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Energy Efficiency of Maize Production Technology: Evidence from Polish Farms

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Abstract: The purpose of this work is to determine the impact of selected silage maize cultivation technologies, including energy inputs in the production chain (cultivation, harvesting, heap placing), on energy efficiency. The analysis of energy inputs, energy efficiency for the silage maize production technology were estimated. The research was performed for 13 farms producing silage maize. The data from the farms covered all the activities and the agrotechnical measures performed. The calculations of energy inputs made for the silage maize production for selected technologies were performed using the method developed by the Institute of Construction, Mechanization and Electrification for Agriculture (IBMER), once the method was verified and adapted to the needs and conditions of own research. Based on the accumulated energy production and the energy accumulated in the yield, energy efficiency index values for 13 silage maize cultivation technologies were calculated. The greatest impact on the results of energy efficiency calculations was shared by fertilizer and fuel inputs. In conclusion, it can be stated that, in terms of energy efficiency, maize cultivation is justified and it can generate energy benefits.

Keywords: energy efficiency; energy accumulated; crop production; silage maize; biomass; farms

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1. Introduction

Crop cultivation is of special importance for covering the demand for consumption and animal feed and, to a growing extent, also for energy [1]. The socioeconomic progress, scientific and technical advancements, and hence the economic development result in an ongoing increase in electricity and transport fuel consumption globally, which triggers an increase in the concentration of pollution and environmental degradation (water, soil, air) [2–4]. The danger that is associated with this matter is the continued increase of unemployment and famine factors, unless intensive and preventive tasks are introduced, especially in saving agro-systems transformation. Past actions were based on previous generations' experience. The increased level of development in various fields requires us to use the results of interdisciplinary research. At the same time, the rapid changes in the conditions of the agro-systems environment and the growing demand for new, more effective technologies require the simultaneous contribution of knowledge not only in the field of food production, but also in the field of the quality of newly created products, their marketing and maintaining the ethical principles of their acquisition, processing and distribution. In particular, it is about the links between the humanities, technical, and agronomic sciences, creating an interdisciplinary consilium of experts on the transformation of agro-systems.

Considerations on the effectiveness of agro-systems transformations, both in the past and in the long-term perspective, lead to the knowledge and explanation of the mechanisms of influence of various environmental factors on the anticipated changes in the parameters describing the energy-technological condition of the considered objects. The development of agriculture in line with the paradigm of sustainable development has become particularly important for industrialized countries, which previously based the development of the agricultural sector on the industrial model. Especially in Europe, the agricultural model based on too intensive fertilization, mechanization, and concentration led to the deterioration of the quality of the natural environment (Stoate et al., 2009). One of the elements of this research from the microeconomic perspective (at the farm level) is the comprehensive energy consumption estimated with the so-called pull method was started at the end of the 1970s [5]. In Europe, the precursor of such research was Pellizzi [6,7]. The energy performance indicators of respective means of production sometimes differ quite considerably depending on the authors, the indicator value changes with time, which is due to the changes in industrial production methods, more complete and more accurate energy consumption research in various areas of human life and production activity [5,8]. The energy technology method to assess the food economy transformation effectiveness was proposed by Nowacki [9], presenting the reasons for the macroeconomic approach to the food system. He covers the problem of the relationships of the economic measures, energy and sociological management effectiveness. As the technological level of an agricultural facility grows, human labor inputs decrease, which is the cause of a significant outflow of people employed in agriculture to other professions.

In the microeconomic approach, the research of the accumulated production energy consumption and efficiency is performed to evaluate the management quality in the enterprise, including an agricultural farm. The evaluation of the outcomes and economic methods management effectiveness often fails as the prices imposed often do not correspond to the cash value of the goods or energy offered. Hence, an increase in the importance of the evaluation of the energy consumption and energy efficiency method based on the values expressed in reference energy units is seen, allowing for their comparison irrespective of the place, time, and price relations. Bearing in mind the preferences, payments and grants for agricultural production, consumables and raw materials, services and credits applied on the EU market, the study of the energy efficiency becomes of special importance even though it will not replace the economic analyses which, under more complete market economy conditions, are definitely the best and the simplest business activity evaluation methods [10].

Because of a growing energy consumption, new methods of energy generation are searched for, the existing ones are improved, and the participation of the renewable resources of energy is increased in the energy balance. The rational use of the resources is nowadays associated with a permanent use of renewable resources, which means using them in such amounts in which their increase occurs [11]. The topic of renewable energy resources is one of the many aspects referring to the limited resources of fossil fuels, a considerable share of the energy sector in the greenhouse gas (GHG) emissions, which contributes to climate changes and an increase in energy security. In 2007 the Member States accepted the so-called climate and energy package, the assumptions of which are, e.g., limiting the GHG emissions and enhancing the energy security. One of the ways to accomplish those objectives is to increase the share of energy from the renewable resources in its total consumption. A special attention must be given to, e.g., agricultural biogas, the gas produced in the process of methane fermentation of agricultural raw materials, agricultural by-products, liquid or solid animal feces, by-products, waste or the remains from the processing of the products of agricultural origin or forest biomass of plant biomass collected from the areas other than recorded as agricultural or forest, except for the biogas produced from materials derived from sewage treatment plants and landfill sites [12]. That renewable energy is considered to show a potential as it is a stable and predictable source (important in terms of energy security) meeting a number of positive functions not only for the electrical power system, next to the energy and economic benefits as well as the environmental ones; it decreases the GHG emissions and provides global and local social benefits. It helps activate the rural areas, it creates new jobs, it enhances the investment attractiveness of the region [13–15].

In Poland, to produce the agricultural biogas, most frequently a mixture of animal feces with energy crops or with by-products of agricultural origin is used. Applying co-substrate with a higher content of dry weight, as compared with its content in animal feces, enhances the production of biogas and the process economic effectiveness [16]. The right combination is conditioned by the biogas potential of each component as well as component interaction [17]. An excellent supplement to the fermentation mass in terms of technology is, e.g., maize silage. Literature provides many reports on the use of maize for energy purposes or [18–20] the relations between the maize prices and the prices of energy materials [21,22].

One must note, however, that growing maize requires high energy inputs, hence a need to perform research to increase the production energy efficiency. Energy efficiency must be defined as a ratio of the energy value of the biomass yield (the accumulated energy contained in biomass) to the total energy inputs (the accumulated energy required to produce the biomass) [10,23]. The cultivation technologies applied affect the environment to a varied extent and so, in terms of maize cultivation for energy purposes, calculating the energy efficiency becomes essential [24]. Estimating the energy consumption and energy efficiency of agricultural materials is indispensable for energy crops in a form of renewable energy. According to the requirements of Directive 2009/28/WE (RED) on the promotion of the use of energy from renewable sources, processors of biofuels are required to prove that the production from agricultural raw materials and the whole process of liquid biofuels production meet the sustainability criteria. It can be demonstrated by the LCA (life cycle assessment) method, that proves the reduction of GHG emissions along the entire chain of production. [25,26]. Those considerations are based on analyses at the microeconomic level concerning only the energy efficiency of various technologies of the maize for silage production in use of raw material for processing into biogas as an energy carrier. The analysis of the drag method by Pellizzi, adapted to Polish conditions by Wójcicki, allows the comparison of results whether the place, time, and price relationship was used. The drag method is successfully used by many authors and institutions, for example IBMER-ITP. The biomass production efficiency is very important in terms of increasing its share in the energy production. Because of the fears of a competition between plant production for energy purposes and crops for human consumption, actions are taken and research is performed to decrease the energy consumption of plant production owing to the optimal planning and possibly the most effective use of the land allocated for cultivation, compliant with the principles of sustainable development. An example of such research can be found, e.g., in the reports by Houshzyara et al. [27,28].

The primary objective of the paper is to determine the energy efficiency of maize with the use of various technologies. With that in mind, the analysis of energy inputs was made and energy efficiency was calculated for the silage maize production technology. To achieve the objective, the results of own research performed on 13 agricultural farms were applied.

The respective sections of the article present the theoretical grounds for the use of maize for energy purposes followed by the experimental part of the energy efficiency analysis. After the introduction, chapter 2 discusses in detail the source material and research methods. The third chapter covers the results of the analyses. With the basic information on the maize market, calculations were made on accumulated energy, the structure of energy inputs and energy efficiency. The last part of the article provides discussion and results.

2. Maize as an Energy Crop

Maize, similarly as most energy crops, is mostly used as a starch material derived from seed and as a material mostly for producing bioethanol [29] and as biomass including leaves, stems, and blade apex. Biomass can be used to produce bioethanol of the second generation, for incineration [30–32] or as silage for biogas production [33,34]. Interestingly, the maize acreage in Poland since 2007 has increased by 146% and in 2018 it was 0.65 m ha (Figure 1), which accounted for 8% of the total acreage of crops in the EU.

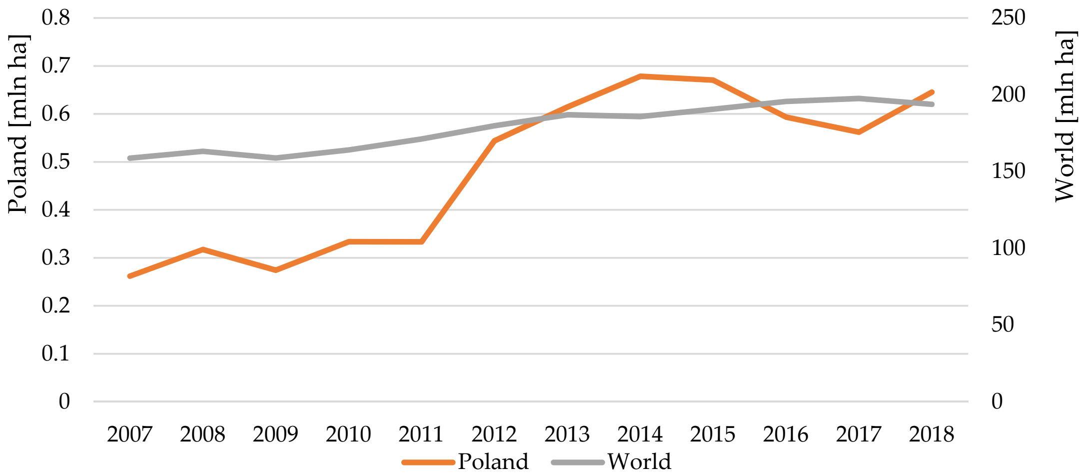

Figure 1. Maize production in 2007–2018, Source: own elaboration based on [35].

Silage maize is a roughage used for cattle feeding. In fact, for the entire year of the fodder crop field harvest structure, maize shows the highest acreage, in 2016 the green maize yields accounted for 73.5% of the total fodder crop yields (Figure 2). Next to the silage allocation to animal feed for livestock or milk production, there also appeared a possibility of using it for energy purposes, as a valuable substrate for methane fermentation bacteria for biogas production. One of the most frequently applied substrates of agricultural origin is slurry, with varied properties depending on the feeding method or the animal species. A relatively low content of dry weight requires supplementation with substrates, e.g., plant substrates. An excellent supplement for the fermentation mass in terms of technology is maize silage which, according to the National Centre for Agriculture Support (KOWR), in 2018, accounted for 12% of the total substrates used in agricultural biogas plants (Figure 3).

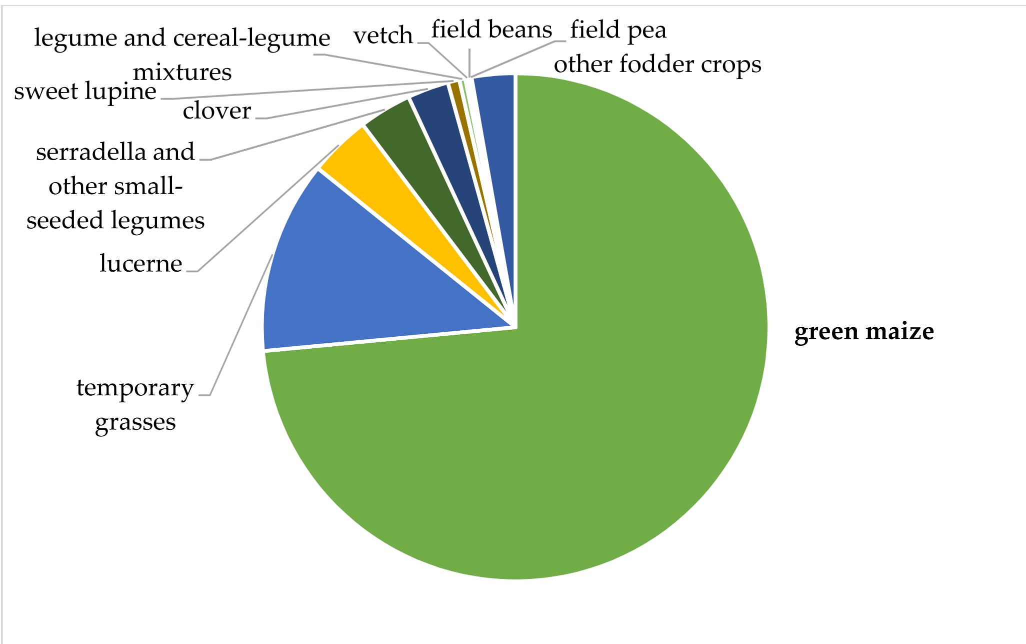

Figure 2. Structure of field green fodder crops production (Total production of field green fodder crops = 100. Source: own elaboration based on [36].

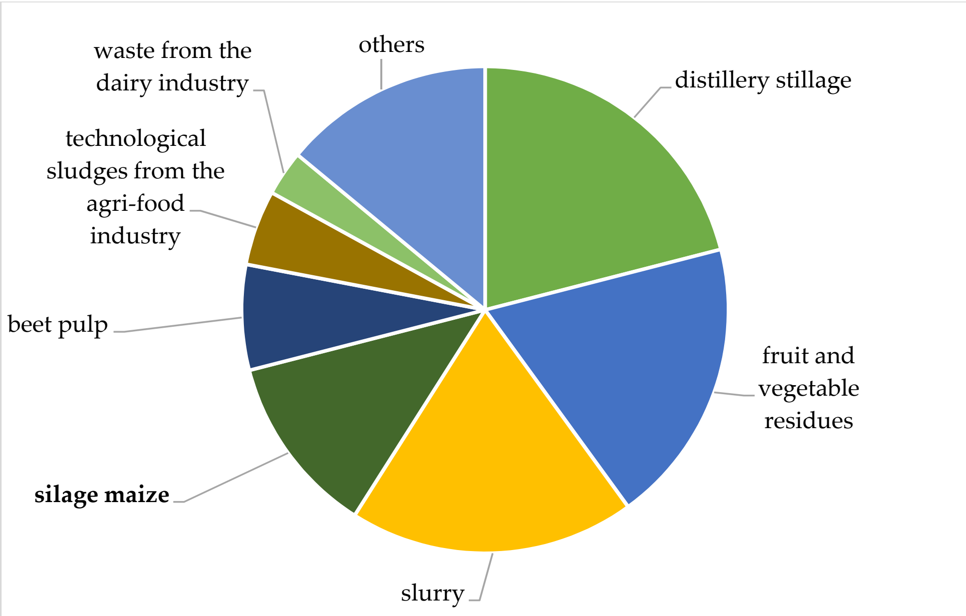

Figure 3. Share of substrates used for agricultural biogas production in 2018. Source: own elaboration based on [37].

The key criterion of the applicability of maize silage for biogas production is the share of dry weight from 28 to 35%, to much extent dependent on the right harvest date [38]. One of the biggest assets of maize is its high yields (photosynthesis C4); most frequently from 30 to 50 t/ha. For comparison, the average rye yield under Poland's conditions is 2.8 t per hectare, wheat—4.7 t per hectare for winter wheat and 3.6 t per hectare for spring wheat; the 2011–2015 means. One hectare of silage maize can produce from 4050 to 6750 m^3 of biogas, which can generate from 87 to 145 GJ of energy (Table 1). Biogas production from 1 ton of silage can reach 200 m^3, and from 1 ton of dry weight of silage the average of 550–650 m^3 of biogas is produced. The amount of methane production ranges from 300 to 400 m^3 per ton of dry silage weight [39–41].

Table 1. Average yields, biogas production, and energy from silage maize.

Average Yield of Fresh Weight, ($t \cdot ha^{-1}$)	Average Biogas Production, ($m^3 \cdot ha^{-1}$)	Average Energy Production, ($GJ \cdot ha^{-1}$)
30–50	4050–6750	87–145

Source: own elaboration based on [42,43].

Maize shows, e.g., high yields of green weight per area unit, a high biogas yield, a good ensilaging capacity [44]. The productivity of photosynthesis in C4 plants is about 1.5–2 times higher than in C3 plants; hence a high interest in those plants to be used for energy purposes [45–48]. The foreseen climate changes have and will have a high impact on crop cultivation conditions. Maize must be definitely considered a species which because of its physiology, gets fast adapted to unfavorable climate changes [49]. Table 2 presents the maize adaptation to climate changes.

The maize cultivation technologies, irrespective of the direction of use, should consider the economic effectiveness, energy efficiency as well as, while facing climate changes, the environmental effectiveness, to alleviate and to decrease the rate of environmental changes, and to limit the GHG emissions [50]. Accomplishing those goals is considered feasible owing to lowering the energy consumption of production technologies and increasing the efficiency. The plant production, including the production of silage maize, requires performing many agrotechnical treatments. The factors affecting the silage maize cultivation success, acquiring a high-quality material in terms of its ensilaging applicability are the adequate agrotechnical practices, the cultivar selection adequate for the climate zone and the stand [39,51]. The basic principles for making maize silage are accurate crushing, adding a preservative, fast placing of the heap or filling the silo, hermetic coverage, and the adequate pick-up, which affects the silage quality and limiting losses [52]. As for an inaccurate packing, the remaining oxygen makes ensilaging longer, it can lead to the development of undesired aerobic microorganisms. The hermetic coverage of the heap with foil prevents from the rainwater penetrating into the silage, and the load—the right ensilage straw deposition [53–55]. The tillage system and the dependent material and energy inputs, the frequency of practices, the dates of the agrotechnical practices performed, the harvest at the optimal date with a minimum level of losses during the practices are the key factors of the production energy efficiency.

Table 2. Maize adaptation and response to an anticipated climate change.

Climate Change	Mazie Adoption
Warming	→Thermophilic plant
Extension of the growing season	→Relatively low water needs
Less rainfall in the summer	→Less risk of crop failure →Longer growing season; later forms have a greater yielding potential

Source: own elaboration based on [49].

3. Materials and Methods

3.1. Source Material and Object Characteristics

The quality of agricultural enterprise management can be estimated with a balance sheet for the production period, breaking down the revenues and inputs and the incomes which can be expressed in a cash unit or the balance sheet for the business activity can be developed by breaking down the inputs and incomes in reference energy units (MJ) and reference grain units (JZ) [10]. The efficiency is a quotient of the outcome to the input [56].

The research was performed on 13 farms in the Podlaskie voivodeship (in south-eastern Poland). The climate of this region is moderate with huge continental influence. This voivodeship is dominated by agriculture, which is the main branch of the region's economy. The fodder area is approx. 55% of the agricultural area. Over 31% stands for sown area on the arable land are fodder plants. In the studied farms the silage maize was grown in real farming conditions. The crop acreage ranged from 2.0 to 13.0 ha. The fields were 0.05 to 2.5 km away from the habitation. The yields varied and ranged from 45 to 80 t·ha^{-1} (Table 3).

Table 3. Selected elements characteristic for silage maize cultivation.

Technology Number	Crop Acreage (ha)	Distance from the Habitat (km)	Yield (t·ha^{-1})
1	3.4	0.8	72
2	2.0	0.1	60
3	13.0	1.5	50
4	5.1	0.5	55
5	3.3	0.6	65
6	4.5	1.0	80
7	2.0	2.5	50
8	3.5	2.5	70
9	10.0	2.2	67
10	5.0	1.6	75
11	8.0	2.2	75
12	5.0	1.0	50
13	3.21	1.5	45

Source: own study.

The data from the agricultural farms on selected silage maize cultivation technologies were provided in the elaborations and process sheets, breaking down all the factors and agrotechnical practices (record of treatments and practices as well as production inputs), especially:

- Types and technical parameters of the machinery, tools and tractors used;
- Machinery aggregate performance;
- Labour inputs;
- Consumables and raw materials and fuel consumption.

With the method of direct interview with farmers, made twice over the vegetation period, there were determined the levels of the agrotechnical factors applied, which provided the data on the means-of-production inputs for the technologies investigated, following the silage maize cultivation technologies applied on a given farm and the consumption of the real sowing material, natural and artificial fertilizers, plant protection agents, and the yields per hectare.

The selected agricultural farms varied in terms of the type and amount of the fertilization applied. As for 12 out of 13 cultivation variants, natural fertilization was involved in 6 variants—manure only (no 3, 4, 9, 10, 11, 13) at the doses from 12.5 $t \cdot ha^{-1}$ (no 13) to 41.4 $t \cdot ha^{-1}$ (no 4), in 1—only slurry at the dose of 20 $t \cdot ha^{-1}$ (no 6), in 5—manure and slurry (no 1, 2, 5, 8, 12), manure—from 30 (no 8, 12) to 47.1 $t \cdot ha^{-1}$ (no 1) and slurry—from 14 $t \cdot ha^{-1}$ (no 5, 8) to 20 $t \cdot ha^{-1}$ (no 12), respectively. The cultivation technology marked with number 7 did not involve natural fertilization, whereas technology 7—used mineral fertilization only.

In the objects under study there were also considerable differences in the tractors and machinery used. The tractors engaged in agrotechnical practices and actions, harvest, technology transport, or placing a heap varied in terms of power and weight. Depending on the type of the work performed, carrying out the actions with own tractors, machinery, and tools or outsourced as services, the power and weight of tractors ranged from 22.4 kW for Ursus C330 of 1675 kg to 114 kW U1634 with 5190 kg. The harvest was made using the aggregate of a tractor with a tractor-operated chaff cutter (8 plantations) and with forage harvesters (5 plantations) with the power of up to 300 kW. For forage kneading and placing a heap of silage, tractors with weight added reaching the weight of up to 6 tons (ZT 232A) were used.

3.2. *Silage Maize Production Energy Consumption*

The energy inputs for silage maize production for selected technologies were calculated with the calculation method developed by IBMER [57,58] following a verification and adapting it to the needs and conditions of own research. The accumulated energy consumption stands for the total consumables and raw material and energy inputs in silage maize production technologies. To calculate it, the following dependence was used:

$$E_{pro} = \sum E_{mat} + \sum E_{tm} + \sum E_{ON} + \sum E_{l}, \tag{1}$$

where, E_{pro}—the sum of energy inputs incurred on the silage maize production, [$MJ \cdot ha^{-1}$], E_{mat}—energy consumption of consumables and raw materials engaged in production, [$MJ \cdot ha^{-1}$], E_{tm}—energy consumption of tractors, machinery, and tools [$MJ \cdot ha^{-1}$], E_{ON}—energy consumption of fuel, [$MJ \cdot ha^{-1}$], E_l—energy consumption generated by human labor, [$MJ \cdot ha^{-1}$].

The total value of accumulated energy consumption includes: energy consumption of consumables and raw materials engaged in production, energy consumption of the use of tractors, machinery and tools, the energy consumption of the fuel, and the energy consumption of the labor. The respective components of accumulated production energy consumption were calculated following the formulae: (E_{mat}, E_{tm}, E_{ON}, E_l).

Energy consumption of materials involved in production:

$$E_{mat} = E_s + E_f + E_{pch}, \tag{2}$$

where, $E_s = M_s * I_s$—energy contained in the seeds of maize, [$MJ \cdot ha^{-1}$], M_s—seed weight, [$kg \cdot ha^{-1}$], I_s—unit energy consumption index of maize seeds, [$MJ \cdot kg^{-1}$], E_f—energy contained in fertilizers, [$MJ \cdot ha^{-1}$],

$$E_f = E_{nf} + E_{mf}, \tag{3}$$

where, E_{nf}—energy contained in natural fertilizers, [MJ·ha^{-1}],

$$E_{nf} = E_{nfm} + E_{nfs}, \tag{4}$$

where:

$E_{nfm} = M_{nfm} * I_{nfm}$—energy contained in manure, [MJ·ha^{-1}],
M_{nfm}—manure mass, [kg·ha^{-1}],
I_{nfm}—unit manure energy consumption index, [MJ·kg^{-1}],
$E_{nfs} = M_{nfs} * I_{nfs}$—the energy contained in the slurry, [MJ·ha^{-1}],
M_{nfs}—slurry mass, [kg·ha^{-1}],
I_{nfs}—unit energy consumption index of slurry, [MJ·kg^{-1}],
E_{mf}—energy contained in mineral fertilizers, [MJ·ha^{-1}],

$$E_{mf} = E_{mfN} + E_{mfP} + E_{mfK} + E_{mfCa}, \tag{5}$$

where:

EmfN = MmfN ∗ ImfN—energy contained in nitrogen fertilizers, [MJ·ha^{-1}],
MmfN—mass of nitrogen fertilizer, [kg·ha^{-1}],
ImfN—unit energy consumption index of nitrogen fertilizers, [MJ·kg^{-1}],
EmfP = MmfP ∗ ImfP—energy contained in phosphorus fertilizers, [MJ·ha^{-1}],
MmfP—mass of phosphorus fertilizer, [kg·ha^{-1}],
I_{mfP}—unit energy consumption index of phosphorus fertilizers, [MJ·kg^{-1}],
$E_{mfK} = M_{mfK} * I_{mfK}$—energy contained in potash fertilizers, [MJ·ha^{-1}],
M_{mfK}—mass of potash fertilizer, [kg·ha^{-1}],
I_{mfK}—unit energy consumption index of potash fertilizers, [MJ·kg^{-1}],
$E_{mfCa} = M_{mfCa} * I_{mfCa}$—energy contained in calcium fertilizers, [MJ·ha^{-1}],
M_{mfCa}—mass of calcium fertilizer, [kg·ha^{-1}],
I_{mfCa}—unit energy consumption index of calcium fertilizers, [MJ·kg^{-1}],
$E_{pch} = M_{pch} * I_{pch}$—energy contained in plant protection chemicals, [MJ·ha^{-1}],
M_{pch}—mass of plant protection chemicals, [kg·ha−1],
I_{pch}—unit energy consumption index of plant protection chemicals, [MJ·kg^{-1}],

Energy consumption of using tractors and machines was calculated according to the formula:

$$E_{tm} = E_t + E_m, \tag{6}$$

where, E_t—energy consumption of tractors, [MJ·ha^{-1}], E_m—energy consumption of the machine/s, [MJ·ha^{-1}].

$$E_t = \frac{M_t * I_t + M_{sp} * I_{sp}}{I_{pet} * I_{oe}}, \tag{7}$$

where:

M_t—mass of the tractor, [kg],
I_t—unit tractor energy consumption index, [MJ·kg^{-1}],
M_{sp}—mass of worn spare parts on the tractor, [kg],
I_{sp}—unit index of energy consumption of spare parts, [MJ·kg^{-1}],
I_{pet}—exploitation potential (standard number of hours of operation of the tractor during its use, [h]
I_{oe}—operational efficiency of the machine when performing a given procedure, [ha·h^{-1}].

$$E_m = \frac{M_m * I_m + M_{sp} * I_{sp}}{I_{pem} * I_{oe}}, \tag{8}$$

where:

M_m—machine weight, [kg],
I_m—unit energy consumption index of the machine, [MJ·kg^{-1}],
M_{sp}—mass of used spare parts in the machine, [kg],
I_{pem}—exploitation potential (standard number of hours of operation of the machine during its use, [h]

Energy intensity brought in the form of human labor:

$$E_l = \frac{N_t * I_{to}}{I_{oe}}, \tag{9}$$

where, N_t—number of employed tractor drivers, machine operators, I_{to}—unit index of energy consumption of work by tractor driver, machine operator, [MJ·rbh^{-1}],

Energy consumption of used fuel:

$$E_{ON} = Z_{ON} \cdot I_{ON}, \tag{10}$$

where, C_{ON}—fuel (diesel) consumption of tractors and self-propelled machines, [dm3·ha^{-1}], I_{ON}—unit fuel energy consumption index, [MJ·kg^{-1}].

Formulas (1)–(10) include unitary indicators of energy consumption, assuming different values reported by respective authors, which is related to the changes in the production methods, living standards, etc. To calculate the energy inputs related to direct energy carriers, mineral fertilizers, agrochemicals, the application of tractors, machinery, and human labor, the accumulated energy consumption indicators for respective energy resources were used (Table 4) [5,10,59–61].

Table 4. Unitary energy consumption indicators.

Indicator	Symbol	Unit of Measure	Value
	Investment measures		
Tractors	I_t	MJ·kg^{-1}	125
Machines	I_m	MJ·kg^{-1}	110
Tractor tools	I_n	MJ·kg^{-1}	100
Spare parts and repair materials	I_{sp}	MJ·kg^{-1}	85
	Human labour		
Tractor drivers, machine operators	I_{to}	MJ·rbh^{-1}	80
	Materials		
Manure	I_{nfm}	MJ·kg^{-1}	0.3
Slurry	I_{nfs}	MJ·kg^{-1}	0.2
Nitrogen fertilizers	I_{mfN}	MJ·kg^{-1} N	77
Phosphorus fertilizers	I_{mfP}	MJ·kg^{-1} P_2O_5	15
Potash fertilizers	I_{mfK}	MJ·kg^{-1} K_2O	10
Calcium fertilizers	I_{mfCa}	MJ·kg^{-1} CaO	6
Plant protection chemicals	I_{pch}	MJ·kg^{-1} SA	300
Maize seeds	I_s	MJ·kg^{-1}	9
	Direct energy carrier		
Diesel	I_{ON}	MJ·kg^{-1}	48
	Agricultural products		
Silage maize	I_{maize}	MJ·kg^{-1}	0.8

Source: own elaboration based on [5,30,60–62].

The unitary energy consumption indicators used for the calculations express the energy equivalent of the unit of given means of production engaged in the production for a given silage maize cultivation technology, e.g., 1 kg of tractor or machinery, 1 kg of the raw materials used, 1 dm3 of fuel and 1 man-hour of human labor.

3.3. Silage Maize Production Energy Efficiency

Energy efficiency of the production of specific yield must be considered a ratio of the energy value of the product to the amount of energy consumed for the production. The energy efficiency index value was calculated following the dependence provided by Harasim [63], Kuś [64] and expressed as a dimensionless coefficient:

$$Ep = Ev/Epro, \quad (11)$$

where, E_p—energy efficiency index of silage maize, E_v—energy value of the maize yield per 1 ha, [MJ·ha^{-1}], E_{pro}—the sum of energy inputs incurred on the silage maize production, [MJ·ha^{-1}].

Using the unitary energy index for silage maize, 0.8 MJ·kg^{-1} [29], the value of the energy of the maize yield was calculated from the dependence:

$$Ev = I_{maize} \cdot Y_m, \quad (12)$$

where, I_{maize}—unit energy index maize silage, [MJ·kg^{-1}], Y_m—maize yield for silage, [kg·ha^{-1}].

The estimates of the energy consumption for the production of respective crops, including silage maize, are applied to determine the energy consumption of respective kinds of agricultural biomass for energy use. The methodology for investigating the energy consumption of plant production, silage maize, is applied to study the outcomes and energy efficiency of agricultural material for human consumption or for energy purposes.

4. Results

4.1. Accumulated Energy

One of the elements affecting the energy consumption of the production process is the energy inputs resulting from the consumption of traditional energy carriers (ON) in the technologies applied. For that group of energy carriers and for the cultivation technologies analyzed and investigated, the diesel oil was considered.

The accumulated energy consumption of the energy carriers in a form of diesel oil for the technologies studied varied. In extreme cases the differences were more than double. The data provided in Figure 4 show that the accumulated energy consumption of energy carriers ranged from 4684.11 (technology 7) to 17,162.61 MJ·ha^{-1} (technology 10). The average value of accumulated energy consumption of the energy carriers for the silage maize cultivation technologies was 10,561.90 MJ·ha^{-1}.

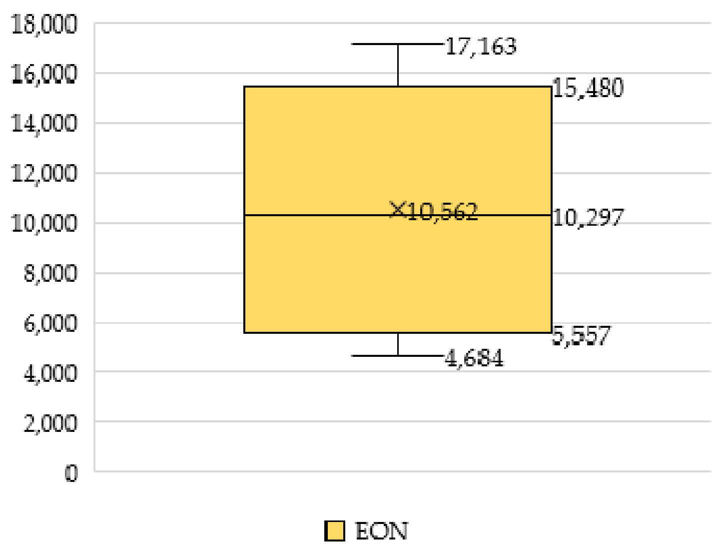

Figure 4. Total energy for the diesel oil consumed [MJ·ha^{-1}]. Source: own study.

The energy consumption for the cultivation technology is also affected by the accumulated energy related to the use of tractors, machinery, and tools for silage maize production (Figure 5). The calculations show that the share of the input of energy accumulated in tractors, machinery, and tools in the total accumulated energy ranged from 524.26 MJ·ha^{-1}, which accounted for 1% (technology 1), to 12,196.21 MJ·ha^{-1}, which accounted for 23.4% (technology 5). The mean value for the calculated accumulated energy consumption in tractors, machinery, and tools was 3886.28 MJ·ha^{-1}. The share of energy generated by human labor is shown in Figure 6.

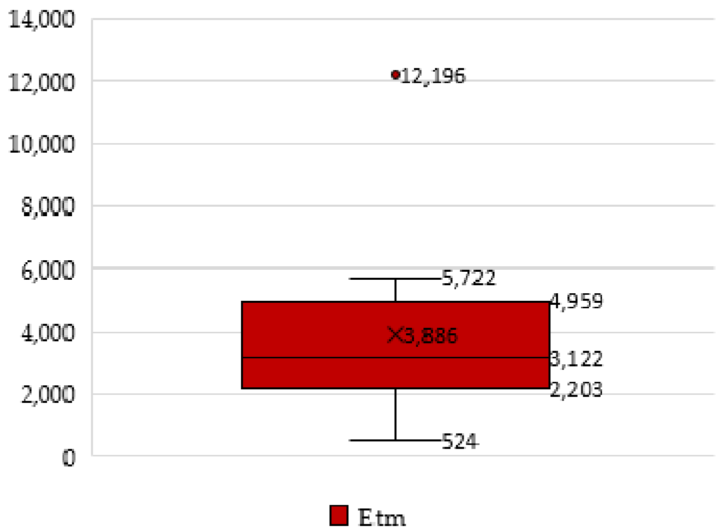

Figure 5. Total energy accumulated in the tractors, machines and tools used [MJ·ha^{-1}]. Source: own study.

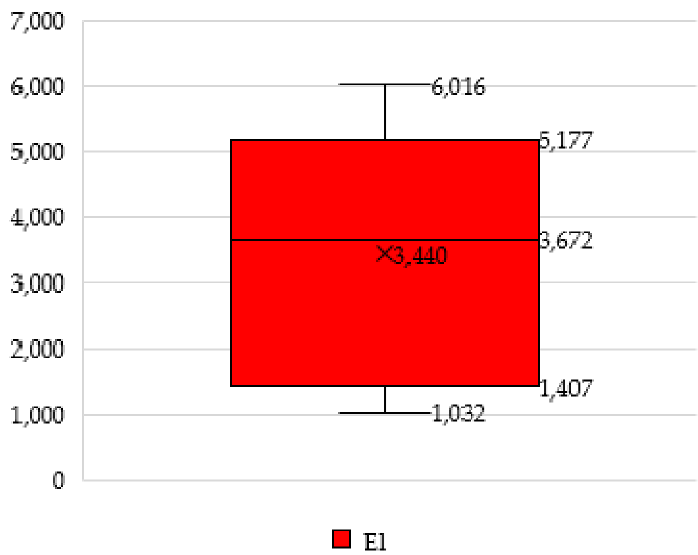

Figure 6. Amount of energy generated by human labor [MJ·ha^{-1}]. Source: own study.

As for the silage maize cultivation technologies investigated, the energy input considered was the consumption of consumables and raw materials. The average value of the energy consumption accumulated in the consumables for the technologies analyzed was 21,051.22 MJ·ha^{-1}. The share of the input of energy accumulated in the consumables in the total accumulated energy ranged from 3924.32 MJ·ha^{-1}, which accounted for 32.1% (technology 13), to 31,845.65 MJ·ha^{-1}, which accounted for 63.0% (technology 1) (Figure 7).

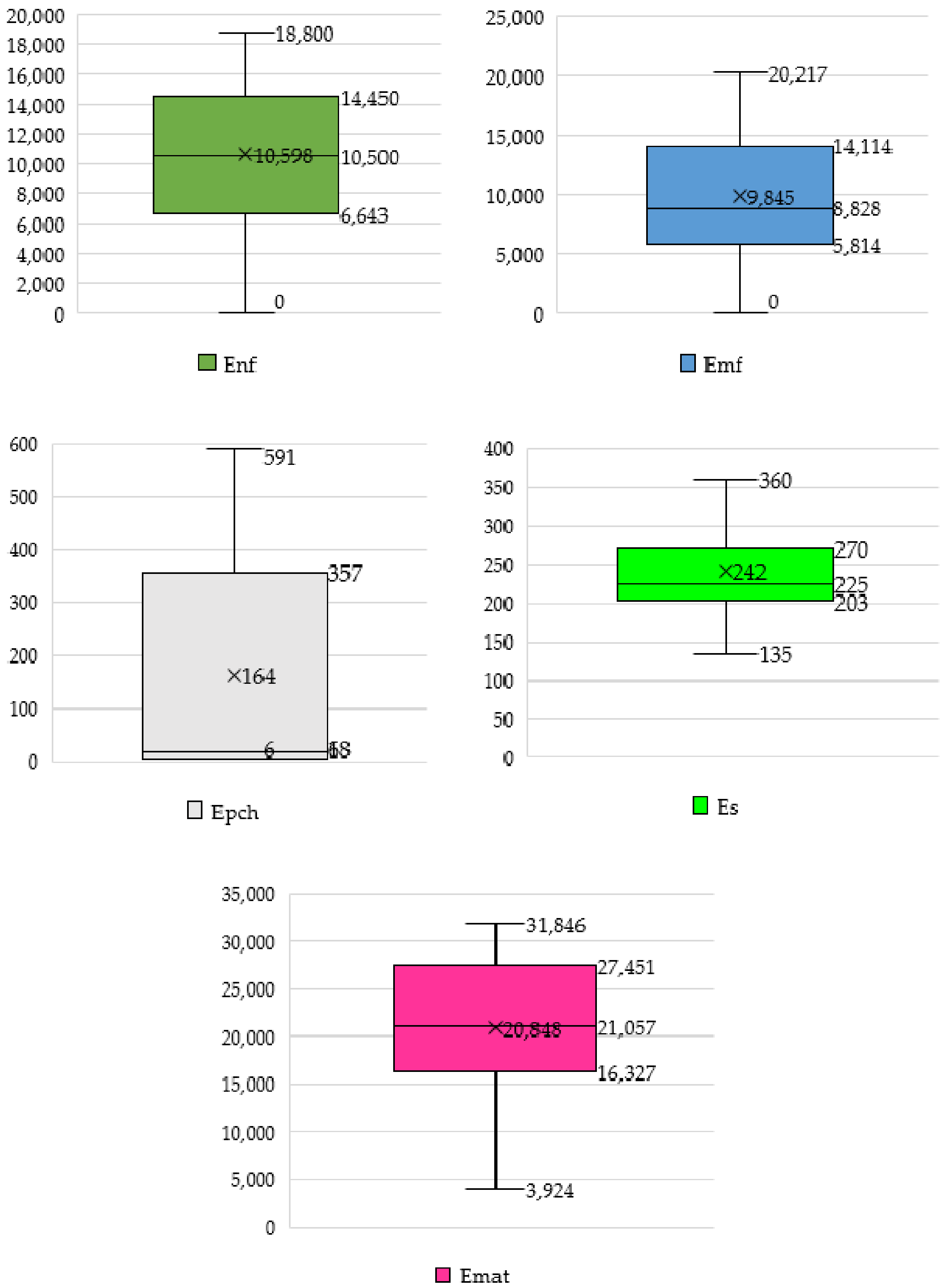

Figure 7. Total energy accumulated in the natural and mineral fertilizers, plant protection products, and seeds used [MJ·ha^{-1}]. Source: own study.

4.2. Energy Inputs Structure

The structure of the energy consumption accumulated for technologies was calculated for respective energy inputs, namely the energy carriers, inputs of labor, the consumables, and raw materials as well as tractors, machinery, and tools. Figure 8 presents the share of accumulated material—energy inputs for the silage maize cultivation technologies from four energy inputs: in tractors, machinery, and tools, means of transport, as well as in the spare parts and materials used for the repairs of that equipment, the direct energy carrier, namely the diesel oil, the consumables, and raw materials used for production and the human labor inputs.

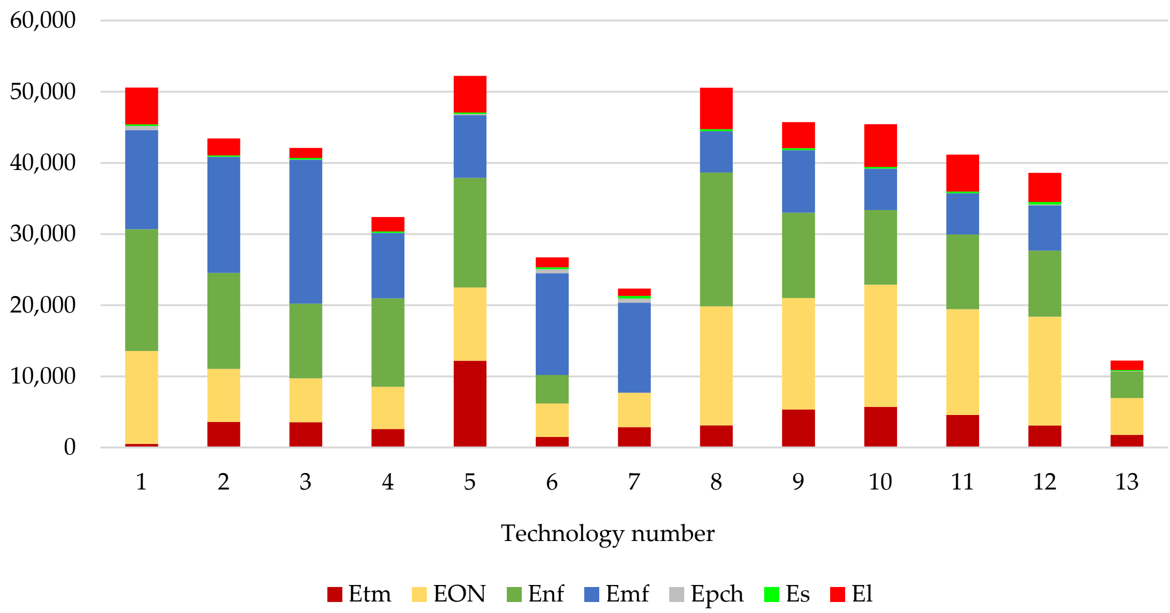

Figure 8. Energy intensity accumulated in the technologies of maize silage from individual energy inputs. [MJ·ha^{-1}]. Source: own study.

Of all the energy inputs analyzed, the greatest share in the total accumulated energy consumption was recorded for the consumables and raw materials; from 32.1% for technology 13 to 73.5% for technology 3. On average the share of the energy accumulated in the consumables and raw materials accounted for 53.7%. A lower share in the total energy consumption was recorded for the energy inputs related to the use of diesel oil for agrotechnical practices and jobs in the production chain. The values ranged from 14.6% (technology 3) to 42.2% (technology 13). The mean share of energy accumulated in the energy carriers accounted for 27.5%. Another element affecting the total production energy consumption was the energy accumulated in tractors, machinery, and tools. The average share of inputs from that input accounted for 10.2%. As for the technologies analyzed, the energy consumption values for tractors, machinery, and tools ranged from 1.0% (technology 1) to 23.4% (technology 5). The lowest share in the total accumulated energy consumption for production was the energy accumulated in human labor. The share of inputs from that energy input ranged from 3.4% (technology 3) to 13.2% (technology 10), and the mean value accounted for 8.6%. Table A1 in the Appendix A provides the results of the calculations of the energy accumulated for all the inputs of energy for each silage maize technology studied. The percentage share of accumulated energy for each of the inputs for the technologies researched has also been given.

4.3. Energy Efficiency

Table 5 demonstrates the calculated index of energy efficiency calculated for 13 silage maize cultivation technologies. The values range from 0.95 (technology 3) to 2.94 (technology 13). As for 11 out of 13 silage maize-growing technologies, the index value was higher than 1. It means that for the biomass produced the value of the accumulated energy was higher than the energy in the energy inputs made.

Table 5. Energy expenditure in means of production, energy accumulated in yield, and energy efficiency index.

Technology Number	Accumulated Energy			E_p
	E_{pro}		E_v	
	$[MJ \cdot ha^{-1}]$	%	$[MJ \cdot ha^{-1}]$	
1	50,587.01	100	57,408.00	1.13
2	43,436.57	100	48,000.00	1.11
3	42,116.45	100	40,000.00	0.95
4	32,400.24	100	44,000.00	1,36
5	52,229.49	100	51,696.00	0.99
6	26,724.37	100	64,000.00	2.39
7	22,338.06	100	40,000.00	1.79
8	50,567.99	100	56,000.00	1.11
9	45,736.91	100	53,600.00	1.17
10	45,440.50	100	60,000.00	1.32
11	41,161.42	100	60,000.00	1.46
12	38,593.77	100	40,000.00	1.04
13	12,233.01	100	36,000.00	2.94

Source: own study.

The most favorable technological variant in terms of energy efficiency was variant 13 for which, assuming as the reference 100% to be the mean value of the inputs of energy accumulated in the consumables and raw materials (20,847.75 MJ·ha^{-1}); the energy accumulated in that input was 81.2% lower than the average value, which had the greatest effect on the result despite a considerably low yield (45 t·ha^{-1}). Assuming the mean value of the inputs of energy accumulated in tractors, machinery, and tools for the technologies to account for 100% (3886.28 MJ·ha^{-1}), for technology 13 those inputs were 53.6% lower than the average. The analysis of the human labor inputs made for production demonstrated that, as for technology 13, they are 61% lower than the mean for the technologies investigated. As compared with the mean value of the inputs of energy accumulated in direct sources of energy; diesel oil (10,561.90 MJ·ha^{-1}, assumed as 100%) for the technologies under study the inputs of the accumulated energy from that input in technology 13 were 51.1% lower than the mean value.

For two plantations of all those investigated, the energy efficiency index value was below 1, which means that the technological solutions applied for the crops marked 3 and 5 showed a lack of energy efficiency and the inputs of accumulated energy used to produce 1 biomass yield unit were higher than the energy accumulated in the yield, which was an unjustifiable solution in terms of energy. The greatest impact on the energy efficiency calculation results, 0.99 for technology 5, was recorded for the energy accumulated in tractors, machinery and tools, and for technology 3 (0.95), the inputs of energy accumulated in the consumables and raw materials.

5. Discussion and Conclusions

According to the union market preferences like grants and subsidies for agricultural production (materials, services, and loans) the studies in the field of energy efficiency have huge importance. Plant production, including silage maize, requires performing many agrotechnical practices. Currently there are undergoing analyses about the possibility of sustainability development use and the reduction of energy inputs to reduce the negative impact on the environment, water, soil, air. It can be afforded by the reduction of the number of treatments performed in order to, among others, replacing the conventional tillage system with simplified or direct sowing [25,65]. The tillage system and the resulting material and energy inputs, the frequency of jobs, the dates of agrotechnical practices, the harvest at the optimum date with a minimum level of losses while performing the jobs are the key factors of production energy efficiency [66].

The plant production energy efficiency has been researched by many authors who referred the index to single agrotechnical practices [67,68], tillage systems [69,70], the entire technologies and agricultural products [71–74], and to elements of crop rotation [67,70,75].

As for the research of silage maize production technologies in the structure of energy inputs made for production, it was found that the highest share is recorded for the inputs of energy accumulated in the consumables and raw materials; 53.7% on average, and for the energy input the highest share is noted for fertilizers (98% on average, assuming 100% mean energy accumulated in consumables and raw materials). Gorzelany et al. [76] and Budzyński et al. [74] also claim that the highest share in the structure of the inputs of energy made for producing silage maize is accounted for the consumables and raw materials, 56%, respectively, and, depending on the technology traditional 76.5%, including fertilizers 71.5%, integrated, including fertilizers—63.8%. Similarly, as provided in the results of this research, the lowest share was found for the inputs of energy in a form of human labor, depending on the technology, 0.6 and 0.9%. The analysis of the results of the research of the technologies covered by these considerations also demonstrates the lowest share of energy of the human labor in the structure of inputs, on average 8.6%. It can be slightly higher for the results reported by the above authors as they did not consider the operation time of the tractors and machinery, and the time of driving to the field. In those analyses the time was factored in and considered essential in terms of performance of the sets of machinery and tools as well as fuel consumption. The inputs of accumulated energy from all the inputs for the technologies studied ranged from 12,233.01 to 52,229.49 MJ·ha^{-1}, respectively for technologies 3 and 5; 38,735.83 MJ·ha^{-1} on average. Szempliński and Dubis [77] generated 22,000–24,000 MJ·ha^{-1} of the energy inputs made for silage maize production technologies, Budzyński et al. [74]—23,900—18,700 MJ·ha^{-1} depending on the input intensity, Gorzelany et al. [76] 24,305 MJ·ha^{-1}, and considering the energy produced in the yield—37,800 MJ·ha^{-1}; the energy efficiency index was 1.5. In the present study the mean result of energy efficiency for the silage maize production technologies was 1.44, the minimum value—1.04 (disregarding the technologies with no such efficiency), the maximum value—2.94. Wielogórska et al. [78] reported on the research performed to evaluate the silage maize-growing technologies on the farms with the agricultural land acreage of at least 5 ha, show that the mean energy inputs made for cultivation were 22,200 MJ·ha^{-1}, and the technologies investigated recorded a high energy consumption index which was the crops mean of 3.2.

The research performed for 13 technologies for the plantation acreage from 2 to 13 has shown that the most favorable technology solution in terms of energy efficiency was variant 13. With the results in mind, it can be claimed that a relatively low natural fertilization and a lack of mineral fertilization decreased the maize silage production energy consumption (12,233.01 MJ·ha^{-1}) enough for, despite the lowest yield for all the technologies, the highest value of the energy efficiency. Assuming that 100% is the mean value of the energy accumulated in the consumables and raw materials for those technologies (20,847.75 MJ·ha^{-1}) in variant 13 the energy accumulated from that input was 81.2% lower than the mean value, which significantly affected the silage maize production energy efficiency index value. The energy accumulated in the yield for that technology was 28.1% lower than the mean value (50,054.15 MJ·ha^{-1}). As for that technology, the value of the energy efficiency index was 182% higher than the value for the technology least favorable in terms of energy, however, with the index value above 0 (1.04 technology 12).

For two plantations of all those investigated, the energy efficiency index value was lower than 1 (0.95 and 0.99). It means that the technological solutions applied in the variants marked 3 and 5, respectively, recorded a lack of energy efficiency, the accumulated energy inputs made to produce a biomass yield unit were higher than the energy accumulated in the yield. A higher yielding and the accumulated energy of the yield, 40,000.00 MJ·ha^{-1}

and 51,696.00 MJ·ha^{-1} (for technologies 3 and 5, respectively) did not compensate for the high energy inputs made for their accomplishment; 42,116.45 MJ·ha^{-1} for technology 3 and 52,229.49 MJ·ha^{-1} for technology 5. Those were the solutions which were unjustified in terms of energy.

When deciding on a given technological solution, it should be remembered that the increase in yields is not linear to the increase in energy inputs. Depending on this, there is a point to which increasing the level of expenditure is justified. Above the optimal value adjusted to e.g., type of crop, farm size, cultivation system, increasing energy inputs are not compensated in the yield.

In agricultural practice, due to a decrease in the inputs and a negative impact on the environment, various production technology modification methods, also for plant production, for simplified tillage systems and limiting the inputs are being searched for [79–81]. The energy calculation should be an essential element for the assessment of plant production, which is frequently limited to economic and production criteria [70,74].

To recapitulate, one can state that, in terms of energy efficiency, growing maize is justifiable and it can trigger energy benefits. The main factors dividing the cultivation technologies and harvesting maize for silage in typical Polish farm are size of plantation, diversity of crops (according to soil and climatic conditions), the level of farmer education, technical procedure and knowledge, machine park and machine services availability, possibility of products managing (using and demanding), types of activities in the adjacent areas, preferences and involvement of production units, and possibility of usage in energy production e.g., in biogas plants. The development of agricultural biogas plants contributes to the new jobs opportunities in rural areas, which enables the diversification of farmers income sources. According to KOWR (31 August 2017), there are nine agricultural biogas plants registered in the Podlaskie voivodeship. The adequately selected silage maize production technologies make it a very attractive crop in terms of energy, which becomes of special importance while facing the need of using the energy from renewable resources. The analyses covered the maize production technology variants: a field production stage, through harvest to the preparation of raw material for ensilaging, and placing a heap. The energy efficiency of a further use will depend on the processing technology applied in the biogas plant, which will be a continuation of the previous considerations and support the research results obtained at this stage. Other limitations resulting from the production of bioenergy from biomass should also be considered. The intensive cultivation of certain crops requires large areas of cultivation because of their future energy potential (so-called energy crops like maize). This is related to the acquisition of a significant amount of the plant and may be associated with the excessive use of fertilizers and other substances polluting the soil and water, and the reduction of areas for food production [82].

According to the EIA (Energy Information Administration) report from 2015, by the year of 2040 world energy consumption will increase by 56%, world energy consumption will increase by 56%, which will lead to an increase in the world CO_2 emissions up to 46% [82]. According to above, the estimation of GHG emissions released into the atmosphere is an important issue, which is planned as a continuation of the present research.

Moreover, in the literature there are analyzes of the relationship between the prices of energy raw materials and the prices of grains and oils [83]. In connection with this, an interesting research issue will also be the analysis of the relationship between the prices of maize and the prices of energy resources.

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Appendix A

Table A1. Value of accumulated energy consumption and the percentage share of accumulated energy in individual energy inputs for the technologies studied.

Technology Number	Accumulated Energy									
	E_{tm}		E_{ON}		E_{mat}		E_l		E_{pro}	
	$MJ·ha^{-1}$	%	$MJ·ha^{-1}$	%	$MJ·ha^{-1}$	%	$MJ·ha^{-1}$	%	$MJ·ha^{-1}$	%
1	524.26	1.0	13,042.99	25.8	31,845.65	63.0	5174.12	10.2	50,587.01	100
2	3606.39	8.3	7443.88	17.1	30,006.30	69.1	2380.00	5.5	43,436.57	100
3	3563.23	8.5	6166.14	14.6	30,960.00	73.5	1427.08	3.4	42,116.45	100
4	2602.04	8.0	5948.59	18.4	21,814.11	67.3	2035.50	6.3	32,400.24	100
5	12,196.21	23.4	10,297.07	19,7	24,581,75	47.1	5154.46	9.9	52,229.49	100
6	1509.79	5.6	4684.11	17.5	19,143.80	71.6	1386.67	5.2	26,724.37	100
7	2862.77	12.8	4844.29	21.7	13,599.00	60.9	1032.00	4.6	22,338.06	100
8	3121.92	6.2	16,722.50	33.1	24,895.00	49.2	5828.57	11.5	50,567.99	100
9	5344.52	11.7	15,662.99	34.2	21,057.40	46.0	3672.00	8.0	45,736.91	100
10	5722.01	12.6	17,162.61	37.8	16,539.88	36.4	6016,00	13.2	45,440.50	100
11	4572.82	11.1	14,868.73	36.1	16,539.88	40.2	5180.00	12.6	41,161.42	100
12	3092.38	8.0	15,296.26	39.6	16,113.71	41.8	4091.43	10.6	38,593.77	100
13	1803.28	14.7	5164.60	42.2	3924.32	32.1	1340.81	11.0	12,233.01	100

Source: own study.

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