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THE EVOLUTION OF AGRICULTURAL ENERGY TRANSITION IN EASTERN EUROPEAN UNION COUNTRIES BETWEEN 1993 AND 2022

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ABSTRACT: The issue of greenhouse gas emissions from energy consumption has remained a major challenge for the European Union. In response, the EU has set itself the target of reducing greenhouse gas emissions by 55% by 2030 and becoming completely carbon neutral by 2050. Energy transition is crucial for reducing greenhouse gas emissions, ensuring agricultural sustainability, and improving energy security. The main aim of this study is to assess the progress made in the transition to renewable energy sources in agriculture in the Eastern European Union countries. This study has used a data review method to examine the transition to renewable energy in agriculture in the Eastern European Union countries, including Bulgaria, Croatia, Czechia, Estonia, Hungary, Latvia, Lithuania, Poland, Romania and Slovakia, for the period between 1993 and 2022. The results have shown that the transition to renewable energy in agriculture has been relatively slow in Romania, Croatia, Estonia, Bulgaria, and Hungary.

KEYWORDS: energy transition, agriculture, renewable energy, European Union

Introduction

The advent of energy-efficient technologies and renewable energy generation represents a pivotal step towards the establishment of a more resilient and environmentally conscious food production system within the agricultural sector. These practices enhance energy independence, provide dependable and cost-effective opportunities for rural communities, and facilitate the creation of a more sustainable agricultural sector over the long term. Also, the implementation of a sustainable energy transition has the potential to contribute to the sequestration of greenhouse gas emissions from the agricultural sector, the mitigation of fossil fuels, and the combating of climate change. The utilisation of renewable energy sources, including solar panels, wind turbines, and biomass, has facilitated the operation of agricultural machinery, irrigation systems, and agricultural processing facilities, while also enabling the generation of energy from waste, thereby reducing the impact of energy depletion. However, the process of energy transition in agriculture has been known to be a more arduous undertaking than in other sectors. The agricultural sector has been engaged in the production of solid and liquid biofuels, as well as biogas, representing a significant contribution to the renewable energy field. A diverse range of plant materials has been utilised in the production of solid biofuels, encompassing firewood, wood chips, bark, sawdust, industrial waste, and animal waste, with the exception of coal. The principal components of biogas are methane and carbon dioxide, which are generated through the anaerobic digestion of biomass or thermal processes. Liquid biofuels, such as biodiesel, have been blended with or have replaced fossil fuels like diesel in a process known as biofuel blending. A considerable share of countries within the European Union have continued to rely on coal and fossil fuels. This energy transition is essential to achieve a reduction in emissions of at least 55% by 2030 and to attain climate neutrality by 2050. The transition of the energy sector and the expansion of renewable energy sources are crucial for the EU to meet its long-term climate objectives (Rokicki et al., 2021; Bathaei & Streimikiene, 2023).

Energy transition is a strategic step to both reduce greenhouse gas emissions and ensure the sustainability of the agricultural sector, while also improving energy security. Moreover, the prioritisation of renewable energy adoption in agriculture has the potential to stimulate economic growth, encourage innovation, and facilitate the creation of green jobs, which are of particular significance for rural development. Collaborative initiatives, such as regional funding mechanisms, knowledge-sharing platforms, and partnerships with the private sector, can expedite this transition and guarantee long-term resilience against climate-related challenges. Nevertheless, a number of challenges remain with regard to regional and sectoral investments in the energy transition within the agricultural sector in the region. The process of energy transition in agriculture has progressed at a relatively slower pace in Eastern European Union countries in comparison to other regions. Therefore, it is vital for Eastern European Union countries to transition to renewable energy in agriculture and invest in technologies that improve energy efficiency.

This study has analysed energy trends in the agricultural sector across Eastern European Union countries between 1993 and 2022, employing data review methods. It has aimed to examine the trends in the energy mix and the share of renewable energy in the agriculture of Eastern European Union countries. The research is structured to address the following questions:

- What trends have been observed with the use of renewable energy in the agricultural sector through the countries of the Eastern European Union over the last thirty years?
- How has the distribution of energy sources (energy mix) used in agriculture in the countries of the Eastern European Union changed over the last thirty years?
- Has the transition to renewable energy in the agricultural sector in the countries of the Eastern European Union been successful over the last thirty years?

Literature Review

By the Green Deal framework, the countries of the European Union have accelerated the transition to renewable energy, with the objective of achieving carbon neutrality by 2050. The aforementioned countries have employed a range of financial instruments, including the Just Transition Mechanism and the Modernisation Fund, in addition to research programmes such as Horizon Europe and

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the European Climate, Infrastructure and Environment Fund (CEF), with the objective of modernising their respective energy infrastructure. Nevertheless, the continued reliance on fossil fuels, inadequate infrastructure, and regulatory shortcomings have constituted significant obstacles to the transition process. As a potential solution, there has been a growing consensus in favour of increased investment in energy storage technologies and grid modernisation, more effective utilisation of EU funds, and the empowerment of local communities to participate in projects. The transition to renewable energy has been accelerated by the implementation of specific measures, including the coal phase-out plans put in place by Poland, the solar energy initiatives undertaken by Romania, and the hybrid energy systems introduced by Bulgaria (European Commission, 2022; European Commission, 2023a; IEA, 2024).

Notwithstanding these practices and developments within the European Union, a divergence has been observed between Eastern and Western European member states with respect to the energy transition. The uneven progress that has emerged can be attributed to persistent disparities in countries' financial capacities, administrative structures, and technological capabilities (Sgaravatti et al., 2023). In Eastern European Union countries, the challenges to the energy transition have proven to be intractable and long-standing. These challenges have resulted primarily from three interrelated factors: ageing transmission infrastructure, limited access to green finance, and continued dependence on coal-based energy systems. The agricultural sector, which has remained an energy-intensive domain—particularly in post-socialist economies—has often been neglected in national energy strategies, despite its substantial potential to integrate decentralised renewable energy solutions such as biogas and solar-powered irrigation systems. The European Commission's Common Agricultural Policy (CAP) has been revised to incorporate mechanisms aimed at promoting climate-resilient agricultural practices and encouraging the use of renewable energy in rural areas. In parallel, the REPowerEU strategy has emphasised the reduction of fossil fuel imports by supporting the expansion of decentralised renewable energy generation (European Commission, 2022). In this context, the existing literature has asserted that financial support alone has not sufficed in ensuring a just and effective energy transition, unless accompanied by robust multi-level governance structures (Bausch et al., 2016). Within the European Union, the energy transition—particularly in the agricultural sector—has increasingly been recognised not merely as a matter of technological advancement, but also as a process that necessitates institutional coordination, policy integration, and inclusive socio-political engagement.

One of the most pivotal stages of sustainable development is the energy transition. The utilisation of renewable energy in agriculture is of significant consequence with regard to environmental pollution and climate change, energy efficiency, energy security, and external dependency on energy. Despite its role as a significant consumer of energy, the agricultural sector has increasingly been recognised as a key contributor to the sustainable energy transition, as it has harboured considerable potential for the integration of renewable energy technologies, including solar panels, biogas systems, and wind turbines. This transition has aimed to mitigate climate change and has supported ongoing efforts to reduce greenhouse gas emissions. In a study conducted by Rokicki et al. (2021), the objective was to determine the consumption of agricultural bioenergy in EU countries between 2004 and 2018, as well as the factors affecting it. To this end, statistical analysis methods (Gini coefficient, Lorenz curve, correlation analysis) were applied using Eurostat and IEA data. The findings indicate that bioenergy consumption is concentrated in economically developed countries with high agricultural production. Furthermore, there are positive correlations with energy and agricultural parameters, and negative correlations with total energy consumption. In a study conducted by Wysokiński et al. (2020), the energy consumption per worker or hectare in European Union countries between 2004 and 2016 was examined using a data analysis method. The results of the study indicate that energy consumption in EU agriculture has decreased by approximately 30% over the past 25 years, which is regarded as a positive development in terms of energy efficiency. The share of energy consumed by the agricultural sector declined from 2.9% in 1990 to 2.2% in 2016. Overall, the energy and economic efficiency of the EU's agricultural sector remains 25% lower than the efficiency of the overall EU economy. However, in Bulgaria, Romania, and Greece, agriculture has demonstrated higher efficiency due to lower energy consumption and production costs.

The transition of the agricultural sector to renewable energy in many countries has been the subject of ongoing investigation in recent studies. In a study conducted by Eyuboglu and Uzar (2020),

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the effects of agricultural production and renewable energy on CO_2 emissions were examined in Colombia, India, Indonesia, Kenya, Malaysia, Mexico, and Poland for the years 1995-2014 using the Panel VECM method. The findings revealed that while agricultural activities resulted in an increase in CO_2 emissions, renewable energy sources played a significant role in reducing them. Furthermore, it was established that economic expansion and energy utilisation were associated with an increase in emissions. The panel analysis results indicate that these factors are the primary determinants of long-term CO_2 emissions. Kwakwa (2023) has examined the effects of growth in the agriculture, industry, and services sectors on greenhouse gas (GHG) emissions, as well as the impact of renewable energy on GHG emissions, for the period 2002–2021 across 32 African countries. The findings have demonstrated that expansion in these sectors has led to an increase in GHG emissions. However, renewable energy has been shown to have a mitigating effect on GHG emissions, particularly in the agricultural and industrial sectors. On the other hand, Krukowski et al. (2024) have analysed the role of agriculture in renewable energy adoption in many countries between 2010 and 2021 using the TOPSIS method. Their findings have revealed that the potential for renewable energy in agriculture has been particularly high in countries such as the Netherlands, Lithuania, Latvia, and Hungary. By 2021, Bulgaria, Denmark, and Spain had also been identified as countries with comparable renewable energy potential in the agricultural sector. It is widely acknowledged that the European agricultural sector relies heavily on fossil fuels as a source of energy, with a strong positive correlation between energy consumption and greenhouse gas emissions (GHG). This reliance on fossil fuels is a significant contributor to GHG emissions, underscoring the importance of reducing fossil energy consumption and transitioning to renewable energy sources to achieve energy independence and mitigate climate change (Paris et al., 2022). Wyrwa et al. (2025) have examined the current status of sustainable development in the energy and agriculture sectors within the European Union for the years 2015 and 2022. By utilising data from Eurostat and FiBL, they have constructed a comparative sustainability index among EU member states using the linear ranking method. The study has revealed significant regional disparities within the Union in terms of both sustainable energy and sustainable agriculture. The countries that have demonstrated the highest levels of sustainable energy have included Estonia, Sweden, Finland, and Austria, whereas Cyprus, Belgium, Greece, and Bulgaria have exhibited the lowest levels. A similar pattern has been observed in sustainable agriculture indicators, with Estonia, Bulgaria, Slovakia, and Lithuania attaining the highest values, while Poland, Malta, Slovenia, and Luxembourg have recorded the lowest. Although a favourable trend in the energy transition has emerged across several EU countries, the study has also highlighted ongoing structural inequalities and notable deviations from the 2030 targets, which require serious attention.

Renewable Energy and Energy Consumption in the Agriculture Sector of Eastern European Union Countries

Renewable energy trends in the agricultural sector have become imperative, as it has provided vital indicators for efforts to combat climate change and reduce greenhouse gas emissions. In this context, a comparative analysis between Eastern European Union countries and other European Union member states has been warranted to capture regional disparities and progress. Figure 1 illustrates the evolution of renewable energy consumption in the agricultural sector across European Union member states between 1993-2022 (Eurostat, 2024). From 1993 to 2022, renewable energy consumption in agriculture across the European Union increased by 155%. In the EU, the trend has been consistently upward from 2005 to 2022. In Eastern European Union countries, renewable energy consumption in agriculture increased by 40% from 1993 to 2022. Notably, there was a significant rise between 2010 and 2016, but there has been no substantial change since then. This increase is below the EU average. While there was a notable rise between 2010 and 2016, subsequent years have not seen a significant upward trend. It may be posited that the relatively modest shift in renewable energy consumption observed in 2022 can be attributed, at least in part, to the impact of the global coronavirus pandemic. Understanding the factors that slowed renewable energy growth in agriculture in Eastern European Union countries post-2016, and identifying strategies to align this growth with the EU average, has been essential.

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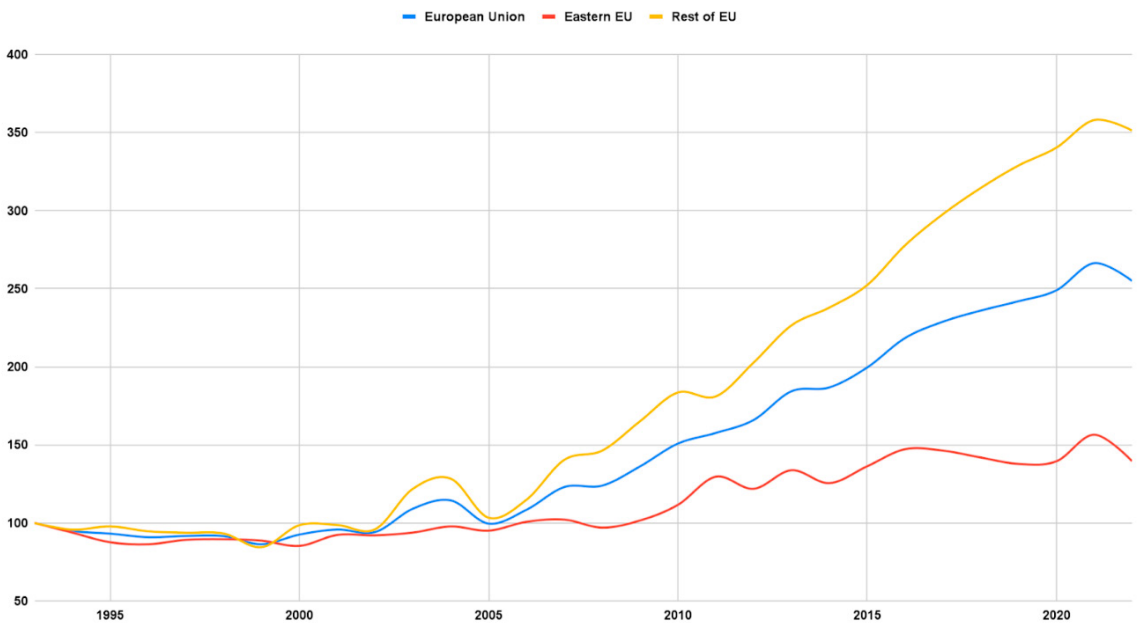

Figure 1. Renewable Energy Consumption Change in Agriculture in European Union Countries between 1993-2022 (1993=100)

Source: author's work based on data from Eurostat.

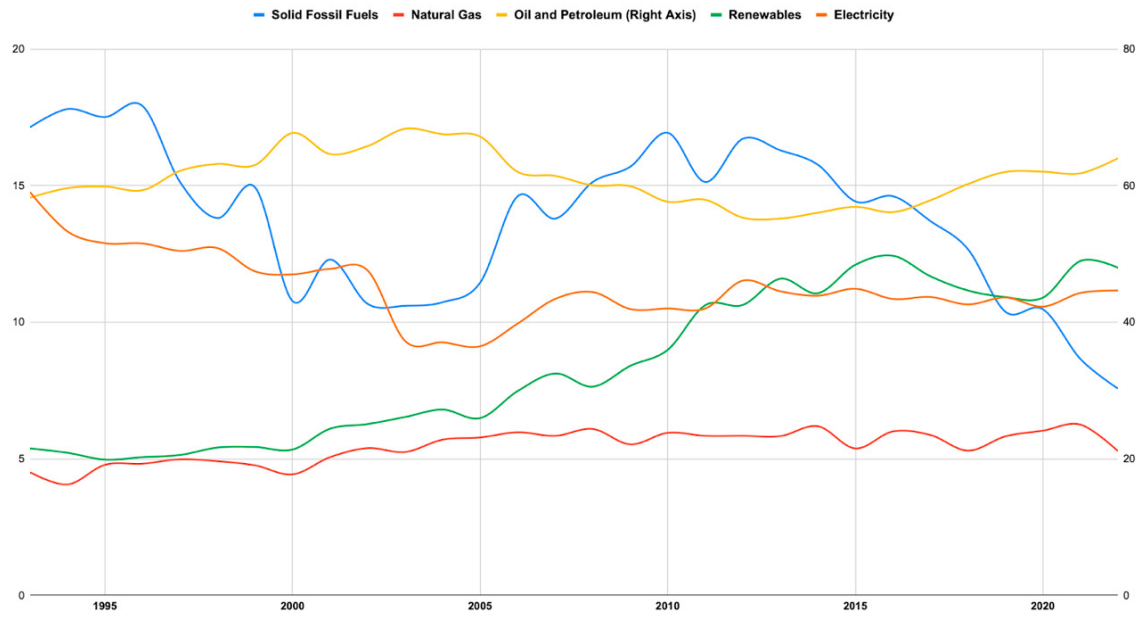

Figure 2. Energy Mix (Energy Share) Change in Agriculture in Eastern European Union Countries between 1993-2022

Source: author's work based on data from Eurostat.

The energy transition in agriculture in Eastern European Union countries has given rise to questions concerning both technological advances and policy constraints. Figure 2 displays the energy mix in agriculture within the Eastern European Union from 1993 to 2022 (Eurostat, 2024). The consumption of renewable energy in agriculture in the European Union has increased by 40% between 1993 and 2022. Nevertheless, a more detailed examination of the energy mix is required in order to

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gain a comprehensive understanding of the sector's progress. An analysis of the energy mix used in agriculture in Eastern European Union countries over the past three decades reveals a notable increase in the share of renewable energy, particularly following 2005. While there was a notable increase in the share of renewable energy up until 2016, this trend reversed in that year. There was a decline in the share of renewable energy from 2016 to 2020. Subsequently, in 2022, the figure reverted to the level observed in 2016. Following a partial increase in the share of natural gas in agriculture after the 2000s, a subsequent period of steady growth was observed. Nevertheless, the figure has never fallen below 20%. Notwithstanding a decline in the share of fossil fuels consumed in Eastern European Union countries, the reliance on oil and petroleum products has remained consistent. While a decline was observed between 2005 and 2012, an upward trend emerged in the following years. In the year 2022, 64% of the energy consumed in the agricultural sector was derived from oil and petroleum products. In recent years, a deceleration in the pace of energy transition has been observed in the agricultural sector of Eastern European Union countries.

The revised Renewable Energy Directive, adopted in 2023, raises the EU's binding renewable energy target for 2030 to a minimum of 42.5% (European Commission, 2023b). Table 1 has shown share of renewable energy in agriculture in the European Union and Eastern European Union countries between 1993 and 2022. In 2022, the share of renewable energy in the EU's total energy consumption was 23%. In 1993, the average share of renewable energy in agricultural energy consumption in European Union countries was 4.19%. In 2015, the rate was 10.3% and in 2022, it reached 12.04%. This has indicated that the share of renewable energy in the agricultural energy mix in the European Union did not experience a notable increase between 2015 and 2022. In 2022, Czechia had the highest share of renewable energy in its agricultural energy mix among Eastern European Union countries, at 25%. The share of renewable energy in the agricultural energy mix was higher than the European Union average in Czechia, Slovakia, Lithuania, and Poland. Conversely, the countries of Latvia, Hungary, Estonia, Bulgaria, Romania, and Croatia exhibited a below-average performance in comparison to the European Union average. It is worth noting that the share of renewable energy in the agricultural energy mix in Romania and Croatia was markedly low.

Table 1. Share of Renewable Energy in the Energy Mix of Agriculture between 1993-2022 in Eastern EU Countries

Countries	1993	2000	2010	2015	2020	2021	2022
Czechia	0	0.37	8.01	20.56	21.57	24.34	25.58
Slovakia	0.69	0.18	3.73	24.41	19.9	20.81	18.02
Lithuania	1.84	7.4	11.12	11.74	15.64	15.14	14.53
Poland	10.23	8.84	13.62	14.9	12.68	15.18	14.33
EU	**4.19**	**4.35**	**7.49**	**10.3**	**11.11**	**11.78**	**12.04**
Latvia	13.1	12.41	9.65	11.77	16.67	11.81	11.67
Hungary	6.02	4.06	5.5	7.51	7.17	7.34	9.57
Estonia	2.21	9.08	4.67	3.12	4.44	6.36	5.37
Bulgaria	0.28	4.65	1.92	6.14	3.23	5.53	5.28
Romania	1.27	0.96	1.86	1.79	1.97	1.39	1.86
Croatia	0	0	0	1.96	1.53	0.73	0.93

Source: author's work based on data from Eurostat.

A thorough analysis of national energy profiles related to the agricultural energy transition has revealed that Czechia has made significant progress compared to other Eastern European Union countries. Figure 3 compares the agricultural energy mix of Eastern European Union countries (left) with that of Czechia in 2022. The agricultural energy mix in Eastern European Union countries has consisted of 64% oil and petroleum products, 12% renewable energy, 11.2% electricity, 7.6% solid fossil fuels, and 5.3% natural gas. In Czechia, the agricultural energy mix has comprised 51.4% oil and petroleum products, 25.6% renewable energy, 15% electricity, 6.8% natural gas, and 1% solid fossil

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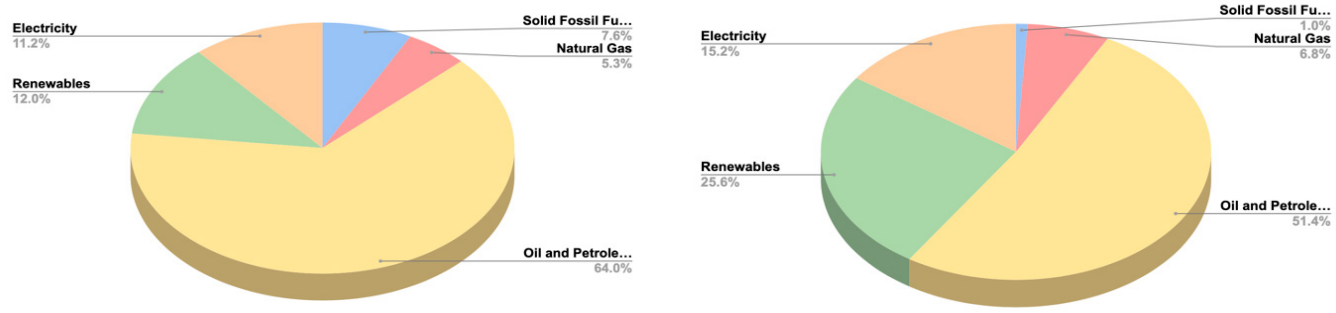
fuels. It has become evident that Czechia's share of renewable energy in the agricultural energy mix has been twice as high as the average in Eastern European Union countries. Furthermore, it has been noted that the consumption of oil and petroleum products, as well as solid fossil fuels, has remained significantly higher in Eastern European Union countries compared to Czechia.



Eastern European Union Countries Czechia

Figure 3. Energy Mix (Energy Share) of Agriculture in Eastern European Union Countries and Czechia in 2022

Source: author's work based on data from Eurostat.

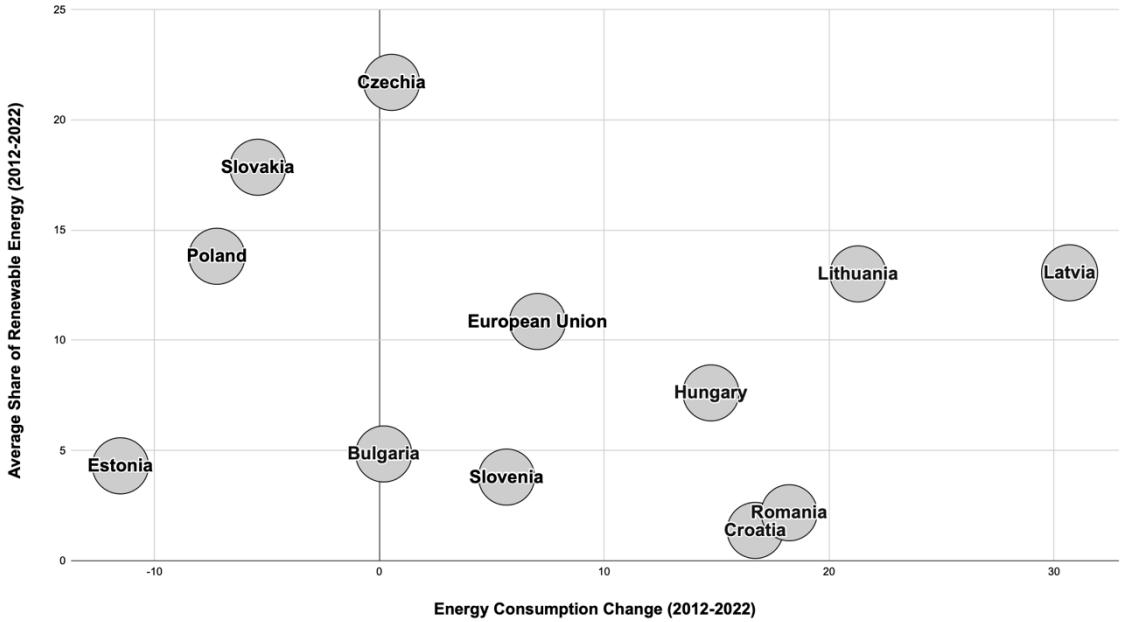


Figure 4. Energy Consumption Change in Agriculture and Average Share of Renewable Energy Consumption between 2012-2022

Source: author's work based on data from Eurostat.

In the European Union, the agricultural sector's high dependence on fossil fuels, as a conventional energy source, has hindered efforts to reduce greenhouse gas emissions. In this context, comparing the relative energy consumption levels in agriculture and the share of renewable energy has provided a valuable perspective on the progress of the energy transition. It has been suggested that such an approach may help identify structural differences and policy support needs in Eastern European Union countries that have diverged from the EU average. Figure 4 shows the changes in energy consumption and the average share of renewable energy in agriculture in the European Union and Eastern European Union countries between 2012 and 2022 (Eurostat, 2024). This combination is crucial from the point of view of fulfilling EU energy policy (Lorek, 2019). The revised Renewable Energy Directive, adopted in 2023, raises the EU's binding renewable energy target for 2030 to a minimum

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of 42.5% (European Commission, 2023a). In 2022, the share of renewable energy in the EU's total energy consumption was 23%. In 2022, the average share of renewable energy in agricultural energy consumption in Eastern European Union countries was 12.5%, while the EU average for agricultural energy consumption was 12.06%. In Czechia, there has been no change in energy consumption in agriculture over the last decade. Furthermore, Czechia has the highest share of renewable energy in the energy mix in agriculture over the last decade. In Poland and Slovakia, there has been a reduction in energy consumption in agriculture over the past decade. However, the share of renewable energy in the energy mix remains above the EU average. In the Eastern European Union countries, Latvia and Lithuania have experienced the most significant increase in energy consumption in agriculture, with a renewable energy share in the energy mix in agriculture that exceeds the EU average. In contrast, Romania, Croatia, and Slovenia have witnessed an uptick in energy consumption in agriculture over the past decade, yet their average share of renewable energy remains below the EU average. The energy transition in agriculture has occurred more slowly compared to other sectors in the Eastern European Union countries.

Energy Mix of Agriculture in Bulgaria

Bulgaria has been regarded as a country possessing considerable potential for the transition to renewable energy sources, with solar energy identified as a key area of focus. The country's geographical location and the high levels of annual solar radiation it receives have been recognised as strategic advantages that can be harnessed in the energy transition process. These opportunities have gained particular significance within the framework of the European Union's Green Deal objectives (Markova et al., 2011; Hristov et al., 2024).

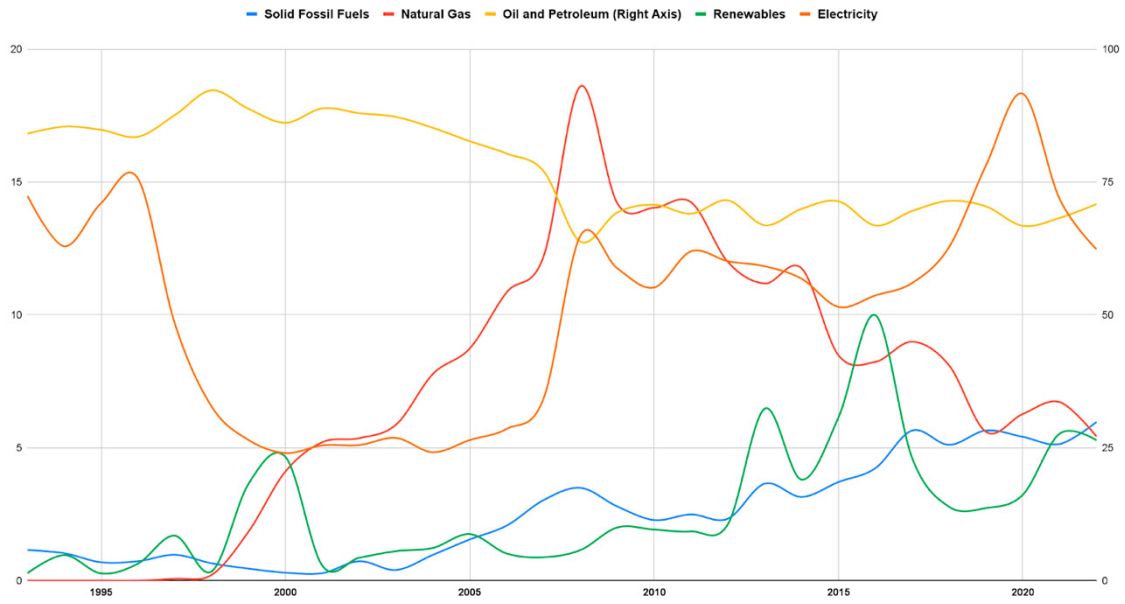

Figure 5. Energy Mix (Energy Share) Change of Agriculture in Bulgaria between 1993-2022

Source: author's work based on data from Eurostat.

In accordance with the objectives of the European Union's Green Deal initiative, a comprehensive analysis of the energy mix for the energy transition in Bulgaria has been deemed imperative. This analysis has been particularly crucial given Bulgaria's substantial regional potential, as it has facilitated a more nuanced and informed observation of the process. Figure 5 shows the changes in the energy mix in Bulgaria's agricultural sector between 1993 and 2022. In general, it can be stated that there has been a notable transition in energy consumption patterns, with renewable energy sources assuming an increasingly prominent role over time. However, this transition has not been stable. It is evident that fossil fuels, particularly oil and natural gas, continue to play a significant role in the agri-

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cultural sector. In 2022, the share of oil and petroleum products in agricultural energy consumption was 70%. From the early 2000s until 2010, there was a notable reduction in the share of oil and petroleum products. However, following the year 2010, there was a notable increase in the share of oil and petroleum products, which remained relatively stable until 2022. In 2022, the share of fossil fuels in the energy mix was 6%. Between 1993 and 2022, the share of fossil fuels in the energy mix increased. Furthermore, the transition to renewable energy sources has been relatively limited. Despite an increase in the share of renewable energy, particularly from the mid-2000s onwards, its contribution to total energy consumption has remained relatively modest. It is worth noting that the aforementioned transition has occurred at a slower pace in the agricultural sector in Bulgaria. Moreover, Bulgaria is situated at the lowest third rank among Eastern European Union countries with regard to the share of renewable energy in its agricultural energy mix, which stands at 5.28%.

Energy Mix of Agriculture in Croatia

Croatia has been considered to have significant potential, especially in solar and biogas technologies, and has been identified as a country where rural areas can be focused on in the energy transition, as stated in the literature. Protić and Pašičko (2014) have stated that isolated grid systems based on renewable energy have been a viable solution for electricity generation in rural areas of Croatia to solve inadequate infrastructure. In addition to ensuring energy security in these rural areas, it has been estimated that it has also contributed to increasing agricultural productivity. However, it has been considered that there has been a mismatch between the policy plans to be implemented in the agricultural sector and the participation of stakeholders in the energy transition process in the agricultural sector in Croatia (Vidaković, 2014). In its report published in 2021, the World Bank has examined Croatia's green growth in the agricultural sector and has emphasised the importance of promoting low-carbon technologies. SolarPower Europe (2023) has reported that Croatia has legislated for the use of agrivoltaic systems in the agricultural sector, which has been an important development in the energy transition. Although Croatia has been moving towards aligning the rural energy transition with the European Union climate targets, policy alignment and strengthening incentives have been needed to fully exploit the potential of renewable energy in agriculture.

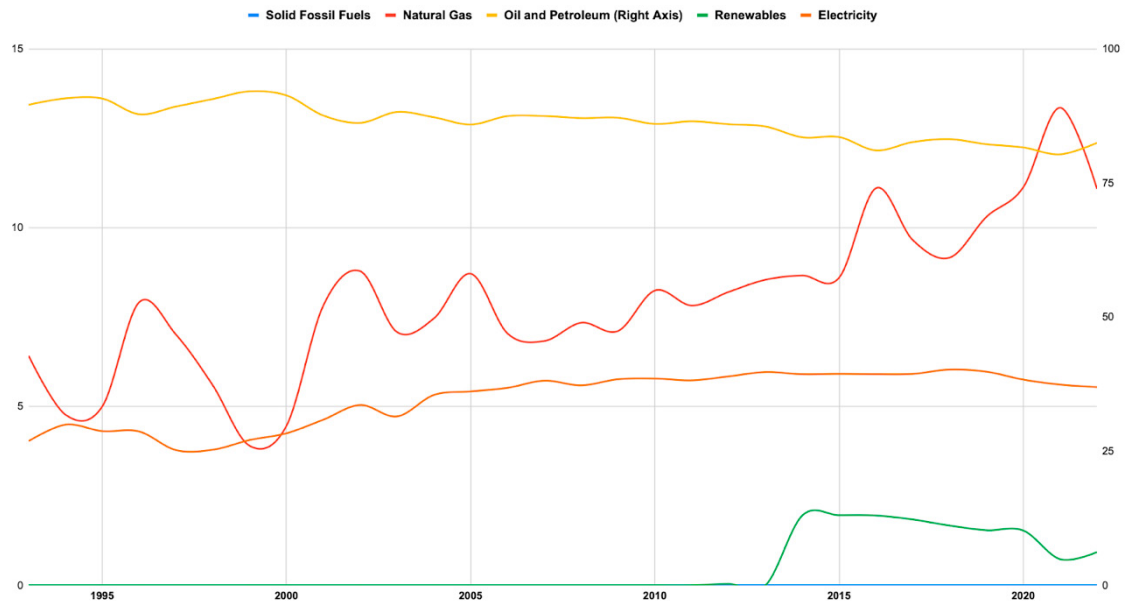

Figure 6. Energy Mix (Energy Share) Change of Agriculture in Croatia between 1993-2022

Source: author's work based on data from Eurostat.

Understanding the trend of Croatia's energy transition in agriculture has become increasingly valuable, particularly in the context of its post-EU accession developments. Figure 6 has shown the changes in the energy mix in Croatia's agricultural sector between 1993 and 2022. Croatia's agricul-

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tural sector is distinguished by a considerable reliance on oil and petroleum products. In 1993, oil and petroleum products accounted for 89% of the energy mix in agriculture. This share rose to 91% in 2000 but declined to 85% in 2005. While the share remained the same in 2010, it did not experience a significant decrease, standing at 82% in 2022. Between 1993 and 2022, the share of oil and petroleum products in Croatia's agricultural energy mix decreased by only 7%. Since 2000, the share of natural gas in the energy mix has followed a generally upward trend despite occasional fluctuations. The share of natural gas has risen from 6% in 1993 to 11% in 2022. Similarly, the share of electricity use, which began to increase in the early 2000s, has not fallen below the 5% threshold. In 2022, electricity accounted for 5.5% of the energy mix. Croatia joined the European Union in 2013, and in 2014, the integration of renewable energy into the agricultural energy mix began. The share of renewable energy in the agricultural energy mix was 1.9% in 2014 and decreased to 0.9% in 2022. After 2014, no significant progress was achieved in the share of renewable energy in agriculture. This has indicated that the transition to sustainable energy in the agricultural sector has been a gradual process, and that more robust policies and incentives have been required to direct investments in renewable energy and modernisation.

Energy Mix of Agriculture in Czechia

The agricultural energy transition in Czechia has received considerable academic attention, particularly regarding renewable energy applications aligned with the European Union's climate policies and targets. Agricultural biogas, voltaic systems, biomass, and community energy initiatives have been considered key contributors to reducing fossil fuel dependency in the country. Moreover, these energy transition practices have been regarded as having significant potential for enhancing sustainability and ensuring energy security in rural areas (Pechancová et al., 2022; Erbach, 2024).

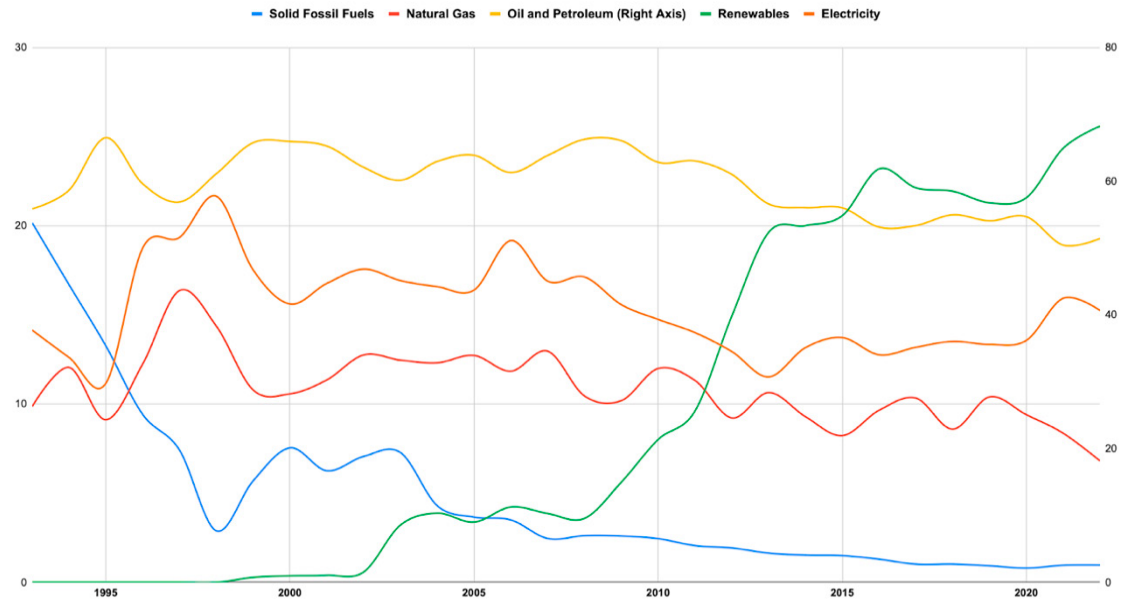

Figure 7. Energy Mix (Energy Share) Change of Agriculture in Czechia between 1993-2022

Source: author's work based on data from Eurostat.

In order to understand the agricultural energy transition in Czechia, it has been necessary to examine the trends in the energy mix. Figure 7 demonstrates the significant alterations in the energy mix in the Czechia agricultural sector between 1993 and 2022. The growth of renewable energy sources has been accompanied by a gradual reduction in the consumption of oil, petroleum products, and natural gas, indicating a clear shift away from fossil fuel dependency. In 1993, oil and petroleum products accounted for 55% of the energy mix in agriculture, while in 2022, this share decreased to 51%, marking a modest 4% reduction. Meanwhile, the share of solid fossil fuels in agricultural energy dropped dramatically, from 20% in 1993 to just 1% in 2022. In 2022, 25.5% of Czechia's agricultural energy mix was derived from renewable sources, representing a significant milestone in the coun-

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try's shift towards cleaner energy use in agriculture and sustainable development. This transition has been driven by investments in biomass, solar energy, and biogas systems, which increasingly replace traditional energy sources for powering irrigation systems, agricultural machinery, and crop processing facilities. Additionally, Czechia's proactive policies and access to European Union funds for renewable energy projects have played a crucial role in facilitating this transformation. As a result, Czechia has emerged as a leading Eastern European Union state in the share of renewable energy used in agricultural practices, setting an example for other countries in the region. These findings underscore that targeted investments, technological innovation, and supportive policies can effectively promote the adoption of sustainable energy practices in energy-intensive sectors like agriculture. However, an important point to focus on here is that while Czechia has reduced its dependence on solid fossil fuels, more attention needs to be given to reducing the share of oil and petroleum products (Recka & Scasny, 2023; European Commission, 2023b; Bellini, 2024; International Monetary Fund, 2024).

Energy Mix of Agriculture in Hungary

The agricultural energy transition in Hungary has encountered a number of persistent structural barriers. Limited investments in decentralised renewable systems and continued reliance on fossil fuels have been identified as key factors that have slowed down the transition process. Furthermore, the energy transition in rural areas in Hungary has been shown to be highly dependent on socio-institutional factors such as education levels, trust in local authorities, and public awareness of biogas technologies (Titov et al., 2021; International Energy Agency, 2022).

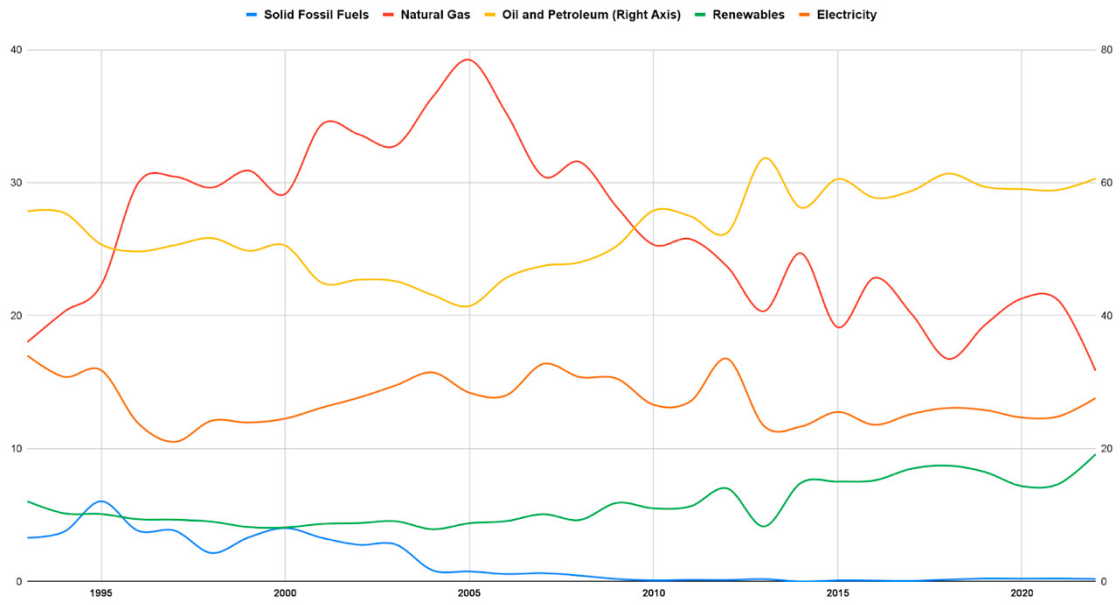

Figure 8. Energy Mix (Energy Share) Change of Agriculture in Hungary between 1993-2022

Source: author's work based on data from Eurostat.

Figure 8 presents the changes in Hungary's agricultural energy mix from 1993 to 2022. The use of electricity in agricultural practices in Hungary exhibited minimal fluctuations between 1993 and 2022. Hungary joined the European Union in 2004. After 2004, natural gas consumption peaked in 2005, followed by a gradual decline until 2022. The share of renewable energy in the agricultural energy mix has shown a slow but steady upward trend since 2004. In 2022, the share of renewable energy sources in the agricultural energy mix was 9.57%. Nevertheless, oil and petroleum products accounted for 60% of the agricultural energy mix in 2022. What is notable here is that after 2004, the share of oil and petroleum products in the agricultural energy mix steadily increased. This is related to Hungary's agricultural production perspective. As a result, Hungary's agricultural sector remains heavily reliant on oil and petroleum products, posing a significant barrier to achieving a sustainable energy transition.

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Energy Mix of Agriculture in Estonia

While Estonia has expedited the transition to renewable energy in numerous domains, the agricultural sector has progressed at a comparatively languid pace with regard to energy transition. The International Energy Agency (2023) has asserted that Estonia's agricultural energy consumption has continued to rely on oil and petroleum products, a situation that has been attributed to the obsolescence of rural infrastructure. As stated in the IEA Bioenergy (2021) country report, more than 90% of Estonia's renewable energy supply has been derived from solid biomass. This has demonstrated the limited utilisation of alternative renewable resources, such as solar or biogas, within the agricultural sector in Estonia. In this context, the transition to alternative renewable energy sources that have reduced dependence on fossil fuels has been regarded as particularly important for the agricultural sector.

Figure 9 illustrates the alterations in the energy mix in Estonia's agricultural sector between 1993 and 2022, thereby offering insight into the evolution of energy sources over this period. Although the share of oil and petroleum products in the agricultural energy mix showed a relatively modest decline in the early 2000s, it began to rise after 2006. Despite showing fluctuations after 2006, it has steadily increased, reaching 78% by 2022. The share of renewable energy in the agricultural energy mix has exhibited unstable movements. In 2022, renewable energy sources accounted for only 5.3% of the total energy consumed in the agricultural sector, which can be viewed as an ongoing challenge for the widespread adoption of sustainable energy practices in this area. This share has not reached a level that could be considered an indicator of a stable or significant energy transition. The observed increase in the consumption of oil and its derivatives highlights the significant dependence of Estonia's agricultural sector on fossil fuels, which presents a challenge for achieving energy sustainability and reducing greenhouse gas emissions.

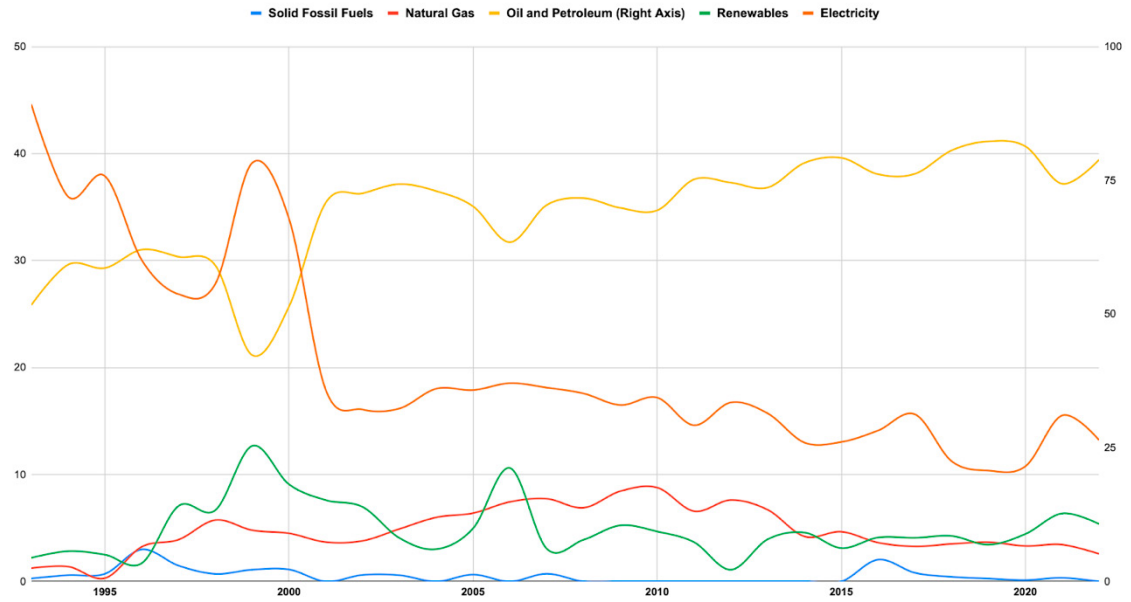

Figure 9. Energy Mix (Energy Share) Change of Agriculture in Estonia between 1993-2022

Source: author's work based on data from Eurostat.

Energy Mix of Agriculture in Latvia

Latvia has faced a number of challenges in the renewable energy transition in agriculture due to policy inconsistency and the limited utilisation of biogas and biomass technologies. The prevailing sentiment has suggested that risk perception, regulatory uncertainty, and insufficient policy support in Latvia's agricultural sector have impeded the adoption of renewable and biomass energy (Rivža et al., 2012). The environmental impact of agricultural biogas production in Latvia has been analysed by Wicki et al. (2022). Their findings have demonstrated that, despite accounting for only 1.6% of total

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energy production, agricultural biogas in Latvia has contributed significantly to the reduction of CO_2 emissions.

An essential step in understanding the imbalances in Latvia's agricultural renewable energy transition has been the analysis of the energy mix. Figure 10 presents the changes in the energy mix in Latvia's agricultural sector between 1993 and 2022. The energy mix in Latvia has exhibited unstable patterns, fluctuating annually. Following Latvia's accession to the European Union in 2004, the agricultural sector has shown an increasing reliance on oil and oil products in its energy mix, with this dependency reaching 78% in 2022. Although agricultural production in Latvia is significant, the share of oil and oil products in the energy mix has been rising since the early 2000s. Meanwhile, the contribution of solid fossil fuels has steadily declined since 1995, nearly disappearing by 2015. The share of renewable energy in Latvia's agricultural energy mix has stood at 11.6%, which is close to the European Union average. However, another notable aspect is that the share of renewable energy in Latvia's agricultural energy mix has declined from 13% in 1993 to 11% in 2022. Latvia has remained the only Eastern European Union country where the share of renewable energy in the agricultural energy mix has decreased. To accelerate energy transition and sustainability in Latvia, increased investment in renewable energy projects and the implementation of incentives to reduce oil dependency are imperative.

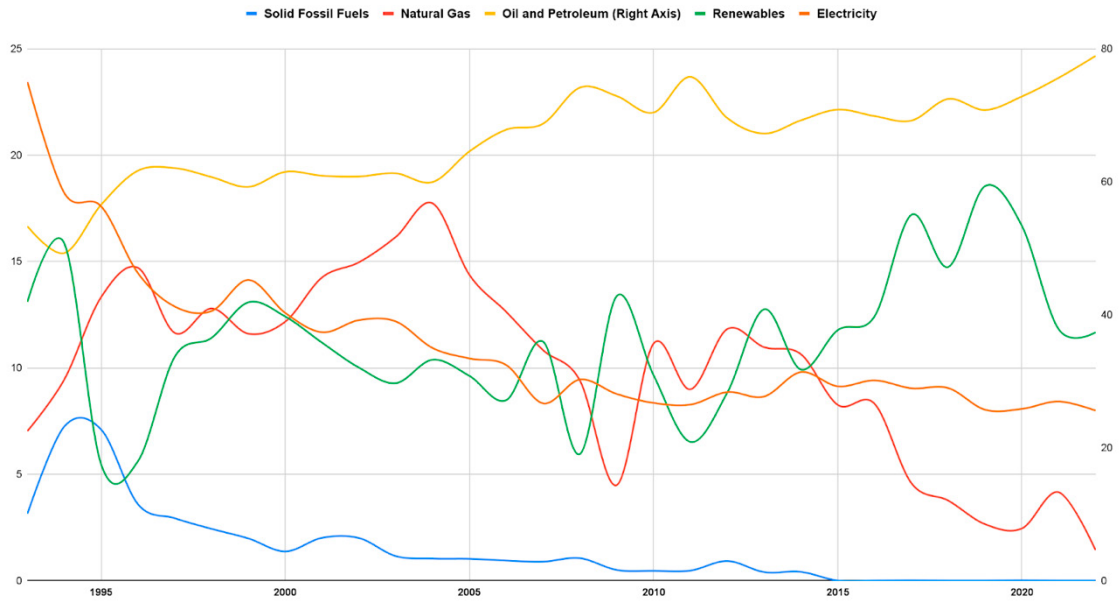

Figure 10. Energy Mix (Energy Share) Change of Agriculture in Latvia between 1993-2022

Source: author's work based on data from Eurostat.

Energy Mix of Agriculture in Lithuania

Significant steps have been taken in Lithuania in the energy transition, especially in the shift to renewable energy in sectors such as electricity and district heating. The state has expressed its intention to continue facilitating the energy transition in the agriculture sector, with the support of EU structural funds. In this context, the gradual integration of solar and bioenergy solutions in rural areas has been pursued. Figure 11 illustrates the changes in Lithuania's agricultural energy mix between 1993 and 2022, showcasing significant developments in its transition to renewable energy. Since 2004, Lithuania has continued its efforts toward energy transition. In 1993, the share of oil and oil products in the agricultural energy mix was 65%, decreasing to 54% by 2022. Although this represents a decline, the share of oil and oil products began to decrease after 1993, but started to rise again after 2001. Following 2006, the share of natural gas declined, although it has remained higher than its 1993 level. After Lithuania joined the European Union, the share of renewable energy initially decreased but began to rise steadily after 2007. By 2022, the share of renewable energy in Lithuania's

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agricultural energy mix had reached 14%. Compared to 1993, the 2022 energy mix has shown an increase in the shares of renewable energy and natural gas, while the shares of other energy sources have declined. Moreover, Lithuania has maintained one of the highest shares of renewable energy in agricultural energy mixes among Eastern European Union countries, at 14%, positioning it behind only Czechia and Slovakia.

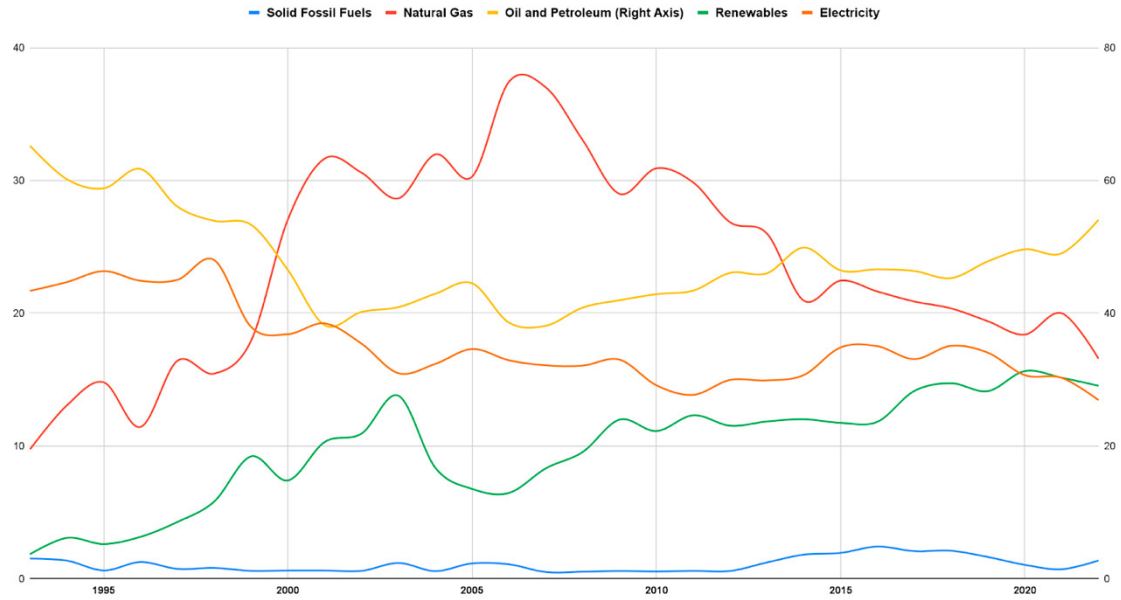

Figure 11. Energy Mix (Energy Share) Change of Agriculture in Lithuania between 1993-2022

Source: author's work based on data from Eurostat.

Energy Mix of Agriculture in Poland

Since Poland joined the European Union in 2004, it has undergone a significant transformation. Empirical evidence has indicated that Poland's accession to the European Union has led to an enhancement in agricultural production within the country, particularly in terms of energy efficiency and harvest. Research has demonstrated that Polish farms have achieved higher agricultural yields and improved energy efficiency, despite having used comparable energy inputs before and after EU accession (Lewandowska-Czarnecka et. al, 2019). In post-socialist Central and Eastern European Union countries such as Poland, a high degree of reliance on coal has resulted in a marked retardation of the agricultural energy transition, despite the presence of EU objectives and strategies for decarbonisation (Maltby & Mišík, 2024). However, despite these observations, Poland has undergone a visible transformation process in the energy transition within the agricultural sector.

Despite the increasing share of renewable energy in Poland, the energy transition has remained a subject that merits critical scrutiny. Figure 12 shows the alterations in the energy mix in agriculture in Poland from 1993 to 2022. In Poland, the share of solid fossil fuels in the agricultural energy mix has experienced a significant decline since 2014. While the share was 32% in 1993, it dropped to 14% by 2022. Since 2010, the share of oil and oil products has increased, reaching levels similar to those observed in 2005. In 2022, the share of oil and oil products rose to 65%. The share of renewable energy in agriculture has been increasing since 2005, reaching 14.3% in 2022. Despite the relatively low share of renewable energy sources in the agricultural energy mix, this level is above the EU average. This has indicated that while Poland has not yet achieved a rapid energy transition, it has made progress compared to other Eastern European Union countries.

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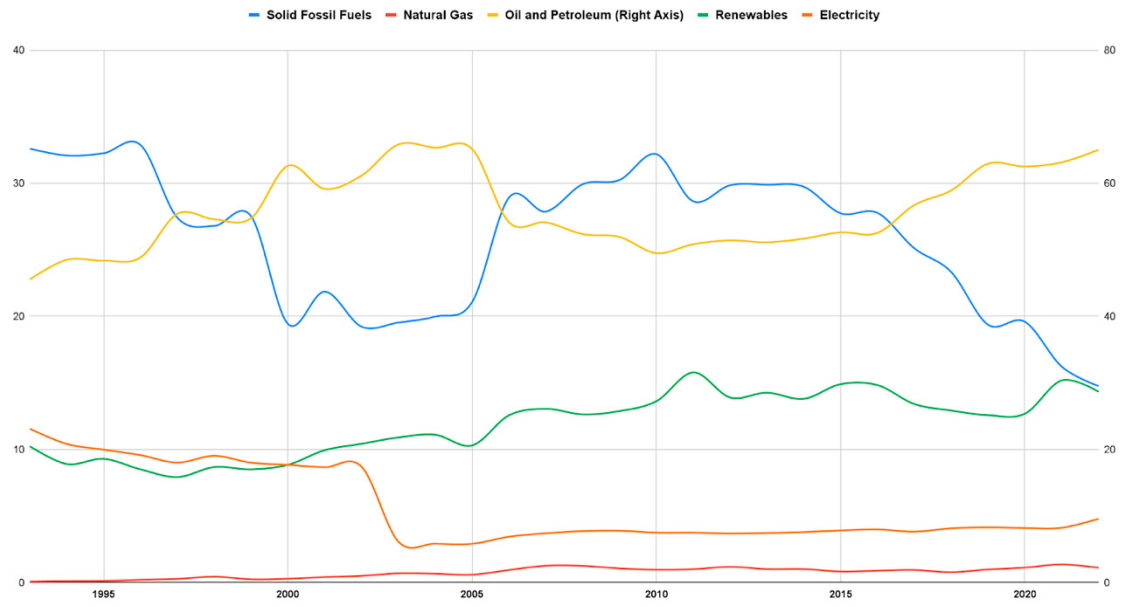

Figure 12. Energy Mix (Energy Share) Change of Agriculture in Poland between 1993-2022

Source: author's work based on data from Eurostat.

Energy Mix of Agriculture in Romania

Rural areas in Romania have been considered to have maintained a positive attitude towards renewable energy, but utilisation rates have remained low compared to the potential. A lack of interest and insufficient awareness in rural areas have stood out as the main factors that have hindered the energy transition (Chiciudean et al., 2018). On the other hand, infrastructure deficiencies and limited incentives have been regarded as some of the most significant factors that have contributed to the instability of Romania's energy transition (Drăgoi et al., 2023).

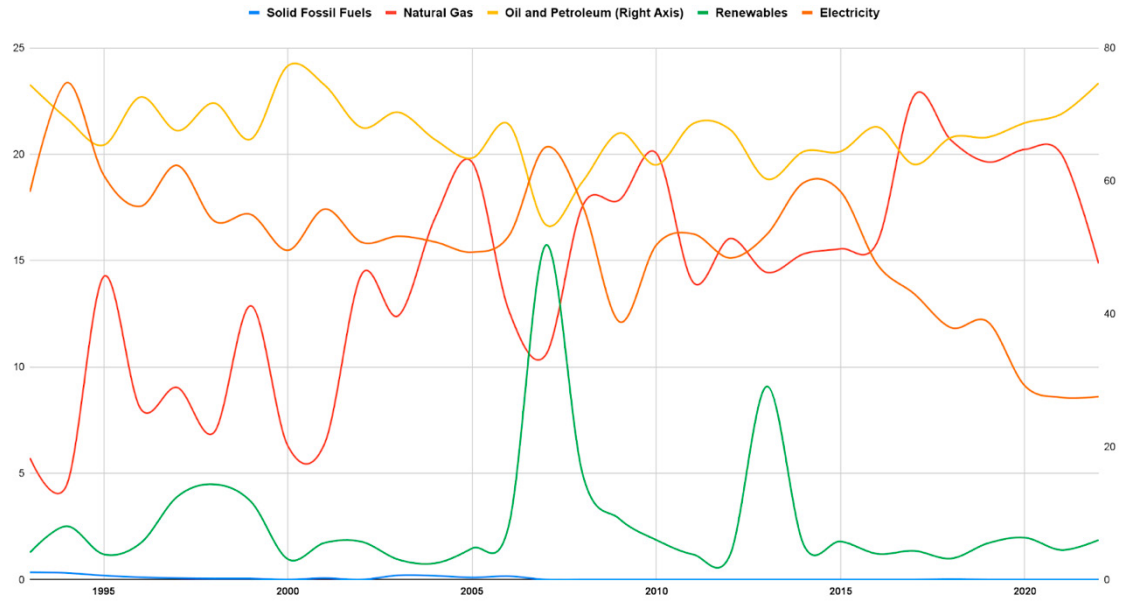

Figure 13. Energy Mix (Energy Share) Change of Agriculture in Romania between 1993-2022

Source: author's work based on data from Eurostat.

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Romania's agricultural energy mix has shown inconsistent patterns over time. Figure 13 shows the alterations in the agricultural energy mix in Romania from 1993 to 2022. In 2022, oil and petroleum products accounted for 74% of the total energy mix, the same share as in 1993. This indicates that no progress has been made in reducing the share of oil and petroleum products in Romania over the past three decades. The share of natural gas in the agricultural energy mix increased from 5% in 1993 to 14% in 2022. However, the share of renewable energy in Romania's agricultural energy mix remains low, accounting for only 1.8% in 2022. This is the second-lowest share among Eastern European Union countries, after Croatia. The minimal presence and limited use of renewable energy sources in agriculture, coupled with continued reliance on oil and petroleum products, reflect a trend seen across other Eastern European Union countries. A range of factors, including insufficient investment in green technologies for agriculture and infrastructure challenges in transitioning to cleaner energy systems, continues to constrain energy transition efforts. Implementing more robust policies to facilitate the adoption of renewable energy technologies and accelerate the energy transition in Romania's agricultural sector is therefore of critical importance.

Energy Mix of Agriculture in Slovakia

Slovakia has attached significant importance to the renewable energy transition in agriculture, albeit with periodic instability. Slovakia has been acting institutionally in line with the European Union's climate targets. It has been imperative to acknowledge that Slovakia's National Energy and Climate Plan has been predicated on the objective of augmenting the share of renewable energy to 19.2% of gross final energy consumption by the year 2030. The country has set targets for hydropower (1,755 MW), solar photovoltaics (1,200 MW), wind power (500 MW), biomass (200 MW), and biogas/biomethane (200 MW). While hydropower has remained the dominant form of energy in the transition, solar PV and biomass have also played important roles (Fabrègue, 2024).

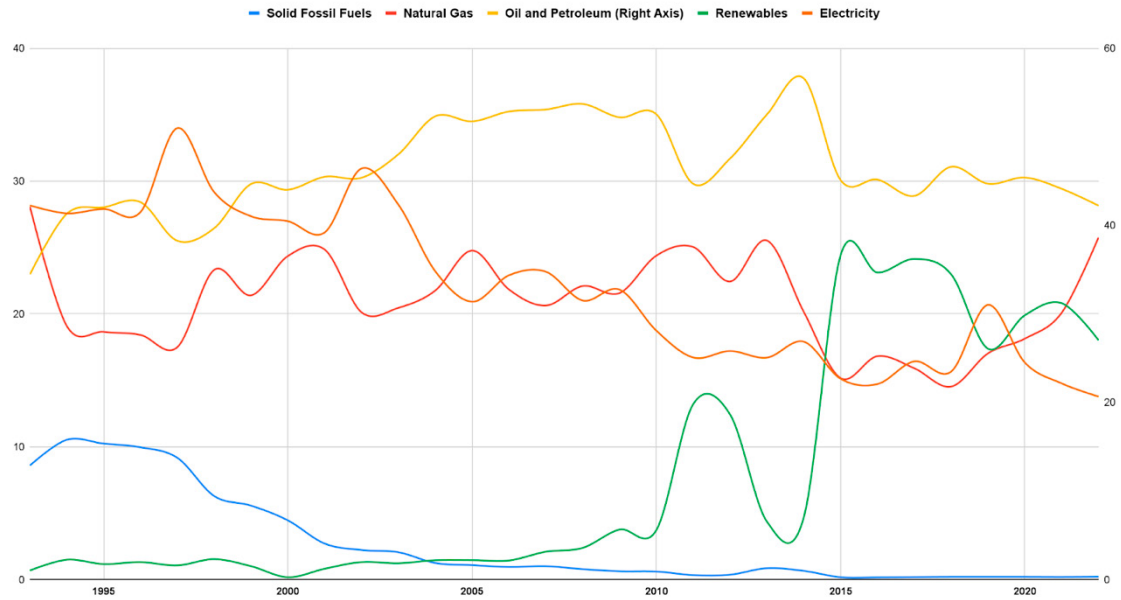

Figure 14. Energy Mix (Energy Share) Change of Agriculture in Slovakia between 1993-2022

Source: author's work based on data from Eurostat.

The energy mix in the agriculture sector of Slovakia has experienced a multifaceted and evolving transition, driven by domestic policy changes. Figure 14 has outlined the changes in the energy mix in agriculture in Slovakia from 1993 to 2022. In Slovakia, the share of renewable energy in agriculture has fluctuated between 2010 and 2015, but has significantly increased following reforms implemented in 2015. During the same year, the shares of natural gas, oil, and petroleum products have decreased, while the share of renewable energy has risen. However, since 2015, the share of renewable energy in agriculture has entered a downward trend. The share of natural gas in the agricultural

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energy mix has declined from 28% in 1993 to 24% in 2022. The sharp increase in natural gas over the past two years has been associated with regional and global developments. In 2022, oil and petroleum products accounted for 42% of the energy mix, while electricity has constituted 13%. Slovakia's agricultural energy mix has been more evenly distributed compared to other Eastern European Union countries. Notably, Slovakia has maintained the second-highest share of renewable energy in agricultural energy mixes among Eastern European Union countries, at 18%, following Czechia.

Conclusion and Discussion

The European Union has provided significant project and financial support for sustainable development and energy. Achieving the fundamental goals established for the future has highlighted the importance of energy transition in the agricultural sector. The reliance on fossil fuels, oil, and petroleum products for many tools used in agriculture has caused the energy transition in this sector to progress more slowly compared to others. Particularly in the energy transition process, it has been necessary to focus on the energy mix in agriculture within Eastern European Union countries. The share of renewable energy in agricultural activities across these countries has remained relatively low, emphasising the need for investments in renewable energy technologies and energy efficiency measures.

The average share of renewable energy in agriculture across the European Union has stood at 12%. According to the data presented in this study, the share of renewable energy in agriculture has been notably low in Romania, Croatia, Estonia, and Bulgaria. In Latvia and Hungary, the share of renewable energy in agriculture has remained below the EU average, although not as distant as in other countries. A striking observation here is that Latvia has remained the only Eastern European Union country where the share of renewable energy in the agricultural energy mix has decreased.

Czechia has distinguished itself among Eastern European Union countries regarding the agricultural energy mix. With a high share of renewable energy, Czechia has served as a noteworthy example for other Eastern European Union countries with similar structural characteristics in energy transition. In 2022, the share of renewable energy in Czechia's agricultural energy mix has reached 25%. This share has stood out not only when compared to other Eastern European Union countries but also in the broader context of the European Union. Following Czechia, Slovakia has emerged as another prominent country. While natural gas consumption in Slovakia has significantly increased in recent years, the consumption of oil and petroleum products has decreased more gradually. Poland, with a renewable energy share of 14% in agriculture, has remained above the EU average; however, its growth in renewable energy share has been relatively low compared to other Eastern European Union countries.

The revised Renewable Energy Directive, adopted in 2023, has raised the EU's binding renewable energy target to at least 42.5% by 2030. The goal of transitioning to low-carbon energy has progressed faster in other sectors across European Union countries than in agriculture. It is noteworthy that while the share of renewable energy in agriculture in some Eastern European Union countries has aligned with or exceeded the EU average, the share of oil and petroleum products has remained relatively high. Therefore, it has been essential for these countries to reevaluate their agricultural energy policies to align them more closely with the EU's renewable energy targets and reduce their dependency on oil and petroleum products. Accelerating the energy transition in agriculture has been crucial to enabling this sector to move in harmony with others. To achieve the EU's ambitious renewable energy targets, it has been essential to implement investments, innovations, and policies addressing the unique challenges faced by agriculture. Providing support and incentives to ensure a fair transition across all regions has remained one of the most critical elements.

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Umutcan MEMO

TRANSFORMACJA ENERGETYCZNA ROLNICTWA W KRAJACH EUROPY WSCHODNIEJ UNII EUROPEJSKIEJ: PRZEGLĄD DANYCH I TRENDÓW Z LAT 1993–2022

STRESZCZENIE: Kwestia emisji gazów cieplarnianych wynikających ze zużycia energii pozostaje dużym wyzwaniem dla Unii Europejskiej. W odpowiedzi UE wyznaczyła sobie cel redukcji emisji gazów cieplarnianych o 55% do 2030 roku oraz osiągnięcia całkowitej neutralności węglowej do 2050 roku. Transformacja energetyczna jest kluczowa dla redukcji emisji gazów cieplarnianych, zapewnienia zrównoważonego rolnictwa oraz poprawy bezpieczeństwa energetycznego. Głównym celem niniejszego badania jest ocena postępów w przechodzeniu na odnawialne źródła energii w rolnictwie w krajach Europy Wschodniej należących do Unii Europejskiej. W badaniu zastosowano metodę przeglądu danych w celu analizy transformacji energetycznej w rolnictwie w krajach Europy Wschodniej UE, takich jak Bułgaria, Czechy, Estonia, Chorwacja, Łotwa, Litwa, Węgry, Polska, Rumunia i Słowacja, w okresie 1993–2022. Wyniki wykazały, że przechodzenie na odnawialne źródła energii w rolnictwie przebiegało stosunkowo wolno w Rumunii, Chorwacji, Estonii, Bułgarii i na Węgrzech.

SŁOWA KLUCZOWE: transformacja energetyczna, rolnictwo, energia odnawialna, Unia Europejska

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