

## Article

# Life Cycle Energy Consumption and Carbon Dioxide Emissions of Agricultural Residue Feedstock for Bioenergy

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**Abstract:** The depletion of fossil fuels and climate change concerns are drivers for the development and expansion of bioenergy. Promoting biomass is vital to move civilization toward a low-carbon economy. To meet European Union targets, it is required to increase the use of agricultural residues (including straw) for power generation. Using agricultural residues without accounting for their energy consumed and carbon dioxide emissions distorts the energy and environmental balance, and their analysis is the purpose of this study. In this paper, a life cycle analysis method is applied. The allocation of carbon dioxide emissions and energy inputs in the crop production by allocating between a product (grain) and a byproduct (straw) is modeled. Selected crop yield and the residue-to-crop ratio impact on the above indicators are investigated. We reveal that straw formation can consume between 30% and 70% of the total energy inputs and, therefore, emits relative carbon dioxide emissions. For cereal crops, this energy can be up to 40% of the lower heating value of straw. Energy and environmental indicators of a straw return-to-field technology and straw power generation systems are examined.

**Keywords:** bioenergy; agricultural residues; power generation; energy; energy analysis



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## 1. Introduction

Since the Industrial Revolution, the world economy has developed on fossil fuel consumption [1]. Our modern civilization relies heavily on fossil fuels (their annual consumption is around 82% of the primary energy consumption) [2]. Their combustion emits greenhouse gasses are causing an increase in the average temperature in the atmosphere. However, extending a prosperous civilization requires energy consumption [3].

Climate changes are worse than expected earlier [4]. In 2017, human-induced warming exceeded 1 °C above the pre-industrial level. The Paris Agreement of 2015 was aimed to achieve a balance between anthropogenic emissions and the removals of these gasses. The above agreement supports efforts to limit the temperature increase to below 1.5 °C [5]. To meet this ambition, it is necessary to reduce carbon dioxide emissions from the burning of fossil fuels using large-scale renewable energy supply systems. This direction corresponds to the UN's Sustainable Development Goal 7: "Ensure access to affordable, reliable, sustainable and modern energy for all" [6].

A primary purpose of the UN climate policy is to hold the anthropogenic global warming to below 2 °C. The power generation sector emits at least 30% of the total greenhouse gas emissions [7]. In 2018, the European Commission put forward an initiative to achieve net-zero emissions by 2050 [8]. The Commission called for studying the sustainability of

biomass power supply systems. Use of agricultural residues is one of the solutions to this problem.

Bioeconomy strategies have been developed by a number of countries [9]. This concept is a spotlight of numerous researches [10]. Currently, the 100% renewable energy concept is accepted by a number of countries such as Sweden, Denmark, Bangladesh, Vietnam, Hawaii in the United States, etc. [11,12]. Hansen et al. [11] analyzed the status and perspective on 100% renewable energy systems.

Many countries have approved political phase-out decisions regarding nuclear and coal-fired plants [13–15]. An alternative to these energy resources is renewable energy biomass. This enables the expansion of renewable power generation.

Since 2009, bioenergy has been promoted by the European Union (EU) as a low-carbon source [16]. The EU strategy is aimed at increasing renewable energy consumption and the reduction in the greenhouse gas emissions [17,18]. Biomass consumption for heat and power generation is increasing [19]. Agricultural residues enable some of this growth [20].

Lehtveer and Fridahl applied a dynamic optimization model to analyze the role of biomass feedstock in the European power generation system in the context of emissions targets for 2050 [21].

The large-scale application of wind and solar power plants has resulted in a number of challenges such as power quality, power balance, flow, stability, etc. [22]. These technologies are variable in the short and long terms. In power supply systems, biomass-based power plants could be used to complement wind and solar power plants and to improve the power stability situation [23].

Agricultural residues are sources of bioenergy worldwide because of their renewability and carbon neutrality. They can be used to generate electricity (direct burning) [20,24–26], biogas production [27,28], for conversion to bioethanol [29], and to produce solid fuels [30]. The use of agricultural crop residues has environmental benefits compared with fossil fuels [31–34]. The use of straw as a source of bioenergy complies with the renewable energy directive of the EU for the period 2021–2030 [35]. Straw is a byproduct of cereal and other crops. Off-field straw could be converted into energy resources such as biogas, bioethanol, heat, and electricity. A detailed understanding of the straw production system is essential to the proper evaluation of energy and environmental indicators [36].

Life cycle energy consumption and carbon dioxide emissions are currently critical information for the development of appropriate energy policy [37,38]. Currently, greenhouse gas emissions are drawing significant attention [39,40]. The energy and environmental indicators of power generation are highly dependent on fuel production and its pathway. A life cycle analysis should cover all upstream stages: from crop cultivation (energy resource extraction) to use. Energy and environmental assessment considers all kind of energy resources such as fuels, electricity, and energy used to produce fertilizers, herbicides, other chemicals, and machinery [41,42].

Energy inputs and the corresponding carbon dioxide emissions for wood and wheat straw productions were studied for conditions in Canada [43]. In this report, the total carbon footprint for straw was calculated by the proportion of straw yield to overall biomass yield (grain and straw). Mishra et al. [44] used the proportional yield of wheat straw to determine the total energy inputs for the production of straw.

Nguyen et al. [45] considered the following system boundary: the straw is collected by machines (a roller baler, self-propelled balers, and self-propelled gathering machines). In this study, direct energy (diesel fuel consumed by machines) and indirect energy (manufacturing and maintenance of the machines) were taken into account. This method provides objective information from the moment the harvest begins. However, it does not consider the process of growing a crop.

Said et al. [46] analyzed a straw-to-energy chain. The chain comprised the following stages: straw collection, transportation, and energy generation. Energy inputs and carbon dioxide emissions were studied. The energy consumption included direct and indirect energy consumption associated with the straw collection and transportation [24,47].

They reported that the energy consumption of straw collection ranged between 1.73 and 2.52 MJ/kg [46]. Shang et al. [48] used the same methodology as Said et al. [46]. However, a product (grain) and a byproduct (straw) have different energy equivalents. This means that their formation needs different energy inputs and, therefore, the mass (yield) indicator does not provide an objective picture of the energy consumption for the production of straw and the carbon dioxide emissions.

In some research, the energy and greenhouse gas emissions analysis was based on organic feedstock transportation [49–51]. A number of researchers such as Migo-Sumagang et al. [52], Nguyen et al. [53], Shafie et al. [24], etc., used the following method: crop production costs are allocated between a product (grain) and a byproduct (straw) in terms of economic value. The allocation factor is applied in the crop production stage and calculated by the formula [52–55]

$$AF = \frac{Y_s \cdot Spr}{Y_s \cdot Spr + Y_g \cdot Gpr} \quad (1)$$

where  $Y_g$  is the yield of grain, kg/ha;  $Spr$  is the price of straw, EUR/kg;  $Y_s$  is the yield of straw, kg/ha;  $Gpr$  is the price of grain, EUR/kg.

Then the energy inputs and the greenhouse gas emissions in the total crop production are multiplied with the allocation factor of straw. There are three primary types of allocation: mass, energy, and economic [54]. Here, there are three methods used to find the embodied energy and greenhouse gas emissions of straw:

- taking into account only the collection and transportation of straw (no cultivation stage);
- the mass allocation (the proportion of straw yield to overall biomass yield);
- the economic allocation (the proportion of straw costs to the overall costs of a product and a byproduct).

In our opinion, for biomass-based power generation projects, the energy and environmental indicators must be analyzed. Therefore, the allocation should be performed by the use of energy allocation. However, this type of allocation has not been sufficiently studied.

The purpose of this study was to develop a systematic and effective method for evaluating the embodied energy and the greenhouse gas emissions in straw production that can be used as a scientific basis for future strategies and policy development. The objectives of this research were:

- to develop a mathematical model for finding the allocation of the total energy inputs and, therefore, the carbon dioxide emissions between grain and straw;
- to determine the energy inputs into the straw formation;
- to compare the mass and energy allocation indicators;
- to explore the impact of energy and the carbon dioxide emissions associated with straw formation on the power generation indicators such as energy-specific costs and specific carbon dioxide emissions;
- to compare energy and the carbon footprint indicators for different pathways of straw utilization: power generation and the substitution of mineral fertilizers.

This research is based on previous studies of alternative fuel markets [56–58] and agricultural feedstock availability analysis [59,60].

## 2. Materials and Methods

A systematic literature review was conducted in this study to gather required data from scientific sources. A number of relevant criteria were applied to analyze the information collected.

### 2.1. Embodied Energy

Energy requirements in agricultural production were divided into three groups: direct and indirect (two subgroups) (Figure 1). A direct energy flow included the energy of fuels

and the electricity that are used by machines. An indirect energy flow consisted of two subgroups. The first was the energy used in the production processes of fertilizers, herbicides, and other chemicals. The second subgroup was the energy used in the manufacturing processes of farm machinery.

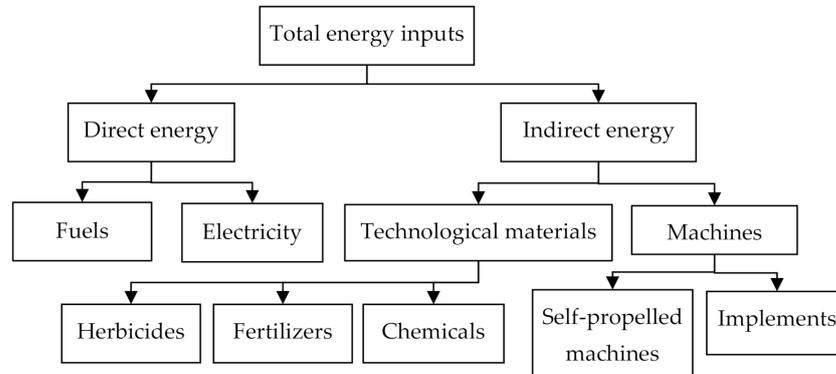


Figure 1. Energy expenditure of agricultural operations.

The direct energy is determined as:

$$DE = \sum_{i=1}^n (B_i \cdot EEf_i) + EEe \cdot W, \text{ MJ/ha}, \tag{2}$$

where  $B_i$  is the fuel consumption of the  $i^{\text{th}}$  type, kg/ha;  $EEf_i$  is the energy equivalent (embodied energy) of the  $i^{\text{th}}$  fuel, MJ/kg;  $W$  is the electricity consumption, kWh/ha;  $n$  is the number of fuels;  $EEe$  is the energy equivalent (embodied energy) of electricity, MJ/kWh.

The indirect energy of the first subgroup is equal to:

$$IDE_1 = \sum_{j=1}^m (M_j \cdot EE_j), \text{ MJ/ha}, \tag{3}$$

where  $M_j$  is the mass consumption of  $j^{\text{th}}$  chemical, kg/ha;  $EE_j$  is the energy equivalent of  $j^{\text{th}}$  chemical, MJ/kg;  $m$  is the number of chemicals.

The manufacturing energy requirements for farm machinery depend on a number of factors such as a certain machinery’s mass, use lifetime, etc., and can be computed by a formula:

$$IDE_2 = \sum_{k=1}^l \left( \frac{EEM_k \cdot MM_k}{ULT_k \cdot OFC_k} \right), \text{ MJ/ha}, \tag{4}$$

where  $EEM_k$  is the embodied energy of  $k^{\text{th}}$  machinery, MJ/kg;  $MM_k$  is the mass of  $k^{\text{th}}$  machinery, kg;  $ULT_k$  is the utilization lifetime of  $k^{\text{th}}$  machinery, h;  $OFC_k$  is the operation field capacity of  $k^{\text{th}}$  machinery, ha/h;  $l$  is the number of machinery.

The total energy inputs are:

$$TE_{input} = DE + IDE_1 + IDE_2, \text{ MJ/ha}. \tag{5}$$

The embodied energy (or energy equivalents) of main fuels, chemicals, and machinery are presented in Table 1. They are used to determine the indirect energy inputs.

**Table 1.** Embodied energy in the main inputs.

Input	Unit	Value	Reference
<b>Fuels:</b>			
Diesel fuel	MJ/kg	56.8	[61]
Petrol	MJ/kg	60.2	[61]
Natural gas	MJ/kg	54.6	[61]
<b>Electricity:</b>			
Coal power plant	MJ/MJ MJ/kWh *	3.14 11.30	[61]
Natural gas power plant	MJ/MJ MJ/kWh *	2.66 9.36	[61]
Nuclear power plant	MJ/MJ MJ/kWh *	3.26 11.74	[61]
Hydro power plant	MJ/MJ MJ/kWh *	1.05 3.78	[61]
Solar power plant	MJ/MJ MJ/kWh *	1.17 4.21	[61]
Wind power plant	MJ/MJ MJ/kWh *	1.05 3.78	[61]
<b>Fertilizers:</b>			
Nitrogen	MJ/kg	52.02–121.21	[61–64]
P <sub>2</sub> O <sub>5</sub>	MJ/kg	12.60–63.02	[61–64]
K <sub>2</sub> O	MJ/kg	6.70–16.77	[61–64]
<b>Manure:</b>			
Poultry manure	MJ/kg	0.30	[61]
Cattle manure	MJ/kg	16.1	[61]
pig	MJ/kg	19.4	[61]
layer	MJ/kg	11.9	[61]
broiler	MJ/kg	17.9	[61]
<b>Chemicals</b>			
Pesticides	MJ/L	447–820	[61]
Herbicides	MJ/L	454.20	[65]
Insecticides	MJ/L	184.20	[65]
Fungicides	MJ/L	97.10	[65]
<b>Machinery:</b>			
Tractor	MJ/kg	138	[61]
Implement	MJ/kg	69	[66]

\* calculated by authors.

The embodied energy of electricity can be presented in different units such as MJ/MJ or MJ/kWh. Consumers usually measure electricity in kWh. However, some sources of information express embodied energy in MJ/MJ. To simplify subsequent calculations, in this study, we converted MJ/MJ to MJ/kWh. For this conversion, we assumed that 1 kWh = 3.6 MJ.

## 2.2. Energy Output Flow

Energy output flow (EOF) of crop production is the energy generated by a product and a byproduct. For cereal crops, EOF is calculated as the sum of the calorific values of grains and straw:

$$EOF = Y_g \cdot LHV_g + Y_s \cdot LHV_s, \text{ MJ/ha}, \quad (6)$$

where  $LHV_g$  is the specific calorific value of grain, MJ/kg;  $LHV_s$  is the lower heating value of straw, MJ/kg.

The yield of straw is calculated based on the grain yield and a residue-to-crop ratio:

$$Y_s = Y_g \cdot RCR, \text{ kg/ha}, \quad (7)$$

where  $RCR$  is the residue-to-crop ratio of a certain crop.

### 2.3. Carbon Dioxide Emissions

Carbon dioxide emissions occur due to the combustion of fuels, well-to-tank emissions (extraction of raw material, refinery, transportation, etc.), the emissions associated with electricity generation (from fuel production to electricity generation, distribution, and transportation), and the production of machinery, fertilizers, and chemicals (Figure 2).

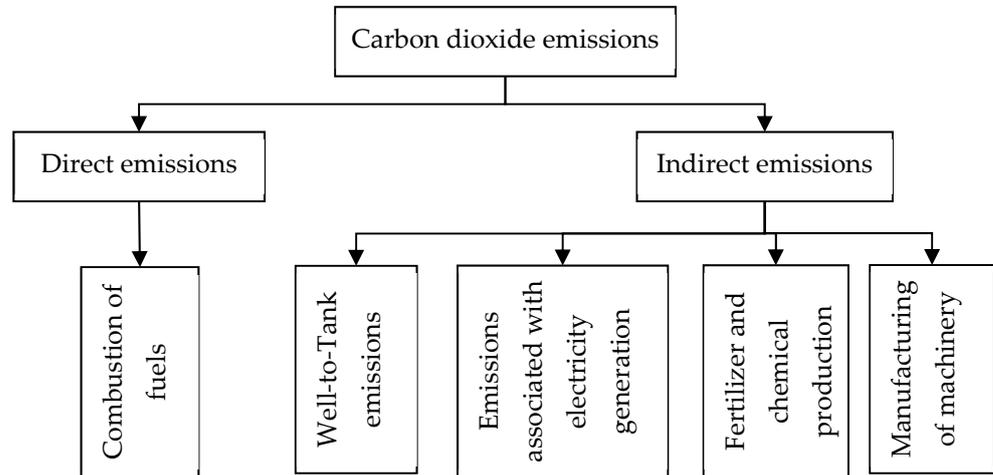


Figure 2. Carbon dioxide emissions.

The carbon emissions caused by fuels are formed by the following components: the fuel consumption per hectare, the carbon content in the vehicle fuel, and the well-to-tank (WTT) emissions of a certain fuel. For standard diesel fuel, WTT-based carbon dioxide emissions vary from 6.7 to 24 g CO<sub>2</sub>/MJ [67]. This corresponds to the following range: from 0.284 to 1.020 kg CO<sub>2</sub>/kg. Thereby, well-to-wheel (WTW) emissions caused by the use of diesel fuel is equal to:

$$WTW = \sum_{i=1}^n B_i \cdot \left( CC_i \cdot \frac{11}{3} + WTT_i \right), \text{ kg/ha}, \tag{8}$$

where  $CC_i$  is the carbon content in  $i^{th}$  type of fuel, kg/kg;  $WTT_i$  is the well-to-tank carbon dioxide emissions of  $i^{th}$  type of fuel, kg CO<sub>2</sub>/kg.

The carbon dioxide emissions from electricity generation are determined by the following formula [68,69]:

$$CDEG = W \cdot EFe, \text{ kg CO}_2/\text{ha}, \tag{9}$$

where  $EFe$  is the emission factor, kg CO<sub>2</sub>/kWh.

During the chemical (fertilizer, pesticides, etc.) production process, carbon dioxide is emitted. Its quantity is computed by:

$$CDF = \sum_{i=1}^n (MF_i \cdot CDE_i), \text{ kg CO}_2/\text{ha}, \tag{10}$$

where  $MF_i$  is the consumption of  $i^{th}$  chemical, kg/ha;  $CDE_i$  is the carbon dioxide emission during the production process of  $i^{th}$  chemical, kg CO<sub>2</sub>/kg.

The manufacturing and assembly of agricultural machinery result in carbon dioxide emissions. Their specific values are equal to:

$$CDM = \sum_{k=1}^l \left( \frac{CDM_k \cdot MM_k}{ULT_k \cdot OFC_k} \right), \text{ kg CO}_2/\text{ha}, \tag{11}$$

where  $CDM_k$  is the specific carbon dioxide emission during the manufacturing and assembly of the  $k^{th}$  machinery, kg CO<sub>2</sub>/kg.

The total carbon dioxide emissions are:

$$CDET = WTW + CDEG + CDF + CDM, \text{ kg CO}_2/\text{ha}. \quad (12)$$

### 3. Results

#### 3.1. Allocation of Energy Inputs between Grains and Straw

The input energy creates the harvest, including grains and straw. Therefore, the energy must be allocated between grain and straw formation. We suggest carrying out this division, considering the energy value of each part of the harvest obtained. The total energy output is formed by the product (grain) and a by-product (straw):

$$E_{out} = EG_{out} + ES_{out}, \text{ MJ/ha}, \quad (13)$$

where  $EG_{out}$  is the energy content of grain, MJ/ha;  $ES_{out}$  is the energy content of straw, MJ/ha.

The straw formation requires the following amount of energy:

$$ESF = \frac{ES_{out}}{E_{out}} \cdot TE_{input}, \text{ MJ/ha}. \quad (14)$$

The share of energy, which is used for the straw formation, is computed as

$$SR = \frac{ES_{out}}{ES_{out} + EG_{out}} = \frac{Y_g \cdot RCR \cdot LHV_s}{Y_g \cdot RCR \cdot LHV_s + Y_g \cdot LHV_g}. \quad (15)$$

After the transformation of Equation (15), we obtained the following expression:

$$SR = \frac{RCR \cdot LHV_s}{RCR \cdot LHV_s + LHV_g}, \quad (16)$$

or:

$$SR = \frac{RCR}{RCR + \frac{LHV_g}{LHV_s}}. \quad (17)$$

A residue-to-crop ratio is not constant, and it depends on the yield [70,71]:

$$RCR = a \cdot \exp(b \cdot Y_g), \quad (18)$$

where  $a$  and  $b$  are the parameters.

Scarlat et al. [71] suggested an exponential relationship between the residue-to-crop ratio and the crop yield. Parameters  $a$  and  $b$  were estimated on the basis of data published by researchers [71–73].

If we use Equation (18), then the share of energy is:

$$SR = \frac{a \cdot \exp(b \cdot Y_g)}{a \cdot \exp(b \cdot Y_g) + \frac{LHV_g}{LHV_s}}. \quad (19)$$

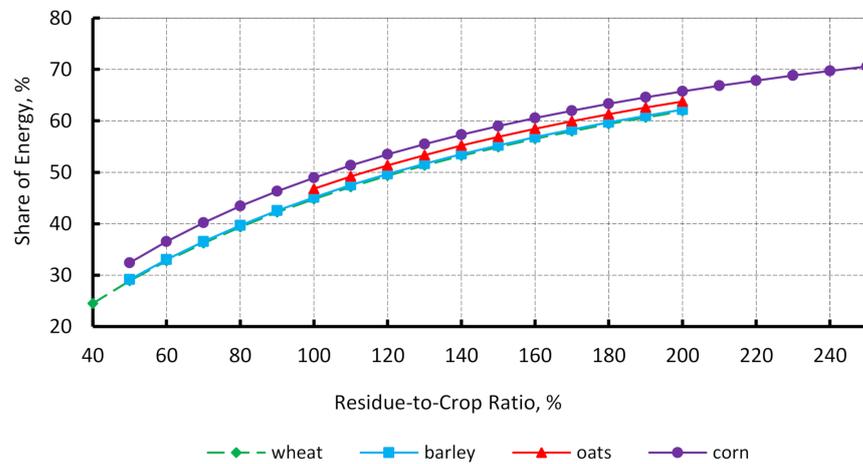
#### 3.2. Energy Input into Straw Formation

The data on the RCRs and the energy parameters per crop type are presented in Table 2 [70,71,74,75].

**Table 2.** Residue-to-crop ratios and energetic parameters of selected crops.

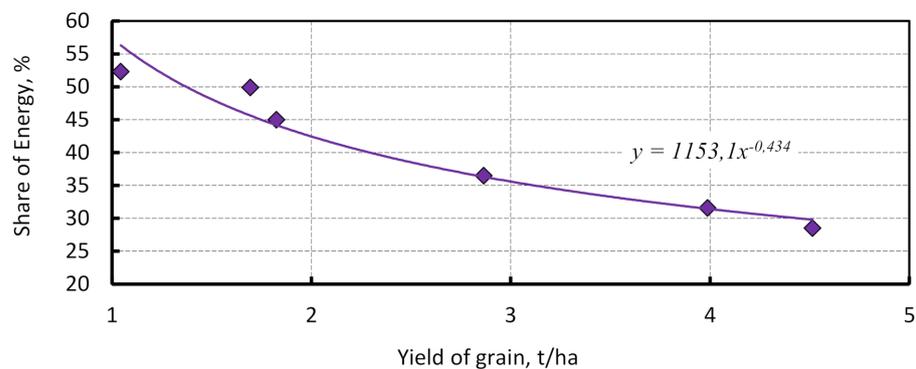
Crop	Residue-to-Crop Ratio	Lower Heating Value of Straw, MJ/kg	Calorific Value of Grain, MJ/kg
Rapeseed	1.1–1.7	27.7–29.0	14.7–19.1
Wheat	0.8–1.8	15.0–18.1	13.7–19.1
Rye	1.7–1.75	15.0–18.1	13.6–19.1
Oats	1.0–2.0	15.0–18.1	12.9–19.1
Barley	0.9–1.8	15.0–18.1	13.4–19.1
Corn	0.7–2.0	16.1	13.9–14.5
Sunflower	1.0–3.0	16.0	25.0

In this study, the residue-to-crop ratios and the shares of energy used for the straw formation are expressed in percent. The results of our calculations are shown in Figure 3. The shares of energy used for straw formation range from 24% to 70% of the total energy inputs.



**Figure 3.** The share of energy associated with straw formation.

The SR indicators for the actual data of wheat production reported in some articles are presented in Figure 4 [76–80]. The increase in yield results in the decrease in the SR.



**Figure 4.** Share of energy for wheat.

The impact of crop yield on the SR was studied using Equation (18). RCR functions for wheat, barley, and corn were taken from the results found by Bentsen et al. [70]. Our calculations showed that the share of energy used for straw formation has a significant dependence on the yield and type of crop (Figure 5). Corn has a higher value than other cereal crops.

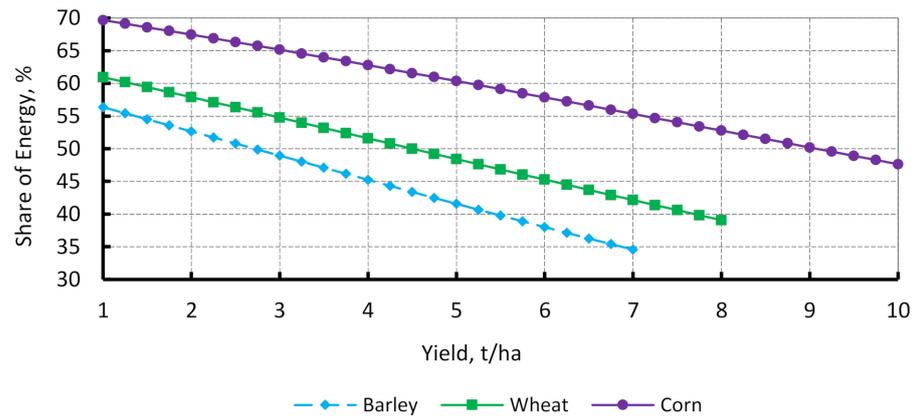


Figure 5. The share of energy associated with straw formation.

The energy consumption for straw formation and the energy consumption for straw collection were compared. Nguyen et al. [45] reported that the energy consumption for straw collection ranged from 0.37 to 0.588 MJ per kg of straw. Ou et al. [50] reported about 0.4256 MJ per kg of straw. However, if the energy consumption for straw formation is taken into account, the embodied energy ranges from 1.1 to 6.2 MJ/kg. Therefore, the energy consumption for straw formation may be up to 10-fold the energy consumption for straw collection, and it should be taken into account in an energy analysis of straw use.

### 3.3. Comparison of Mass and Energy Allocation Indicators

The mass allocation indicator is calculated by the following formula:

$$MA = \frac{RCR}{RCR + 1} \tag{20}$$

This expression resembles Equation (17), which is used to determine the energy allocation indicator. The only difference is that the energy allocation indicator takes into account lower heating values of grain and straw. Based on Figure 6, it is apparent that the mass allocation indicator can be considered as a special case of the energy allocation indicator.

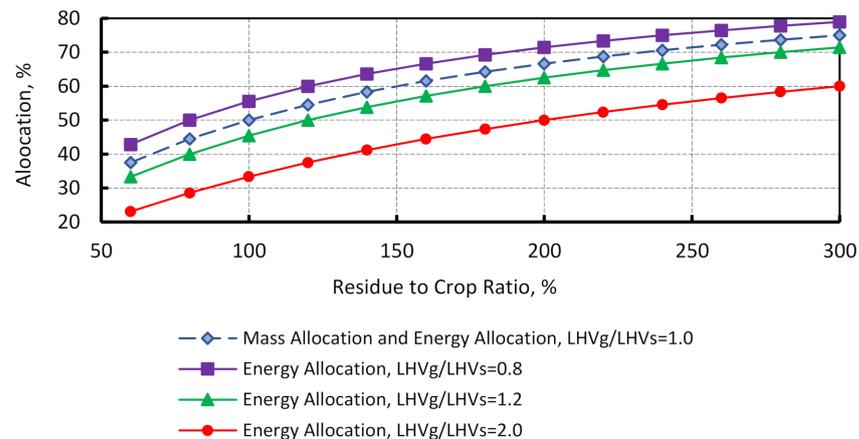


Figure 6. Comparison of mass and energy allocation indicators (share of energy for straw formation).

We took the derivative of Equation (17) with respect to the lower heating value of the grain-to-straw ratio and found the rate of change:

$$RC = 100 \cdot \frac{\partial(SR)}{\partial\left(\frac{LHV_g}{LHV_s}\right)} = 100 \cdot \frac{\partial\left(\frac{RCR}{RCR + \frac{LHV_g}{LHV_s}}\right)}{\partial\left(\frac{LHV_g}{LHV_s}\right)} = -100 \cdot \frac{RCR}{\left(RCR + \frac{LHV_g}{LHV_s}\right)^2} \quad (21)$$

The results of our calculations are presented in Figure 7. The shape of the graph (Figure 7) depicts that the increase in the lower heating value of the grain-to-straw ratio results in a decrease in the rate of change of the energy allocation indicator.

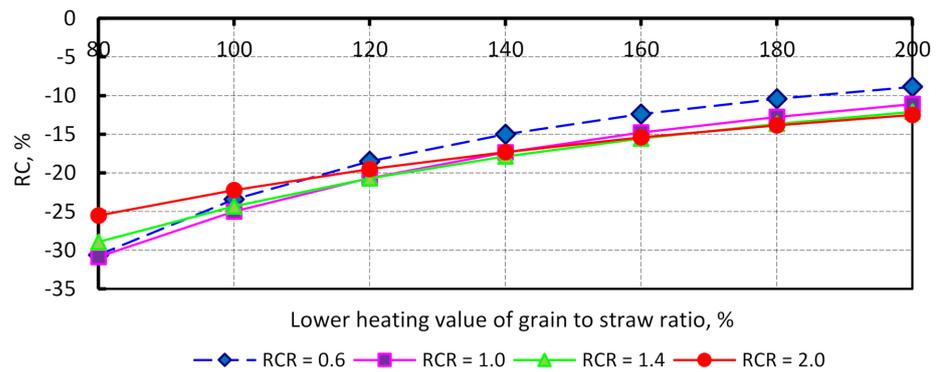


Figure 7. Derivative of energy allocation indicator.

### 3.4. Power Generation: Energy Specific Costs and Carbon Dioxide Emissions Associated with Straw Formation

The carbon dioxide emissions of straw-fired power generation can be expressed as:

$$CDE = \frac{3.6}{\eta_e \cdot LHV_s} \cdot EF_s, \text{ kg CO}_2/\text{kWh}, \quad (22)$$

where  $\eta_e$  is the efficiency of power generation;  $EF_s$  is the carbon dioxide emission factor associated with straw formation,  $\text{kg CO}_2/\text{kg}$ .

And the saving of carbon dioxide emissions compared with a fossil fuel power plant can be expressed as:

$$SCDE = EF_{cf} - \frac{3.6}{\eta_e \cdot LHV_s} \cdot EF_s, \text{ kg CO}_2/\text{kWh}, \quad (23)$$

where  $EF_{cf}$  is the carbon dioxide emissions factor (fossil fuel),  $\text{kg CO}_2/\text{kWh}$ .

The carbon dioxide emissions factor associated with straw formation was calculated for conventional wheat production technology used in Ukraine. The following initial data were used: the yield of grain—4110  $\text{kg}/\text{ha}$ ; the yield of straw—5138  $\text{kg}/\text{ha}$ ; the total carbon dioxide emissions—1747.9  $\text{kg CO}_2/\text{ha}$ ; the share of energy that is used for straw formation—0.5. Our calculations showed that the carbon dioxide emissions factor associated with straw formation is around 0.17  $\text{kg CO}_2/\text{kg}$ . It results in 0.146  $\text{kg}$  carbon dioxide emissions per  $\text{kWh}$  for a straw-fired power plant.

Energy specific costs ( $ESC$ ) are the energy-input-to-electricity-production ratio:

$$ESC = \frac{LHV_s + \Delta H}{W_s}, \text{ MJ}/\text{kWh}, \quad (24)$$

where  $\Delta H$  is the energy used for straw formation,  $\text{MJ}/\text{kg}$ ;  $W_s$  is the quantity of electricity generated by one kilogram of straw,  $\text{kWh}/\text{kg}$ .

One kilogram of straw generates:

$$W_s = \frac{\eta_e \cdot LHV_s}{3.6}, \text{ kWh/kg.} \tag{25}$$

Then, the required energy specific costs are:

$$ESC = \frac{3.6 \cdot (LHV_s + \Delta H)}{\eta_e \cdot LHV_s} = \frac{3.6}{\eta_e} \cdot \left[ 1 + \frac{\Delta H}{LHV_s} \right], \text{ MJ/kWh.} \tag{26}$$

Energy specific costs were calculated for the following conditions:

- The efficiency ranges from 10% to 40%.
- The relative energy used for straw formation ( $100 \Delta H/LHV_s$ , %) has two meanings: 0% (energy for straw formation is not taken into account) and 40% (maximum possible value for biomass direct-fired power plants).

Figure 8 presents the results of our computation. This figure depicts that the increase in the efficiency results in a decrease in the influence of the embodied energy of straw on the absolute energy specific costs.

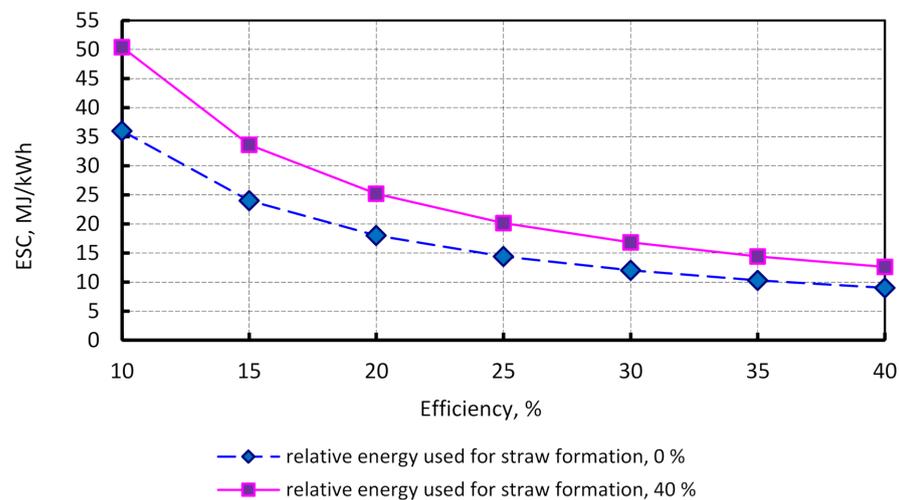


Figure 8. Energy specific costs.

### 3.5. Power Generation or Biofertilizer: Energy and Carbon Dioxide Footprint Comparison

There are some forms of straw use, such as straw-to-energy and straw return-to-field. Liu et al. [51] studied the benefits of straw return-to-field. Straw retained in arable lands can increase organic nitrogen, phosphates, and potassium, which enhance crop yield [81–83]. Researchers found a number of disadvantages of straw return-to-field technology, such as nitrous emissions, methane emissions, and the possible reduction in crop yield (in the case of high levels of straw retained) [84–88].

In this study, we evaluated the environmental and energy indicators of straw use as biofertilizers compared with power generation.

Crop residues can be used for power generation and use as fertilizers. The use of agricultural residues as a substitute for mineral fertilizers can reduce the energy consumption and carbon dioxide emissions of agricultural practice. That is why the comparison of different pathways for crop residues is of scientific and practical interest.

The use of crop residues as fertilizers saves the following amount of energy:

$$FES = \sum_{i=1}^n \left( \frac{NG_i \cdot EEq_i}{100} \right) - \Delta H, \text{ MJ/kg,} \tag{27}$$

where  $NG_i$  is the content of the  $i^{th}$  nutrient component in a crop residue, %;  $EEq_i$  is the energy equivalent of the  $i^{th}$  nutrient component, MJ/kg.

An organic fertilizer produced from crop residues can reduce carbon dioxide emissions caused by the production process of mineral fertilizers as such:

$$CDEFS = \sum_{i=1}^n \left( \frac{NG_i \cdot CDFP_i}{100} \right) - \frac{CDET \cdot SR}{Y_s}, \text{ kgCO}_2/\text{kg}, \tag{28}$$

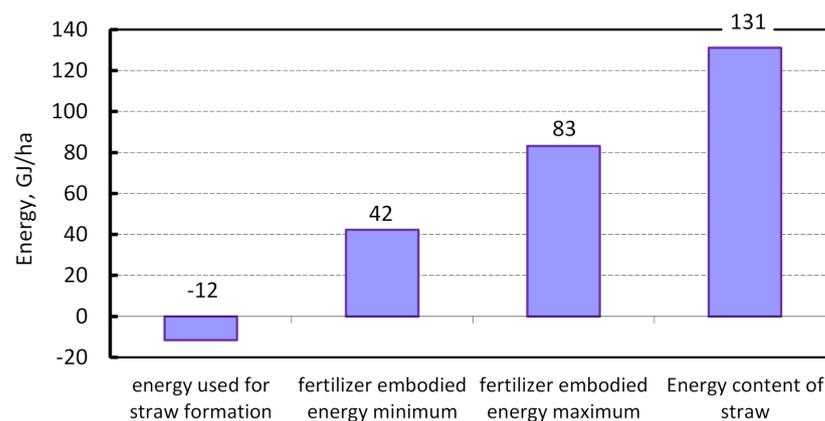
where  $CDFP_i$  is the carbon dioxide emissions caused by the production of the  $i^{th}$  nutrient component in a mineral fertilizer, kg CO<sub>2</sub>/kg.

The carbon dioxide emissions and energy used by the production process of mineral fertilizers are presented in Table 3 [62–64].

**Table 3.** Carbon dioxide emissions and energy used by production processes.

Fertilizer Product	Primary Component	Percentage (by Weight)	Primary Energy Consumption, MJ/kg (Primary Component)	Carbon Dioxide Emissions, g CO <sub>2</sub> /kg (Primary Component)
Ammonium nitrate	N	33.5	90.30–121.21	2298–7108
Urea	N	46	52.02–112.17	913–4018
Ammonia	N	82		1491–2637
Single superphosphate	P	21	61.90	–238–1051
Triple superphosphate	P	48	16.50–63.02	–416–1083
Potassium chloride	K	60	16.77	583

As an example, corn stover was considered. Corn stover has the following composition of nutrient components: nitrogen—5.95; phosphorus—0.56; potassium—7.91 g/kg [89]. In our study, we used the data reported by Kim et al. [90,91]. The energy used for straw formation is around 8.81% of the total energy potential of straw (Figure 9). The embodied energy of mineral fertilizers substituted by straw is at least four-fold compared with the energy used for straw formation. Therefore, the use of straw for energy generation is more energy-efficient.



**Figure 9.** Energy parameter of straw production and utilization.

Carbon dioxide emissions were analyzed too. The total carbon dioxide emissions of corn production are around 1895 kg CO<sub>2</sub>/ha. The energy associated with straw formation is 1048 kg CO<sub>2</sub>/ha of straw. Therefore, WTT is equal to 0.112 kg CO<sub>2</sub>/kg. In our calculation, the following emission factor (power generation) was assumed: average—0.578; minimum—0.146; maximum—1.593 kg CO<sub>2</sub>/kWh [90]. Our study revealed that the use of straw for power generation saves more carbon dioxide emissions compared with the straw return-to-field technology (Figure 10).

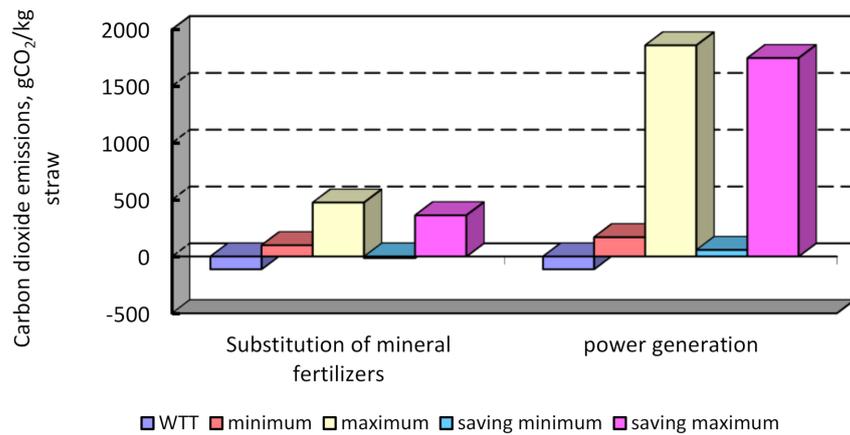


Figure 10. Carbon dioxide emissions saving.

Energy saving was analyzed too. The straw return-to-field technology can reduce primary energy consumption in the range of 3.28 to 7.65 MJ/kg. Straw for power generation can produce electricity in the range of 2.55 (the electricity efficiency is 20%) to 5.11 MJ/kg (the electricity efficiency is 40%) (Figure 11).

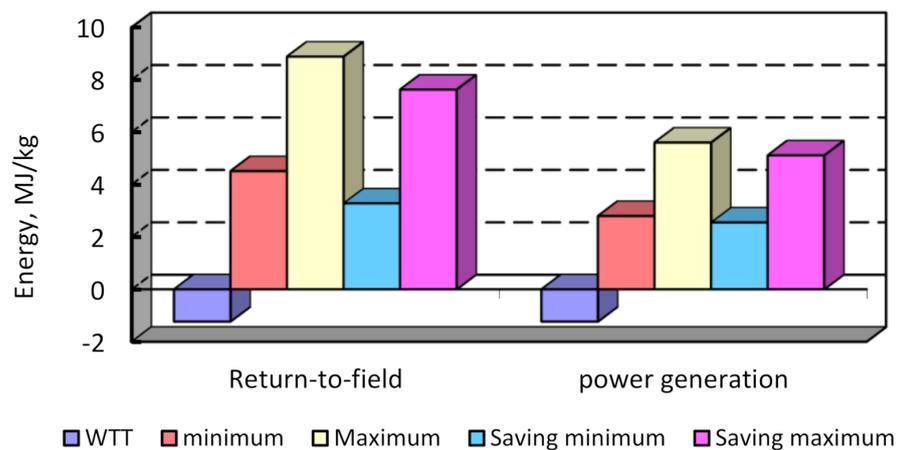


Figure 11. Straw utilization: energy transformation efficiency.

#### 4. Conclusions

Agricultural residues including straw play a significant role in renewable energy supply systems. The use of agricultural residues can mitigate climate changes. They can also complement unstable renewable power technologies such as solar and wind in electricity generation systems. This study of energy and the environmental evaluation of straw as a fuel for generating power resulted in the following findings:

The energy consumption of straw production accounts for 30–70% of the total energy inputs. This value depends on the yield and species of crop.

The use of straw for power generation has better energy and environmental indicators compared with the return-to-field technology (biofertilizer production).

Energy allocation provides the opportunity to account for the effects of the agricultural byproduct (straw) production on the energy and ecological indicators of power generation.

The authority should take into account the environmental protection and energy efficiency indicators when designing straw use policies and strategies. From the perspective of carbon dioxide emissions mitigation, straw-to-electricity is superior to the straw return-to-field strategy.

This study provides a framework for the energy allocation of energy inputs and, therefore, carbon dioxide emissions between a product and a byproduct.

There are some limitations in the present study. Bioelectricity is generated by straw-fired power plants; however, there are different environmental-friendly and energy-effective technologies for straw use, such as the production of biogas, bioethanol, construction materials, etc. In addition, there are problems associated with the high cost of transporting and storing straw, as well as the use of advanced technologies for power generation, including biomass gasification). They can be the topics of future research explorations.

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