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Renewable energy sources management in the EU-27 countries

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Abstract
Effective ways of reducing harmful emissions in the energy sector include, in particular, increasing the efficiency of energy conversion from non-renewable energy sources, the wider use of renewable energy sources and on the other hand, the rational use of energy by consumers. This study deals with the application of renewable energy sources (green energy), which, in addition to environmental benefits, also increase the state's independence from the import of fossil fuels. The world trend is clearly moving towards more intensive use of these clean green energies. Therefore, their higher use is included among the strategic goals of energy policy in most countries of the world, in EU countries, including Slovakia. The paper aims to examine the most important renewable energy sources producing green energy in the EU-27 member states in the period of 2010-2020. The subject of the research is the indigenous production of geothermal energy, solar thermal energy, primary solid biofuels, biogases, and renewable municipal waste. The analyzed EU countries differ in the most important renewable energy production. The countries of northern Europe are the Union leaders in producing energy from waste. Italy is a leader in the use of geothermal energy. The countries of northern Europe, including the Baltic States, are making progress in the production of solar energy. The cluster analysis resulted in the identification of countries with similar characteristics in the case of the development of domestic production of selected renewable sources in the examined period. The analysis showed the development of indicators had not changed significantly over the last decade, although some countries have moved within the established clusters.

Keywords
renewable energy sources, energy management, cluster analysis, indigenous energy production, crisis, EU countries

Introduction

In the last three decades, there has been observed an increasing trend in greenhouse gas (GHG) emissions and a huge increase in carbon dioxide (CO_2) emissions in the world (Shahnazi & Dehghan Shabani, 2020). Therefore, most developed countries are moving toward renewable energy production with fewer negative environmental effects (Brini et al., 2017; Neagu et al., 2022) to help mitigate climate change (Stupak et al., 2007) and increase energy security (Aized et al., 2018).

The European Union (EU) has been particularly active in tackling global warming in regard to engaging in international climate change agreements, as well as setting out clear targets to curb environmental pollutants (Skare et al., 2023). To this extent, the EU has been a signatory part of several climate action agreements and has set clear, long-term targets for reducing GHGs (Green House Gases) (Halicioglu & Ketenci, 2018). The EU has been spearheading the implementation of the legally binding Paris Agreement (also known as 'the 21st Conference of the Parties' short COP21) on climate change, which was signed by 195 countries in 2015. This agreement does not set out any detailed timetable or country-specific goals for GHGs; the agreement set a goal of limiting global warming to 1.5°C, which requires zero emissions sometime between 2030 and 2050. But the EU sets out more ambitious targets to reduce the GHGs; it aims at reducing GHGs by at least 40% by 2030 compared with 1990. By 2050, the EU wishes to achieve an 80–95% reduction in GHGs compared with 1990. In order to achieve these targets, the EU promotes green energy production by substituting non-renewable energy production with renewable energy production. The EU targeted that the share of renewable energy in production will be at least 27% by 2030 (Halicioglu & Ketenci, 2018). According to the International Energy Agency (IEA, 2021), the worldwide capacity for renewable power will increase by 50% in the coming years, including the expected solar photovoltaic energy growth of 60%. In addition, bioenergy capacity is expected to increase, especially in China, India, and the EU (Marra & Colantonio, 2022; Stankuniene et al., 2020). In the EU, primary renewable energy production (REP) increased by 49% between 2008 and 2018. The most important source was wood and other biofuels, which accounted for more than 40%. Despite low levels of production, the output of biogas and solar energy increased fast, accounting for 7% and 6%, respectively, of the EU's REP (EC, 2021). The aim of the paper is to examine the most important renewable energy sources producing green energy in the EU-27 member states in the period of 2010-2020.

Theoretical background

Since the world faced the oil crisis in 1973 and the interruption of European natural gas supplies caused by the Ukraine-Russia natural gas conflict in 2009, people started to realize the limitation of fossil energy resources coupled with concerns over the effects of increasing carbon dioxide in the atmosphere, major efforts were devoted to the search for alternative energy sources (deLlano-Paz et al., 2016; Laimer et al., 2015; Demski et al., 2018). The European Union imports most of its gross energy consumption from non-EU member states. Dependence on energy imports also became apparent during the crisis caused by the COVID-19 pandemic, and it is also fully evident at this time when the war in Ukraine is raging. Its import dependency is particularly high for crude oil (88%) and natural gas (70%). A number of studies measured and monitored energy dependence by investigating the diversity and fossil fuels import dependence (Vonsée et al., 2019; Streimikiene et al., 2021). In this context, the huge potential of energy sources, which could replace fossil fuels, has generated a significant interest towards the sustainable production of renewable energy. The term 'sustainable development' is used to mean development that meets the needs of the present generation without compromising the needs of future generations. In the strictest sense, the sustainability of a resource is dependent on its initial quantity, its rate of generation and its rate of consumption (Simionescu et al., 2022; Can et al., 2022; Ahmad et al., 2022). In addition to environmental benefits, the application of renewable energy sources also increases the state's independence from fuel and energy imports, saves foreign exchange, and generates potential economic benefits for companies (Belas et al., 2019; Akram et al. 2022; Oláh et al., 2022) and creates new jobs, with an impact on the living standards of employees (Vrabcova et al. 2022; Suhányiová & Suhányi, 2017; Gavurova et al., 2022). Renewable energy sources include, for example, geothermal sources, solar thermal sources, primary solid biofuels, biogases and also renewable municipal waste.

Geothermal energy is the energy contained as heat in the Earth's interior. Despite the fact that this heat is present in huge, practically inexhaustible quantities in the Earth's crust, not to mention the deeper parts of our planet, it is unevenly distributed, seldom concentrated, and often at depths too great to be exploited industrially (Barbier, 2002). The temperature of rocks increases with depth, proving that a geothermal gradient exists: this gradient averages 30°C/km of depth. The average heat flow from the continental crust (granite) is 57 mW/m^2, and through the oceanic crust (basalt) is 99 mW/m^2. The Earth's average heat flow is 82 mW/m^2, and the total global output is over 4×10^{13} W (Uyeda et al., 1988), four times more than the world energy consumption, which is 10^{13} W (Silvestri, 1989). The energy gap caused by declining fossil resources has to be filled by expanding the production of other sources. Geothermal energy is one of the most important options for filling this gap (Acar & Sorgun, 2009). Over the last ten years, a substantial number of projects have been developed throughout the EU, and geothermal power is on its way to become an important player in the EU energy mix (EGEC, 2017). From an economic point of view, geothermal power is a relatively cheap technology. The levelized cost of electricity (LCOE) production of geothermal is close to onshore wind power (Li et al., 2015).

The solar energy industry develops methods and resources for using solar emissions or solar radiation to produce electrical, thermal and other types of energy (Bórawski et al., 2019). However, this industry has a significant disadvantage. The sun's rays that fall on the Earth's surface do not have a specific concentration point, which is why it needs to be captured and converted into an energy form that could be used more readily. There is also a problem with the availability of solar energy at night and on dark days. But these problems can be solved. Now the main thing is to make the cost competitive. Two popular ways of converting solar energy are photovoltaics (PV) and concentrated solar power. But photovoltaic technology has much wider use in the field for several reasons (Bórawski et al., 2019). Despite the fact that if only one-tenth of solar energy were collected and distributed, the problems of energy supply on Earth would disappear (Laustsen, 2008), the installation of new solar capacities for electricity production has slowed down worldwide (Stević et al., 2019). If solar energy collected in a single year could be preserved and converted into electric energy, it would cover global energy consumption for the next 6000 years (Finnveden et al., 2003); the potential of solar energy is enormous: about 885 million terawatt hours (TWh) per year.

Bioenergy (in the form of **biofuels**) is also a promising option to replace fossil fuels and to mitigate emissions that cause anthropogenic climate change (Arodudu et al., 2017; Cross et al., 2017). Biomass represents an abundant carbon-neutral renewable resource for the production of bioenergy and biomaterials (Ragauskas et al., 2006). Biomass for energy purposes (bioenergy) contributes around 10% to the total global primary energy supply (Edenhofer et al., 2011). For its production are also used so-called bioenergy buffers, which are linear landscape elements cultivated with perennial herbaceous or woody biomass crops placed along arable field margins and watercourses (Ferrarini et al., 2017). Almost two-thirds of the bioenergy is used locally in traditional cooking and heating applications (WHO, 2014). The remaining one-third is used in a more effective way, with higher conversion efficiency and for the production of high-temperature heating, power, or road transportation (Lamers et al., 2012; Edenhofer et al., 2011; IEA, 2010; Chum et al., 2011). While solid biofuels are not yet traded to the extent of liquid biofuels, they are expected to become the next global commodity; their trade has grown in the last two decades. Wood pellets grew strongest; other relevant streams included wood waste, fuelwood, wood chips, residues, and roundwood (Lamers et al., 2012, Christoforou & Fokaides, 2018). Forest-derived solid biofuels are the most utilized forms of bioenergy and the main source of renewable energy worldwide (Ghaderi et al., 2016), but they face numerous sustainability challenges (Wolf et al., 2016) as land use changes, biodiversity loss implications of forest impacts, the emission of pollutant gases, high water use, and emission of greenhouse gases (Harris et al., 2015; Mohr & Raman, 2013; Gasparatos et al., 2017; Ferrarini et al., 2017).

Natural degradation of organic material results in the production of **biogases** by microorganisms under anaerobic conditions. Anaerobic digestion converts organic material into biogas, a renewable fuel that could be used to produce electricity, heat or vehicle fuel (Scarlat et al., 2018). As part of a green economy, the bio-based economy plays a key role in replacing fossil fuels on a large scale, not only for energy applications but also for chemicals and materials applications (Scarlat et al., 2015). Biogas production plants for the treatment of wet-waste biomass, from wastewater treatment plants and landfill gas recovery, are expanding in a number of countries. Biogas upgrading to higher-quality biomethane is also increasing for use as a vehicle fuel or for injection into the natural gas grid (Scarlat et al., 2018). Several countries in Asia have large programmes for domestic biogas production (Vögeli et al., 2014). Thanks to the favourable support schemes in several EU countries, biogas production has seen significant growth in the last years, also in Europe. Most of the biogas in the EU is used as a fuel for electricity generation, in electricity only or combined heat and power plants. Gas engines are most commonly used, which can reach electrical efficiency of 35–40%, depending on gas engine type and size (Foreest, 2012).

Appropriate management of **municipal solid waste** involves controlling atmospheric emissions and aqueous effluents from landfills, waste collection, transportation, and waste processing (Tan et al., 2014). Transforming waste to energy is recognized as a promising alternative to overcome the waste generation problem and a potential renewable energy source. Energy can be recovered from biodegradable and non-biodegradable matter through thermal and biochemical conversions (Johri et al., 2011). Waste-to-energy technologies such as pyrolysis, gasification, incineration (in other words, thermochemical processes), and biomethanation and composting (biological processes) can convert municipal solid waste, as an appropriate source of renewable energy, into useful energy (electricity and heat) in safe and eco-friendly ways (Chand Malav et al., 2020; Tozlu et al., 2016). There are currently over 1700 WtE plants globally. Out of them, Asia Pacific holds 62%, followed by Europe (33%) and North America (4.5%) (Chand Malav et al., 2020). As stated by Levaggi et al. (2020), waste-to-energy could prevent the production of up to 50 million tons of CO_2 emissions in Europe that fossil fuels would otherwise generate. But the support for a large deployment of waste-to-energy plants is not universal. Concerns are reiterated that energy from waste may discourage more extensive recycling practices (Gradus et al., 2017; Dijkgraaf & Vollebergh, 2004; Miranda & Hale, 1997; Cucchiella et al., 2017).

Material and methods

The data subject to the following trend and cluster analysis are secondary data from Eurostat, the statistical office of the European Union. We examined the most important renewable sources to produce "green energy" in European countries, namely geothermal energy, solar thermal energy, primary solid biofuels, biogases, and renewable municipal waste. The status and development of indicators were analyzed in all 27 Member States. Some of the examined indicators are aggregated quantities; a more detailed breakdown is given in the following chapter.

We have monitored the development of indigenous production of selected renewable energy sources for the period from 2010 to 2020. Tab. 1 contains data on the development of the production of the five most important forms of "green" energy in the EU Member States. The development is shown by the AAGR (Average Annual Growth Rate) indicator.

The five calculated variables were then inputting variables for the cluster analysis. The AAGR is determined by taking the numerical mean of specified or calculated year-on-year growth rates. The formula is as follows:

$$Annual\ Average\ Growth\ Rate = [(Growth\ Rate)_y + (Growth\ Rate)_{y+1} + \ldots (Growth\ Rate)_{y+n}] / N \quad (1)$$

Where:
Growth Rate (y) – Growth rate in year 1
Growth Rate (y + 1) – Growth rate in the next year
Growth Rate (y + n) – Growth rate in the year "*n*"
N – Total number of periods

Tab. 1: AAGR of renewable energy indigenous production from 2010 to 2020 in the EU

Country	*Code*	*Geothermal*	*Solar thermal*	*Primary solid biofuels*	*Biogases*	*Renewable municipal waste*
Belgium	BE	0.9994	1.0411	0.9921	1.0272	1.0117
Bulgaria	BG	1.0044	1.0505	1.0291	***1.1614***	***1.4528***
Czechia	CZ	*zero*	1.0394	1.0184	1.0625	1.0214
Denmark	DK	0.9263	1.0855	0.9930	1.0830	***0.9965***
Germany	DE	1.0730	1.0224	0.9973	1.0291	1.0148
Estonia	EE	*zero*	*zero*	1.0293	1.0877	1.0118
Ireland	IE	*zero*	1.0321	1.0080	0.9945	1.1692
Greece	EL	0.9489	1.0097	1.0011	1.0518	*zero*
Spain	ES	1.0000	1.0809	1.0040	1.0078	1.0153
France	FR	1.0516	1.0569	0.9976	1.0486	1.0010
Croatia	HR	1.1136	1.0589	1.0061	1.1308	*zero*
Italy	IT	1.0056	1.0287	1.0008	1.0714	1.0040
Cyprus	CY	*zero*	1.0101	1.0456	1.0360	1.0207
Latvia	LV	*zero*	*zero*	1.0181	1.0939	1.0308
Lithuania	LT	***0.9133***	*zero*	1.0120	1.0700	1.0474
Luxembourg	LU	*zero*	1.0532	***1.0649***	1.0217	1.0130
Hungary	HU	1.0211	1.0526	0.9929	1.0463	1.0047
Malta	MT	*zero*	1.0181	*zero*	1.1184	*zero*
Netherlands	NL	***1.1600***	1.0084	1.0119	1.0188	1.0012
Austria	AT	1.0026	1.0053	1.0022	1.0141	1.0167
Poland	PL	1.0328	1.1095	1.0214	1.0531	1.2146
Portugal	PT	1.0049	1.0377	1.0017	1.0508	1.0076
Romania	RO	0.9963	***1.1103***	0.9932	1.0936	1.2489
Slovenia	SI	0.9738	1.0113	***0.9889***	***0.9940***	*zero*
Slovakia	SK	1.0060	1.0323	1.0294	1.1169	1.0194
Finland	FI	*zero*	1.0482	1.0037	1.0742	1.0419
Sweden	SE	*zero*	***1.0005***	1.0034	1.0260	1.0088
Maximum		*1.1600*	*1.1103*	*1.0649*	*1.1614*	*1.4528*
Minimum		*0.9133*	*1.0005*	*0.9889*	*0.9940*	*0.9965*

Source: authors according to Eurostat data

The most significant growth in geothermal energy production was recorded in the Netherlands over the decade under review (production grew by approximately 16% per year over the period 2010-2020), followed by Croatia (11.4%) and Germany (7.3%). According to the AAGR level, the most significant decrease was recorded in Lithuania in the same period (an average annual decrease of about 8.7 per cent). A positive finding is that solar energy production has increased on average each year in all Member States producing this form of energy. Romania recorded the highest AAGR (production grew by 11% per year), while Sweden recorded the lowest. Investment in solar energy in northern Europe has been rising sharply in recent years because it is cheaper than wind energy. The countries of northern Europe, including the Baltic states, are making unobtrusive advances in solar energy. The progress is largely because green energy currently accounts for more than half of all electricity production in Sweden, for example.

Domestic production of primary solid fuels increased highly in the observed period in Luxembourg (+ 6.5%). In the case of biogas, the highest growth was recorded in Bulgaria. Bulgaria is also at the top of the rankings in terms of renewable municipal waste production growth.

The goal of the Cluster analysis (CLU) is to cover a set of objects with their subsets, which may not be disjunctive. After identifying significantly different groups of objects, it is possible to concretize them. Groups can differ, for example, by the level of the monitored character (variable) or its variability (Kráľ et al., 2009).

Cluster analysis assumes that the characters examined do not correlate with one another. We used Spearman's correlation coefficient to determine the tightness of the relationship between the variables studied. Histograms of interval variables confirmed the condition of normality distribution. The coefficient has indicated a low correlation between variables. (Tab. 2)

Tab. 2: Spearman's Correlation Coefficient

	GT – AAGR	**ST – AAGR**	**PSB – AAGR**	**BG – AAGR**	**RMW – AAGR**
GT – AAGR	1.00000000	0.33483984	-0.2002836	-0.01492797	-0.22613096
ST – AAGR	0.33483984	1.00000000	-0.1423336	0.13927920	0.08718266
PSB – AAGR	-0.20028362	-0.14233356	1.00000000	0.13736264	0.53775667
BG – AAGR	-0.01492797	0.13927920	0.1373626	1.00000000	0.11739543
RMW – AAGR	-0.22613096	0.08718266	0.5377567	0.11739543	1.00000000

Source: authors

A correlogram (also called Auto Correlation Function ACF Plot or Autocorrelation plot) is a visual way to show a serial correlation in data that changes over time. The visual graph also did not confirm the presence of autocorrelation between the data examined (Fig. 1).

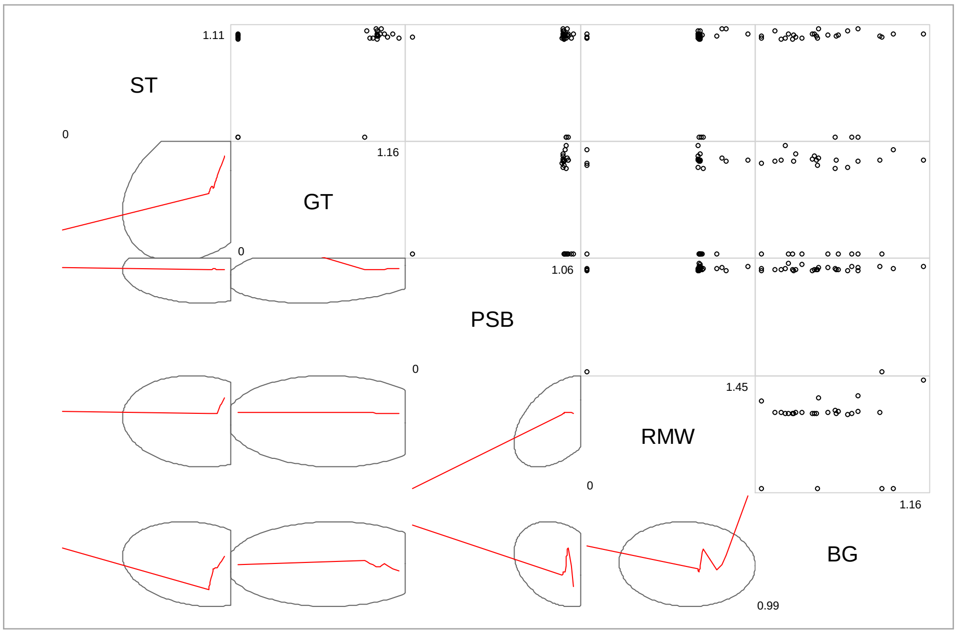

Fig. 1: Correlogram - AAGRs of examined variables (minimum and maximum values involved)
Source: authors

Hierarchical clustering

Since practical data mining problems, high-dimensional data are clustered, the resulting clusters are high-dimensional geometrical objects which are difficult to analyze and interpret. A low-dimensional graphical representation of the clusters could be much more informative than such a single value of cluster validity. One can cluster by eye and qualitatively validate conclusions drawn from clustering algorithms (Abonyi & Feil, 2007).

The most used measure of the distance of objects is the Euclidean distance or geometric distance. The Euclidean distance forms the basis of Ward's clustering method, which we used in our model. That is the so-called divisional clustering, which is based on the set of all objects (countries) as a single cluster, and its gradual division leads to a system of more individual clusters. The advantage of hierarchical methods is that it is unnecessary to know the number of clusters before the clustering process.

Euclidean distance is defined by the formula:

$$d_{ij} = \sqrt{\sum_{k=1}^{K}(x_{ik} - x_{jk})^2} \tag{2}$$

Where x_{ik} is the value of k variable for i-th object, and x_{jk} is the value of k variable for j-th object. The rule of linking statistical units into clusters is then determined for calculated distance.

The principle of Ward's clustering method is to minimize the heterogeneity of clusters according to the criterion of the minimum increment of the intra-group sum of squares of deviations of objects. If the cluster consists of j objects that are characterized by m characters, a matrix "j x m" with elements x_{ik} (value of the k-th character for the j-th object) is available. Variability within clusters (SS_W) is given by:

$$SS_W = \sum_{k=1}^{m}\sum_{i=1}^{j}(x_{ik} - \bar{x_k})^2 \tag{3}$$

where:

$$\bar{x_k} = \frac{1}{j}\sum_{i=1}^{j} x_{ik} \tag{4}$$

Adding extra clusters with j_1 objects increases the number of rows in the original matrix to $j + j_1$, and SS_W counts for a larger number of objects.

Non-hierarchical clustering

Non-hierarchical methods use the optimization procedure. During the formation of clusters, happens object (country) is closer or further from the currently located cluster. Then the optimization procedure places it in another (closer) cluster. A key problem with non-hierarchical methods is the choice of the number of clusters in advance. For that reason, we first implemented a hierarchical clustering, which showed the number of clusters in the set of countries surveyed. After that, we used the same number as well. The last step was to optimize clusters number according to the location of the objects.

In the next clustering process, we used the K-means method, which consists in dividing n objects with m characters into k clusters so that the inter-cluster (SS_B) sum of squares is minimized:

$$SS_B = \frac{nm}{nm-m}\sum_{l=1}^{k}\sum_{i=1}^{m}\sum_{j=1}^{n_k}(1-\delta_{ijl})(y_{ij} - c_{il})^2 \tag{5}$$

We assume n objects divided into k clusters. Then the k-th cluster contains n_k objects. Each object is described by m characters. The missing value of the i-th character in the j-th line and in the k-th burst is denoted as δ_{ijk}. The x_{ij} data is pre-standardized and denoted as y_{ij}. The value of c_{ik} is the mean value (average) of the i-th character in the k-th cluster (Meloun et al., 2012).

Results and discussion

In the following graphs, we monitored the level and development of individual forms of renewable sources; we chose GJ per capita as the unit of measurement. The comparison showed that most Member States are currently on the same or similar level of use of examined renewables. The trend in their use over the last decade is proving to be positive in the European Union and is growing in most cases.

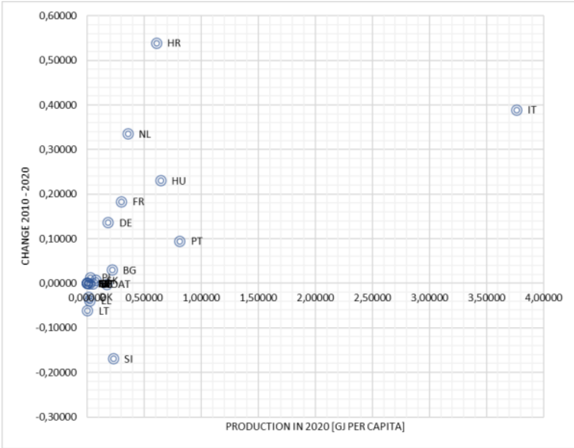

Fig. 2: Indigenous production of geothermal energy in the EU
Source: authors according to Eurostat data

Fig. 2 shows the level of domestic geothermal energy production in the EU in 2020 ("x" axis), as well as the change in the monitored indicator compared to 2010 ("y" axis). According to the graph, the production of this form of energy is clearly dominated by Italy, which in 2020 produced approximately 223.7 million GJ, which represents about 3.8 GJ of energy per capita. The most significant increase in geothermal energy production was recorded in Croatia (+ 0.54 GJ per capita) compared to 2010. On the contrary, production decreased the most in Slovenia (-0.17 GJ per capita).

In many European countries, geothermal energy has been used to generate electricity, heat, and cold for decades. Unlike the sun or wind, it is a source independent of external influences – it is available 24 hours a day without significant fluctuations, which is why it is considered one of the most reliable sources in terms of transmission system stability. According to the European Geothermal Energy Council (EGEC), there were 130 geothermal power plants in 10 European countries in 2019. The use of geothermal energy in Europe is growing rapidly, with the installed capacity of its facilities doubling in the last decade. Geothermal power plants can also be found in Germany, Portugal, Croatia, France, Hungary, Austria, and Romania. Slovakia does not yet have its geothermal power plant.

The Union's position and the Member States' goals could also pave the way for new projects in the field of geothermal energy use in Slovakia, which fits into the concept of increasing the share of renewable resources. Although these projects often have higher initial investments, the benefits are clear – sustainable and local energy sources with minimal operating costs that are environmentally friendly.

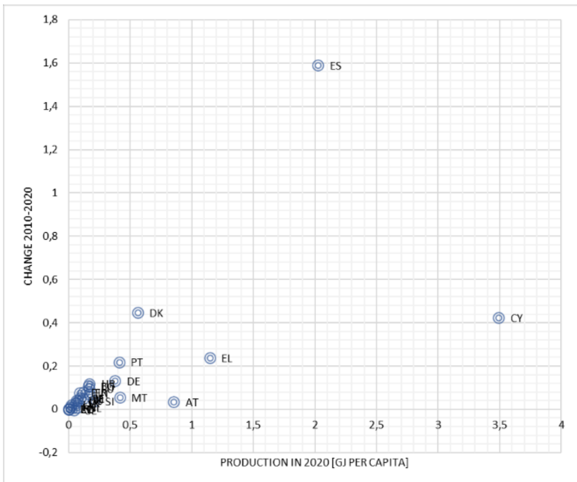

Fig. 3: Indigenous production of solar thermal energy in the EU
Source: authors according to Eurostat data

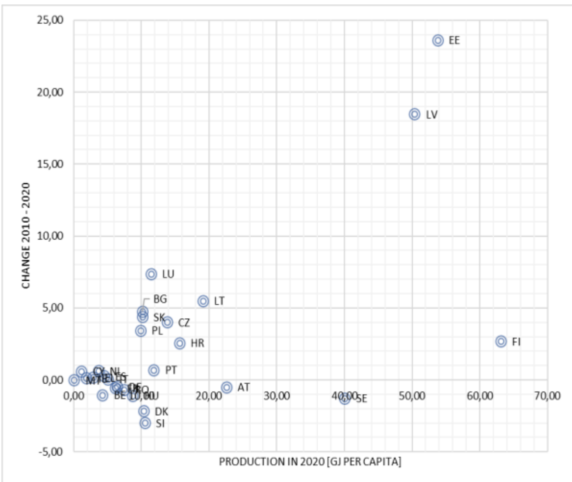

Fig. 4: Indigenous production of primary solid biofuels in the EU
Source: authors according to Eurostat data

Fig. 3 shows the level of indigenous solar energy production in 2020 and its change compared to 2010. Cyprus produced the most solar energy per capita in 2020 (approximately 3.5 GJ). It was followed by Spain (2 GJ per capita) and Greece (1.15 GJ per capita). Estonia and Lithuania produced the lowest renewable energy from the sun's rays in the same year. The most significant increase in production compared to 2010 was achieved in Spain (+ 1.59 GJ per capita), followed by Denmark (+ 0.45 GJ) and Cyprus (+ 0.42 GJ). Only Sweden (-0.01 GJ) showed a slight decrease within the Member Countries.

Solar energy technologies convert energy from sunlight to electricity, either directly through photovoltaics or indirectly through concentrated solar power, or a combination of both. Due to a strong industrial foundation, solar energy has fast become one of the cheapest technologies for electricity generation. The solar market is expected to continue to grow from 2020 onwards, making solar capacity a keystone of the clean energy transition.

Fig. 4 shows the inland production of primary solid biofuels. The highest levels of the indicator in 2020 were reached by Finland, Estonia, Latvia, and Sweden in the range of 63.05 and 40.04 GJ per capita. The most significant increase in the production of solid biofuels compared to 2010 was achieved by Estonia (+ 23.63 GJ) and Lithuania (+ 18.47 GJ). The production of primary solid biofuels includes the following forms of fuels:

- fuelwood, wood residues and by-products;
- wood pellets;
- bagasse;
- animal waste;
- black liquor;
- other vegetal material and residues;
- renewable fraction of industrial waste.

Primary solid biofuels have several advantages and disadvantages compared to other renewable sources. They are considered long-term stable energy sources with less dependence on short-term weather fluctuations and seasonal climate variability. Their use for energy purposes requires relatively low investment costs. However, unlike all other sources, the economic and emission balance of obtaining energy from primary solid biofuels depends on the input raw material's distance, sufficiency, and price.

The economic, energy, ecological, and political importance of primary solid biofuels has risen sharply in other years. The pressure to obtain energy from that kind of biofuels continues and is growing, mainly for the following reasons:

- the depletion of the world's reserves of non-renewable fossil energy sources and their declining availability;
- the rapid pace and global nature of climate change;
- economic, social, and environmental consequences of global climate change;
- initiative strategies and policies as incentives for the use of primary solid biofuels;
- more expansive market and infrastructure for renewable energy trade.

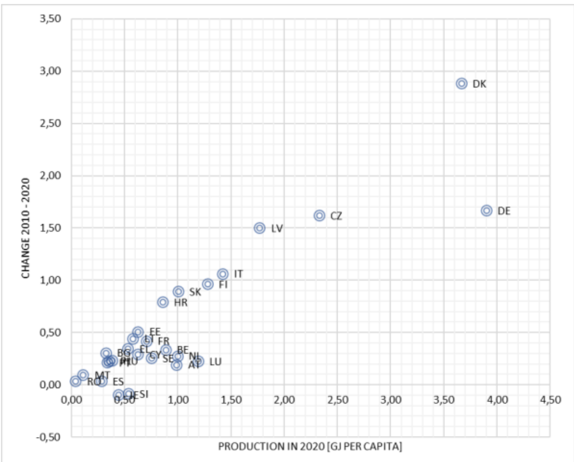

Fig. 5: Indigenous production of biogases in the EU
Source: authors according to Eurostat data

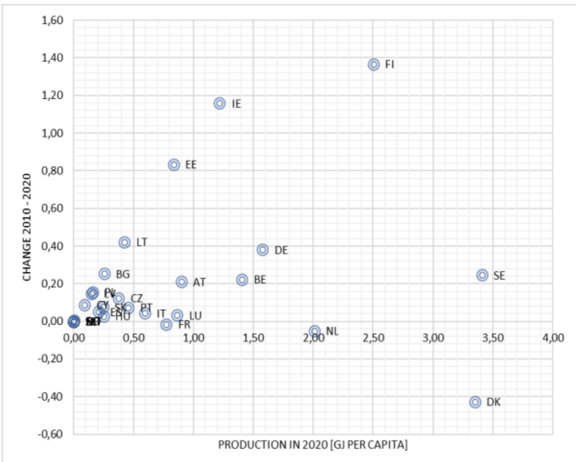

Fig. 6: Indigenous production of renewable municipal waste in the EU
Source: authors according to Eurostat data

Fig. 5 and 6 show indicators of the production of other renewable energy forms in the Member States. In terms of the level of energy production expressed in GJ per capita, these are comparable abundant resources. Germany and Denmark showed the highest levels of biogas production in the EU-27 in 2020 (3.90 GJ and 3.67 GJ per capita). Denmark recorded the highest increase in biogas production in the decade under review (+ 2.88 GJ). There was only a slight decrease in Ireland and Slovenia. The average per capita biogas production in the EU-27 in 2020 was 1 GJ; the median was 0.7 GJ. Biogas production includes the following forms:

- biogases from anaerobic fermentation;
- landfill gas;
- sewage sludge gas;
- other biogases from anaerobic fermentation;
- biogases from thermal processes.

The best results in the production of renewable waste in recent years have been recorded in the countries of northern Europe. In 2020, Sweden was at the top of the ranking of Member States, followed by Denmark and Finland, which in 2020 produced 2.50 to 3.41 GJ of energy per capita. The most significant progress compared to 2010 was made by Finland (+1.37 GJ). Production fell the most in Denmark (-0.43 GJ). The average production of renewable waste per capita in the EU-27 in 2020 was 0.82 GJ; the median was 0.42 GJ.

Waste management ensures the collection, transport, processing, disposal, and recycling of materials. Such activities result in the protection of human health and reduce negative effects on the environment. Europe generates a huge amount of municipal waste every year, with each person in the EU generating an average of almost 500 kilograms of municipal waste per capita each year.

The objective of the CLU was to achieve such groups of states, which would be characterized by certain homogeneity in the case of selected tax indicators. Cluster analysis sorted data into sets with the greatest possible similarity within the group and the largest difference between groups. The choice of features of objects must be preceded by an analysis of theoretical and practical criteria for their justification. Therefore, even in our case, the cluster analysis was preceded by other relevant statistical surveys.

Hierarchical methods are based on sequentially joining clusters; their number decreases continuously until all clusters are combined into one. The wards method involves an agglomerative clustering algorithm. It looks for groups of leaves that it forms into branches, the branches into limbs and eventually into the trunk. Ward's method starts out with n clusters of size 1 and continues until all the observations are included in one cluster.

There were j objects in the analyzed group, namely 27 EU countries in which were pursued k quantitative characters as follows:

1. five variables – indigenous production AAGR values (2010-2020)
2. five variables – indigenous production in GJ per capita values in 2010
3. five variables – indigenous production in GJ per capita in 2020

The result of clustering is a tree diagram (dendrogram). Each node represents one phase of the clustering process, and the vertical axis represents the proximity coefficients. With increasing distance (differences in the values of clustering variables), objects that were completely different at the beginning of grouping also join into clusters.

Fig. 7 shows a cluster diagram created after entering 5 AAGR variables. There are five clusters of countries with similar characteristics:

1. Spain, Austria, the Netherlands, Belgium, Germany, Poland, Portugal, France, Hungary, Bulgaria, Denmark, Italy, Romania, Slovakia;
2. Czechia, Finland, Ireland, Luxembourg, Cyprus, Sweden;
3. Lithuania, Estonia, Latvia;
4. Croatia, Greece, Slovenia;
5. Malta.

The five clusters as the output of the hierarchical Ward clustering method determined 5 clusters for further clustering using the K-means method (Fig. 8).

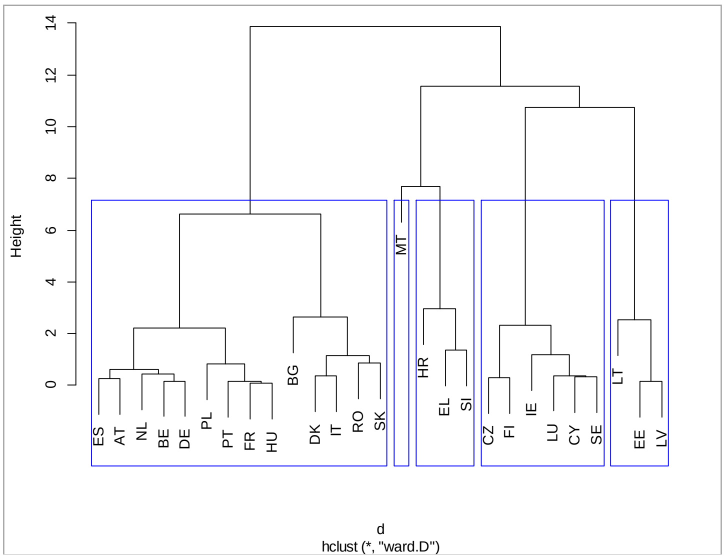

Fig. 7: Cluster dendrogram of EU Member States using AAGR values (2010-2020)
Source: authors

We consider the data set, which contains *n*=27 objects, and partition it into *k*=5 clusters. The ellipses are based on the average and the covariance matrix of each cluster, and their size is such that they contain all the points of their cluster. The ellipses sizes of clusters 4 and 5 are similar. Cluster no. 5 displays less variability of Component 1. The larger shading intensity indicates the largest density of divided objects in an ellipse.

The cluster analysis outlines potentially existing clusters competing in green energy production within the EU. It aimed to identify similarities between the Member States. Considering the two most significant variables, we can visualize clusters using the non-hierarchical method of K-means. It requires the analyst to indicate in advance the number of clusters extracted. In this case, the two variables explain 58.75 % of the point variability of the set.

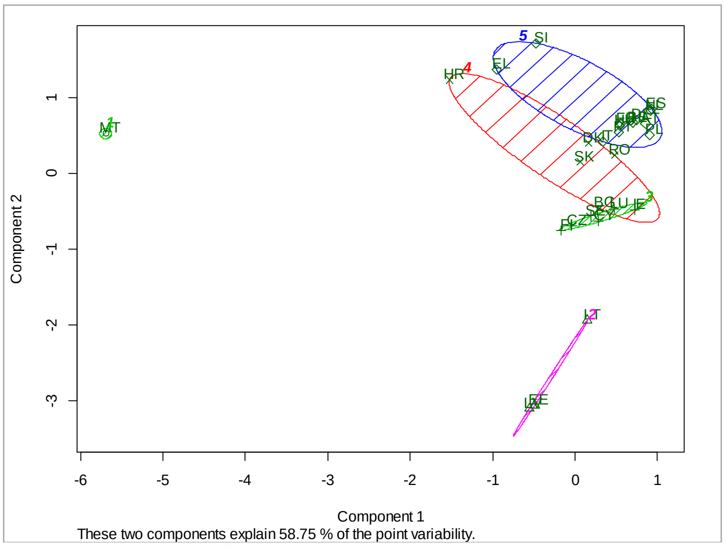

Fig. 8: Scatterplot of EU Member States using AAGR values (2010-2020)
Source: authors

Neither the test for the presence of correlation between the examined variables nor the correlogram confirmed statistically significant correlation relationships between the variables used in the following analysis. The correlogram selected the following minimum and maximum values of indicators for 2010, shown in Tab. 3.

Tab. 3: Minimum and maximum values of the examined variables in 2010 (GJ per capita)

Variable (indigenous production)	Minimum	Maximum
Geothermal	0 *(Czechia, Estonia, Ireland, Cyprus, Latvia, Luxembourg, Malta, Finland, Sweden)*	3,37 *(Italy)*
Solar thermal	0 *(Estonia, Latvia, Lithuania)*	3,07 *(Cyprus)*
Primary solid biofuels	0 *(Malta)*	60,36 *(Finland)*
Biogases	0,01 *(Romania)*	2,23 *(Germany)*
Renewable municipal waste	0 *(Estonia, Greece, Croatia, Cyprus, Latvia, Lithuania, Malta, Romania, Slovenia)*	3,78 *(Denmark)*

Source: authors' calculations

Further, we searched for clusters of countries using the data on domestic production of the examined energy sources for the years 2010 and 2020. Production was expressed as the GJ of energy produced per capita. The aim was to find out which countries produce equal or similar amounts of green energy and to distinguish them from others. Also, find out what changes in the clusters occurred over the last decade. The following figures are the result of the clustering.

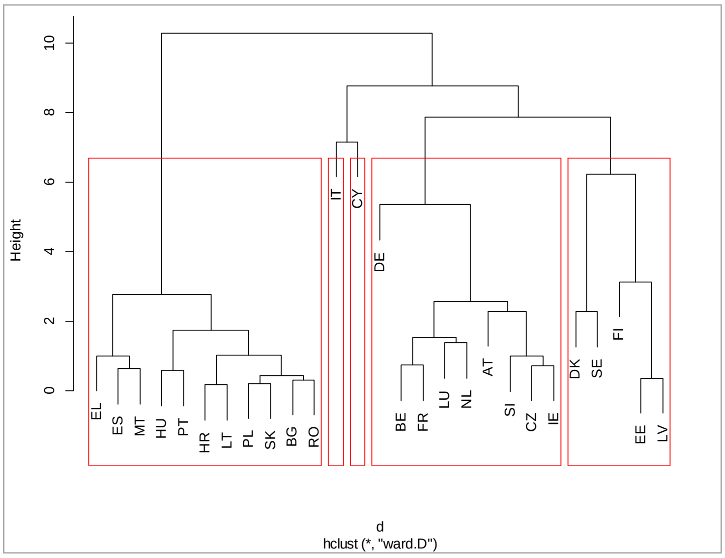

Fig. 9: Cluster dendrogram of EU Member States using "Indigenous production in 2010" (GJ per capita)
Source: authors

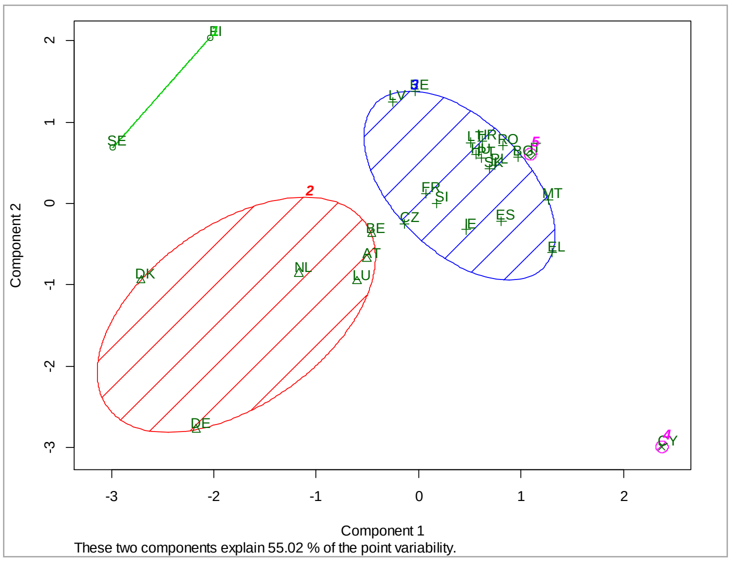

Fig. 10: Scatterplot of EU Member States using "Indigenous production in 2010" (GJ per capita)
Source: authors

The tree diagram (Fig. 9) again shows five clusters of countries. The results of the hierarchical clustering are two larger clusters, one cluster made up of northern European countries and two isolated countries, Italy and Cyprus. Italy excels, especially in the production of geothermal energy, and Cyprus in the production of solar energy. The countries of northern Europe and the Baltic States lag mainly in the production of geothermal energy; on the other hand, they are among the countries with the highest production of primary solid biofuels.

Fig. 10 shows the clusters of the examined countries in the scatterplot in the form of ellipses. The highest variability of components is shown by clusters no. 2 and 3. Cluster no. 2 mainly due to Denmark and Germany, cluster no. 3 due to Estonia and Latvia, which are on the edges of the ellipses. Cyprus is lonely and differs significantly from the other Member States in terms of green energy production. Cyprus does not use geothermal energy at all nor renewable municipal waste. Italy is near cluster no. 3, which brings it closer to the countries in this cluster. Italy is closer thanks to the production of other renewable resources (apart from geothermal energy). The graphs in Figures 9 and 10 were the starting point for monitoring changes in country clusters 10 years later.

Neither the test for the presence of correlation between the examined 2020 variables nor the correlogram confirmed statistically significant correlation relationships between the variables. The correlogram selected the following minimum and maximum values of indicators for 2020, shown in Tab. 4.

Tab. 4: Minimum and maximum values of the examined variables in 2020 (GJ per capita)

Variable (indigenous production)	Minimum	Maximum
Geothermal	0 *(Czechia, Estonia, Ireland, Cyprus, Latvia, Lithuania, Luxembourg, Malta, Finland, Sweden)*	3,76 *(Italy)*
Solar thermal	0 *(Estonia, Lithuania)*	3,49 *(Cyprus)*
Primary solid biofuels	0 *(Malta)*	63,05 *(Finland)*
Biogases	0,04 *(Romania)*	3,90 *(Germany)*
Renewable municipal waste	0 *(Greece, Croatia, Malta, Slovenia)*	3,41 *(Sweden)*

Source: authors' calculations

In terms of the minimum or maximum production of the researched renewable energy sources, no significant changes happened within the EU over the last decade. Figures 11 and 12 show the clusters of countries in 2020, as well as some changes compared to 2010.

The dendrogram (Fig. 11) shows five clusters of countries according to similarities in renewable energy production. Italy remained alone in its cluster. A new cluster with Denmark and Germany was added. They were already on the edge of the cluster ellipse in 2010 and therefore tended to form their common cluster. Most Member States are in a single cluster, suggesting that renewable energy production is being consolidated in the European Union. Production has not changed in Estonia, Latvia, Finland, and Sweden; compared to 2010, Denmark has just dropped out of the crowd. Cyprus, unlike Italy, joined Greece and Spain. It has improved mainly in the production of primary solid biofuels, biogases, and renewable municipal waste.

In the scatterplot (Fig. 12), clusters 1 and 4 show the highest variability of components. The farthest cluster represents Italy. In comparison to 2010, Italy increased the production of geothermal energy; biogas production increased significantly. Variability of cluster no. 1 increases, in particular, Finland, which is at the top of the Member States in terms of primary solid biofuel production. Cyprus has joined Spain, which has significantly increased its solar energy production over the last ten years.

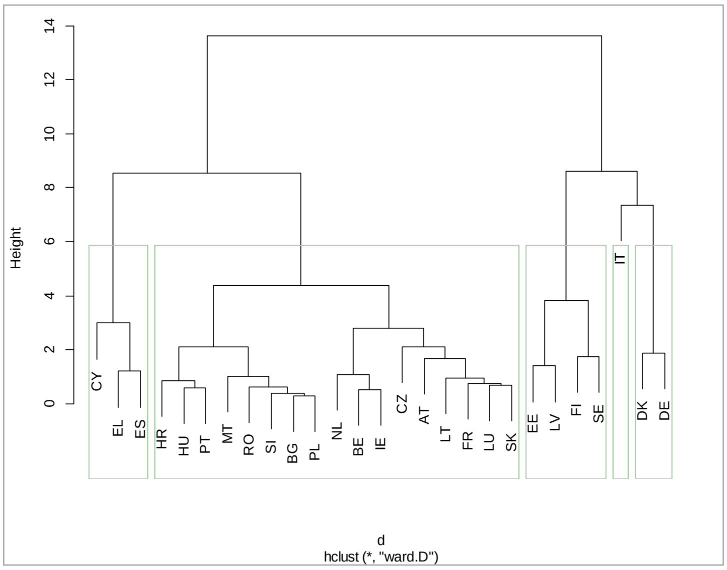

Fig. 11: Cluster dendrogram of EU Member States using "Indigenous production in 2020" (GJ per capita)
Source: authors

The K-means clustering requires the analyst to indicate in advance the number of clusters extracted. In this case, the two most significant components explain 57.75% of the point variability of the set (Fig. 12).

The centres of gravity of individual characters in clusters are the characters' mean values (averages), and the standard deviations of the characters are the characteristics of individual clusters. Subsequently, countries belonging to the individual clusters and their distances from the cluster's centre of gravity are dispersed. The largest distance from the centre of gravity in cluster no. 1 has Finland in cluster no. 4, Malta and Greece.

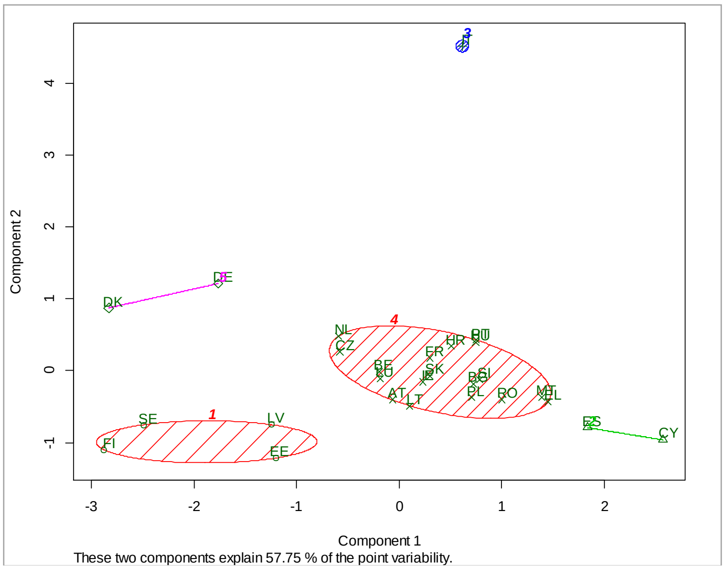

Fig. 12: Scatterplot of EU Member States using "Indigenous production in 2020" (GJ per capita)
Source: authors

Conclusion

Energy poverty has been an active issue in the European Union for decades. It is the result of a combination of several factors, such as the low income of selected population groups, high household expenditure on energy, and low energy efficiency of buildings, but also the insufficient use of the potential of renewable energy sources. Large groups of people are subsequently exposed to the cold, respectively heat, i.e., inappropriate conditions in the home as well as the work environment. The adverse effects of stress from the inability and inability to provide themselves and their family with suitable housing harm individuals' mental and physical health.

Member States differ significantly in the most important renewable energy and heat source production. The main reasons are climatic conditions in individual parts of the continent, the availability of renewable resources, or the infrastructure for their efficient use. The countries of northern Europe are the Union leaders in the production of energy produced from waste. Waste management ensures the collection, transport, processing, disposal, and recycling of materials. The consequence of such activities is the protection of human health and the reduction of negative effects on the environment. Italy is a leader in the use of geothermal energy. At the top of the rankings in electricity and heat consumption are the countries of northern Europe, which face the highest number of cold days a year. In this case, however, it is important to say that investing in solar energy in northern Europe has been growing rapidly in recent years because it is cheaper than wind energy. The countries of northern Europe, including the Baltic States, are making progress in the production of solar energy. The progress is large since green energy currently accounts for more than half of total electricity production in Sweden, for example.

The aim of the cluster analysis was to find countries with similar characteristics in the case of the development of domestic production of selected renewable sources. The analysis showed that the development of indicators has not changed significantly over the last decade, although some countries have moved within the established clusters. The results in the form of tree graphs and scatter plots indicated mutual similarities and differences in the production of renewable energy in the regions of Europe. At the same time, they paved the way for possible cooperation between Member States, first within clusters, then on the grounds of the entire integration group. Cooperation, exchange of information and know-how, but also trade in the field of renewable energy sources could subsequently contribute to the elimination, respectively reducing energy poverty in Europe.

Increasing the production of electricity and heat from renewable sources is one of the primary conditions for the European Union's strategy for further development. It requires the implementation of stricter measures to protect the various components of the environment, the careful and maximum efficient use of each energy source, modern procedures, and technologies to increase the energy potential of resources and reduce energy losses. It is necessary to expand the existing and build new energy infrastructure to increase the production of green energy and trade with it efficiently. Renewable energy production is also important for ensuring the energy independence and security of the European Union countries, especially in times of crisis, such as the oil crisis, the COVID-19 pandemic crisis, the previous gas crisis, but also the current crisis caused by the war in Ukraine.

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