

Article

The Impact of the Common Agricultural Policy on Energy Efficiency in Agriculture: Between Farmer Support and Sustainable Development in the Visegrad Group

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Abstract

This study examines the relationship between energy efficiency in agricultural production and its determinants, considering technological, economic, political, and social factors. The aim was to determine the impact of the CAP on the energy efficiency of agricultural production, as well as technological, market, and social changes. The impact of time effects was also taken into account. The study focuses on the four Visegrad Group countries over the 2004–2023 period. Both fixed-effects and dynamic panel models were employed to capture structural changes over time. The significance of agriculture, as a result of structural transformations, is relatively small and hovers around 3% in these countries. The CAP was found to have a significant impact on the energy efficiency of agricultural production. However, it was not the amount of support but rather its structure that played a crucial role, particularly environmental support (0.04). The inertia effect was also of fundamental importance (0.41—elasticity in the inertia model). The total value of transfers, especially in the long term, proved to be a discouraging factor for this process. Market conditions, including energy prices (0.456), structural changes in farms (0.016), and labor input (−0.04), were also significant factors. However, it was not so much the size of support but rather the structure of support that was crucial. The total value of transfers, especially in the long term, was a demotivator for this process. Market conditions, including energy prices, structural changes on farms, and labor inputs, were also important factors. A key recommendation for agricultural financial support policy is to focus support more on environmental and low-emission issues, which are linked to improving the energy efficiency of production while maintaining its growth. Transfers related to the growing importance of renewable energy sources and support for rural development, which do not yield beneficial effects in the considered scope, require increased conditionality.

Keywords: energy efficiency; economic conditions; economic transfer; economic policy; CO₂ emission



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1. Introduction

The European Union's Common Agricultural Policy (CAP) is one of the most distinctive and key elements of the community's influence on the socio-economic well-being of its members. Over the years, CAP expenditure has represented a significant share of the EU budget. Although the role of the agricultural sector itself at the macroeconomic level has declined with the socio-economic progress of member states, as evidenced by the

decline in agricultural value added in GDP, this sector still plays a strategic role due to the numerous functions it performs in the socio-economic system [1,2]. It can even be noted that in light of recent crises (COVID-19, energy, and climate), its importance has increased. It was not a growth in economic terms, but rather in social, environmental, and security aspects [3–5]. The importance of public goods provided by farms has been increasing. The provision of public goods by farms has gained increasing recognition. Moreover, ongoing structural transformations and the rising importance of non-food and non-market outputs have contributed to a growing complexity in agricultural policy, making its assessment even more challenging [6]. This makes it even more difficult to assess. One of the main goals of the European Union's economic policy and development strategy is to achieve a low-emission and resource-efficient economy [7,8]. This objective has been reflected in successive reforms of the CAP. Notable milestones include the Health Check in 2008 and the 2014–2023 reform, which introduced “greening” requirements—obligating farmers to adopt environmentally beneficial practices—as well as broader application of subsidy degressivity. Another significant step was the 2024–2027 CAP reform, which enhanced the role of conditionality and introduced eco-schemes. Therefore, it would be interesting to examine the impact of financial support for agriculture and the socio-economic conditions accompanying agricultural production on the energy and environmental efficiency of this sector. The impact of individual groups of support instruments on the aforementioned effects is particularly interesting. It should be noted that the EU allocates significant budget transfers to improving resource efficiency. At the same time, based on multiannual data, a clear contradiction should be noted between the entire economy and agriculture in the area under consideration. If we evaluate the years 2012–2023, energy consumption in the entire EU economy, expressed as Final Energy Consumption (FEC), decreased by 6.58% [9]. During the same period, direct energy consumption in agriculture increased by 7.71% (this only covers direct consumption) [10].

Energy use in agriculture can be assessed from both narrow and broad perspectives. Direct consumption encompasses various processes occurring in agriculture (e.g., the use of machinery) [11]. Indirect energy consumption, on the other hand, includes the energy needed to produce fertilizers, chemicals, and pesticides used in agriculture, and the production of these products is growing rapidly. Energy consumption for the production of mineral fertilizers (primarily nitrogen fertilizers) is very high [12]. Fertilizer production, particularly nitrogen fertilizers, is one of the most energy-intensive processes in agriculture and the chemical industry. Therefore, agriculture's actual contribution to the energy intensity of the economy is substantially higher than suggested by direct consumption alone. The observed decline in overall energy consumption at the economy-wide level was primarily driven by deindustrialization and the growing importance of the service sector, which is significantly less energy-intensive. Additionally, increasingly strict regulations were introduced in the construction and transport sectors. In agriculture, by contrast, the trend reflected an ongoing industrialization of farming. This included rising levels of mechanization and automation, the substitution of manual labor with capital-intensive inputs, increased use of fertilizers, and the expansion of greenhouse production. There was also a notable rise in feed production and intensification of livestock farming.

Furthermore, it is important to note the impact of climate change on energy consumption, particularly in terms of greater demand for irrigation, cooling, and weather-related risk mitigation in agricultural production systems.

As can be seen, the EU allocates significant support to improving resource efficiency, transitioning to renewable energy sources, and reducing greenhouse gas emissions. Directive 2023/1791 on energy efficiency sets a target of reducing final energy consumption by 11.7% by 2030 [9]. Renewable energy sources such as solar energy, biomass, wind, and

geothermal energy are widely used in agriculture and rural areas. Their use can improve energy efficiency. This shapes the possibility of their widespread application, lowering agricultural production costs and reducing greenhouse gas emissions [13]. Sustainable energy not only reduces greenhouse gas emissions but also facilitates an effective energy transition, balancing economic, social, and environmental needs and, consequently, improving the efficiency of production processes [14]. In the face of increasing competition in the global market, this has a significant impact on product prices, especially for homogeneous products. Research conducted to date indicates that a decrease in energy intensity significantly contributes to reducing greenhouse gas emissions related to energy used in EU agriculture [15]. This is particularly important in countries with a significant share of non-renewable fuels in the energy mix, such as the Visegrad Group countries. Consequently, the contribution of agriculture to energy production and its use is a key issue in ongoing considerations regarding agricultural support policies, given its impact on food security and the potential for agricultural development and energy transition. Although recent years have seen an increase in renewable energy production in EU countries, it is still insufficient to meet energy demand [16]. Furthermore, the effects are not always improved.

Energy efficiency in agricultural production is decreasing, further weakening this effect. Furthermore, the observed increase in energy prices, also as an indirect cost of the ongoing transformation, is resulting in a deterioration in the global competitive position of EU agriculture, which has long-term consequences [17]. Therefore, methods that improve energy efficiency and the use of renewable energy sources on farms can help agricultural producers reduce production costs. Under these conditions, subsidizing the use of renewable energy in agriculture improves its competitiveness on international markets [18]. Consequently, with regard to changes in agricultural policy, the question arises of how the CAP and its individual groups of instruments impact energy efficiency. Research shows that this issue should be addressed in regional groups due to the structural specificity of both agriculture and the structure of the energy mix [19]. The complexity of socio-production systems at the farm level, but also at the regional level, means that the heterogeneity of farms and social needs must be taken into account when developing policies. These are among the main factors influencing the complexity of the CAP. Importantly, the CAP is undergoing further stages of transformation, which require a fresh look at the effects of individual financial streams flowing into agriculture. The CAP reform after 2027 continues the trend toward greater redistribution, sustainable development, digitalization, and regional flexibility, as well as the need to achieve a balance between economic support and ecological requirements. Hence, there is a need for research and answers to these questions.

2. Conceptual Framework of Energy Efficiency in Agriculture—Literature Review

The study of energy efficiency raises questions well-known in the literature. The first concerns the broad approach and refers to the aforementioned division into direct and indirect energy consumption in agriculture. Furthermore, the analysis method can be divided into partial energy efficiency and total energy efficiency [20]. The former approach ignores the importance of other factors. The latter approach, however, is more comprehensive, although it also has different applications. Energy is only one of the inputs analyzed. In such cases, methods such as DEA, SFA, or the Malmquist Index are used [21,22]. Here, the former approach is applied, taking into account the determinants of efficiency. Research conducted in China's industry has shown that energy efficiency is negatively related to the GDP expenditures of budgetary, state-owned enterprises, and secondary industry, but is positively related to the share of renewable energy in energy consumption [23]. Research also demonstrates a close relationship between energy and environmental goals. Agri-

cultural policy measures aimed at improving energy efficiency simultaneously effectively reduce CO₂ emissions [24,25]. Therefore, improving energy efficiency is an important factor in improving environmental efficiency. Technological changes and the introduction of innovations in agricultural production have similar significance, but also at the level of the entire economy. Changes also concern technological advancements in the field of renewable energy sources, including the application of optimization techniques [26,27]. The use of integrated agricultural techniques improves energy efficiency by reducing energy inputs without affecting production efficiency [28]. This applies to both low-input agriculture and integrated agricultural systems. Central and Eastern European countries, including the Visegrad Group, also have low levels of agricultural technology compared to many Western European countries [29]. Therefore, according to Czubak and Zmysłony's research, the decline in energy intensity occurred on farms that implemented comprehensive investments, while the worst results were recorded on farms with negative investments, meaning those that experienced asset depreciation [30]. However, the type of investment was a significant differentiator. Studies conducted on a group of 28 OECD countries indicate that the introduction of environmental technologies not only improves energy efficiency but also reduces energy consumption [31,32]. Therefore, the overall effect is very significant. In this context, a synergistic effect emerges, as these technologies can help reduce the negative impact of energy consumption, further reducing greenhouse gas emissions and environmental pressure. Consequently, this also points to the need for structural investment in sustainable agricultural mechanization, one of the tangible results of which will be improved energy efficiency. In the global context, energy efficiency varies depending on the income group of the economy [33]. Analyzing the volume of various streams of financial support for agriculture, the results are not as clear-cut and often reveal negative consequences. Higher levels of payments from Pillars I and II of the CAP, measured as a percentage of total agricultural income, have a negative impact on technical change on farms and energy efficiency [34]. The results in these studies were consistent across the surveyed farms. Therefore, the overall value of support aimed at increasing income relative to agricultural-related resources does not necessarily stimulate efficiency improvements. However, the orientation of policies that influence investment efficiency is crucial [35,36]. The conclusions and the studies referenced pointed to a negative relationship with energy efficiency, but the issue of small farm survival or other differentiated impacts was not addressed in the cited article. In the case of Pillar II of the CAP, the subsidies are decoupled from production volume, and thus assumed to be more uniform in their effects [37,38]. The structure of agricultural production and the importance of organic production are also important aspects. Most organic farming systems are more energy-efficient than their conventional counterparts [39].

Economic policy also plays a significant role in changes in energy intensity at the general level, specifically by influencing investment processes. Higher energy prices resulting from such measures have a positive impact on lower energy consumption, forcing investments in more energy-efficient technologies [40]. The problem, of course, is the adjustment process, during which price differences between countries will negatively impact the price competitiveness of products from a country with higher production costs due to higher energy prices. This also has unfavorable social effects in the form of higher food prices in a given country [41], thus creating an imbalance in the context of sustainable development, at least in the short term. On the other hand, a clear contradiction appears. Countries characterized by high environmental standards, such as Germany, Sweden, and Austria, are less energy-efficient in agricultural production than countries with lower standards, such as Spain, France, and Ireland [42,43]. Furthermore, a number of Eastern

European countries achieve low efficiency results, which can be considered expected due to the low level of technology implemented [41,44].

The research emphasizes the diversity of individual countries. Hence, studies were often conducted by dividing them into clusters. Only for relatively homogeneous groups of countries can institutional measures leading to increased energy and environmental efficiency be developed [45]. Similar regional variations were observed in other studies, which additionally noted that regional differences were also evident in the effectiveness of financing energy transformations under the CAP, suggesting that farm structure, institutional capacity, and climatic conditions also influence EU expenditure on energy sustainability [46]. This is particularly important for shaping the CAP, which encompasses such a broad group of countries with heterogeneous structures. Successful implementation of technological change, however, requires the removal of numerous technical, economic, and political barriers [47]. This may be the source of the existing diversity among countries operating within institutions such as the EU or, more narrowly, the CAP. Microeconomic analysis at the farm level, however, highlights the importance of farm size and specialization [48]. These factors influence the results obtained and point to the need for multidimensional research.

In the context of energy efficiency research, the problem of energy poverty also arises, especially in lower-income countries and regions. A clear interrelationship can be demonstrated between these phenomena, and both impact the ability to achieve food security and sustainable agriculture [49–52]. Furthermore, as demonstrated by the results of some studies, the introduction of modern technologies, especially the transition to renewable energy sources, is insufficient to meet energy demand at the current stage of this transition. Energy efficiency is therefore a key element of any policy aimed at ensuring sustainable, inclusive economic growth [53,54]. Research across the EU also indicates differences in the benefits received by agricultural producers in different countries or, more specifically, regions. Therefore, one may wonder whether similar differences exist in the impact of financial support streams on energy efficiency. Analyzing the structure of support also reveals varying effects. Subsidies linked to production and the environment (based on eco-schemes) reduce temporary technical inefficiencies, but environmental subsidies from rural areas increase historically entrenched technical inefficiencies [55]. In this context, it can be noted that there is still a lack of research that simultaneously considers structural changes, fossil fuel energy consumption, and the importance of financial support for agriculture, which is also subject to cyclical changes. Sectoral studies are also lacking, with analyses at the level of entire economies predominating.

Therefore, this study aims to fill the identified research gaps and propose recommendations for policymakers and farms. The research scope includes the Visegrad Group countries due to their identified specificities, but also the way the CAP is designed, allowing for the selection of preferred support areas and the reallocation of funds between measures, as well as the introduction of national solutions and financing. The aim of the study is to determine the impact of groups of instruments on agricultural energy efficiency in the selected group of countries and the implementation of renewable energy sources. The aim was to determine the impact of the CAP on the energy efficiency of agricultural production, as well as technological, market, and social changes. The impact of time effects was also taken into account. This will help provide recommendations based on analytical evidence and theoretical insights.

3. Materials and Methods

3.1. Data and Variables

In our approach, we proposed an econometric study using panel data for the Visegrad Group countries. Among the factors often considered are the energy transition, which leads

to an increased share of renewable energy sources, as well as issues related to greenhouse gas emissions [56,57]. Rapid increases in energy prices and the debate on energy security once again highlight the need to increase the share of renewable energy sources; hence, they were also included in the assessment. Based on literature and our own assessment, the following variables were considered: financial support and its structure (CAP, CAP_green, CAP_rural), the share of renewable energy sources (RES_share), technological factors (digitalization), economic conditions (energy price), agricultural structure (farm size—Agri_size, labor input—Labor_input), and environmental impact (Gas_emission) (a detailed explanation is included in Appendix C). Access to the internet (House_digital) plays a crucial role in modern farming, as it facilitates the use of digital tools such as applications, sensors, online advisory systems, weather forecasting, and remote monitoring—all of which contribute to more efficient energy management. The relevance of this variable is also supported by other studies that highlight how internet access can: enhance environmental and energy awareness by providing access to information on energy-saving technologies and best practices, enable the implementation of remote and automated technologies (e.g., sensors, IoT), which require network connectivity, facilitate access to online training and knowledge resources, improving farmers' capacity to manage energy use more effectively.

The study analyzed factors influencing energy efficiency. Internal mechanisms linking CAP support with energy security were taken into account by assessing the impact of technology and price effects. Therefore, the share of renewable energy and energy prices were selected as control variables. The share of renewable energy serves as a key indicator of the technological transformation process in the energy sector, while energy prices reflect market responses.

Data were obtained from the following databases: Eurostat (energy consumption, greenhouse gas emissions, agricultural production, CAP, agricultural production data), FADN (farm structure, CAP, labor input), and FAO (data on agricultural production and its structure). Due to data availability and the scope of the macroeconomic-level analysis referring to entire national structures, individual operations related to agricultural production in its various types were not analyzed.

3.2. Methodology

The following approaches are used in the literature: input-output analysis—energy balance assessment, generally encompassing direct and indirect energy consumption, partial efficiency indicators, comparative analysis of different production systems, life-cycle analysis, econometric modeling, and simulations [23,58]. These various approaches characterize the complexity of the conducted research and the obtained results.

In this study, a panel analysis was conducted, first static and then dynamic. Subsequently, the appropriate model specification was selected using the Hausman and Breusch–Pagan tests. In the next step, the static model was estimated, and diagnostic tests were performed to assess the model's suitability and its results. Then, the dynamic model specification (Arellano-Bond model) was chosen and estimated. In this case, model validation was also carried out (AR(1), AR(2), Sargan, and Hansen tests).

It is important to acknowledge the limitations of this approach. Panel analysis using the Arellano-Bond method is applied when there is a small number of units and a relatively large number of periods (in this case, years), as well as endogeneity issues. However, it has its limitations. The first risk is a large number of instruments, which increases with the number of periods under estimation. This may lead to overfitting the model. To address this limitation, the range of lags used was reduced. The Hansen test was also satisfactory, ultimately indicating no problem with instrument validity.

Furthermore, when lagged variables correlate weakly with the differences in the dependent variable, instruments become weak, and GMM estimators are biased. In the Arellano-Bond method, it is assumed that variables are not correlated over time from the second order onward. Therefore, as mentioned, autocorrelation tests (AR(1), AR(2)) were conducted after estimation. Naturally, the small number of cross-sectional units remains a potential source of estimator instability.

In this study, the analytical model, developed based on previous research and taking into account the theoretical considerations presented, takes the following form:

$$EE_{it} = \beta_0 + \beta_1 RES_share_{it} + \beta_2 CAP_green_{it} + \beta_3 CAP_RES_support_{it} + \beta_4 House_digital_{it} + \beta_5 Energy_price_{it} + \beta_6 Agri_size_{it} + \beta_7 Labor_input_{it} + \beta_8 CAP_rural_{it} + \beta_9 Gas_emission_{it} + \beta_{10} Energy_agri_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (1)$$

where

- variables (Appendix C);
- i —country (CZ, HU, PL, SK)
- t —year;
- μ_i —individual country effects;
- λ_t —time effects (global shocks, e.g., energy prices);
- ε_{it} —random component.

In the next step, a dynamic model was introduced, taking into account and estimating the persistence and inertia of energy efficiency and the impact of previous investments. This approach stems from the fact that many processes do not change immediately, but their transformations are distributed over time. Therefore, they answer the question of whether the energy efficiency under consideration is sustainable (if close to 1, it changes slowly). For the remaining variables, the short-term effect was examined, allowing for the estimation of the long-term impact. The Arellano–Bond one-step GMM estimator was applied. Model verification included the Arellano–Bond test for autocorrelation, the Sargan test for instrument validity, and additional diagnostic tests to confirm the robustness of the results (see Appendices A and B). Dynamic model specification:

$$EE_{it} = \alpha EE_{i,t-1} + \beta_1 RES_share_{it} + \beta_2 CAP_green_{it} + \beta_3 CAP_RES_support_{it} + \beta_4 House_digital_{it} + \beta_5 Energy_price_{it} + \beta_6 Agri_size_{it} + \beta_7 Labor_input_{it} + \beta_8 CAP_rural_{it} + \beta_9 Gas_emission_{it} + \beta_{10} Energy_agri_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (2)$$

where

- α —coefficient for the lagged dependent variable;
- μ_i —fixed effect constant (unobserved, heterogeneous effect across individuals);
- λ_t —time effects;
- ε_{it} —random error;
- Remaining variables as in the previous equation.

The moment conditions are

$$\begin{aligned} E[EE_{i,t} - s \cdot \Delta \varepsilon_{it}] &= 0, s \geq 2 \\ E[\Delta EE_{i,t} - 1 \cdot (\varepsilon_{it} - \varepsilon_{i,t-1})] &= 0 \end{aligned} \quad (3)$$

The contribution of this study to the existing body of research lies in combining static analysis (fixed-effect panel regression) with dynamic panel estimation in order to identify both short-term effects and lasting impacts of Common Agricultural Policy (CAP) instruments on the energy efficiency of agricultural production in the V4 countries. Compared to previous studies, which primarily analyzed static relationships or focused on individual aspects of energy efficiency (e.g., technical or market-related issues), this study presents a more comprehensive approach, placing strong emphasis on the role of agricultural policy, which has a significant influence on agricultural production in EU countries. The con-

ducted analysis and its results take into account a broader set of agricultural structural variables, external environmental effects, and policy components, while also considering their interdependencies.

4. Findings and Discussion: The Role of Policy and Market Structures in Shaping Energy Efficiency

4.1. Differences in Energy Efficiency and Its Underlying Factors

The similar operating conditions of the selected countries, relating to political transformation, proximity in location and climate, baseline GDP per capita levels, or the period of EU accession, do not automatically guarantee high convergence of results. In fact, the data reveal considerable variation in both values and standard deviations (Table 1). The ranges of values suggest the possibility of conducting robust panel regression analysis, including the use of dynamic models.

Table 1. Characteristics of variables.

Variable	Obs.	Mean	Std. Dev.	Min	Max
country	80	2.5	1.125088	1	4
year	80	2013.5	5.802662	2004	2023
EE	80	251.8502	93.22135	100.5461	414.444
Gas_emission	80	5.729862	2.052969	1.96597	7.74126
RES_share	80	12.42771	6.517498	2.049	25.792
CAP_green	80	7.334588	7.146438	0	29.534
CAP_RES_support	80	60.43291	55.65467	2.035	169.185
House_digital	80	62.52838	23.89329	6.65	92.89
Energy_price	80	99.90337	17.33468	66.66	160.59
Agri_size	80	197.4244	195.2842	15.73	615.33

When characterizing the importance of agriculture in the analyzed countries and its internal diversity, several key variables can be identified. The average share of agriculture in GDP for the years 2022–2024 was as follows: Czechia—1.9%, Hungary—2.9%, Poland—2.8%, and Slovakia—2.0%. Cereal production in 2023 in the respective countries was as follows: 7.995 million tonnes in Czechia, 15.034 million tonnes in Hungary, 35.184 million tonnes in Poland, and 3.381 million tonnes in Slovakia [59]. In Poland, crop production is dominated by cereals, particularly wheat (13.195 million tonnes) and maize (8.345 million tonnes). In Hungary, cereals also play a dominant role (accounting for over 50% of crops on average), with maize (6.279 million tonnes) and wheat (5.942 million tonnes) being the main types. Sunflower cultivation is also significant, with a production volume of 1.970 million tonnes. In the case of Czechia, cereal production accounted for 39.7% of total crop production. Wheat (4.56 million tonnes) and rapeseed (1.045 million tonnes) were of particular importance. In Slovakia, cereals represented about 60% of the cultivated area. Wheat harvest amounted to 2.21 million tonnes, while maize reached 1.12 million tonnes [59].

Regarding the basic variables included in this study, it can be noted that during the period under study, there was significant divergence in energy efficiency, farm size, and labor inputs (Table 1). These variables accounted for substantial differentiation among the units under analysis.

Changes in the energy efficiency of agricultural production across the Visegrad Group countries during the period under consideration were not uniform (Figure 1). Stable growth occurred only in Poland (a total of 61.4% over the entire study period). In the Czech Republic and Hungary, efficiency declined for a longer period, with improvement

only occurring in the last two years. Overall, there was an increase, but at a modest level (3.1% and 12%, respectively). In Slovakia, energy efficiency fluctuated between 2004 and 2023, with a total increase of 17.8% (Figure 1). Against this backdrop, there was an increase in the amount of financial support for agriculture, but due to structural differences (both in terms of volume and production), this increase was also uneven. The slowest growth per farm was observed in Czechia and Slovakia (183.4% and 131.4%, respectively). The fastest increase in support occurred in Poland and Hungary (291.2% and 275.8%, respectively) (Figure 1). Structural changes in financial support for agriculture were significantly more dynamic (Figure 2). Support for rural areas was more important, especially in the initial period. However, the importance of environmental subsidies was relatively low across all agricultural support. Both structural elements were subject to significant annual fluctuations, demonstrating a somewhat cyclical nature.

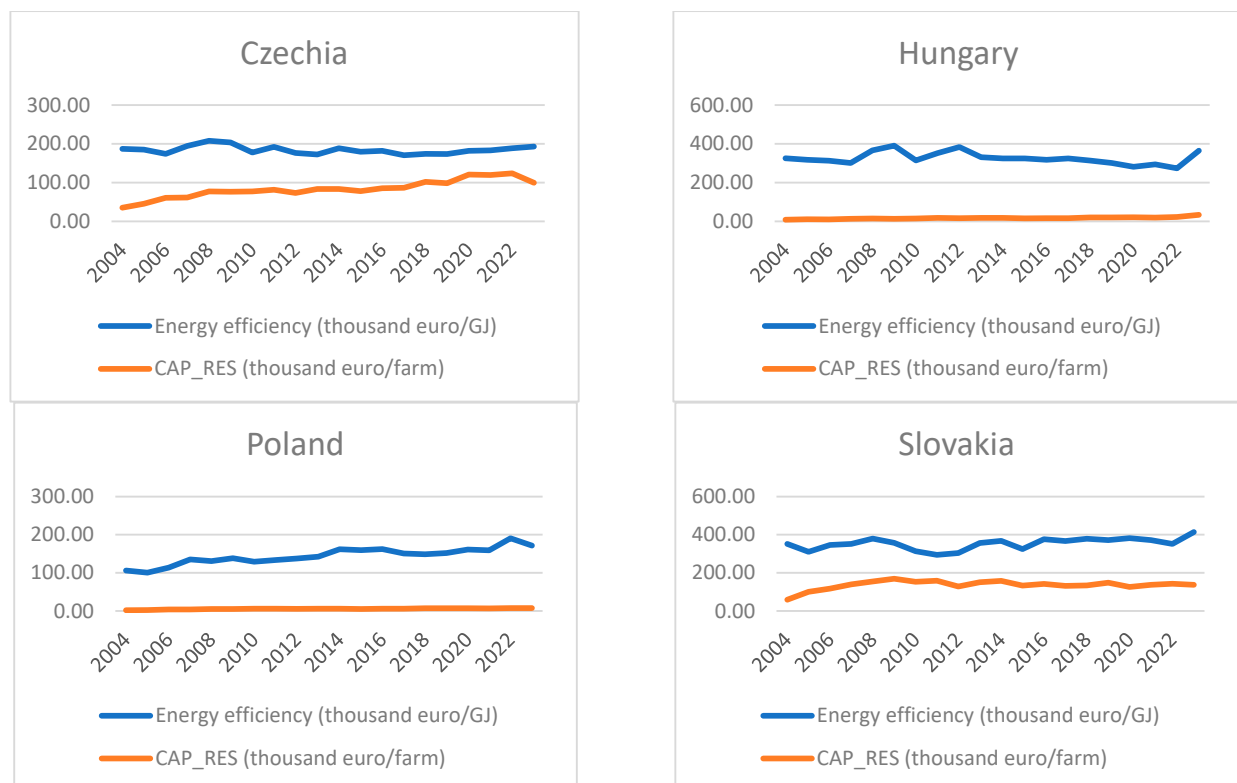


Figure 1. Changes in the energy efficiency of agricultural production and the level of support for agriculture in the Visegrad Group countries in 2004–2023.

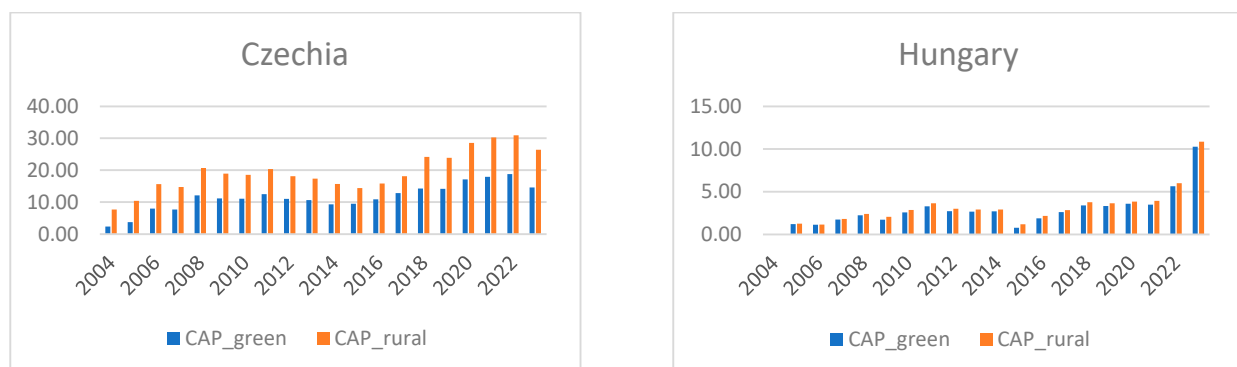


Figure 2. Cont.



Figure 2. Changes in the size and structure of agricultural support in the Visegrad Group countries in 2004–2023 (thousand euro/farm).

4.2. The Influence of Agricultural Policy and Structural Determinants on Energy Efficiency: A Static Perspective

Based on the results of the Breusch–Pagan Lagrange Multiplier test for panel random effects, there is no basis to reject the null hypothesis (H_0), indicating that random effects are not significant. This suggests that the data do not exhibit substantial variability between countries, and thus the use of a random effects (RE) model is not justified. These findings support the validity of conducting the analysis at the level of the selected group of countries as a whole. However, according to the Hausman test, we reject the null hypothesis H_0 : the differences in the estimators are not systematic (p -value = 0.0002). Therefore, the fixed effects (FE) model is identified as the most appropriate specification for the panel analysis (Table 2).

It is worth noting that the energy efficiency of agricultural production has been increasing systematically since 2008. The model explains nearly 60% of the variation in energy efficiency within countries (R^2 (within) = 0.5971). It also indicates a good fit (R^2 (overall) = 0.7112). Consequently, as much as 90.5% of the variation in the model is attributable to differences between countries, while changes over time are of low significance. These effects are therefore permanently tied to a given country. This applies, for example, to stable differences in the production structure and farm size in the studied countries. Similarly, the F-test confirmed the significance of differences between the studied countries, making the fixed-effects model appropriate for analyzing energy efficiency. The obtained results in many cases lead to deeper reflection. Regarding the impact of the CAP, it had a multi-directional impact on energy efficiency. Similar references can be found in other studies, although to varying degrees [60,61]. In total, agricultural policy transfers (CAP_RES_Support) negatively impacted energy efficiency improvements. They increased the energy burden resulting from the introduction of additional equipment and technological processes in agricultural production, disproportionately to its growth. However, within the structure of financial support itself, environmental support proved to be a beneficial transfer. Its importance (under standardized variables) proved relatively high in improving energy efficiency. Public transfers related to rural development also had an unfavorable impact. Market factors, including energy prices and the structure of entities, also served as a strong driver, which is consistent with expectations. The increase in farm size and the rise in energy prices favored energy efficiency improvements. Therefore, economies of scale were evident in this area, both in the short and long term. Interestingly, but also unfavorable from the perspective of the ongoing energy transformation, the increased importance of renewable energy sources did not translate into efficiency improvements. This clearly indicates the need to improve the efficiency of these energy sources and the current accounting system. However, technologies that reduced greenhouse gas emissions

were directly linked to improved energy efficiency in agricultural production. Therefore, this trend was convergent and mutually reinforcing between these processes in agricultural production.

Table 2. Estimation of the parameters of the panel model with fixed effects (FE).

Variable	Coef.	Std. Err.	t	$p > t $	[95% Conf. Low]
RES_share	−3.29257	2.702013	−1.22	0.229	−8.728319
CAP_green	4.260862	3.680107	1.16	0.053	−3.142558
CAP_RES_support	−0.1227	0.424017	−0.29	0.774	−0.9757087
House_digital	−1.44317	1.223786	−1.18	0.244	−3.905113
Energy_price	0.403712	0.439354	0.92	0.426	−0.994507
Agri_size	0.223437	0.202944	1.1	0.277	−0.1848322
Labor_input	−0.08276	0.029864	−2.77	0.008	−0.1428364
CAP_rural	−2.5088	2.455308	−1.02	0.312	−7.44824
Gas_emission	−29.6785	10.79902	−2.75	0.008	−51.40337
Energy_agri	−0.4663	0.908121	−0.51	0.61	−2.293204
2005	−6.4774	15.18251	−0.43	0.672	−37.02066
2006	9.134657	19.04646	0.48	0.634	−29.18188
2007	42.79654	26.39677	1.62	0.112	−10.30691
2008	87.49185	36.76783	2.38	0.021	13.52451
2009	101.2361	44.16221	2.29	0.026	12.39323
2010	81.64336	50.25446	1.62	0.111	−19.45558
2011	92.7632	56.62282	1.64	0.108	−21.14722
2012	116.424	60.53005	1.93	0.06	−5.128339
2013	131.9452	61.6383	2.14	0.038	7.944935
2014	154.1035	63.77314	2.42	0.02	25.80849
2015	137.039	6.23195	2.07	0.044	3.797491
2016	160.1825	69.46343	2.31	0.026	20.44008

R-sq: within = 0.5971, between = 0.7227, overall = 0.7112, $F(29, 47) = 2.40$, $\text{corr}(u_i, Xb) = -0.4863$, $\text{Prob} > F = 0.0037$, $\sigma_u = 62.505865$, $\sigma_e = 20.255103$, $\rho = 0.90496984$ (fraction of variance due to u_i) F test that all $u_i = 0$: $F(3, 47) = 7.70$, $\text{Prob} > F = 0.0003$. RES_share—share of energy from renewable sources in gross electricity consumption; CAP_green—environmental subsidies; CAP_RES_support—total subsidies, excluding investments; House_digital—households' level of internet access; Agri_size—average farm size; and CAP_rural—total support for rural development. Detailed explanation of variables—Appendix C.

4.3. A Dynamic Approach to Agricultural Efficiency Analysis

To deepen the analysis obtained from the fixed-effects model tests, a dynamic panel model (Arellano-Bond) was used (Table 3). Diagnostic tests for the dynamic panel model demonstrate its validity. The AR (1) and AR (2) autocorrelation tests show a lack of significant second-order autocorrelation, confirming the validity of the instruments used in the estimation and the selection of the overall model. Similarly, the Sargan test indicates no problems with overidentification, meaning the instruments were appropriately selected, and in light of these interpretations, the model is reliable. The lag effect applied in the dynamic model in relation to the dependent variable is entirely justified. It presents time dependence and dynamics in the data, confirming the continuity of the ongoing processes in agricultural production. Furthermore, the absence of problems with residual autocorrelation should be confirmed, which increases the reliability of the estimation.

The model as a whole provides a good fit (Wald $\chi^2 = 24.33$; $p < 0.001$). Furthermore, the tests included in the Appendix B confirm the validity of the analyses. The Levin–Lin–Chu test for the energy efficiency (EE) variable indicates stationarity of the dependent variable. Furthermore, the Im–Pesaran–Shin (IPS) test for the EE variable indicates its stationarity (such stationarity occurs for at least one country). In light of these results, FM and GMM models can be used, and there is no need to differentiate the variable or employ cointegration models.

Table 3. Arellano-Bond dynamic panel-data estimation.

Variable	Coef.	Std. Err.	z	$p > z $	[95% Conf. Low]	[95% Conf. High]
EE L1.	0.409384	0.123937	3.3	0.001	0.166473	0.652296
RES_share	−0.34475	1.914264	−0.18	0.857	−4.09664	3.407138
CAP_green	0.004425	0.002928	1.51	0.131	−0.00131	0.010163
CAP_RES_support	0.000309	0.000365	0.84	0.398	−0.00041	0.001024
House_digital	−0.50725	0.327438	−1.55	0.121	−1.14902	0.134517
Energy_price	0.455958	0.347342	1.31	0.189	−0.22482	1.136735
Agri_size	0.016168	0.146556	0.11	0.912	−0.27108	0.303411
Labor_input	−0.04061	0.029868	−1.36	0.174	−0.09915	0.017933
CAP_rural	−0.0028	0.001868	−1.5	0.133	−0.00647	0.000858
_cons	155.168	60.11718	2.58	0.01	37.34053	272.9956

These considerations revealed the existence of many interesting relationships. The introduction of lags in the dynamic model in relation to the dependent variable highlighted the added relationship between period t and period $t - 1$. This indicates the presence of an inertia effect in energy efficiency (0.409). This is because it is a result of the stability of technological change and is not subject to rapid, short-term changes. Therefore, this phenomenon was expected, but the strength of the “carry-over” effect may vary. This confirms the validity of considering energy efficiency from a dynamic perspective, and the process of influencing or stimulating change must also be spread over time and requires long-term stimulation. Furthermore, the “carry-over” coefficient from previous years is less than one, indicating that, although the effects accumulate, they are increasingly weaker over time. Therefore, we are dealing with the durability of the transformation effects, but also their long-term consequences. This confirms the stability of the adopted model and is consistent with the adopted assumptions and the literature. If we infer the impact of the CAP on changes in energy efficiency based on the dynamic model, then, similarly to the FE model, the effects are multidirectional. Therefore, the structure of support is more important than the amount. If we consider total financial support, the effect is also negative, albeit insignificant. In the long term, it can be indicated that high levels of support do not promote improved energy efficiency in agricultural production. This may be the result of “overinvestment” and the unjustified excessive expenditure on machinery and equipment supported by CAP funds, generating high energy costs. However, instruments related to financing environmental support demonstrate a positive correlation, favoring improved energy efficiency in agricultural production. They promote the introduction of technologies that reduce energy consumption (e.g., subsidies for lower-consumption machinery). They also stimulate a reduction in the consumption of natural resources.

Funds allocated to the broader development of rural areas also do not support improved energy efficiency. The growing demand for automation, digitalization, and continued mechanization in agricultural production does not automatically lead to improved energy efficiency. Technological changes indirectly influence energy efficiency. It is noticeable that reducing greenhouse gas emissions is accompanied by improved efficiency. This is undoubtedly related to the introduction of modern, more efficient, and also lower-emission solutions in agricultural production. These investments simultaneously improve energy efficiency in agricultural production, also in a dynamic sense. This focus was decisive in this situation. Interestingly, simply supporting renewable energy sources in agriculture does not translate into improved efficiency (in fact, there is a negative, albeit insignificant, effect). The ongoing growth in electricity from renewable energy sources encounters the problem of aging infrastructure and ever-increasing demand for electricity, burdening the entire system [62]. The billing system for electricity from renewable energy sources is also

a drawback [63]. They are also not always efficient compared to conventional solutions, although they do conserve resources. Therefore, the observed effects are not unusual, but they are different from the expected ones. Market factors, however, play a significant role. Changes in energy prices are a particularly strong driver. Increases in energy prices encourage changes that improve energy efficiency in agricultural production [64]. This indicates the significant importance of efficiency-enhancing fees (e.g., excise tax), although they should be considered in the context of changes in the price competitiveness of agricultural products, which are often homogeneous in nature. The positive impact of economies of scale in agricultural production can also be observed. Increasing the size of farms clearly contributes to improving energy efficiency in the long term, which indicates that agricultural production technology itself does not demonstrate such far-reaching flexibility in terms of energy efficiency. Only changes in production volume stimulate changes in energy efficiency. In this context, it can be assumed that sustainable production systems are energy efficient [65,66], and this volume is on the path of growth, meaning things should improve. Institutional inertia resulting from barriers limiting the development of energy systems and the role of growth path dependence were analyzed [67]. Labor inputs also play a significant role. This relationship is positive, indicating that increased labor inputs are accompanied by improved energy efficiency. In this regard, it should be assumed that higher labor intensity promotes the use of more sustainable practices in agricultural production, acting as a counterbalance to the excessive share of capital in the form of machinery and equipment. Furthermore, rising labor costs force a reduction in energy consumption, acting as a counterbalance to its changes under conditions of increased labor input.

According to the results of the dynamic model, transfers flowing from environmental support and changes in the structure of renewable energy sources have no short-term impact on the energy efficiency of agricultural production. In the context of the previous calculations, the effects, particularly with regard to environmental payments, are deferred. However, in the short term, the overall policy has a positive impact, but this effect is insignificant. Therefore, over time, this effect reverses, becoming a negative factor. Adaptability to changing agricultural policy conditions adversely affects the impact of the CAP on efficiency, although the initial interactions are different.

5. Conclusions and Policy Implications

The analyses revealed a number of potential factors influencing improved energy efficiency along the path of agricultural production growth with reduced greenhouse gas emissions. Energy efficiency in agricultural production exhibits strong inertia processes and therefore requires stable and long-term impact to transform it. Considering the substantial importance of inertia effects, agricultural policy at both the EU and national levels should adopt a longer-term, predictable, and purpose-driven approach to effectively facilitate the energy modernization of agricultural holdings. This is especially pertinent with regard to the targeting of support measures and the integration of environmental objectives alongside production development. Improving energy efficiency itself is essential to maintaining agricultural production growth amidst increasing mechanization and digitalization. Otherwise, it means increasing energy costs. Implemented measures, particularly within the CAP, cannot be short-term. This involves investment processes, which must be targeted. Maintaining investment processes alone can have a different effect, as noted in relation to total budget transfers under the CAP. Investment measures supported by transfers should be conditional upon the implementation of energy-efficient technologies, digitalization, renewable energy sources, and infrastructure modernization. Furthermore, programs targeting the agricultural sector should combine production objectives with support for energy-efficient technological solutions in order to mitigate rising energy costs. In this re-

gard, it would be beneficial to introduce measurable criteria for evaluating the effectiveness of applications.

In the current agricultural policy framework and structure, it does not support improved energy efficiency in agricultural production, becoming a demotivator, especially in the long term. It should be more focused on environmental effects and reducing greenhouse gas emissions; then, in fact, it will significantly support the process of improving energy efficiency. Transfers that are not aimed at energy transformation or pro-environmental processes have a different effect on energy efficiency. This also applies to broadly understood support for rural development. They are therefore an important determinant of the effectiveness of the CAP itself. The support structure should be reformed by increasing the conditionality of funds, thereby rewarding pro-climate, efficiency-enhancing, and investment-oriented actions.

A good driver of change in this area is the price mechanism. Increasing energy prices clearly stimulates improved energy efficiency, which, of course, requires further research. This requires assessing the changes in the competitiveness and profitability of agricultural production. This process is also linked to the relationship between capital and labor in production processes. Focusing efforts on reducing labor inputs in agriculture, which is also a natural process, promotes improved energy efficiency. In this area, as with increasing agricultural production, economies of scale become apparent. Therefore, this direction of stimulating changes in agricultural production should also be supported within the CAP. However, digitalization and the transformation towards renewable energy sources are poorly utilized in the process of improving the energy efficiency of agricultural production. This requires increased conditionality in allocating these funds to designated areas and changes to the entire infrastructure. Therefore, from the perspective of improving the energy efficiency of agriculture, it requires changes in the structure of financial support for agriculture. Furthermore, agricultural policy should support farms in responding to market signals through subsidies for renewable energy sources, energy audits, and energy modernization. Further research should focus on evaluating specific agricultural support programs and their impact on energy efficiency. In such assessments, it is also important to highlight the significance of characteristics of selected agricultural production sectors and the costs of equipment installation, which influence the evaluation of technical efficiency. Future studies should take into account both the technical parameters of renewable energy installations and their costs, availability, and suitability to the specific features of production sectors.

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Abbreviations

The following abbreviations are used in this manuscript:

CAP	Common Agriculture Policy
DEA	Data Envelopment Analysis
EAFRD	European Agricultural Fund for Rural Development
FADN	Farm Accountancy Data Network
FE	Fixed Effects
FEC	Final Energy Consumption
RE	Random Effects
SFA	Stochastic Frontier Analysis

Appendix A

Breusch and Pagan Lagrangian multiplier test for random effects:

$$EE [\text{country}, t] = Xb + u [\text{country}] + e [\text{country}, t]$$

Table A1. Estimated results Breusch and Pagan Lagrangian multiplier test.

Order	Var	sd = sqrt (Var)
EE	8690.22	8690.22
e	410.2692	20.2551
u	0	0

Test: Var (u) = 0, chibar2 (01) = 0.00, Prob > chibar2 = 1.0000.

Hausman's specification test

$$\text{chi2} (28) = 23.92$$

$$\text{Prob} > \text{chi2} = 0.6859$$

Appendix B

Levin–Lin–Chu unit root test for EE.

Ho: Panels contain unit roots;

Ha: Panels are stationary;

AR parameter: Common Asymptotics: $N/T \rightarrow 0$;

ADF regressions: 1 lag;

LR variance: Bartlett kernel, 8.00 lags average (chosen by LLC);

Adjusted $t^* - 1.6225$ (Statistic) 0.0424 (p -value).

Im–Pesaran–Shin unit root test for EE.

Ho: All panels contain unit roots;

Ha: Some panels are stationary;

AR parameter: Panel-specific Asymptotics: $T, N \rightarrow \text{Infinity}$;

Time trend: Not included;

ADF regressions: No lags included.

Table A2. Estimated results Im–Pesaran–Shin unit root test.

Order	Statistic	p -Value	sd = sqrt (Var)		
			1%	5%	10%
$\bar{t}$ -bar	−2.332		−2.500	−2.190	−2.040
$\tilde{t}$ -bar	−2.0604				
$Z\text{-}\tilde{t}$ -bar	−1.7297	0.0418			

Arellano–Bond test for autocorrelation in first-differenced errors.

Table A3. Estimated results Arellano–Bond test for autocorrelation.

Order	z	Prob > z
AR (1)	−3.25	0.0011
AR (2)	−0.88	0.3770

Hansen test of overidentifying restrictions:

$$\text{Chi2 (66)} = 65.42$$

$$\text{Prob} > \text{chi2} = 0.497$$

Sargan test of overidentifying restrictions.

H0: overidentifying restrictions are valid.

$$\text{chi2(66)} = 70.12329$$

$$\text{Prob} > \text{chi2} = 0.3411$$

Appendix C

Table A4. Description of variables.

Variable	Description	Unit of Measurement	Data Source
EE	Energy efficiency of agricultural production	thousand €/GJ	Eurostat
Gas_emission	Greenhouse gases (CO ₂ , N ₂ O in CO ₂ equivalent, CH ₄ in CO ₂ equivalent, HFC in CO ₂ equivalent, PFC in CO ₂ equivalent, SF ₆ in CO ₂ equivalent, NF ₃ in CO ₂ equivalent) in agriculture production	1000 tonnes of CO ₂ equivalent	Eurostat
RES_share	Share of energy from renewable sources in gross electricity consumption	%	Eurostat
CAP_green	Environmental subsidies	thousand €/farm	FADN
CAP_RES_support	Total subsidies—excluding on investments	thousand €/farm	FADN
House_digital	Households' level of internet access	%	Eurostat
Energy_price	Average index and rate of change electricity prices	index	Eurostat
Agri_size	Average farm size	ha/farm	FADN
Labor_input	Agricultural labor input statistics—absolute figures	thousand annual work units	FADN
CAP_rural	Total support for rural development	thousand €/farm	FADN

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