is evident, Hungary's proportion of renewable energy in the construction industry lags behind that of its competitors, mostly as a result of its prolonged dependence on gas sources. However, the transformation of the building industry is still in its early stages in all of the four Visegrád nations because of their lately started recent installation of green technology such as heat pumps or extracted heat. It is possible that the "EU Recovery and Resilience Facility" support, which comprises investments in this direction, may provide some support in this instance.

4.3 Renewable energy in transport

The Renewable Energy Directive (RED) mandated in 2009 that all Member States use renewable energy for at least 10% of their transport energy needs by 2020. The RED introduced the concept of counting only biofuels that adhere to specific sustainability standards for renewable energy contribution. Since 2005, when it was just under 2%, the percentage of renewable energy used in transport in the EU has steadily increased, reaching 10.2% in 2020. This means that the EU met its 2020 goal of 10% [43]. Our PCA reveals that transport accounts for a growing share of renewable energy consumption in both the Czech Republic and Slovakia. In contrast to Slovakia, where it has shown significantly more volatility, the number of people using renewable energy in various modes of transport has been gradually rising in the Czech Republic. According to our analysis, Hungary is well-positioned to become a Visegrad country leader in renewable

energy sources in the transportation industry. To facilitate this, the Hungarian government should introduce incentives for the adoption of renewable energy in the transport sector. Moreover, Hungary should prioritise research and development in renewable energy technologies to ensure the long-term sustainability of this sector.

Furthermore, different countries have made different amounts of improvements. Only 12 EU member states (Sweden, Finland, the Netherlands, Luxembourg, Estonia, Hungary, Belgium, Slovenia, Italy, Malta, Austria, and Ireland) appear to have met the 2020 objective of 10%, according to figures from Eurostat. According to preliminary estimates, Italy and Ireland also saw declines below the 2020 goal of 10% in 2021. As economic activity recovered following the COVID-19 pandemic, the gross final consumption of energy from all fuels in transportation increased. Meanwhile, in 2021, the objective of 10% was met in Denmark, Portugal, and Spain. Energy and carbon taxes are used in Sweden, the country with the largest share of renewable energy in transport, to meet the country's lofty goals in this area. Since 1991, a carbon tax has been applied to fuels; sustainable biofuels qualify for exemptions and reduced rates. Another major energy consumption sector is the transport industry, which is facing considerable obstacles to ecological restoration due to remarkably minimal usage of renewable energies across the Visegrád nations. In terms of increasing the proportion of renewable energy in their transport networks, the countries don't seem to be falling behind. All Visegrád nations, with the exception of Poland, have reached the required levels of green energy production that are comparable to Austria and other EU countries. The research of Riepl & Zavarská [38]shows that among the nations under consideration, Hungary has the largest percentage of energy derived from renewable sources in its transportation sector. Notably, among all the Visegrád nations (as well as the other EU countries), the majority of green energies are utilizing for the transport sector depends on compatible biofuels.

The concern point is that e-fuels are facing large challenges because of their poor level of energy efficiency. In comparison, a biofuel-powered car can only convert 10–15% of the energy it uses into acceleration, whereas a vehicle powered by electricity can convert 70 to 80% of the energy it uses. Because of this, experts have discarded the concept that biofuels would play an integral role in the transformation of the transportation industry to a more environmentally friendly one[41]. Consequently, the future for compliant biofuels seems less promising since only a very small percentage of transportation is powered by other renewable energy sources. This is evidence of a poor political choice made throughout the European Union to gamble on biofuels over the last several decades rather than electrified public transport as well as train infrastructure.

The Visegrád Group of countries will be able to tackle major obstacles with the help of the policies and strategies suggested here:

1. According to our research and projections, high levels of consumption of renewable energy will be seen in the following sectors in the year 2022: 29.78% in the Electricity sector in Hungary and 22.48% in Slovakia; 24.60% in the consumption of heating and cooling in Checzia and 16.71% in Poland; and 8.44% in the transportation sector in Hungary and 7.71% in Slovakia. The V4 countries will need to increase the share of their economies that use renewable and alternative resources to keep up with projected energy demand growth.

2. The level of public acceptance and support for climate mitigation measures is crucial to the V4 country government's efforts to transition to a greener economy. The results will be a decrease in carbon emissions and increased interest in environmental preservation. Also, it can potentially increase employment opportunities and boost the renewable energy industry.

3. Investment in renewable energy technologies such as solar and hydropower in Hungary, bioenergy in Poland, and wind power in Slovakia and the Czech Republic can help reduce the environmental impact of human activities and create a more sustainable future.

4. Despite significant recent advances in modernising the building sector, the Visegrád countries have not placed enough focus on the development of in-novative technologies such as derived heat or heat pumps.

5. Our projection shows that Hungary has the most significant potential to increase 24.6% renewable energy use in the heating and cooling sectors by 2022. So, in Hungary, expanding the utilisation of renewable energy sources for heating and cooling can be accomplished by applying thermoelectric systems, energy storage, and various renewable energy resources.

6. The Visegrád Group Countries should collaborate to promote energy decou-pling towards renewables to ensure energy independence and security to pave the path for carbon neutrality by 2050.

This research proposes that the use of renewable energy sources in Visegrád countries has both advantageous economic outcomes and accompanying costs. The deployment of renewable energy in the European Union (EU) and its Member States (MS) offers several

advantages, such as reduced carbon dioxide (CO2) emissions and savings in fossil fuel consumption. These benefits are somewhat lower than the associated regulatory costs. The increasing utilisation of renewable energy sources in electricity generation within the Visegrád countries will have a significant impact on electricity prices. Specifically, Hungary and Slovakia which have embraced a higher proportion of renewable energy in their energy mix have experienced a decline in prices, while those with limited adoption of renewable energy sources like Checzia and Poland have witnessed price escalations. The net positive impact of renewable energy utilisation in the European Union (EU) during the oil price cycle can be attributed to the increasing adoption of renewable energy sources. In Czechia and Poland, renewable energy sources are increasingly important in the production of heating and cooling. The adoption of environmentally friendly biofuels in the transportation sector can help Visegrád countries reduce CO2 emissions and transportation costs, and it will improve human well-being. Additionally, the EU's commitment to reducing greenhouse gas emissions has promoted the development and implementation of renewable energy technologies. The transition towards renewable energy sources not only mitigates reliance on non-renewable fossil fuels but also engenders novel employment prospects and nurtures advancements in technology. Consequently, the European Union (EU) is making notable strides in attaining its renewable energy objectives and addressing the adverse consequences of climate change.

5. Conclusions

Despite significant progress towards a greener economy, the Visegrád countries lag behind their EU counterparts on a wide range of critical aspects of the green energy transition. As a result, it is imperative that the Visegrád economies identify and overcome the primary obstacles impeding the spread of green technologies if they are to successfully converge on the route to climate neutrality. Despite the widespread cross-country variances in the progress made thus far, it is helpful for EU policymakers to have a better grasp of the unique difficulties faced by the Visegrád countries in order to facilitate a productive climate discussion. We pinpoint five primary areas of progress and concern.

1. Checzia's renewable energy use in the transport sector was on the rise, whereas in Slovakia it was subject to significantly wider swings. Increasing the use of renewable energy in transport is a crucial step towards meeting Europe's carbon emissions reduction target.

2. The percentage of electricity generated from renewable sources rose by 116% in Poland and 87% in Checzia over that period. As a result, it ap-pears that both nations are expanding their reliance on sustainable forms of energy production.

3. Heating and cooling demand in Slovakia is up 149% from 2010 demonstrating the fastest proportional rate of change. As a result, renewable energy demand in Slovakia is growing to meet rising heating and cooling demands in buildings due to an uptick in industrial production, an ex-pansion of service sectors, and new residential construction.

4. Our forecast indicates that between 2020 and 2022, Hungary will have the highest penetration of renewable energy consumption in both the transportation (8.44%) and electrical (29.78%) industries. And as a market leader in heating and cooling, Checzia will hold a significant 24.60% share of the industry in 2022.

5. Our research showed that the growth of renewable energy had increased by 149% in Slovakia, 116% in Poland, and 87% in the Czech Republic. But in Hungary, it has either slowed down or is shrinking. These findings in-dicate that the V4 countries have made significant strides towards relying on renewable energy. Nevertheless, necessary measures must be taken to ensure that Hungary will be able to achieve the same level of success as its neighbours.

Solidarity in the green transition among Visegrad member states is crucial for reaching the ambitious climate targets set by the EU, given the accompanying positive externalities and the constraints discussed in this article. With its advanced position on the transition pathway and extensive ties to Central European economies, Hungary is in a prime position to aid the Visegrád countries in their efforts to achieve the green revolution.

However, this research has some limitations, such as its narrow focus on the current performance of renewable energy in the V4 nations and its projections for future generation, which may not be reliable and constantly fluctuate due to the ongoing armed conflict between Russia and Ukraine. Furthermore, the unavailability of the latest data was another constraint. The purpose of this study was to assess statistics on the share of renewable energy between 2010 and 2019 and to extrapolate the energy performance between 2020 and 2022. Nevertheless, transitioning to a sustainable and clean energy system requires rapid and radical changes in critical sectors such as transportation, electricity, and heating and cooling, as well as establishing the required infrastructure and governance, which requires

more research. Moreover, it is imperative to comprehend the social, economic, and environmental ramifications associated with this transition. The analysis of possible benefits for job creation, economic growth, and public health, along with the identification of potential bottlenecks and problems that could impede the adoption of renewable energy, is of utmost importance. Furthermore, it is imperative for policymakers and stakeholders to engage in collaborative efforts aimed at formulating comprehensive laws and regulations that effectively encourage the transition to environmentally friendly energy sources and facilitate the advancement of renewable technology. The achievement of a successful and sustainable transition to a renewable energy system necessitates the undertaking of extensive study and further research.

Patents

Data Availability Statement: The data that were used to support this article can be accessed at https://ec.europa.eu/eurostat/web/main/data/database.

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References

[1] European Environmental Agency, “Share of energy consumption from renewable sources in Europe,” *EEA*, 2021. https://www.eea.europa.eu/ims/share-of-energy-consumption-from (accessed Jan. 15, 2022).

[2] European Commission, “Communication from the Commission: Energy for the Future: Renewable Sources of Energy–White Paper for a Community Strategy and Action Plan,” 1997. [Online]. Available: http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Communication+from+the+Commission+ENERGY+FOR+THE+FUTURE+:+RENEWABLE+SOURCES+OF+ENERGY+White+Paper+for+a+Community+Strategy+and+Action+Plan#0

[3] N. Afsharzade, A. Papzan, M. Ashjaee, S. Delangizan, S. Van Passel, and H. Azadi, “Renewable energy development in rural areas of Iran,” *Renew. Sustain. Energy Rev.*, vol. 65, pp. 743–755, Nov. 2016, doi: 10.1016/j.rser.2016.07.042.

[4] R. Rezaei and M. Ghofranfarid, “Rural households’ renewable energy usage intention in Iran: Extending the unified theory of acceptance and use of technology,” *Renew. Energy*, vol. 122, pp. 382–391, Jul. 2018, doi: 10.1016/j.renene.2018.02.011.

[5] M. F. Rabbi, J. Popp, D. Máté, and S. Kovács, “Energy Security and Energy Transition to Achieve Carbon Neutrality,” *Energies*, vol. 15, no. 21, p. 8126, Oct. 2022, doi: 10.3390/en15218126.

[6] “The European Green Deal - Florence School of Regulation,” *FSR*, 2020. https://fsr.eui.eu/the-european-green-deal/ (accessed Jan. 23, 2022).

[7] R. Hinrichs-Rahlwes, *Sustainable Energy Policies for Europe: Towards 100% Renewable Energy*, 1st ed. London: CRC Press, 2013. doi: 10.1201/b15934.

[8] C. V. Sager-Klauß, *Energetic communities: Planning support for sustainable energy transition in small- and medium-sized communities*, vol. 5. 2016.

[9] B. L. Göke, C. Kemfert, M. Kendziorski, and C. Von Hirschhausen, “Expansion Planning Needed Coordinated Expansion Planning Needed,” 2021. doi: https://doi.org/10.18723/diw_dwr:2021-29-1.

[10] Energy Research Institute, “China’s Sustainable Energy Future: Scenarios of Energy and Carbon Emissions,” Berkeley, CA, Mar. 2003. doi: 10.2172/882064.

[11] T. Rokicki and A. Perkowska, “Changes in Energy Supplies in the Countries of the Visegrad Group,” *Sustainability*, vol. 12, no. 19, p. 7916, Sep. 2020, doi: 10.3390/su12197916.

[12] R. MAGDA, N. Bozsik, and N. Meyer, “An evaluation of gross inland energy consumption of six Central European countries,” *J. East. Eur. Cent. Asian Res.*, vol. 6, no. 2, pp. 270–281, Nov. 2019, doi: 10.15549/jeecar.v6i2.291.

[13] BloombergNEF, “Climatescope 2022 | Czechia,” 2023. https://www.global-climatescope.org/markets/cz/ (accessed Sep. 14, 2023).

[14] “Czech Statistical Office - Online Database.” Accessed: Jan. 16, 2022. [Online]. Available: https://vdb.czso.cz/vdbvo2/

[15] H. Obrusnikova, “Czech Republic - Energy,” *Privacy Shield Framework*, 2017. https://www.privacyshield.gov/article?id=Czech-Republic-Energy (accessed Jan. 16, 2022).

[16] Hnutí Duha, “Energie 2020 – část Uhelná energetika,” 2020. [Online]. Available: https://www.hnutiduha.cz/sites/default/files/publikace/2020/06/vytahnute_uhli_focus_pro_hnuti_duha_energie_2020.pdf

[17] “CEZ plans to cut coal-fired output, raise renewables by 2030,” *Reuters*, 2021. https://www.reuters.com/business/energy/cez-plans-cut-coal-fired-output-raise-renewables-by-2030-2021-05-20/ (accessed Jan. 16, 2022).

[18] I. Bart, D. Csernus, and F. Sáfián, "Analysis of climate-energy policies & implementation in Hungary," 2018. [Online]. Available: https://eko-unia.org.pl/wp-content/uploads/2018/06/mini-report-1_Hungary.pdf

[19] BloombergNEF, "Climatescope 2022 | Hungary," 2023. https://www.global-climatescope.org/markets/hu/ (accessed Sep. 14, 2023).

[20] Hungarin Ministry of National Development, "National Energy Strategy 2030," 2012. [Online]. Available: https://2010-2014.kormany.hu/download/7/d7/70000/Hungarian Energy Strategy 2030.pdf

[21] Mycle Schneider, "The World Nuclear Industry - 2020 Status Report," Paris, Frabce, 2020. [Online]. Available: https://www.fsb.org/wp-content/uploads/P291020-1.pdf

[22] M. Antal, "How the regime hampered a transition to renewable electricity in Hungary," *Environ. Innov. Soc. Transitions*, vol. 33, no. April, pp. 162–182, Nov. 2019, doi: 10.1016/j.eist.2019.04.004.

[23] REGlobal, "Assessment of Poland's renewable energy policy," 2023. https://reglobal.org/assessment-of-polands-renewable-energy-policy/ (accessed Sep. 14, 2023).

[24] L. Gawlik, "The Polish power industry in energy transformation process," *Miner. Econ.*, vol. 31, no. 1–2, pp. 229–237, May 2018, doi: 10.1007/s13563-017-0128-5.

[25] H. Nyga-Łukaszewska, K. Aruga, and K. Stala-Szlugaj, "Energy Security of Poland and Coal Supply: Price Analysis," *Sustainability*, vol. 12, no. 6, p. 2541, Mar. 2020, doi: 10.3390/su12062541.

[26] M. Ruszel, "The significance of the Baltic Sea Region for natural gas supplies to the V4 countries," *Energy Policy*, vol. 146, no. July 2019, p. 111786, Nov. 2020, doi: 10.1016/j.enpol.2020.111786.

[27] "Poland - Energy Sector," *International Trade Administration*, 2021. https://www.trade.gov/country-commercial-guides/poland-energy-sector (accessed Jan. 21, 2022).

[28] BloombergNEF, "Climatescope 2022 | Slovakia," 2023. https://www.global-climatescope.org/markets/sk/ (accessed Sep. 14, 2023).

[29] ITA, "Energy Resource Guide - Slovakia - Renewable Energy," *International Trade Administration*, 2021. https://www.trade.gov/energy-resource-guide-germany-renewable-energy (accessed Jan. 22, 2022).

[30] Energiewende Team, "The Slovak energy transition – decarbonisation and energy security," *Energy Transition*, 2017. https://energytransition.org/2017/05/the-slovak-energy-transition-decarbonisation-and-energy-security/ (accessed Jan. 22, 2022).

[31] J. W. McKean, "Robust Analysis of Linear Models," *Stat. Sci.*, vol. 19, no. 4, pp. 562–570, Nov. 2004, doi: 10.1214/088342304000000549.

[32] H. Hotelling, "Analysis of a complex statistical variables into principal components 8. Determination of principal components for individuals.," *J. Educ. Psychol.*, vol. 24, pp. 498–520, 1933.

[33] P. D. R. Hammer, Øyvind, Harper, David A.T., "Past: Paleontological Statistics Software Package for Education and Data Analysis," 2001. [Online]. Available: https://palaeo-electronica.org/2001_1/past/past.pdf

[34] N. M. Pham, T. L. D. Huynh, and M. A. Nasir, "Environmental consequences of population, affluence and technological progress for European countries: A Malthusian view," *J. Environ. Manage.*, vol. 260, no. December 2019, p. 110143, Apr. 2020, doi: 10.1016/j.jenvman.2020.110143.

[35] M. Shahbaz, C. Raghutla, K. R. Chittedi, Z. Jiao, and X. V. Vo, "The effect of renewable energy consumption on economic growth: Evidence from the renewable energy country attractive index," *Energy*, vol. 207, p. 118162, Sep. 2020, doi: 10.1016/j.energy.2020.118162.

[36] M. Hasan, M. Z. Abedin, M. Bin Amin, M. Nekmahmud, and J. Oláh, "Sustainable biofuel economy: A mapping through bibliometric research," *J. Environ. Manage.*, vol. 336, no. March, p. 117644, Jun. 2023, doi: 10.1016/j.jenvman.2023.117644.

[37] F. Heilmann, R. Popp, and A. D. A. Ámon, *The Political Economy of Transition in Central and Eastern Europe*, no. January. Routledge, 2019. doi: 10.4324/9780429438509.

[38] T. Riepl and Z. Zavarská, "Towards a Greener Visegrád Group: Progress and Challenges in the Context of the European Green Deal," 2023. [Online]. Available: https://wiiw.ac.at/towards-a-greener-visegrad-group-progress-and-challenges-in-the-context-of-the-european-green-deal-dlp-6430.pdf

[39] "Renewable energy," *European Environment Agency*, 2023. https://www.eea.europa.eu/en/topics/in-depth/renewable-energy (accessed Jul. 12, 2023).

[40] C. Hann, *Repatriating Polanyi: Market Society in the Visegrád States*. Budapest, 2019. doi: 10.14434/aeer.v39i1.35398.

[41] K. H. Bachanek, B. Tundys, T. Wiśniewski, E. Puzio, and A. Marouškovᡠ, "Intelligent Street Lighting in a Smart City Concepts—A Direction to Energy Saving in Cities: An Overview and Case Study," *Energies*, vol. 14, no. 11, p. 3018, May 2021, doi: 10.3390/en14113018.

[42] "Renewable energy for heating and cooling," *Eurostat*, 2020. https://ec.europa.eu/eurostat/web/products-eurostat-news/-/ddn-20200211-1 (accessed May 22, 2023).

[43] EEA, "Use of renewable energy for transport in Europe," 2021. https://www.eea.europa.eu/ims/use-of-renewable-energy-for (accessed May 22, 2023).