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Changes in Energy-Related Carbon Dioxide Emissions of the Agricultural Sector in Poland from 2000 to 2019

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Abstract: This paper analyzes the changes in carbon dioxide (CO_2) emissions related to energy consumption in the Polish agricultural sector between 2000 and 2019. Based on the Logarithmic Mean Divisia Index (LMDI), the changes in agricultural CO_2 emissions are viewed in the context of changes in six factors, i.e., CO_2 emission intensity, substitution of fossil fuels, penetration of renewable energies, energy intensity, labor productivity and number of employees. The analysis demonstrated that total energy consumption declined over the study period; this was related to a reduction in the intake of energy derived from solid fossil fuels (−1.05%), crude oil (−1.01%), electricity (−4.89%), and heat (−1.37%), and to an increased consumption of natural gas (5.78%) and biofuels (0.82%). Furthermore, it follows from the analysis that changes in CO_2 emissions witnessed in that period were consistent with changes in energy consumption levels; this resulted from a negligible transformation of the energy mix (largely determined by fossil fuels). Generally, CO_2 emissions declined over the study period at a rate comparable (−0.9%) to that of the reduction in energy consumption (−1.03%). In light of the LMDI method, the reduction in CO_2 emissions from fuel consumption in the Polish agricultural sector was mainly driven by a reduction in energy intensity and in employment. Conversely, rapid growth in labor productivity was the key factor in increasing carbon dioxide emissions. Compared to these impacts, changes in other factors (i.e., emission intensity, energy mix and penetration of renewable energies) had an extremely small or marginal effect on the variation in CO_2 emissions.

Keywords: energy consumption; CO_2 emissions; agricultural sector; Poland; decomposition analysis; logarithmic mean divisia index

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1. Introduction

The total amount of greenhouse gas emissions (GHG) from the European Union's (EU) agricultural sector did not vary significantly over the last decade (2009–2019), remaining within a quite narrow interval of 501–516 Mt [1,2]. In that period, the agricultural sector's share in EU's total GHG (in CO_2-eq) emissions did not practically change either; as it was 11–12%, including 9–10% of emissions from livestock and crop farming plus 1.8–2.0% from the impact of the agricultural use of energy [1,2]. According to these statistics, the agricultural use of energy does not on average represent a major source of GHG emissions in the EU. However, the above does not mean the EU countries do not differ in that respect [3,4]. For instance, in 2009–2019, emissions from agricultural energy consumption had a relatively high share in total national emissions in the Netherlands (5.1–5.8%), Latvia (3.2–4.7%), Spain (2.8–3.8%), Denmark (3.1–3.3%), and Poland (2.8–3.1%), whereas a low share (not in excess of 1%) was recorded in the agricultural sector of the Czech Republic, Cyprus, Bulgaria, Malta, Slovakia, Germany and Greece [1,2]. The EU countries differ even more in the structure of agricultural emissions. Between 2009 and 2019, the share of energy-related emissions of the total emissions of the EU's agricultural sector remained stable (15.5–16.7%) at an average level of 16%. However, while it was 26.6% (24.5–27.1%)

in Poland and 37.1% (34.7–41.3%) in the Netherlands, it did not exceed 6% (2.9–5.3%) in Luxembourg or Lithuania [1,2].

The main goal of this paper is to identify the determinants of CO_2 emissions from energy consumption in the Polish agricultural sector, which stands out from other EU countries with its high level of energy consumption (only France and the Netherlands report higher values) and with the highest level of CO_2 emissions from agricultural uses of energy across the EU. The main research goal formulated in this way was developed into the following specific goals:

(1) examination of the level, structure and vectors of change in agricultural uses of energy,
(2) examination of the level, structure and vectors of change in CO_2 emissions from agricultural uses of energy,
(3) identification of the main driving forces affecting the changes in CO_2 emissions from agricultural uses of energy in Poland.

Having considered other analyses, the decision was made to employ the Index Decomposition Method (IDA) in identifying the drivers of CO_2 emissions from agricultural uses of energy. As emphasized by Baležentis et al. [5] and Roinioti and Koroneos [6], three properties formulated by Hoekstra and van den Bergh [7] (based on research by Ang and Zhang [8]) play a crucial role in the decomposition analysis. These properties are met by IDA since IDA is a residual-free method (it demonstrates completeness), it satisfies the time-reversal test, and it is robust to zero values. Also, IDA offers a greater diversity of index forms, mathematical specifications (additive and multiplicative) and indexes [7]. Considering these properties, the author of this paper opted for the weighted logarithmic mean Divisia index (LMDI), one of the most commonly used and recommended methods of IDA for research on emissions and energy [6–12].

This paper has several aspects that make it an original contribution. First, according to the best knowledge of the author, this is the first study of factors affecting the changes in CO_2 emissions in the Polish agriculture based on a six-factor identity and on the method of index decomposition analysis. Hence, it actively contributes to the discussion on agricultural emissions from the perspective of current EU objectives as defined in its climate and energy policy. Second, the approach adopted in this paper can inspire subsequent research projects which could take into account a greater number of characteristics of the Polish agricultural sector. It can also encourage the discovery of more efficient and sustainable approaches to reducing greenhouse gas emissions in the future. Finally, the results of this analysis could contribute to the debate on the agricultural policy whose instruments should place greater focus on the problem of GHG emissions from agricultural uses of energy (in addition to GHG emissions from livestock, production and farmland use).

This paper consists of five sections. Following the introduction, Section 2 presents a literature review, Section 3 discusses the data and methodology, Section 4 shows the main results, and Section 5 provides the conclusions.

2. Literature Review

As mentioned earlier in the introduction, livestock and crop farming is the major source of agricultural GHG emissions. There is ample literature on these GHG sources, represented by a series of publications which present the results of research carried out from various angles and at different data aggregation levels, i.e., farms, agricultural production industries, country groups, and at a regional and global level. However, in these studies, the issue of emissions from agricultural uses of energy is either restricted to a description of the relationships between emissions and energy consumption or not addressed at all e.g., [13–17]. Moreover, only a few papers e.g., [18–22] tackled these problems in the context of causative links.

In turn, the agricultural emissions/energy topic is usually addressed as part of multi-sectoral benchmarks that rely upon a series of different decomposition models (either sector-specific or applicable to all sectors). In terms of geographies, there is a clear dominance of analyses focusing on Asia, especially including China, whereas other regions are addressed in a smaller number of research projects.

Xu et al. [23] used LMDI in analyzing the factors that affect energy-related CO_2 emissions in six sectors of the Chinese economy from 1995 to 2011. Their study demonstrated that the main factors of agricultural CO_2 emissions were economic growth per capita and population growth, whereas the decreasing emission intensity, changes in the energy mix, the decreasing energy intensity and the decreasing share of agriculture in GDP had an opposite effect. However, in the period covered by their analysis, the impact of emission drivers was largely offset by counteracting factors. Ultimately, this translated into a small decline in CO_2 emissions.

The determinants of CO_2 emissions in the agriculture and other economic sectors of China were also addressed in analyses carried out by Xu et al. [24]. In their study period (1996–2011), CO_2 emissions from agricultural energy uses in China nearly doubled, primarily because of general economic growth and, though to a smaller degree, due to the rise in energy intensity and to changes in the energy mix. While other factors, i.e., emission intensity and the share of agriculture in GDP, had a restrictive effect on emissions, their impact was clearly weaker than that of emission boosters.

The conditions of emissions from energy consumption in agriculture and four other sectors of the Chinese economy were also examined in analyses by Chen et al. [25]. Their LMDI-based research found that between 1985 and 2007, agricultural energy-related emissions grew considerably, mostly due to economic boom and population growth. These impacts were much stronger than the alleviating effect of other factors. Indeed, the influence of economic activity and changes in population was incomparably greater than the influence of changes in the energy mix, energy intensity and economic structure, all of them having a beneficial effect on emission reductions.

In turn, Chen et al. [26] analyzed the evolution of energy-related CO_2 emissions in Chinese agriculture between 2005 and 2013 from a perspective of technological, structural, and population changes. Their study used two different methods of LMDI distribution and attributed the changes in CO_2 emissions to factors such as emission intensity, productivity of farming incomes, structure of rural incomes, income disparity between rural and urban areas, structure of national income, economic progress, population structure by province, and total population. Generally, both distribution methods ended up with similar conclusions: the key impacts on agricultural CO_2 emissions were economic growth and changes in the distribution of national income (having a boosting effect on emissions) as well as changes in rural income structure (having a restrictive effect). They also found that the increase in CO_2 emissions was additionally driven by total population growth and technological changes resulting in a greater intensity of emissions from agricultural production.

Energy-related CO_2 emissions in different sectors of the Chinese economy between 1991 and 2006 were also examined by Zhang et al. [27], who relied on a decomposition method based on the Laspeyres index. Their study demonstrated that agricultural CO_2 emissions were mainly driven by economic growth, whereas the changes in other factors, especially including lower energy intensity and the declining share of agriculture in GDP, contributed to reductions in emissions. They also found that emission intensity went down over the 15-year study period, which testifies to the progress in improving fuel quality and in effectively reducing emissions from agriculture.

Another research project dealing with factors contributing to CO_2 emissions from energy consumption in the Chinese economy was carried out by Pan et al. [28], who used LMDI in a multi-sectoral analysis. They found that the increase in production per capita had a prevailing effect on growth in agricultural CO_2 emissions between 2003 and 2016, whereas the changes in the energy mix, energy intensity and population had a restrictive effect.

In turn, Akram et al. [29] used LMDI to examine the conditions of CO_2 emissions in three main sectors of the Pakistani economy. Depending on the sector, they analyzed the impact of four or five factors. As regards the agricultural sector, their study found that in 1990–2016, the main sources of growth in CO_2 emissions were a significant population growth and increasing levels of activity. Conversely, the reduction in energy intensity and the structural changes related to the declining share of agriculture in GDP had a restrictive effect on emissions.

An LMDI-based analysis of changes in CO_2 emissions in several sectors of the Irish economy was also performed by O'Mahony et al. [30] in the context of six factors, i.e., the emission coefficient, substitution of fossil fuels, penetration of renewable energies, energy intensity, structural changes and economic growth. According to their research, the Irish agriculture witnessed a minor increase in energy-related emissions over the study period. It was mostly driven by general economic growth and, though to a smaller degree, by changes in the fuel mix and the increase in energy intensity. In turn, other factors varied in their contribution to reducing agricultural emissions. Structural changes and the reduction in the emission index had the relatively greatest impact whereas the penetration of renewable energies had the smallest effect.

Agriculture was also addressed as part of a multi-sectoral analysis of the Spanish economy by Cansino et al. [31]. They examined the changes in CO_2 emissions distribution in 1995–2009 from a perspective of six factors, i.e., carbonization, energy intensity, technology, structural demand, and energy consumption patterns and levels. When it comes to agriculture, they demonstrated that in the light of structural decomposition (SDA), the low variability in that sector's CO_2 emissions was strongly determined by an increased consumption of energy. However, that increase was nearly totally offset by energy decarbonization; a reduction in energy intensity and structural demand, and technological change.

In turn, the conditions of emissions from energy consumption in agriculture and four other sectors of the Greek economy between 1990 and 2002 were addressed in analyses by Diakoulaki et al. [32], who used the Laspeyres model in their analytical procedure. According to their study, the main drivers of energy-related CO_2 emissions were the increased levels of economic activity in agriculture, the increase in energy intensity, and the adverse changes in the energy mix, all of them having a comparable impact.

In turn, Roinioti and Koroneos [6] analyzed the changes in CO_2 emissions from energy consumption in five sectors of the Greek economy prior to and after the economic downturn. Their study used a 4-factor IDA based on the Laspeyres index, which found that the strong reduction in agricultural CO_2 emissions (witnessed throughout the 2003–2013 period) was mainly caused by a decline in energy intensity, by structural changes and, though to a smaller degree, by energy decarbonization. The impact these factors had on reducing CO_2 emissions in Greek agriculture was extremely strong and largely compensated for the opposite effect of general economic growth.

The conditions of emissions from energy consumption in agriculture and other main sectors of the Indian economy were examined in analyses by Shyamal and Bhattacharya [33]. According to their study, the key contributors to escalating CO_2 emissions in the agricultural sector were the increase in energy intensity, economic growth and, though to a smaller degree, the growing emission intensity. Shyamal and Bhattacharya [31] conclude that the above can be explained by such aspects as the lack of an appropriate technology to replace fuels and restrict emissions and the availability of energy subsidies which lead to inefficient energy uses in the agricultural sector.

In turn, Oh et al. [34] analyzed the changes related to CO_2 emissions from energy consumption in selected sectors of the South Korean economy. Their LMDI-based research found that between 1990 and 2005, the increase in emissions from agricultural uses of energy was driven by the increase in energy intensity and by economic growth. Meanwhile, shifts in the energy mix and structural changes had an opposite effect.

The literature focusing on the issue of energy-related carbon dioxide emissions in agriculture is relatively scarce. Li et al. [35] combined a measurement of environmental performance with an analysis of key factors affecting energy-related CO_2 emissions in the agriculture of 18 EU countries in 1995–2009. Their IDA-based study followed Shapley's method, and demonstrated that EU countries differed in their decomposition profiles.

However, generally, the main cause behind the drop in CO_2 emissions in the group of countries covered by the study was the declining energy intensity, whereas the changes in other factors (i.e., economic activity and energy mix) had an opposite effect.

Yan et al. [36] also made an attempt to decompose the changes in energy-related CO_2 emissions in agricultural sectors of 17 UE countries from 1995 to 2012. They used the generalized Divisia index, which allowed them to define the relationships between absolute and relative indexes and, thus, to increase the number of factors affecting the changes in emissions. The use of that methodology demonstrated some quite noticeable differences in decomposition profiles between the countries. In turn, at an aggregate level, it suggests that the reduction in CO_2 emissions was mostly driven by a decrease in energy consumption and emission intensity, and by a drop in energy intensity (though to a smaller degree). Conversely, rapid growth of agricultural production was a booster of energy-related emissions in the group of EU countries covered by their study.

3. Data and Methodology

This analysis used two sources of data. The first was aggregate sectoral data on CO_2 emissions and energy consumption in the national agricultural sector, as published on the EUROSTAT pages [1,2,37]. The Economic Accounts for Agriculture (EAA) were used as the second source, which provides detailed insights into the agricultural sectors of EU countries, i.e., global output values, intermediate consumption costs, subsidies and taxes, consumption of fixed assets, etc. All values are available in current prices and in constant prices [38]. Agricultural employment statistics also form an integral part of EAA [39].

The determinants of changes to CO_2 emissions from energy use in Polish agriculture were analyzed using a decomposition model which generally relies on the Kaya identity [40] and is formulated as follows:

$$CO_2 = \sum \frac{CO_2}{EFF_i} \times \frac{EFF_i}{EFF_T} \times \frac{EFF_T}{TE} \times \frac{TE}{OUT} \times \frac{OUT}{AWU} \times AWU = \sum EF_1 \times EF_2 \times EF_3 \times EF_4 \times EF_5 \times EF_6 \quad (1)$$

The following terminology is used in the above identity:

- CO_2: greenhouse gas emissions from energy use (in CO_2 equivalent),
- $EF_1 = CO_2/EFF_i$: CO_2 emission coefficient for a fossil fuel (EFF_i) of type i (coal, oil, gas),
- $EF_2 = EFF_i/EFF_T$: share of energy derived from a fossil fuel of type i (EFF_i), in total fossil energies (EFF_T), where $EEF_T = EFF_i$ + electricity + heat,
- $EF_3 = EFF_T/TE$: share of total fossil energies (EFF_T) in total energy (TE),
- $EF_4 = TE/OUT$: aggregate energy intensity measured by the relation of total energy (TE) to total agricultural output (OUT),
- $EF_5 = OUT/AWU$: labor productivity measured as total agricultural output (OUT) per full-time work unit (AWU),
- $EF_6 = AWU$: number of full-time employees in the agricultural sector,
- EF_{1-6}: designation of particular factors of the CO_2 decomposition model.

The EF_1-EF_6 indexes used in model (1) enable the analysis of changes to CO_2 emissions from agricultural energy consumption in the context of six effects, i.e.,: CO_2 emission intensity (EF_1), the fossil fuels substitution effect (EF_2), the penetration effect of renewable energies (EF_3), the effect of changes in energy intensity (EF_4), the effect of changes in labor productivity (EF_5), and the effect of changes in agricultural employment (EF_6). When using the additive specification and considering the factors listed above, aggregate changes in CO_2 emissions can be represented as:

$$\Delta CO_2 = CO_2^t - CO_2^{t-1} = \Delta EF_1 + \Delta EF_2 + \Delta EF_3 + \Delta EF_4 + \Delta EF_5 + \Delta EF_6 \quad (2)$$

As mentioned earlier in the introduction, the analysis of model (2) was based on the IDA method in one of its most widely applied forms, i.e., the Logarithmic Mean Divisia Index (LMDI) proposed by Ang [11]. In its additive specification, the use of LMDI translates into the following formulas that specify the impact of each factor (EF_1–EF_6) on changes in CO_2 emissions from energy consumption in agriculture:

$$\Delta EF_1 = L\left(CO_2^{t-1}, CO_2^t\right) \times \ln\left(EF_1^t / EF_1^{t-1}\right) = \frac{CO_2^t - CO_2^{t-1}}{\ln\left(CO_2^t / CO_2^{t-1}\right)} \times \ln\left(EF_1^t / EF_1^{t-1}\right) \quad (3)$$

$$\Delta EF_2 = L\left(CO_2^{t-1}, CO_2^t\right) \times \ln\left(EF_2^t / EF_2^{t-1}\right) = \frac{CO_2^t - CO_2^{t-1}}{\ln\left(CO_2^t / CO_2^{t-1}\right)} \times \ln\left(EF_2^t / EF_2^{t-1}\right) \quad (4)$$

$$\Delta EF_3 = L\left(CO_2^{t-1}, CO_2^t\right) \times \ln\left(EF_3^t / EF_3^{t-1}\right) = \frac{CO_2^t - CO_2^{t-1}}{\ln\left(CO_2^t / CO_2^{t-1}\right)} \times \ln\left(EF_3^t / EF_3^{t-1}\right) \quad (5)$$

$$\Delta EF_4 = L\left(CO_2^{t-1}, CO_2^t\right) \times \ln\left(EF_4^t / EF_4^{t-1}\right) = \frac{CO_2^t - CO_2^{t-1}}{\ln\left(CO_2^t / CO_2^{t-1}\right)} \times \ln\left(EF_4^t / EF_4^{t-1}\right) \quad (6)$$

$$\Delta EF_5 = L\left(CO_2^{t-1}, CO_2^t\right) \times \ln\left(EF_5^t / EF_5^{t-1}\right) = \frac{CO_2^t - CO_2^{t-1}}{\ln\left(CO_2^t / CO_2^{t-1}\right)} \times \ln\left(EF_5^t / EF_5^{t-1}\right) \quad (7)$$

$$\Delta EF_6 = L\left(CO_2^{t-1}, CO_2^t\right) \times \ln\left(EF_6^t / EF_6^{t-1}\right) = \frac{CO_2^t - CO_2^{t-1}}{\ln\left(CO_2^t / CO_2^{t-1}\right)} \times \ln\left(EF_6^t / EF_6^{t-1}\right) \quad (8)$$

where: $L\left(CO_2^{t-1}, CO_2^t\right)$ is the logarithmic average of two positive numbers, defined as:

$$L\left(CO_2^{t-1}, CO_2^t\right) = \begin{cases} \frac{CO_2^t - CO_2^{t-1}}{\ln CO_2^t - \ln CO_2^{t-1}}, & CO_2^t \neq CO_2^{t-1} > 0 \\ CO_2^{t-1}, & CO_2^{t-1} = CO_2^t > 0 \end{cases} \quad (9)$$

4. Results and Findings

4.1. Changes in Energy Consumption and in CO_2 Emissions

Table 1 and Figure 1 show the statistics for energy use and energy mix in the Polish agricultural sector from 2000–2019. The analysis indicates that over the period considered, total energy consumption decreased at an average annual rate (ΔR) of 1.03%, declining from 4654 ktoe in 2000 to 3813 ktoe in 2019, i.e., by 18.1% (Table 1). As shown by a detailed analysis, Polish agriculture witnessed a clear and steep reduction of energy consumption. Indeed, the statistics presented in this paper suggest that a considerable decline in energy consumption started in 2006, i.e., right after the accession to the EU, and continued until 2015, where the lowest consumption level (3300 ktoe) was recorded. However, that trend was not present in the following years. Between 2016 and 2019, the Polish agricultural sector witnessed a significant (ca. 17%) increase in energy consumption to a level of ca. 3900 ktoe.

In turn, when looking at specific sources of energy, it can be concluded that total energy consumption generally followed a downward trend over the study period; this was related to a reduction in the consumption of energy derived from solid fossil fuels, crude oil, electricity and heat, and to an increased consumption of natural gas, renewables and biofuels (R&B). However, the sources clearly differed in the pace of changes in energy consumption over the study period. Moreover, these changes generally did not follow a straight trend. The consumption of energy declined at an average annual rate of only 1.05% for fossil fuels, 1.01% for crude oil, 4.89% for electricity, and 1.37% for heat. Meanwhile, the consumption of energy derived from natural gas and R&Bs went up at an average annual rate of 5.78% and 0.89%, respectively. Hence, it follows from the analysis of these statistics that the smallest change was recorded for the main sources of energy, i.e., crude oil and solid fossil fuels (highest emission fuels). As shown in Table 1, the penetration of renewable energies was a sluggish process as well. Although their consumption grew over the study period, the renewables had a marginal importance in the energy balance of the Polish agricultural sector throughout that time. What also needs to be emphasized is that biofuels account for nearly 100% of the "renewables and biofuels" aggregate. This means that in practice, traditional sources of renewable energies do not have any uses in the national agriculture sector. Also, the trends followed by the consumption of particular energies generally do not merge into a clear positive tendency that would reflect a drop in agricultural energy consumption. Indeed, different vectors of change in energy use levels can be noticed in specific sub-periods of 2000–2019. This is particularly true for the consumption of energy derived from solid fossil fuels: it declined between 2000 and 2004, then went sharply up in 2005–2014, and re-embarked on the downward trend in 2015–2019. Despite these changes, the Polish agricultural sector continues to be the largest consumer of solid fossil fuels (coal and lignite), both in absolute and relative terms. In 2019, the amount of energy derived from solid fossil fuels in all EU agriculture was 770.2 ktoe, i.e., ca. 2.6% of total energy consumption. Meanwhile, the consumption of energy from that source in the Polish agricultural sector was at an estimated level of 735.1 ktoe. This means that as much as 19.3% of total energy consumption in Polish agriculture comes from solid fossil fuels [37]. These figures also suggest that the Polish agricultural sector accounts for as much as 95.4% of solid fossil energy consumed in the whole EU agricultural sector [37].

Table 1. Energy consumption and structure in Polish agriculture in 2000–2019 (ktoe—thousand tons of oil equivalent) [1].

Years	Total	Solid FossilFuels		NaturalGas		Oil and Petroleum Products [2]		Renewables andBiofuels (R&B)		Electricity		Heat	
	ktoe	ktoe	%	ktoe	%	ktoe	%	ktoe	%	ktoe	%	ktoe	%
2000	4645.5	897.7	19.3	12.8	0.28	2893.6	62.3	408.7	8.8	408.4	8.8	23.9	0.51
2001	4608.7	1000.7	21.7	18.6	0.40	2709.0	58.8	455.1	9.9	396.4	8.6	28.7	0.62
2002	4379.6	837.3	19.1	21.8	0.50	2663.4	60.8	454.0	10.4	379.1	8.7	23.9	0.55
2003	4191.6	813.9	19.4	28.6	0.68	2743.6	65.5	454.2	10.8	127.8	3.0	23.5	0.56
2004	4300.9	854.7	19.9	28.2	0.66	2794.7	65.0	474.8	11.0	125.1	2.9	23.3	0.54
2005	4438.1	931.0	21.0	25.9	0.58	2878.1	64.8	454.9	10.3	128.5	2.9	19.7	0.44
2006	3819.3	1098.6	28.8	35.6	0.93	2056.8	53.9	477.2	12.5	130.8	3.4	20.4	0.53
2007	3510.8	972.3	27.7	44.0	1.25	1888.0	53.8	455.3	13.0	129.0	3.7	22.2	0.63
2008	3640.0	1081.9	29.7	45.4	1.25	1893.0	52.0	456.6	12.5	139.5	3.8	23.6	0.65
2009	3571.6	1072.7	30.0	37.7	1.05	1841.6	51.6	456.8	12.8	138.1	3.9	24.8	0.69
2010	3730.3	1192.0	32.0	35.5	0.95	1833.0	49.1	504.6	13.5	139.0	3.7	26.3	0.70
2011	3679.7	1046.9	28.5	36.6	0.99	1858.2	50.5	576.9	15.7	137.1	3.7	23.9	0.65
2012	3666.5	1086.8	29.6	42.9	1.17	1872.5	51.1	506.4	13.8	134.1	3.7	23.9	0.65
2013	3578.3	1062.2	29.7	35.9	1.00	1817.2	50.8	506.9	14.2	132.2	3.7	23.9	0.67
2014	3420.9	1010.6	29.5	34.4	1.00	1756.5	51.3	469.0	13.7	128.9	3.8	21.5	0.63
2015	3329.9	917.9	27.6	27.3	0.82	1741.1	52.3	493.0	14.8	129.3	3.9	21.3	0.64
2016	3537.6	976.2	27.6	31.2	0.88	1846.8	52.2	521.4	14.7	140.4	4.0	21.5	0.61
2017	3881.0	969.3	25.0	36.3	0.93	2188.8	56.4	517.6	13.3	147.5	3.8	21.5	0.55
2018	3918.9	909.7	23.2	30.3	0.77	2297.3	58.6	503.8	12.9	158.8	4.1	19.1	0.49
2019	3813.4	735.1	19.3	37.2	0.98	2388.0	62.6	477.1	12.5	157.5	4.1	18.4	0.48
$\overline{x}$	3883.1	973.4	25.4	32.3	0.85	2198.1	56.2	481.2	12.6	175.4	4.4	22.8	0.59
V (%)	10.4	11.6	17.8	25.9	31.4	19.5	9.9	7.5	14.6	54.2	42.6	10.8	12.7
ΔR (%)	−1.03	−1.05	−0.01	5.78	6.89	−1.01	0.03	0.82	1.87	−4.89	−3.90	−1.37	−0.34

[1] $\overline{x}$: average value, V: coefficient of variation in %, ΔR: average annual growth in %, [2] excluding the biofuel portion.

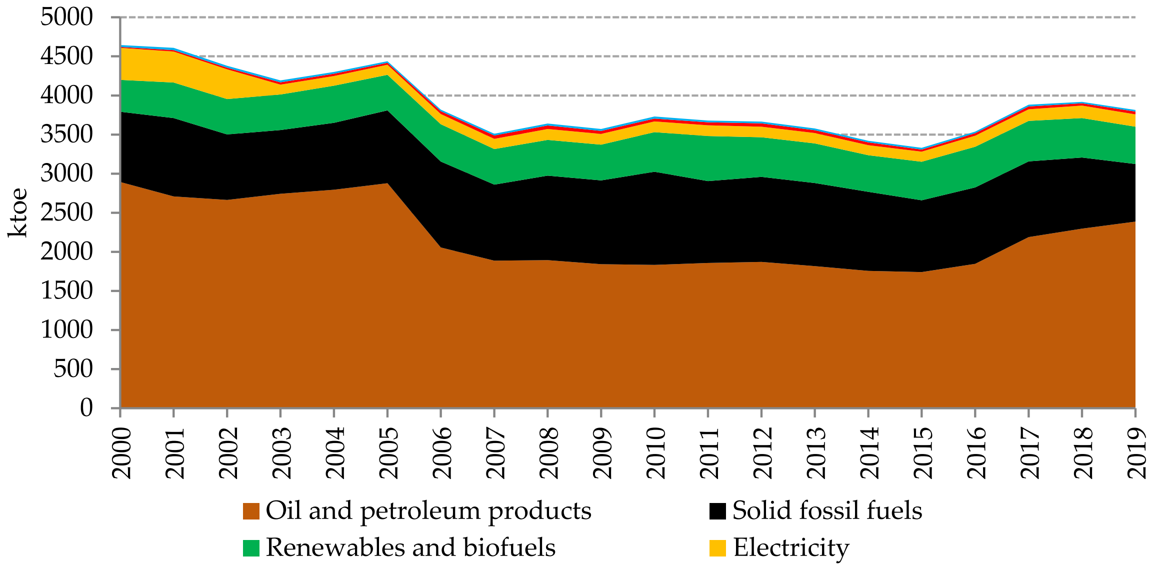


Figure 1. Energy consumption in Polish agriculture in 2000–2019 (ktoe).

As emphasized above, different vectors of change in consumption levels of specific energy sources can be noticed in specific sub-periods of 2000–2019. The lack of a clear trend results in only minor changes to the energy consumption structure. When comparing the years preceding the accession to the EU and the last years of the period considered, it can indeed be observed that the changes in the share of solid fossil fuels, crude oil and heat in the Polish agricultural sector's energy mix were actually of marginal importance. While some favorable symptoms of changes are visible in that area, their intensity is generally very low. The share of R&B in the energy mix grew from ca. 9–10% (2000–2001) to 12.5–12.9% (2018–2019). However, despite the growth, that source of energy continues to be of minor significance to Polish agriculture. In the Czech, German, Finnish, Austrian and Swedish agricultural sectors, the share of renewables and biofuels in the energy mix went above 21% in 2019 (21–36%). This is because traditional sources of renewable energies (especially including biogas) were used to a much greater extent than in Poland, as was solar energy (though to a lesser degree) [37].

Table 2 and Figure 2 show the statistics (level and structure) of greenhouse gas emissions from energy consumption in the Polish agricultural sector in 2000–2019. It follows from this analysis that changes in GHG emissions witnessed in that period were consistent with changes in energy consumption levels. The above corroborates that the energy mix (largely determined by fossil fuels) underwent only a marginal transformation. Generally, greenhouse gas emissions declined at an average annual rate of 0.90% over the study period, which is comparable to that of the reduction in energy consumption ($\Delta R = -1.03\%$). That convergence is noticeable for both the whole 2000–2019 period and selected sub-periods. Data shown in Table 2 and Figure 2 suggests that the greatest emissions from energy consumption were mostly witnessed in 2000–2005, i.e., generally prior to the accession to the EU. In that period, they varied in the range of 13,233 to 14,277 kt CO_2 and coincided with the greatest consumption of energy. In the following years, as the energy consumption followed a downward trend, CO_2 emissions declined consistently until 2015 when they reached the lowest level (10,362 kt CO_2) of the whole study period. This was followed by an increase in CO_2 emissions due to increased energy consumption. Between 2016 and 2019, the consumption of energy in the Polish agriculture sector grew by nearly 14% and translated into a comparable growth (14.4%) in CO_2 emissions (reaching ca. 12,000 kt).

Table 2. The amount and structure of emissions from energy consumption in Polish agriculture in 2000–2019 (CO_2 equivalent, kt—thousand tons) [1].

Years	Total CO_2	Including:					
		CO_2		CH_4		N_2O	
	kt	kt	%	kt	%	kt	%
2000	14,243.6	12,835.8	90.1	424.7	2.98	983.1	6.90
2001	14,097.9	12,703.7	90.1	470.7	3.34	923.5	6.55
2002	13,233.5	11,897.7	89.9	418.5	3.16	917.4	6.93
2003	13,362.4	12,023.6	90.0	411.8	3.08	927.1	6.94
2004	13,730.9	12,354.0	90.0	431.3	3.14	945.6	6.89
2005	14,277.6	12,861.5	90.1	449.5	3.15	966.6	6.77
2006	12,218.8	10,981.8	89.9	504.7	4.13	732.2	5.99
2007	11,113.6	9982.8	89.8	457.5	4.12	673.4	6.06
2008	11,592.6	10,425.3	89.9	491.6	4.24	675.8	5.83
2009	11,436.9	10,291.2	90.0	488.7	4.27	657.1	5.75
2010	11,869.7	10,665.2	89.9	541.3	4.56	663.1	5.59
2011	11,374.5	10,188.3	89.6	517.3	4.55	668.9	5.88
2012	11,571.1	10,392.7	89.8	507.6	4.39	670.7	5.80
2013	11,293.9	10,138.1	89.8	499.5	4.42	656.4	5.81
2014	10,822.5	9719.3	89.8	470.7	4.35	632.4	5.84
2015	10,362.0	9288.6	89.6	448.6	4.33	624.8	6.03
2016	11,000.3	9861.9	89.7	476.5	4.33	661.9	6.02
2017	12,172.4	10,915.9	89.7	474.5	3.90	782.0	6.42
2018	12,276.3	11,033.4	89.9	452.1	3.68	820.8	6.69
2019	11,994.1	10,746.0	89.6	400.6	3.34	847.4	7.07
$\overline{x}$	12,202.2	10,965.3	89.9	466.7	3.87	771.5	6.29
V (%)	9.91	10.05	0.18	8.11	14.70	16.87	7.96
ΔR (%)	−0.90	−0.93	−0.03	−0.31	0.60	−0.78	0.12

[1] $\overline{x}$: average value, V: coefficient of variation in %, ΔR: average annual growth rate in %.

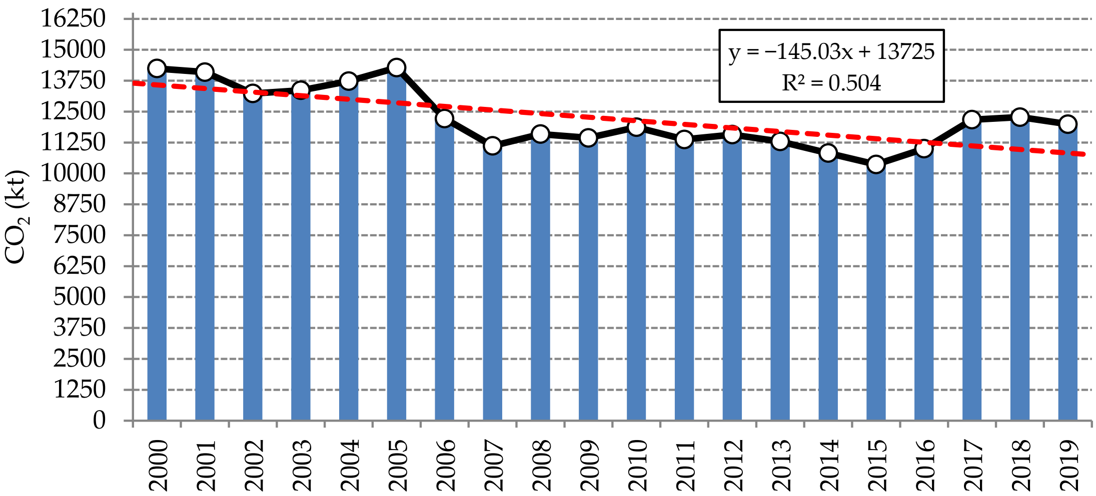


Figure 2. Emissions from energy consumption in Polish agriculture in 2000–2019 (CO_2 equivalent, kt—thousand tons).

Data presented in Table 2 also show that there were marginal changes to the structure of emissions from agricultural energy uses. The share of carbon dioxide in total emissions proved to be nearly invariant over time (V = 0.18%), as it declined at an annual average rate of only 0.03%. As a result, the share of CO_2 in total emissions varied in a very narrow range of 89.6% to 90.1%. Generally, similar conclusions can be drawn from the analysis of changes in the share of methane (CH_4) and nitrous oxide (N_2O) in total emissions. Although relatively greater than in the case of CO_2, the changes for both of these gases were of a marginal nature as well. The coefficients of variation (V) of the share of these gases were extremely low (14.7% and 7.96%) in 2000–2019, and matched well with the negligible average annual growth rates of their shares (at 0.60% and 0.12%, respectively).

4.2. Decomposition Analysis

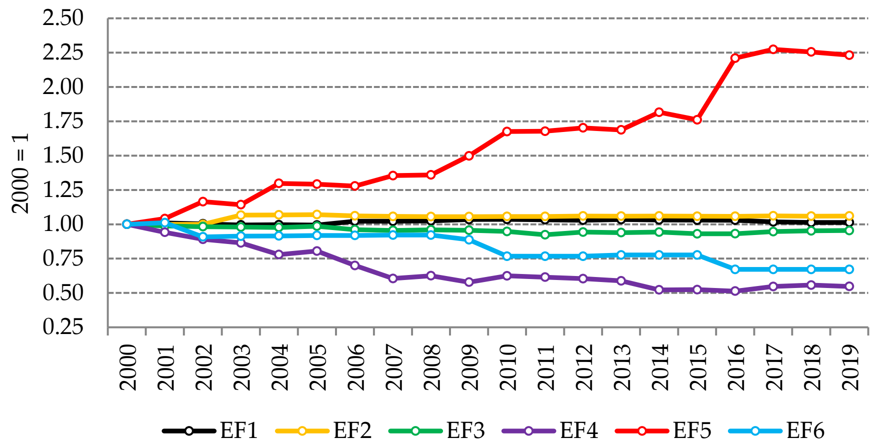
This section presents the findings from the analysis of main factors that affect the relationship between energy consumption and CO_2 (in CO_2-eq) emissions in the Polish agriculture sector in line with the LMDI methodology presented earlier in this study. Changes in emissions were considered in a 20-year perspective (2000–2019) and in the context of six determinants. The decomposition analysis was preceded by the presentation of changes in the values of factors used in model (1).

Data shown in Table 3 and in Figure 3 suggests that the model's factors changed at a different pace over the period considered, and therefore strongly differed in their impact on changes in CO_2 emissions. It can be noticed that the emission intensity of fossil fuels (EF_1) was very stable in the study period. Indeed, the amount of CO_2 emissions from the consumption of energy derived from fossil fuels (coal, natural gas, crude oil and petroleum products) fell within an extremely narrow interval of 3.72–3.88 kt/toe. The marginal extent of changes is also corroborated by the descriptive statistics used in this study. The low levels of V = 1.41% and ΔR = 0.08% clearly show that in Polish agriculture, the intensity of CO_2 emissions from fossil fuel uses remained at a virtually unchanged level between 2000 and 2019.

Table 3. Changes in the factors of the decomposition model for Polish agriculture in 2000–2019 [1,2].

Years	$\mathbf{EF_1 = \frac{CO_2}{EFF_i}}$	$\mathbf{EF_2 = \frac{EFF_i}{EFF_T}}$	$\mathbf{EF_3 = \frac{EFF_T}{TE}}$	$\mathbf{EF_4 = \frac{TE}{OUT}}$	$\mathbf{EF_5 = \frac{OUT}{AWU}}$	$\mathbf{EF_6 = AWU}$
2000	3.74	0.90	0.91	0.30	6.11	2494.9
2001	3.78	0.90	0.90	0.29	6.37	2524.3
2002	3.76	0.90	0.89	0.27	7.12	2266.8
2003	3.73	0.96	0.89	0.26	6.99	2279.4
2004	3.73	0.96	0.89	0.24	7.94	2283.6
2005	3.72	0.96	0.90	0.25	7.90	2291.9
2006	3.83	0.96	0.87	0.21	7.82	2291.9
2007	3.83	0.95	0.87	0.18	8.28	2299.3
2008	3.84	0.95	0.87	0.19	8.31	2299.3
2009	3.87	0.95	0.87	0.18	9.16	2213.8
2010	3.88	0.95	0.86	0.19	10.25	1914.8
2011	3.87	0.95	0.84	0.19	10.26	1914.8
2012	3.85	0.95	0.86	0.18	10.41	1914.8
2013	3.87	0.95	0.85	0.18	10.32	1937.1
2014	3.86	0.95	0.86	0.16	11.10	1937.1
2015	3.86	0.95	0.85	0.16	10.77	1937.1
2016	3.85	0.95	0.85	0.16	13.51	1675.8
2017	3.81	0.96	0.86	0.17	13.90	1675.8
2018	3.79	0.95	0.87	0.17	13.79	1675.8
2019	3.80	0.95	0.87	0.17	13.64	1675.8
$\bar{x}$	3.81	0.95	0.87	0.21	9.70	2075.2
V (%)	1.41	2.10	2.21	22.30	26.03	13.48
ΔR (%)	0.08	0.28	–0.24	–2.95	4.32	–2.07

[1] EF_1: emission coefficient for fossil fuel i; EF_2: share of fossil energy from fuel type i in total fossil energy; EF_3: share of total fossil energy in total energy; EF_4: energy intensity; EF_5: labor productivity; EF_6: number of employees. [2] $\bar{x}$: average value; V: coefficient of variation in %; ΔR: average annual growth rate in %.



Note: EF_1: changes in emission intensity; EF_2: changes in fossil fuel substitution; EF_3: changes in renewable energy (R&B) penetration; EF_4: changes in energy intensity; EF_5: changes in labor productivity; EF_6: changes in employment.

Figure 3. Pace of changes in factors of the decomposition model for CO_2 emissions from energy consumption in the Polish agricultural sector in 2000–2019 (2000 = 1).

Similar conclusions can be drawn from the analysis of the next factor (EF_2), which specifies the share of energy derived from fossil fuels (i.e., coal, gas and crude oil) in total fossil energy. The data shown in Table 3 proves that this index also remained at a stable level (0.90–0.96), and hence demonstrated very low variation over time (V = 2.10%, ΔR = 0.28%). It was virtually constant (0.95–0.96) from 2003 onwards, which means that practically no changes take place in the Polish agricultural sector's energy mix. That conclusion is justified by the analysis of changes in the next factor (EF_3), which specifies the importance of renewable energies (R&B). In light of descriptive statistics (V = 2.21%, ΔR = −0.24%), this is yet another factor that varied only slightly over time. Although it went down from 0.90–0.91 (2000–2001) to 0.87 (2018–2019), the extent of these changes suggests that renewable energy penetration is a sluggish process, and that renewables continue to be of minor importance to the agricultural sector.

From the perspective of statistical metrics used (V = 22.3%, ΔR = −2.95%), a considerably greater extent of changes was recorded for the energy intensity of agricultural production (EF_4), which dropped from 0.29–0.30 (2000–2001) to 0.17 (2017–2019), i.e., by ca. 42%. However, according to a detailed analysis of data shown in Table 3, a significant reduction in energy intensity was actually witnessed only in 2000–2007, a period when energy consumption per production unit declined from 0.30 to 0.18. Generally, no further progress was recorded in the next years. In 2008–2019, energy intensity was relatively stable and varied in a narrow range of 0.16 to 0.18.

In turn, labor productivity (EF_5) is the factor that underwent the biggest changes over the study period (V = 26.03%). Measured with total income from agricultural production (at 2010 constant prices), labor productivity grew at an average annual rate of as much as 4.32%. As a consequence, its level in 2018–2019 (13.64–13.79 EUR thousand/AWU) was as much as ca. 117% higher than that recorded in 2000–2001 (6.11–6.37 EUR thousand/AWU). The dynamic growth in labor productivity in the Polish agricultural sector resulted from both the scaling up of production and the significant reduction (ΔR = −2.07%) in agricultural employment. As shown by Table 3 data, agricultural employment (EF_6) went down from ca. 2500 thousand AWU (2000–2001) to ca. 1676 thousand AWU (2016–2019), i.e., by nearly 33% over the analysis period.

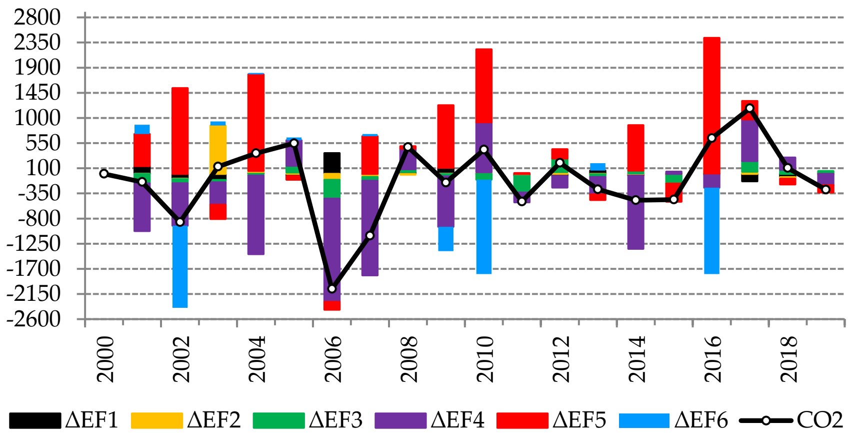
The direction and pace of changes in each of the factors of the CO_2 decomposition model clearly demonstrate that they strongly differed in their effect on the amount of greenhouse gas emissions from energy use in Polish agriculture over the period considered.

The importance of these differences is confirmed by data in Table 4 and Figures 4 and 5, which present the results of CO_2 emission decomposition.

Table 4. Decomposition of change in CO_2 emissions from energy consumption in Polish agriculture in 2000–2019.

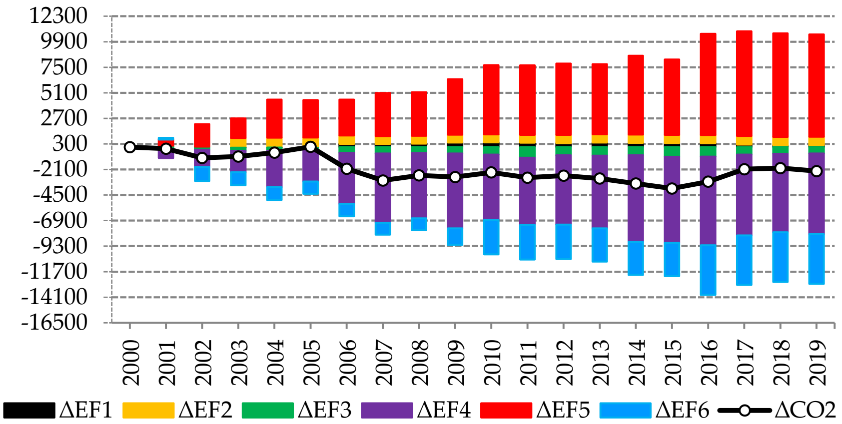
Periods	ΔEF_1	ΔEF_2	ΔEF_3	ΔEF_4	ΔEF_5	ΔEF_6	ΔCO_2
				kt CO_2			
2000–2001	139.8	−1.9	−170.8	−851.0	572.2	166.0	−145.7
2001–2002	−89.0	−5.6	−73.3	−758.8	1532.2	−1469.9	−864.4
2002–2003	−108.9	863.5	−42.3	−401.8	−255.3	73.7	128.9
2003–2004	27.0	25.7	−32.8	−1404.6	1728.2	24.9	368.5
2004–2005	−39.6	24.3	122.3	453.5	−64.7	50.8	546.6
2005–2006	371.5	−108.3	−336.9	−1844.1	−141.1	0.0	−2058.8
2006–2007	−7.7	−48.0	−67.6	−1693.8	674.4	37.6	−1105.1
2007–2008	34.5	−15.3	49.7	368.6	41.5	0.0	479.0
2008–2009	107.9	−3.6	−41.8	−902.3	1120.4	−436.3	−155.7
2009–2010	12.0	18.0	−103.8	895.2	1301.9	−1690.7	432.7
2010–2011	−35.3	−1.0	−300.0	−172.4	13.6	0.0	−495.1
2011–2012	−36.8	34.5	240.1	−207.8	166.6	0.0	196.6
2012–2013	58.6	−10.0	−47.6	−309.9	−100.8	132.4	−277.2
2013–2014	−31.1	9.3	47.8	−1309.5	812.0	0.0	−471.4
2014–2015	−16.1	−15.2	−143.7	38.6	−324.0	0.0	−460.4
2015–2016	−9.0	−6.1	7.5	−231.3	2424.5	−1547.3	638.3
2016–2017	−131.2	39.1	191.7	742.4	330.2	0.0	1172.1
2017–2018	−59.2	−27.3	71.5	221.1	−102.2	0.0	103.9
2018–2019	9.7	10.9	28.4	−203.7	−127.6	0.0	−282.2
2000–2019	**197.1**	**783.0**	**−601.6**	**−7571.6**	**9602.0**	**−4658.8**	**−2249.4**
				percentage weights of factors (%)			
2000–2001	−96.0	1.3	117.2	584.1	−392.7	−113.9	100
2001–2002	10.3	0.6	8.5	87.8	−177.3	170.0	100
2002–2003	−84.5	669.9	−32.8	−311.7	−198.1	57.2	100
2003–2004	7.3	7.0	−8.9	−381.2	469.0	6.8	100
2004–2005	−7.2	4.4	22.4	83.0	−11.8	9.3	100
2005–2006	−18.0	5.3	16.4	89.6	6.9	0.0	100
2006–2007	0.7	4.3	6.1	153.3	−61.0	−3.4	100
2007–2008	7.2	−3.2	10.4	77.0	8.7	0.0	100
2008–2009	−69.3	2.3	26.8	579.5	−719.6	280.2	100
2009–2010	2.8	4.2	−24.0	206.9	300.9	−390.7	100
2010–2011	7.1	0.2	60.6	34.8	−2.7	0.0	100
2011–2012	−18.7	17.5	122.1	−105.7	84.7	0.0	100
2012–2013	−21.1	3.6	17.2	111.8	36.4	−47.8	100
2013–2014	6.6	−2.0	−10.1	277.8	−172.3	0.0	100
2014–2015	3.5	3.3	31.2	−8.4	70.4	0.0	100
2015–2016	−1.4	−1.0	1.2	−36.2	379.8	−242.4	100
2016–2017	−11.2	3.3	16.4	63.3	28.2	0.0	100
2017–2018	−57.0	−26.3	68.8	212.8	−98.4	0.0	100
2018–2019	−3.4	−3.9	−10.1	72.2	45.2	0.0	100
2000–2019	**−8.8**	**−34.8**	**26.7**	**336.6**	**−426.9**	**207.1**	**100**

Note: EF_1: effect of changes in emission intensity; EF_2: effect of fossil fuel substitution; EF_3: effect of renewable energy (R&B) penetration; EF_4: effect of changes in energy intensity; EF_5: effect of changes in labor productivity; EF_6: effect of changes in employment; ΔCO_2: increase in emissions.



Note: EF_1: effect of changes in emission intensity; EF_2: effect of fossil fuel substitution; EF_3: effect of renewable energy (R&B) penetration; EF_4: effect of changes in energy intensity; EF_5: effect of changes in labor productivity; EF_6: effect of changes in employment.

Figure 4. Graphical presentation of the decomposition of changes in CO_2 emissions from energy consumption in Polish agriculture in 2000–2019 (**annual effects**).



Note: EF_1: effect of changes in emission intensity; EF_2: effect of fossil fuel substitution; EF_3: effect of renewable energy (R&B) penetration; EF_4: effect of changes in energy intensity; EF_5: effect of changes in labor productivity; EF_6: effect of changes in employment.

Figure 5. Graphical presentation of the decomposition of changes in CO_2 emissions from energy consumption in Polish agriculture in 2000–2019 (**aggregate effects**).

It can be noted that changes in the emissions factor (ΔEF_1) generally had a negative effect on reducing CO_2 emissions throughout the period 2000–2019. Indeed, despite the relatively small variation in this factor, a minor increase in its level resulted in a significant increase in total emissions in selected years. In the study period, CO_2 emissions per energy unit derived from fossil fuels generally followed an upward trend. As a consequence, total emissions went up by a total of 197.1 kt CO_2. However, Table 4 data suggests that this factor can be observed to have had a positive impact on the emissions volume only in seven sub-periods, especially in 2000–2001 (ΔEF_1 = 139.6 kt CO_2), 2005–2006 (ΔEF_1 = 371.5 kt CO_2), and 2008–2009 (ΔEF_1 = 107.9 kt CO_2), when the increase in emission intensity per unit of energy reached the relatively highest level and was actually decisive for how that factor's impact on emissions is viewed throughout the period 2000–2019. Moreover, the structure of deviations suggests that this factor had the smallest impact on changes in CO_2 emissions from energy consumption in Polish agriculture. Indeed, its average contribution to total variation (ΔCO_2) was only −8.8% for the whole period 2000–2019.

The analysis of the amount of greenhouse gas emissions from agricultural uses of energy in the context of impacts of EF_2 (substitution of fossil fuels) gives rise to similar remarks. The results of the decomposition show that aggregate changes in EF_2 generally also resulted in an increase in CO_2 emissions from energy consumption (ΔEF_2 = 783 kt CO_2). However, just like in the case of EF_1, changes in the fuel substitution factor played a relatively insignificant role in determining the variation of CO_2 emissions. This is because in the whole period from 2000 to 2019, that factor's average contribution to total variation (ΔCO_2) was −34.8%. What also needs to be emphasized is that the positive impact of that factor on CO_2 emissions—recorded in the study period as a whole—mostly resulted from a considerable increase in the share of fossil fuels in 2002–2003 (from 90% to 96%). Afterwards, their share stabilized at 95–96% and therefore had a minor impact on changes in CO_2 emissions from agricultural uses of energy.

The results of the decomposition suggest that in the study period, the reduction in CO_2 emissions from energy consumption was related to the growing importance of renewable energies (EF_3) which, in Polish agriculture, involved an increasingly wider adoption of biofuels. However, from the perspective of reducing GHG emissions, the positive impacts of using that source of energy were insignificant and varied over time. Indeed, on an aggregate basis (2000–2019), the increase in penetration intensity of R&Bs translated into a reduction in CO_2 emissions by 601.6 kt, and contributed approximately 27% to total variation in CO_2 emissions. This also means that the extent of reduction in GHG emissions due to the use of renewables and biofuels failed to compensate for the increase in emissions caused by the combined disadvantageous trend followed by EF_1 (emission intensity) and EF_2 (substitution of fossil fuels). Note also that the last four years of the study period witnessed a decline in the consumption of R&Bs in Polish agriculture, and their share in the energy balance dropped from 14.7% to 12.5%. The consequences of these developments are noticeable in the decomposition results: the reduction in the use of renewables and biofuels entailed a considerable growth in CO_2 emissions between 2016 and 2019.

In turn, it can be observed that changes in energy intensity (EF_4) were an extremely strong determinant of changes in CO_2 emissions. Data presented in Table 4 suggest that a significant reduction in energy consumption per unit of income from agricultural production brought CO_2 emissions down by a total of 7571.6 kt over the study period, and the importance of that factor is strongly emphasized by its contribution to total variation in emissions (nearly as much as 337%). In light of decomposition results, the beneficial changes in energy intensity levels (EF_4) related to a reduction in energy consumption per output unit were key in restricting the increase in CO_2 emissions over the study period. However, that factor's impact on reducing CO_2 emissions weakened over time. As shown by the analyses presented in Table 3 and by the decomposition results, its favorable effect on reducing CO_2 emissions came to a sharp stop after 2014. The period 2015–2019 did not witness any further drop in energy intensity of production; on the contrary, there were moderate though noticeable symptoms of growth in that factor, generally resulting in increased CO_2 emissions.

Conversely, the next factor of the decomposition model used in this paper, labor productivity (EF_5), contributed the most to increasing CO_2 emissions in the Polish agriculture over the study period. This is because on an aggregate basis (2000–2019), the dynamic growth in labor productivity resulted in increasing CO_2 emissions by as much as 9602 kt, and translated to a contribution of ca. 427% to total variation in CO_2 emissions. The above means that technological change—reflected by the progress in labor productivity—was the very factor that had a strong impact on increasing carbon dioxide emissions over the period considered. Data shown in Table 4 suggest that dynamic growth in labor productivity was strongly related to the reduction in agricultural employment. Over the study period, the number of full-time employees went down from 2.5 million AWU (2000–2001) to 1.67 million AWU (2018–2019), i.e., by more than 33%. The trend followed by agricultural production employment translated into favorable changes in carbon dioxide emissions. In light of the decomposition results, EF_6 is responsible for a 4659 kt reduction in energy-related CO_2 emissions; in the relative approach, it contributes 207% to total variation in CO_2 emissions from 2000 to 2019.

The labor productivity and employment factors can also be viewed from the perspective of their combined impact on changes in CO_2 emissions. Seen from that angle, they provide information on the impact of changes in the scale of agricultural production on CO_2 emissions, as can be implied from the following equation: $OUT = \frac{OUT}{AWU} \times AWU = EF_5 \times EF_6$. Considering the equation and data presented in Table 4, it can be concluded that on an aggregate basis (2000–2019), the scaling up of production (OUT) in the Polish agricultural sector increased CO_2 emissions by 4943 kt; whereas in relative terms, it contributed −220% to determining the amount of these emissions.

5. Conclusions

The results of this research show that total energy consumption in Polish agriculture decreased at an average annual rate of 1.03% over the period considered, going down from 4654 ktoe in 2000 to 3813 ktoe in 2019, i.e., by 18.1%. However, the reduction in energy consumption in Polish agriculture was a steep process. It clearly dropped in 2006, i.e., in the first years following the accession to the EU. That trend continued until 2015 when the lowest consumption level was recorded. In the next years, these developments came to a stop; between 2016 and 2019, the Polish agricultural sector witnessed a significant increase in energy consumption. Total energy consumption generally followed a downward trend; this was related to a reduction in the consumption of energy derived from solid fossil fuels, crude oil, electricity and heat, and to an increased consumption of natural gas, renewables and biofuels. However, the sources clearly differed in the pace of changes in energy consumption. Moreover, these changes generally did not follow a straight trend. The smallest change was recorded for the main sources of energy, i.e., crude oil and solid fossil fuels (highest emission fuels). Furthermore, the penetration of renewable energies and biofuels (R&B) was a sluggish process (in practice, it was limited to biofuels). While their consumption grew over the study period, R&Bs had a marginal importance in the energy balance of the Polish agricultural sector throughout that time. It also needs to be emphasized that the trends followed by the consumption of particular energies generally do not merge into a clear tendency that would reflect a drop in agricultural energy consumption. Indeed, different vectors of change in energy use levels were witnessed in specific sub-periods. This is particularly true for the consumption of energy derived from solid fossil fuels: it declined between 2000 and 2004, then went sharply up in 2005–2014, and re-embarked on the downward trend in 2015–2019. Despite these changes, the Polish agricultural sector continues to be the largest consumer of solid fossil fuels in EU agriculture, both in absolute and relative terms.

Since particular energies did not follow a clear trend, there were only minor changes to the energy consumption structure. When comparing the years preceding the accession to the EU and the last years of the study period, the conclusion is that the changes in the share of solid fossil fuels, crude oil and heat in the Polish agricultural sector's energy mix were actually of marginal importance. While some favorable symptoms of changes are visible in that area, their intensity is generally very low. Indeed, the share of renewables and biofuels (R&B) in the energy balance went up from 9–10% (2000–2001) to 12.5–12.9% (2018–2019). However, despite gaining in popularity, renewables continue to be of minor significance to Polish agriculture. In the Czech, German, Finnish, Austrian and Swedish agricultural sectors, the share of R&B in the energy mix exceeded 21% (21–36%) in 2019.

The analysis carried out in this paper also shows that changes in CO_2 emissions are largely consistent with changes in energy consumption levels. The aforementioned corroborates that the energy mix (largely determined by fossil fuels) underwent only a marginal transformation. Generally, CO_2 emissions declined over the study period at an average annual rate comparable to that of the reduction in energy consumption. The largest amounts of CO_2 emissions were recorded primarily in 2000–2005, i.e., prior to the accession to the EU, when the agricultural sector's energy consumption reached its peak level. In the next years, as the energy consumption followed a downward trend, CO_2 emissions declined consistently until 2015, when they reached the lowest level of the whole study period. This was followed by an increase in CO_2 emissions due to increased energy consumption.

In light of the LMDI method, the reduction in CO_2 emissions from fuel consumption in the Polish agricultural sector was mainly driven by a reduction in energy intensity and, though to a lesser degree, in employment. Conversely, the factor that contributed the most to increasing carbon dioxide emissions was the rapid growth in labor productivity which, combined with a reduction in agricultural employment, generated a positive relationship between production scale and CO_2 emissions. Compared to these impacts, changes in other factors, i.e., emission intensity, energy mix and the penetration of renewable energies (R&B) had an extremely small or marginal effect on the variation in CO_2 emissions.

The decomposition results suggest that the Polish agricultural sector faces significant opportunities for reducing CO_2 emissions related to energy consumption. First of all, it is necessary to eliminate coal, which accounts for ca. 30% of CO_2 emissions. Secondly, having in mind the limited capability to increase biofuel consumption, it is essential to promote and implement traditional renewable sources of energy (which are of marginal use in the national agriculture sector). Without these changes, the energy mix will continue to be dominated by high-emission fossil fuels. Moreover, as the development of the agricultural sector is forecasted to continue (and thus the production scale will have an increasingly stronger impact on CO_2 emissions), there is the need for a broadly defined agricultural restructuring. This primarily means reducing the number and increasing the size of farms and equipping them with state-of-the-art energy-efficient technical appliances. Currently in Poland, there are ca. 1.51 million active farms with an average area of only 11.1 ha. The degree of wear of their fixed assets is as high as nearly 80% [41]. These characteristics are not conducive to a reduction in energy intensity, and will require essential technological changes. Otherwise, the progress in reducing energy consumption and, at the same time, CO_2 emissions in the national agriculture sector will be strongly hampered.

The outcomes of this research carry several policy implications. First, it follows from the study that the reduction in CO_2 emissions is mainly driven by an increase in energy efficiency. This means there is a need to intensify the measures for a wider adoption of state-of-the art technologies and of energy-efficient machinery, buildings and farming practices. Also, much more focus should be placed on the development of renewable energies which, in the national agricultural sector, are virtually limited to biofuels, with other renewables being of marginal importance. The fulfillment of these tasks also requires that attractive financial policies be put in place, e.g., in the form of tax exemptions, investment subsidies and subsidized loans. Another factor of importance is the promotion of energy-efficient farming practices, which should be among the priorities of agricultural consultancy centers and agricultural universities, a number of which can be found in Poland.

The study presented in this paper faces certain limitations, namely the use of aggregate variables that refer to the agricultural sector as a whole. Hence, further research could focus on other factors and, thus, on other aspects affecting CO_2 emissions from agricultural uses of energy by taking into account the differences between regions (which are significant in the Polish agricultural sector).

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