

Energy and Environmental Assessment of Straw Production for Power Generation

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Abstract. Agricultural residues, including straw, are important energy feedstock for electricity generation. This study aims to develop a model for energy and environmental assessment of straw production, taking into account its life cycle. The proposed mathematical model allows us to distribute input energy (into any crop production) and emit carbon dioxide (during crop production) between grain and straw formation. It takes into account direct energy input (fuels, electricity, etc.), indirect energy input (fertilizer, herbicide, etc.), and energy required in manufacturing agricultural tractors and implements. It has been found that straw formation consumes from 41 to 66 % of the total energy input and CO₂ emissions.

1 Introduction

Fossil fuel scarcity risks constraining human development [1, 2]. Uneven distribution of fossil energy resources can increase the risk [2]. Moreover, climate change and environmental issues also call for a more efficient energy policy [3, 4, 5].

Distributed generation or local power supply systems may be one of the solutions for solving environmental and energy issues [6, 7, 8]. Biomass based power plants could be the solution to the regions that suffer from energy scarcity and harmful emissions [2, 6]. The widespread development of bioenergy is a factor for the sustainability of the power supply systems.

To mitigate climate changes and to ensure energy security, the European Union (EU) is promoting bioenergy. According to a new EU energy strategy, the targets for 2030 include at least 27 % of energy to be delivered from renewable sources [9]. It reduces greenhouse gas (GHG) emissions by 40 % compared to the levels of 1990 [10]. The energy and climate policies in the EU have encouraged the development of biomass-based power generation. Unlike solar or wind power, biomass based power plants provide a reliable energy supply. Currently, biomass provides 13% of the world's energy consumption. Biomass supply from agriculture is about 61 % of the total organic feedstock [11, 12]. Therefore, the use of biomass for energy production is of significant parts of reaching the above.

Agriculture may be a supplier of green energy. The term agricultural feedstock encompasses energy crops, agricultural residues and animal waste. The main types of biomass used for electricity production are the following:

woody crops (oxtree, willow, etc.); energy crops (sorghum, maize silage, etc.); straw; manure; etc. Woody crops and straw are directly combusted in thermal power plants. Energy crops, straw, and manure, can be used as a substrate for biogas plants.

Some research papers have dealt with biomass energy and environmental performance for power generation [13, 14, 15, 16]. However, integrated analysis for agricultural residue based power supply systems is still absent. Thus, the energy analysis of agricultural residue does not take into account all kinds of energy consumption (direct, indirect, manufacturing, and assembly energy requirements for agricultural tractors, machinery, etc.) [17, 18].

The purpose of this study is to develop a life cycle assessment model for the energy and environmental (greenhouse gas emission) performance of straw production (from the seeding of crop to utilization).

2 Methodology

The agricultural feedstock data (energy crops, crop residues, process-based residue, livestock manure) is presented in tons. Residue quantity is calculated based on the yields and Residue to Crop Ratio (*RCR*). The yield of straw is equal to

$$Y_s = Y_g \cdot RCR, \text{ kg/ha}, \quad (1)$$

where Y_g is the yield of a certain crop, kg/ha; RCP is the Residue to Crop Ratio of a certain crop.

Crop yields are available in Statistical Yearbooks. At the same time, information about residue yields is not collected. The information about Residue to Crop Ratios was summarized by Scarlat et al., Bentsen et al., Cardoen

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et al., and Geletukha et al. [19, 20, 21, 22]. The residue-to-crop ratios range from 0.8 to 3.4. The residue removal rates vary from 15 to 82 % [19, 22, 23, 24, 25]. Their values depend on a lot of factors.

The Well-to-Wall (WTW) analysis is planned to study the energy supply systems [17]. This method takes into account all the stages of a fuel life cycle. The WTW analysis for biomass considers the impact of the following: crop cultivation, biomass storage, biomass transportation, biomass processing, and biomass utilization in power plants. This method for agricultural residues is planned to be developed.

The WTW and LCA analysis focus on the total primary energy harvested or cumulative energy demand (CED). The cumulative energy demand represents direct and indirect energy use throughout the life cycle. It includes the energy consumed from the extraction to burning. CED is calculated by the following formula

$$CED = \sum_{i=1}^n EC_i, \text{ MJ/kg}, \quad (2)$$

where E_i is the energy consumption at i^{th} stage, MJ/kg; n is the number of stages.

In our calculation, we factored in emissions from fuel supply pathways. It is a so-called well-to-tank (WTT) emissions. Its value was determined by using information about tillage technologies. Therefore, WTT depends on technology applied for crop cultivation.

The environmental and energy impacts of human labor were not considered. All the technological processes included to the life cycle analysis are presented in Figure 1.

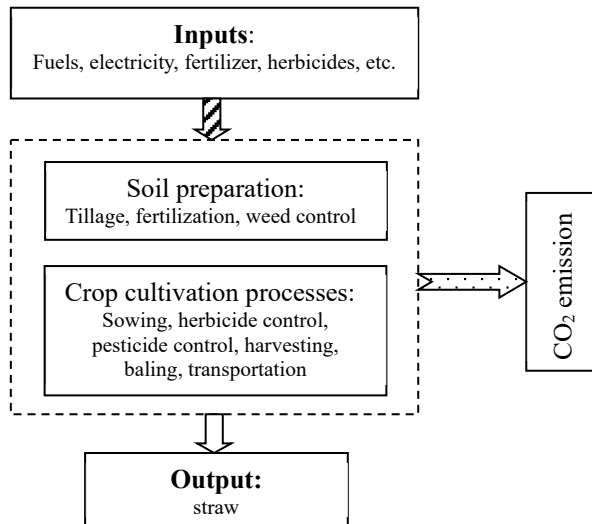


Fig1. The system boundaries for the straw production

3 Results

The input energy forms harvest both grains and straw. This energy needs to be shared into two parts: grain and straw. We suggest doing this by the amount of energy in each part of the harvest. The total harvest energy output comprises the energy of grain and the energy of straw.

$$EH = EG + ES, \text{ MJ/ha}, \quad (3)$$

where EG is the energy content of the grain, MJ/ha; ES is

the energy content of straw, MJ/ha.

Then the following amount of energy is used on the formation of straw

$$ESF = \frac{ES}{EH} \cdot Ein, \text{ MJ/ha}, \quad (4)$$

where Ein is the total input energy, MJ/ha.

The share of energy which is used to form the straw is

$$SR = \frac{ES}{ES + EG} = \frac{Y_g \cdot RCR \cdot LHV_s}{Y_g \cdot RCR \cdot LHV_s + Y_g \cdot LHV_g}, \quad (5)$$

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

After transformation of (5) we obtain the following equation

$$SR = \frac{RCR \cdot LHV_s}{RCR \cdot LHV_s + LHV_g}. \quad (6)$$

To evaluate the energy indicators, primary properties of biomass feedstock were used (Table 1).

Table1. Properties of selected crop residues

Crop	Lower heating value, MJ/kg	Bulk density, kg/m ³	References
Wheat	17.2	20-60	[26]
Barley	15.9	54-78	[26]
Rapeseed	15.3	33-67	[26]
Soybean	15.9	27-43	[26]
Corn stalk	8-17	35-80	[27]
Sunflower stalk	16	112	[28]

The share of energy that is used to form the straw depends on crop type and RCR . Scarlat et al. [29] provided the RCR per crop type: rye – from 0.91 to 1.75; oats – from 0.91 to 2.0; summer wheat – from 0.9 to 1.7; winter wheat – from 0.8 to 1.8; barley – from 0.9 to 1.8; rapeseed – 1.0 to 1.7; corn – from 0.8 to 2.0; rice – from 0.8 to 2.3. The share of energy ranges from 0.41 to 0.66 (Figure 2). This value shows the share of input energy was used to form the straw.

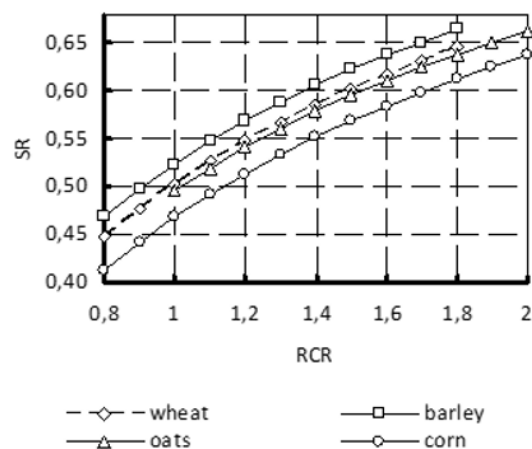


Fig2. The share of energy associated with straw

The total energy input comprises direct, indirect and investment energy consumptions

$$Ein_{input} = E_{direct} + E_{indirect} + E_{ma}, \text{ MJ/ha}, \quad (7)$$

where *E_{direct}* is the direct energy input (fuels, electricity, etc.), MJ/ha; *E_{indirect}* is the indirect energy inputs (technological materials such as fertilizer, herbicides, pesticides, etc.), MJ/ha; *E_{ma}* is the manufacturing and assembly energy required for tractors and implements, MJ/ha.

The energy required in manufacturing agricultural implements and tractors were used in this analysis. These values are based on their weight [30]. The same goes for fertilizers. Primary energy consumption and carbon dioxide emission are presented in Table 2.

Table2. Burdens for producing the main types of fertilizers and machines [31, 32]

Fertilizer, machine	Primary energy consumption, MJ/kg	Carbon dioxide emission, kgCO ₂ /kg
Nitrogen	29.8-51.6	0.98-2.49
Phosphate	13.0	1.0-1.6
Potash	10.06	0.58
Tractor	51.55	4.77
Implement		

Specific carbon dioxide emissions depend on fuel consumption, the carbon content in the fuel, and well-to-tank emissions. For standard diesel fuel, WTT CO₂ emissions are within the range vary from 6.7 to 24 gCO₂/MJ [33] or from 0.284 to 1.020 kgCO₂/kg. Therefore, Well-to-Wheel, carbon dioxide emissions associated with diesel fuel application is calculated by the formula

$$WTTW = B \cdot \left(CC \cdot \frac{11}{3} + WTTe \right), \text{ kg/ha}, \quad (8)$$

where *B* is the fuel consumption for crop growing, kg/ha; *CC* is the carbon content in the fuel, kg/kg; *WTTe* is the well-to-tank carbon dioxide emissions for any fuel, kgCO₂/kg.

Carbon dioxide emissions from electricity consumed is [34, 35]

$$CDEE = ETC \cdot EFC, \text{ kgCO}_2/\text{ha}, \quad (9)$$

where *ETC* is the electricity consumption for crop growing, kWh/ha; *EFC* is the emission factor from grid electricity, kgCO₂/kWh.

During fertilizer production, there is energy consumption. It results in carbon dioxide emissions which is computed by the following expression

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

where *MF_i* is the consumption of *ith* fertilizer, kg/ha; *CDE_i* is the carbon dioxide emissions during the production process of *ith* fertilizer, kgCO₂/kg.

We have considered the application of this approach using the example of growing wheat in Ukraine by conventional technology. The results of our calculations are the following. Cumulative energy consumption for straw production is 6364 MJ/ha or 1238.74 MJ/t (Table 3). This value is equal to approximately 10% of the calorific value of straw and, therefore, must be taken into account in the energy assessment of biomass power plants.

Table3. Cumulative energy consumption for straw production

Parameter	Unit	Value
Total energy consumption:	MJ/ha	11655.69
Direct	MJ/ha	3767.63
Indirect	MJ/ha	6056.01
Energy required in manufacturing agricultural implements and tractors	MJ/ha	1832.05
Yield of grain	t/ha	4.11
Yield of straw	t/ha	5.138
The share of energy which is used to form the straw	-	0.546
The energy which is used to form the straw	MJ/ha	6364.00
	MJ/t	1238.74

Ecological footprint has been computed too (Figure 3).

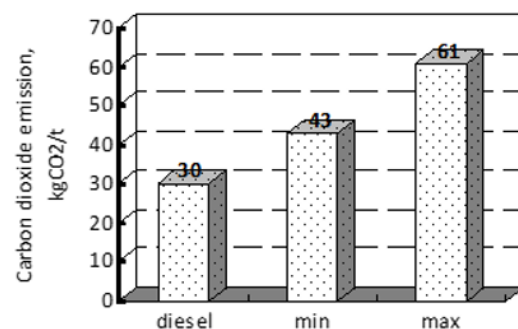


Fig3. Ecological footprint

The carbon dioxide emissions for straw production vary from 43 to 61 kgCO₂/t. Accounting for the use of fertilizers, herbicides, and agricultural machinery increases the CO₂ emissions by 50-100% compared to diesel fuel utilization. Therefore, it is necessary to take into account the indirect energy consumption when performing environmental analysis.

4 Conclusion

Renewable energy sources, including cereal straw, are a priority of green power generation on the local levels. Therefore, a life cycle energy and greenhouse gas emissions analysis of straw is of great importance.

The model for determining cumulative energy consumption and Well-to-Tank carbon dioxide emissions for straw production (from seed sowing to harvesting) has been developed. It has been found that the share of energy consumed by straw formation is within the range from 41 to 66 % (for wheat production in conditions of Ukraine). It is around 10 % of its calorific value. Carbon dioxide emissions vary from 43 to 61 kg/t. Therefore, the above indicators are significant and must be taken into account when analyzing straw-based power plants.

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