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On-Farm Production of Renewable Energy in 2014–2022

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Abstract: The main purpose of this study is to present family farms as consumers and producers of renewable energies which provide them with an opportunity to reduce operating costs. The time scope of the study is 2014–2022, and the Farm Accountancy Data Network is used as the data source. The following research methods were employed: comparative and descriptive analysis, intensity indicators, ranking assignment and panel regression. Based on the values of energy output and energy costs, the rankings revealed a strong position of the Netherlands and Germany. As demonstrated by the study, energy production and consumption volumes depend on the farms' economic size, but are not impacted by production type. Another finding is that energy production covers only one-third of its costs. Also, both production volumes and costs were on a growth path on a year-over-year basis, with similar growth ratios. The European Union's leaders in energy consumption and production are the Netherlands, Germany, Belgium, Denmark, Czech Republic, Hungary, Luxembourg, Slovakia and Sweden. The study included the structuring of panel models for energy output and costs and identified their determinants. Energy output depends on total inputs and grows as they grow. Energy costs, in turn, are related to utilized agricultural area, total output and family farm income. An important limitation of this study is that FADN is a provider of high-level data. Hence, it is impossible to tell what specific sources of renewable energy are used by farms, and how they are affected by such exogenous factors as climate, earmarked subsidies or energy policy. The findings from this study are discussed in the context of the European Commission's recommendations laid down in the Bioeconomy Strategy of the EU (2013), the Seventh Environment Action Program, the New Innovation Agenda of the European Union, the Report "Transforming Our World: the United Nations 2030 Agenda for Sustainable Development" and the Circular Economy Action Plan.

Keywords: energy cost; energy output; European Union; family farm; renewables

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1. Introduction

Due to energy and food systems being associated with one another, it is necessary to adopt a joint approach with a view to implementing the Sustainable Development Goals and the Paris Agreement on Climate Change. The shift towards a renewables-based energy system cannot be completed without taking into account energy use in the agri-food sector and the delivery of sustainable energies [1]. Rural areas are where different forms of renewables come from, whether derived from solar and geothermal sources, wind or specific kinds of bioenergy. All of them contribute to creating rural jobs, driving local economic progress, substituting fossil fuels and ensuring energy security [2–4] and therefore represent an important alternative to the existing coal-based economy. Also, they can be viewed as a harbinger of the next stage of economic development, while bringing opportunities for employment, innovation and growth and contributing to reindustrialization across Europe [5,6]. It is worth emphasizing that solar radiation, tides, winds and hydropower are inexhaustible resources with guaranteed long-term availability. This comes in contrast to some natural renewables (geothermal power, fresh water, timber and biomass) which need to be managed cautiously in order not to exceed the environment's natural replenishment capacity [7].

It is no secret that resources available to humans are limited. Current challenges such as population growth going hand in hand with land and ecosystem degradation make humans look for new production and consumption patterns that can respect the environmental limits of the Earth. As a consequence, farmers have no other option but to improve and innovate the way materials, products and food are manufactured and consumed [8]. This is directly reflected in their approach to energy production and consumption.

Over the last few years and decades, rapid economic growth has been coupled with a strong surge in global energy consumption. Also, most countries, especially including developing and emerging economies, have witnessed a significant increase in greenhouse gas emissions. Across the globe, this situation has aggravated the issues related to energy safety, climate change and environmental degradation [9]. An important role was played by high and unstable energy prices, posing an economic challenge to the farmer community. This is the reason why more producers look for alternative energies in an effort to become more energy-independent while increasing revenue. Those who demonstrate an innovative attitude explore new ways of reducing energy consumption and improving their agricultural efficiency. This sparks their interest in renewables and biofuels derived from sustainable production processes [10]. There are different forms of renewables, such as solar energy, plant oil, wind and hydropower, and sustainably grown timber. They also include other kinds of plant material (biomass) and biogas, a product derived from the fermentation of crop residue and compost [11]. Hence, farmers have a wide variety of non-standard energy sources to choose from. They are encouraged to stay up to date with new solutions and to revise their energy consumption models once in a while [12].

Different energy services are required at each link of the agricultural and food system. They differ considerably from one another depending on how value chains are structured and what their nature is. As renewable energy solutions form a dispersed system, they are perfectly suited to meet energy requirements in an environmentally friendly, sustainable, economic and safe way. The socioeconomic profits brought by this system can be of particular importance to the hundreds of millions of people whose livelihood and subsistence depend on agriculture, and who become increasingly precarious due to being exposed to climate impacts [1].

Note that renewable energy issues have been addressed by EU regulations for many years as part of introducing the bioeconomy concept. As emphasized in the relevant provisions, Europe must totally rethink its production and consumption patterns and the way of processing, recycling, storing and disposing of its biological resources [13,14]. Such a modern development model blends together scientific research with innovation, spanning a large number of disciplines, including agronomy, biotechnology and chemistry, environmental sciences, economics, engineering, food processing, genetics and social sciences [15]. Also, many official documents are underpinned by some shared concepts, such as the chain approach, biorefining, sustainability, research and innovation, and societal transition towards sustainability, e.g., the Bioeconomy Strategy of the EU (2013), the Seventh Environment Action Program (7th EAP), the New Innovation Agenda of the European Union, the Report Transforming Our World: the United Nations 2030 Agenda for Sustainable Development, and the Circular Economy Action Plan [16–20].

All of the processes mentioned therein are supposed to make more efficient use of natural resources, which poses a tremendous challenge [21,22]. Rural areas are likely to demonstrate a strong interest in developing those concepts and in taking care of naturally valuable areas. Implementing the above assumptions will redefine the rural economy and social structure. Even now, the agri-food sector is of particular importance to the environment because of the direct impact it has on food safety, ecosystems and rural conditions [23,24].

It needs to be emphasized that Europe's current shift towards an oil-independent economy is a pressing necessity rather than just an option to consider. That process should be driven by innovation, scientific research and investment projects, whether on a small or large scale. In it, farms can play an important role because they combine modern and

traditional instruments provided for in the Common Agricultural Policy and employ them in the agricultural production system. Hence, farms are producers of agricultural goods while also providing opportunities for multipurpose rural development. It therefore seems that the first step of the transition might consist in individuals producing energy themselves and having control over the related costs.

Having the above in mind, the main purpose of this study is to present family farms as consumers and producers of renewable energies which provide them with an opportunity to reduce operating costs and become more independent and innovative.

2. Materials and Methods

This study relies on available statistics from the Farm Accountancy Data Network (FADN). FADN provides an in-depth insight into the key determinants of farm performance in productive, economic and financial terms, as recorded in EU countries between 2014 and 2022. That time interval was selected because data relating to on-farm energy production have been available only since 2014. Currently (as of 30 August 2024), the database does not contain complete data for 2022 and lacks information for 6 countries: Croatia, Germany, Greece, Malta, Slovenia and Spain. Also, United Kingdom data is excluded from this research.

This study is an attempt to address the following questions:

1. What were the European family farms' earnings from energy production, what were their energy costs, and how did they compare to their area, total output, costs and farm income between 2014 and 2022?
2. In which European country do family farms report the highest average energy production volume, and do they also face the highest energy costs there?
3. Do the farms' energy output and costs depend on their economic size or production type?
4. Which categories (e.g., area, assets, cash flow, equity, income, investments, labor, liabilities, output, taxes) are correlated with energy output and energy costs?

Average figures were retrieved from the FADN in order to answer questions 1 to 3. In turn, Gretl 2024c-git (64.exe) software was used to develop panel models based on 1094 individual FADN observations with a view to answering question 4.

In its general form, a panel data model can be expressed as [25]

$$y_{i,t} = \alpha_i + X'_{i,t}\,\beta + u_{i,t} + \varepsilon_{i,t} \quad (1)$$

where the following definitions hold:

- i ($i = 1, \ldots, N$) means individuals;
- t ($t = 1, \ldots, T$) means time intervals;
- $X'_{i,t}$ is the observation of K explanatory variables (in country i at time t);
- α_i is a time-invariant parameter accounting for any effects that are specific to the individual concerned and are not covered by the regression equation.

Two basic models may be distinguished depending on how α_i is interpreted: either the Fixed-Effect Panel Data Model (FEM) or the Random-Effect Panel Data Model (REM) [26]. The group of one-way error models includes fixed-effect models and variable-effect models, and the difference between them consists in how individual effects are addressed (as either random or non-random variables). The former are based on the assumption that group effects are constant parameters. Hence, they are also called models with artificial variables or models with intercept decomposition. Conversely, variable-effect models are referred to in the literature as models with error terms or models with random term decomposition. The assumption behind them is that group effects are a random variable that follows a known distribution. In addition to group effects, two-way error models also take into account the existence of temporal effects. Therefore, they assume that at a given moment, the same random effect might impact all units covered by the study. Deciding which type of panel model to choose is difficult because several conditions must be considered, including

statistical and substantive aspects. Caution must be exercised so as not to rely solely on the results of significance tests [27].

The first step in deciding between the use of Random- and Fixed-Effect models is performed by applying the Hausman test. The rationale behind it is that a random-effect model should be used unless rejected by the Hausman test. In practice, when not rejected, it suggests that both models are so similar to one another that any of them is a good fit, or that the sample is highly heterogeneous, making it impossible to determine whether any differences are statistically significant [28]. Thus, the conclusion is that other parameters of the sample should also be used in picking one of these model types. As regards an FE model, its estimator may be inadequate for short time series, but seems to be a better fit in a scenario where the objects covered by the analysis are a non-random sample and it is important to estimate the effects for each object separately [29].

Moreover, the structure of the database used as the source of observations must be taken into account. The FADN does not store primary data; instead, it aggregates information per group of 15 farms with a view to protecting sensitive data. This approach makes it impossible to identify information specific to an individual farm.

Taking into account all of the above considerations, the decision was made to proceed with FE (fixed-effect) models. This is consistent with what the Hausman test established.

3. Results

In the study period, the average farm output in the European Union varied between EUR 70,000 in 2014 and EUR 129,300 in 2022. Over that time, there was only a small increase in farm area (from 31.2 to 40.4 hectares). Renewable energy output was in the range of EUR 1442 to EUR 2990 and did not exceed 2.5% of total farm output. Meanwhile, farm inputs varied in the range of EUR 60,100 to EUR 104,300. Note that total inputs include direct costs, general economic costs, depreciation and amortization and the cost of external factors, i.e., all agricultural production expenditures. Energy costs were in the range of EUR 4387 to EUR 8869, accounting for 6.8% to 8.5% of total inputs. It should be explained that energy costs include the consumption of engine fuel, lubricant oils, electricity and heating fuel. The ratio between energy outputs and costs in the study period varied in the range of 29.2% to 36.4%, with 33.7% as the average level. Another remark is that family farm income increased from EUR 17.1 in 2014 to EUR 41.2 in 2022 (Table 1, Figure 1). Hence, it can be concluded that farms improved their production and financial standing over the study period despite an increase in costs, including those of energy. What also needs to be looked at is the relationship between energy outputs and costs: while production grows slowly, costs increase by leaps and bounds (Figure 2).

The farms were arranged in a ranking in order to identify the countries with the greatest energy outputs and costs. This was done based on 2021 EU country-level data because information about five countries is missing in the 2022 dataset (Table 2). As the ratio between energy outputs and costs is constant, the countries with the highest costs can reasonably be expected to also demonstrate the greatest production volume. Checking this assumption was the guiding principle behind the creation of four rankings. The first is that of total energy costs per farm, whereas the second uses a per-hectare approach. In turn, the purpose of the third and fourth rankings was to show the energy output on a per-farm and per-hectare basis, respectively. The countries were arranged in descending order, and their position in the ranking was equivalent to their rank. Next, the ranks were added up to calculate the average levels.

The Netherlands and Germany stand out in the ranking as countries with high energy output and costs in both absolute terms (per farm) and on a relative basis (per hectare). Thus, it was decided to pay closer attention to them later in the study. Ranked next were Belgium and Denmark (ex aequo), followed by the Czech Republic, Hungary, Luxembourg, Slovakia and Sweden. Conversely, Croatian, Bulgarian, Polish, Spanish, Lithuanian, Irish, Portuguese and Romanian farms were located at the bottom of the four rankings (Table 2).

Table 1. Key financial details about European Union * farms in 2014–2022 **.

Year	2014	2015	2016	2017	2018	2019	2020	2021	2022
Utilized agricultural area (ha per farm)	31.2	31.7	31.9	32.4	40.1	40.1	40.3	40.3	40.4
Output (EUR per farm), including the following:	66,953.0	68,553.0	68,499.0	72,504.0	92,005.0	96,952.0	97,364.0	108,370.0	129,341.0
-Energy output (EUR per farm)	1442.0	1685.0	1590.0	1640.0	1965.0	2035.0	2084.0	2196.0	2990.0
-Share of energy output in total output (%)	2.2	2.5	2.3	2.3	2.1	2.1	2.1	2.0	2.3
Inputs (EUR per farm), including the following:	60,147.0	61,479.0	61,304.0	62,607.0	81,218.0	84,392.0	85,662.0	91,408.0	104,325.0
-Energy costs (EUR per farm)	4936.0	4634.0	4387.0	4655.0	6141.0	6206.0	5853.0	6763.0	8869.0
-Share of energy costs in total inputs (%)	8.2	7.5	7.2	7.4	7.6	7.4	6.8	7.4	8.5
Net farm income (EUR per farm)	17,053.0	17,427.0	18,006.0	21,026.0	24,900.0	26,954.0	26,597.0	32,176.0	41,214.0
Ratio between energy outputs and costs (%)	29.2	36.4	36.2	35.2	32.0	32.8	35.6	32.5	33.7

* Excluding the United Kingdom. ** Without 6 countries: Croatia, Germany, Greece, Malta, Slovenia and Spain. Source: own calculations based on 2024 FADN data.

Table 2. European * farms ranked by energy costs and energy output in 2021 **.

Rank	Member State	Energy Costs (EUR per Farm)	Member State	Energy Costs per ha (EUR/ha)	Member State	Energy Output (EUR per Farm)	Member State	Energy Output per ha (EUR/ha)	Member State	Average Ranks
1	Slovakia	54,871.0	Malta	1465.8	Denmark	27,889.0	Netherlands	448.4	Netherlands	2.0
2	Czech Republic	41,652.0	Netherlands	870.0	Netherlands	18,212.0	Hungary	236.6	Germany	5.0
3	Netherlands	35,338.0	Cyprus	387.5	Czech Republic	16,882.0	Denmark	186.5	Belgium	6.0
4	Germany	26,188.0	Belgium	295.4	Germany	15,835.0	Belgium	178.1	Denmark	6.0
5	Denmark	22,572.0	Slovenia	270.6	Slovakia	14,967.0	Luxembourg	157.7	Czechia	6.8
6	Sweden	22,479.0	Germany	253.3	Luxembourg	14,708.0	Germany	153.2	Hungary	8.3
7	Finland	16,997.0	Greece	253.0	Hungary	12,253.0	Italy	82.6	Luxembourg	8.8
8	Belgium	16,138.0	Italy	223.9	Belgium	9733.0	Austria	82.5	Slovakia	9.0
9	Estonia	15,250.0	Finland	217.5	Estonia	8269.0	Czechia	66.0	Sweden	9.3
10	Luxembourg	14,956.0	Sweden	215.6	Sweden	4131.0	Estonia	54.2	Austria	11.3
11	France	12,840.0	Austria	199.0	Austria	2780.0	Sweden	39.6	Italy	11.3
12	Hungary	9255.0	Hungary	178.7	Latvia	2236.0	Slovakia	36.4	Finland	12.0

Table 2. *Cont.*

Rank	Member State	Energy Costs (EUR per Farm)	Member State	Energy Costs per ha (EUR/ha)	Member State	Energy Output (EUR per Farm)	Member State	Energy Output per ha (EUR/ha)	Member State	Average Ranks
13	Latvia	8505.0	Czechia	162.9	France	2137.0	Slovenia	32.9	Estonia	13.0
14	Bulgaria	7723.0	Luxembourg	160.3	Italy	1914.0	Latvia	30.5	France	14.0
15	Austria	6702.0	Denmark	151.0	Finland	1320.0	France	22.7	Slovenia	14.3
16	Italy	5185.0	Poland	151.0	Slovenia	378.0	Croatia	17.7	Latvia	14.8
17	Spain	4977.0	France	136.5	Croatia	283.0	Finland	16.9	Greece	16.8
18	Lithuania	4609.0	Slovakia	133.6	Greece	171.0	Greece	16.5	Cyprus	18.0
19	Cyprus	4553.0	Croatia	129.0	Ireland	123.0	Portugal	3.3	Malta	18.3
20	Malta	4412.0	Latvia	115.9	Bulgaria	122.0	Ireland	2.7	Croatia	19.8
21	Ireland	4046.0	Spain	112.9	Lithuania	113.0	Lithuania	2.2	Bulgaria	20.0
22	Poland	3226.0	Portugal	103.3	Portugal	81.0	Poland	2.1	Poland	20.8
23	Slovenia	3107.0	Bulgaria	100.6	Poland	44.0	Bulgaria	1.6	Spain	21.5
24	Greece	2629.0	Estonia	99.9	Spain	3.0	Spain	0.1	Lithuania	21.5
25	Portugal	2507.0	Romania	95.7	Cyprus	0.0	Cyprus	0.0	Ireland	21.8
26	Romania	2389.0	Lithuania	88.4	Malta	0.0	Malta	0.0	Portugal	22.0
27	Croatia	2067.0	Ireland	87.6	Romania	0.0	Romania	0.0	Romania	26.3
-	EU27	6763.0	EU27	167.6	EU27	2196.0	EU27	54.4	-	-

* Excluding the United Kingdom. ** The best and the second-best scores are highlighted in green and blue, respectively. Yellow indicates the third, fourth and fifth ranks. Bottom-ranked countries (in average terms for the four categories) are marked in grey. Source: own compilation based on 2024 FADN data.

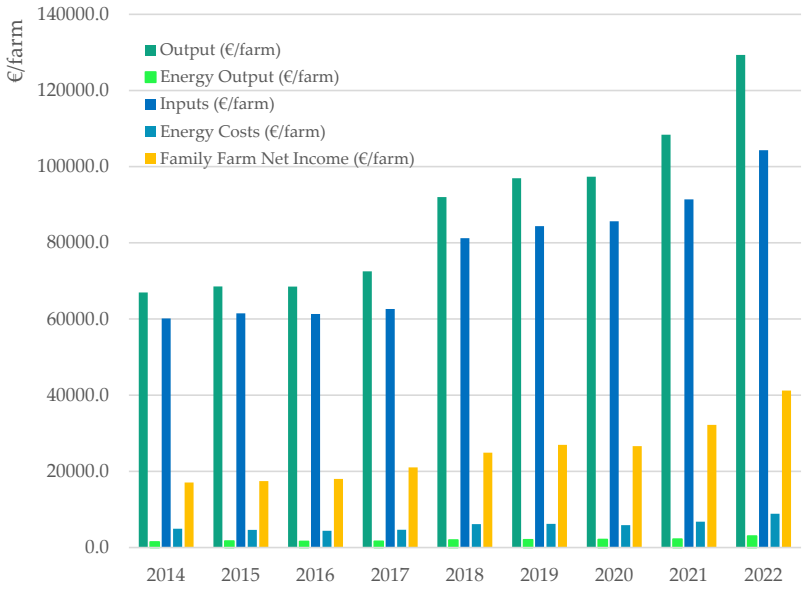


Figure 1. Total output, inputs, family farm income vs. energy output and costs of European Union (excluding the United Kingdom) farms in 2014–2022 (without 6 countries: Croatia, Germany, Greece, Malta, Slovenia and Spain). Source: own compilation based on Table 1.

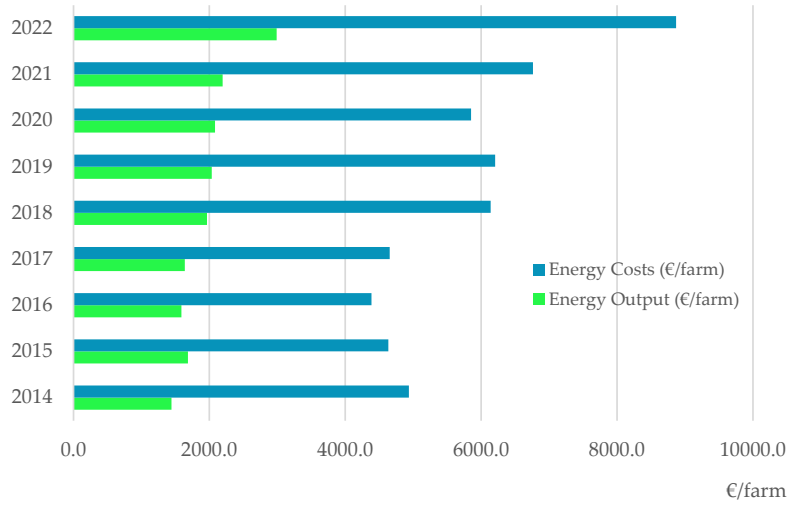


Figure 2. Farm energy output and energy costs in the European Union (excluding the United Kingdom) between 2014 and 2022 (without 5 countries: Croatia, Germany, Greece, Slovenia and Spain). Source: own compilation based on Table 1.

The farms' economic size had an impact on the values covered by the study. Namely, the larger the farm, the greater its interest in having a high energy output, because energy costs are also greater. In addition, the larger the farm, the greater the share of its costs covered by its energy output (i.e., larger holdings can be considered more energy-efficient). On the other hand, the smallest farms had only little capacity to produce energy despite incurring a heavy burden of energy costs (Table 3).

In the case of the Netherlands and Germany, small and very small farms were not taken into account, but the largest holdings proved to also be the most energy-efficient ones. Medium-small farms were also found to be on par with the relative performance of the largest ones, although in absolute terms, their output and energy costs were much lower (Table 3).

Table 3. Average values of energy parameters and additional financial data of European Union * farms grouped by size in 2021.

Details	Economic Size Classes					
	1 **EUR 2000 ≤ 8000** **Very Small**	**2** **EUR 8000 ≤ 25,000** **Small**	**3** **EUR 25,000 ≤ 50,000** **Medium-Small**	**4** **EUR 50,000 ≤ 100,000** **Medium-Large**	**5** **100 000 ≤ 500 000 €** **Large**	**6** **≥EUR 500,000** **Very Large**
			EU-27			
Utilized agricultural area (ha per farm)	6.0	13.9	27.2	48.1	97.9	252.8
Output (EUR per farm), including the following:	8474.0	20,730.0	44,781.0	85,175.0	251,093.0	126,5074.0
-Energy output (EUR per farm)	22.0	107.0	894.0	1067.0	3452.0	40,521.0
-Share of energy output in total output (%)	0.3	0.5	2.0	1.3	1.4	3.2
Inputs (EUR per farm), including the following:	7268.0	15,231.0	35,878.0	67,698.0	209,852.0	1125,294.0
-Energy costs (EUR per farm)	814.0	1704.0	3439.0	5883.0	14,896.0	71,585.0
-Share of energy costs in total input (%)	11.2	11.2	9.6	8.7	7.1	6.4
Ratio between energy outputs and costs (%)	2.7	6.3	26.0	18.1	23.2	56.6
			Netherlands			
Utilized agricultural area (ha per farm)	-	-	15.8	22.8	38.5	57.7
Output (EUR per farm), including the following:	-	-	90,572.0	138,822.0	364,407.0	1486,655.0
-Energy output (EUR per farm)	-	-	6423.0	6010.0	3807.0	47,341.0
-Share of energy output in total output (%)	-	-	7.1	4.3	1.0	3.2
Inputs (EUR per farm), including the following:	-	-	88,307.0	121,442.0	319,371.0	1294,096.0
-Energy costs (EUR per farm)	-	-	4788.0	6381.0	16,689.0	82,448.0
-Share of energy costs in total input (%)	-	-	5.4	5.3	5.2	6.4
Ratio between energy outputs and costs (%)	-	-	134.1	94.2	22.8	57.4
			Germany			
Utilized agricultural area (ha per farm)	-	-	33.9	49.3	91.0	340.2
Output (EUR per farm), including the following:	-	-	60,703.0	102,793.0	308,850.0	1308,528.0
-Energy output (EUR per farm)	-	-	5189.0	4157.0	7517.0	81,155.0
-Share of energy output in total output (%)	-	-	8.5	4.0	2.4	6.2
Inputs (EUR per farm), including the following:	-	-	62,156.0	98,603.0	282,820.0	1311,022.0
-Energy costs (EUR per farm)	-	-	6296.0	9664.0	23,117.0	93,794.0
-Share of energy costs in total input (%)	-	-	10.1	9.8	8.2	7.2
Ratio between energy outputs and costs (%)	-	-	82.4	43.0	32.5	86.5

* Excluding the United Kingdom. Source: Own calculations based on 2024 FADN data.

It can be clearly stated that the farms' economic size had an impact on the aspects covered by the study. It is now necessary to check whether output and energy costs are also affected by the farms' production type.

However, as regards production, it was difficult to reach a conclusive assessment. It was impossible to state that either plant or animal production was more energy-efficient, generated more energy or involved higher energy costs. Any conclusions were later refuted by data for the Netherlands and Germany (Table 4). In view of the inconclusive results, this issue would require further investigation as part of separate research.

Next, the technique referred to as the forward stepwise variable technique was employed to meet the main goal of this study. Basic farm information was used as independent variables for the models. Namely, it was data relating to their production and financial situation. The set of dependent and independent variables included the following:

- Y01: Energy Output;
- Y02: Energy Costs;
- X01: Labor Inputs;
- X02: Utilized Agricultural Area;
- X03: Total Output;
- X04: Total Inputs;
- X05: Taxes;
- X06: Family Farm Income;
- X07: Assets;
- X08: Liabilities;
- X09: Gross Investment;
- X10: Net Investment;
- X11: Cash Flow;
- X12: Balance of Current Subsidies and Taxes.

Therefore, models were built with either energy output or energy costs as the dependent variable. Gretl software was used in structuring the FE models (Table 5). In some cases, the Hausman test suggested the use of FEMs. However, because FEMs were similar to those ultimately used in the study (and on top of that are dedicated to some specific databases), only FEMs were employed with no adverse effects on the final results. All dependent variables in these models are statistically significant at the 0.05 level.

When energy output was set as the dependent variable, labor input, net investment, cash flow and balance of current subsidies and taxes were found not to have any impact on it. In this case, total inputs turned out to be the strongest determinant: the higher they are, the greater the energy output, regardless of the farm's economic size. It is difficult to tell what factors have an impact on each economic size class because they all seem to be unstable and unlikely to recur. It is only fair to say that when taxes grow, energy output declines (as illustrated by the example of medium-sized members of classes 3 and 4). In turn, when utilized agricultural area, family farm income and assets increase, the farms become less interested in energy production (as is the case for some of the classes from 3 to 6). This may indicate that when farms enjoy favorable conditions for agricultural and economic development (providing them with income streams), they care less about energy security. It can also be stated that in some classes of farm economic size, the increase in total output and gross investment had a positive effect on energy output, whereas the increase in liabilities had a negative impact on it (Table 5). In addition, a statistically weak model was created for class 1 (Table 5). All of the above arguments suggest that energy output is also influenced by factors other than production, economic or financial aspects. These may include situations where people follow trendy lifestyles, seek independence, want to become environmentally friendly or are simply curious about how some solutions work in practice.

Table 4. Energy output, costs and other details of European Union * farms grouped by production in 2021.

Details	Production Type							
	Field Crops	Horticulture	Wine	Other Permanent Crops	Milk	Other Grazing Livestock	Granivores	Mixed
				EU-27				
Utilized agricultural area (ha per farm)	52.7	7.3	16.4	13.8	49.7	53.3	43.0	40.7
Output (EUR per farm), including the following:	84,278.0	242,889.0	104,567.0	47,848.0	192,509.0	66,967.0	490,316.0	88,654.0
-Energy output (EUR per farm)	2204.0	9521.0	554.0	464.0	3094.0	738.0	7107.0	2381.0
-Share of energy output in total output (%)	2.6	3.9	0.5	1.0	1.6	1.1	1.4	2.7
Inputs (EUR per farm), including the following:	68,617.0	188,288.0	72,553.0	31,899.0	166,710.0	64,460.0	448,381.0	84,079.0
-Energy costs (EUR per farm)	6417.0	16,623.0	3762.0	2711.0	10,988.0	4626.0	21,726.0	6157.0
-Share of energy costs in total input (%)	9.4	8.8	5.2	8.5	6.6	7.2	4.8	7.3
Ratio between energy outputs and costs (%)	34.3	57.3	14.7	17.1	28.2	16.0	32.7	38.7
				Netherlands				
Utilized agricultural area (ha per farm)	51.5	16.5	-	16.1	61.5	28.0	11.6	46.6
Output (EUR per farm), including the following:	308,020.0	1560,037.0	-	461,989.0	470,080.0	230,074.0	1124,691.0	786,972.0
-Energy output (EUR per farm)	5250.0	69,942.0	-	21,228.0	5105.0	8431.0	14,054.0	5722.0
-Share of energy output in total output (%)	1.7	4.5	-	4.6	1.1	3.7	1.2	0.7
Inputs (EUR per farm), including the following:	277,047.0	1245,078.0	-	402,632.0	417,969.0	215,720.0	1127,413.0	719,400.0
-Energy costs (EUR per farm)	18,588.0	10,6993.0	-	15,767.0	19,290.0	12,150.0	37,102.0	27,468.0
-Share of energy costs in total input (%)	6.7	8.6	-	3.9	4.6	5.6	3.3	3.8
Ratio between energy outputs and costs (%)	28.2	65.4	-	134.6	26.5	69.4	37.9	20.8
				Germany				
Utilized agricultural area (ha per farm)	138.1	12.5	15.5	42.2	92.2	73.2	82.8	162.0
Output (EUR per farm), including the following:	276,095.0	790,269.0	186,812.0	300,755.0	398,198.0	140,205.0	522,686.0	471,212.0
-Energy output (EUR per farm)	12,488.0	113,497.0	6419.0	29,013.0	10,596.0	4746.0	13,455.0	31,316.0
-Share of energy output in total output (%)	4.5	14.4	3.4	9.6	2.7	3.4	2.6	6.6
Inputs (EUR per farm), including the following:	274,000.0	688,116.0	135,927.0	283,739.0	353,913.0	145,515.0	544,979.0	496,272.0
-Energy costs (EUR per farm)	24,555.0	48,169.0	7648.0	18,383.0	29141.0	12,836.0	32,046.0	37,855.0
-Share of energy costs in total input (%)	9.0	7.0	5.6	6.5	8.2	8.8	5.9	7.6
Ratio between energy outputs and costs (%)	50.9	235.6	83.9	157.8	36.4	37.0	42.0	82.7

* Excluding the United Kingdom. Source: own calculations based on 2024 FADN data.

Table 5. PFM models with energy output and costs as dependent variables for European * farms grouped by economic size in 2014–2021.

Details	Economic Size Classes					
	1 **EUR 2000 ≤ EUR 8000** **Very Small**	**2** **EUR 8000 ≤ EUR 25,000** **Small**	**3** **EUR 25,000 ≤ 50,000** **Medium-Small**	**4** **EUR 50,000 ≤ EUR 100,000** **Medium-Large**	**5** **EUR 100,000 ≤ EUR 500,000** **Large**	**6** **≥EUR 500,000** **Very Large**
Number of observations	105	173	209	216	216	175
			Energy Output models (Y01)			
LSDV R2 Within R2	0.6108 0.0398	0.8872 0.2050	0.9207 0.4021	0.9182 0.3538	0.8700 0.0575	0.9145 0.2681
const	−126.5520 (0.3314)	−199.2900 (0.7498)	−2245.7800 (0.3375)	−1303.0800 (0.6802)	3406.9000 (0.4211)	94,860.7000 (0.0000)
X02: Utilized Agricultural Area	-	-	−233.3140 (0.0000)	-	−55.9753 (0.0266)	−147.4130 (0.0003)
X03: Total Outputs	-	-	-	0.3372 (0.0000)	-	0.2444 (0.0025)
X04: Total Inputs	0.0338 (0.0567)	0.1347 (0.0000)	0.4091 (0.0000)	-	0.0443 (0.0031)	−0.1882 (0.0141)
X05: Taxes	-	-	−3.5478 (0.0229)	−2.8264 (0.0418)	-	-
X06: Family Farm Income	-	-	-	−0.3152 (0.0000)	-	−0.2762 (0.0008)
X07: Assets	-	-	−0.0097 (0.0125)	−0.0278 (0.0000)	-	-
X08: Liabilities	-	−0.0644 (0.0000)	-	-	-	-
X09: Gross Investment	-	-	-	0.0718 (0.0500)	-	-
Hausman Test	χ^2 (1) = 0.2188 (0.6400) REM Rejected	χ^2 (2) = 18.3722 (0.0010) REM Not Rejected, FEM Sufficiently Close	χ^2 (4) = 6.0772 (0.1935) REM Rejected	χ^2 (5) = 14.3278 (0.0137) REM Not Rejected, FEM Sufficiently Close	χ^2 (2) = 3.3770 (0.1848) REM Rejected	χ^2 (4) = 12.8339 (0.0121) REM Not Rejected, FEM Sufficiently Close

Table 5. *Cont.*

Details	Economic Size Classes					
	1 **EUR 2000 ≤ EUR 8000** **Very Small**	**2** **EUR 8000 ≤ EUR 25,000** **Small**	**3** **EUR 25,000 ≤ 50,000** **Medium-Small**	**4** **EUR 50,000 ≤ EUR 100,000** **Medium-Large**	**5** **EUR 100,000 ≤ EUR 500,000** **Large**	**6** **≥EUR 500,000** **Very Large**
Energy Costs models (Y02)						
LSDV R2	0.9280	0.9462	0.9348	0.9312	0.9494	0.9755
Within R2	0.7072	0.4271	0.4715	0.4234	0.5267	0.5169
const	121.2400 (0.0726)	−13.3703 (0.9455)	−61.6414 (0.8593)	−807.2930 (0.2529)	−10,798.5000 (0.0000)	−28,514.4000 (0.0054)
X02: Utilized Agricultural Area	-	95.8487 (0.0000)	90.5202 (0.0000)	67.4532 (0.0000)	124.2020 (0.0000)	142.2290 (0.0000)
X03: Total Outputs	0.1104 (0.0000)	0.0172 (0.0000)	0.0276 (0.0000)	0.0490 (0.0000)	0.0880 (0.0000)	0.0499 (0.0000)
X06: Family Farm Income	−0.1187 (0.0000)	-	−0.0318 (0.0002)	−0.0199 (0.0332)	−0.0982 (0.0000)	-
X08: Liabilities	-	-	-	-	−0.0168 (0.0003)	-
X11: Cash Flow	-	-	-	-	-	−0.0614 (0.0006)
X12: Balance of Current Subsidies and Taxes	0.1248 (0.0000)	-	-	-	-	-
Hausman Test	χ^2 (3) = 0.5861 (0.8996) REM Rejected	χ^2 (2) = 4.6274 (0.0989) REM Rejected	χ^2 (3) = 8.7148 (0.0333) REM Not Rejected, FEM Sufficiently Close	χ^2 (3) = 4.8540 (0.1828) REM Rejected	χ^2 (4) = 14.1556 (0.0068) REM Not Rejected, FEM Sufficiently Close	χ^2 (3) = 10.5646 (0.0143) REM Not Rejected, FEM Sufficiently Close

* Including the United Kingdom. The significance level is specified in parentheses. Source: own compilation based on 2024 FADN data.

In turn, labor inputs, total inputs, taxes, assets, gross investment and net investment proved to have no impact on energy costs in models that used them as the dependent variable. Instead, there was a strong correlation between energy costs and utilized agricultural area, total output and family farm income, regardless of the farm's economic size. The greater the area and total output, the higher the energy costs. The higher the income, the smaller the energy costs; this can be explained by the fact that while being the result of economic activity, family farm income also includes money earned from areas other than agricultural production. The balance of current subsidies and taxes played an important role for the smallest farms, whereas liabilities and cash flow were significant factors for large and extremely large holdings, respectively (Table 5).

To sum up this section of the research, it can be concluded that while Europe witnessed an increase in energy output and costs on a year-over-year basis, energy production covers only one-third of the demand. While the largest holdings—which derive a significant part of their income from agricultural production—are in a position to invest in energy production, they also face the greatest costs, including those related to energy. This phenomenon was witnessed in the Netherlands, Germany, Belgium, Denmark, Czech Republic, Hungary, Luxembourg, Slovakia and Sweden. Conversely, the smallest energy output and energy costs were recorded by Croatian, Bulgarian, Polish, Spanish, Lithuanian, Irish, Portuguese and Romanian farms.

In the case of an unexpected surge in energy costs, the above relationships become a matter of great importance. Hence, in today's context of growing energy prices, these findings need in-depth attention.

4. Discussion

In theory, farmers can produce energy on their own to become even more self-sufficient by reducing external inputs. The research covered by this paper revealed the gap between actual energy costs and energy production revenues.

It is common knowledge that modern agriculture needs much more energy than traditional farming which strongly relies on fossil fuels in order to power its machinery, dry grain, manufacture fertilizers and generate electricity for lighting and heating. It should be emphasized that climate change and related impacts can be mitigated by promoting the use of renewables in agriculture. Nevertheless, shifting from a traditional (non-renewable-energy-based) approach to a modern (renewables-based) system poses a number of difficulties. The transformation towards renewable energy should be instant and orderly. Hence, it needs incentive-based policies for all countries, whether with lower or higher income levels [30].

In Europe, the key problem behind energy transformation is the on-farm production of clean and affordable energy. However, the broad range of regulations, business models and available technologies frequently adds to the complexity of the decision-making process related to the introduction and promotion of farm renewables. Also, it poses some challenges for those who design and assess the relevant promotion policies. As a consequence, the legislative and regulatory framework does not always address the potential behind and characteristics of on-farm renewables. Indeed, its key purpose is to support a centralized energy production and distribution model, and it is sometimes difficult to delimit its components [31].

Although regions strongly differ in energy use and development level of agri-food systems, renewables prove to be useful in most contexts and therefore require an adapted policy, adequate technology, delivery models and financing solutions. Cross-sector partnerships are a way to mobilize measures and drive investments at scale in an effort to seize the opportunities derived from agricultural uses of renewable energies while remaining focused on sustainability issues. Engaging government representatives and local stakeholders is key for having a complete picture of what is actually needed, creating market links, and delivering financial and other resources as part of a broader strategy for food system transformation driven by renewables [1].

The only feasible solution to the non-renewable energy problem involves finding renewable sources and using them as a replacement for affordable and useful (yet increasingly scarce) fossil resources. Note that renewable energy has only one true source, namely the Sun, which will keep providing solar power for the next couple of billion years, if not longer. Waterfalls, windmills, photovoltaic cells and solar collectors are all forms of renewable solar sources. The most widespread collectors of solar power are green plants, which comes as no surprise since today's fossil energy is stored in them. Therefore, it is totally reasonable to view the agricultural sector as a source of renewable or alternative energy for future uses. Nevertheless, realistic assumptions must be made as to the degree to which energy derived from agriculture can replace today's fossil resources. Although experts in this field may disagree on specific ratios or percentages, it is generally clear that the amount of energy produced by agricultural holdings has some known basic limits [32].

The European Commission recognizes the importance of these attempts and offers dedicated financial support under the Europe 2020 Strategy and the Common Agricultural Policy. Bearing in mind the significance of this problem, it launched its Horizon 2020 research program to address the need for increased public funds earmarked for research and innovation. A total of EUR 4.5 billion has been allocated for activities under the measure "Food Security, Sustainable Agriculture and Forestry, Marine and Maritime and Inland Water Research and the Bioeconomy", with some supplementary financial resources being expected in other domains of Horizon 2020 [33]. Some of that money will be spent on supporting farm development with a view to improving farms' economic standing, including that of small holdings.

Members of the European Economic Community might play a pivotal role in driving green investments. In this context, note that some processing sectors (including food and feed) keep lagging behind. Potential profits may be reaped by small and moderate innovators, and whether they succeed or not in their modernization efforts will have a substantial effect on overall progress. Hence, the challenges faced around the world require giving a new priority to modernization which relies on new funding streams. As a consequence, new projects might provide unprecedented opportunities for progress, provided that the countries concerned adequately focus their investment measures [34]. If they do, green growth and competitiveness will attract much interest, and new opportunities for productivity gain in national industries will emerge, driven by the implementation of new technologies. Moreover, these efforts can help countries become less dependent on raw material imports by revitalizing their marginalized areas [35–37].

Over the last twenty years, research and innovation projects have been promoted in Germany, the Netherlands and Finland—which appear as pioneering countries—as a way of tapping into the full potential of these changes and bringing benefits to society and the economy [38]. The results of this study corroborate the important and dominant role these countries play.

Nowadays, over 50 countries have a dedicated strategy or policy in place [39]. In designing their strategies, they remain focused on their bio-economic development goals and use adequate tools for measuring, monitoring and reporting the outcomes as crucial enablers of success in the long run [40]. These strategies gradually shift from an environmental to a social and market focus. Thus, their priorities and vision evolve around gross value added, economic growth, entrepreneurship, employment, competitiveness and technological development [41].

The burden of changes so introduced falls on individual entities and often requires them to radically restructure their existing business models and new projects. They must completely redefine the value they offer and modify the way their products or services are created, delivered and disposed of [42]. As shown by this study, not all farms are able to successfully introduce solutions contributing to increased energy output. Over the 11 years studied, energy production increased, but was followed by rising costs of energy consumption. Hence, while improvements are noticeable in absolute terms, there are only small changes on a relative basis, as confirmed by data in Table 1 and Figures 1 and 2.

These thoughts are corroborated by other researchers. However, businesses still have not widely adopted circular economy models underpinned by remanufacturing and reusability concepts which carry a promise of considerable cost savings accompanied by a strong reduction in industrial impacts on the environment [43]. Entrepreneurs generally believe that they can contribute to sustainable development mostly by creating new knowledge and jobs and are not necessarily guided by social or environmental aspects [44]. That attitude reveals a need for new business models to be implemented in the future. At first, innovation gives rise to excitement and inspiration, but it needs to be followed by an operationalization stage to ensure a successful implementation and start the shift to a circular economy. That process is expected to significantly alleviate the adverse environmental impacts, reduce the amount of waste and decrease the consumption of resources while also having positive social and environmental effects [45].

It will probably take many more years and a number of political and economic solutions to change the facts. Also, the evolution witnessed in farms requires further support and efforts to make it widespread. This is especially true for smaller holdings based in regions that lag behind the leaders in introducing renewable energies.

5. Conclusions

Over time, the renewable energy concept has not only attracted more interest, but also become the subject of dedicated political and economic solutions. For the agricultural sector, this is an important future-proof solution that will help make it more competitive. However, this is true under the assumption that on-farm energy production provides agricultural holdings with an opportunity to improve their economic situation. The author of this paper is of the opinion that European Union farms have the potential they need to implement such modern solutions.

At the beginning, four questions were asked, formulated as follows:

1. What were the European family farms' earnings from energy production, what were their energy costs, and how did they compare to their area, total output, costs and farm income between 2014 and 2022?
2. In which European country do family farms report the highest average energy production volume, and do they also face the highest energy costs there?
3. Do the farms' energy output and costs depend on their economic size or production type?
4. Which categories (e.g., area, assets, cash flow, equity, income, investments, labor, liabilities, output, taxes) are correlated with energy output and energy costs?

The first question can be answered by stating that energy production covered only one-third of its costs in the period covered by the analysis. Also, both production volumes and costs were on a growth path on a year-over-year basis, with similar growth ratios. This was accompanied by growth in utilized agricultural area, family farm income and, obviously, total output and total inputs. Thus, while the farms' financial situation was improving, there was nothing special about the energy output itself.

Four rankings were made to address the second question and were then used in arranging the countries and identifying those with the highest energy output and costs in relative and absolute terms. The leaders are the Netherlands and Germany, followed by Belgium and Denmark (ex aequo), the Czech Republic, Hungary, Luxembourg, Slovakia and Sweden.

The answer to the third question is not fully satisfactory. The farms' economic size had an impact on the aspects covered by the study. Namely, the larger the farm, the greater its interest in having a high energy output, because energy costs are also greater. In addition, the larger the farm, the greater the share of its costs covered by its energy output. The smallest farms had only a little capacity to produce energy despite incurring a heavy burden of energy costs. However, it was difficult to grasp and describe the importance of the farms' production type for their energy-related aspects. This requires further investigation because

it was impossible to state that either plant or animal production generated more energy or involved higher energy costs.

The answer to the fourth question brought some interesting conclusions. The most important determinant of energy output was total inputs. It was difficult to tell what factors had an impact on each economic size class because the results seem to be unstable and unlikely to recur. Taxes (classes 3 and 4), utilized agricultural area, family farm income and assets (in some of the classes from 3 to 6) proved to be factors of importance. It can also be stated that in some classes of farm economic size, total output, gross investment and liabilities played a significant role. The above findings suggest that energy output is also influenced by factors other than production, economic or financial aspects. These may include situations where people follow trendy lifestyles, seek independence, want to become environmentally friendly or are simply curious about how some solutions work in practice. Energy costs, in turn, are related to utilized agricultural area, total output and family farm income. They are significantly impacted by the balance of current subsidies and taxes (class 1), liabilities (class 5) and cash flow (class 6). Some variables turned out to be completely irrelevant. As regards energy output, these were labor inputs, net investment, cash flow and balance of current subsidies and taxes. In turn, with respect to energy costs, these were labor inputs, total inputs, taxes, assets, gross investments and net investments.

The research covered by this paper requires further observation. It would be worth checking whether the trends outlined by the study continue in the years to come. For the time being, complete data for 2022 are unavailable, but it is worth monitoring the situation in countries that have already submitted their annual dataset.

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