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Model for Energy Analysis of *Miscanthus* Production and Transportation

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Abstract: A computational tool is developed for the estimation of the energy requirements of *Miscanthus x giganteus* on individual fields that includes a detailed analysis and account of the involved in-field and transport operations. The tool takes into account all the individual involved in-field and transport operations and provides a detailed analysis on the energy requirements of the components that contribute to the energy input. A basic scenario was implemented to demonstrate the capabilities of the tool. Specifically, the variability of the energy requirements as a function of field area and field-storage distance changes was shown. The field-storage distance highly affects the energy requirements resulting in a variation in the efficiency if energy (output/input ratio) from 15.8 up to 23.7 for the targeted cases. Not only the field-distance highly affects the energy requirements but also the biomass transportation system. Based on the presented example, different transportation systems adhering to the same configuration of the production system creates variation in the efficiency of energy (EoE) between 12.9 and 17.5. The presented tool provides individualized results that can be used for the processes of designing or evaluating a specific production system since the outcomes are not based on average norms.

Keywords: biomass; operations analysis; biomass logistics

1. Introduction

Miscanthus x giganteus has recently been identified as a crop with a high potential for energy production [1–3]. It is a C_4 photosynthetic plant with a high content of lignin and linocellulose fibre [4]. Another attractive feature of *Miscanthus* is its adaption capability to various climates and soils. Overall, *Miscanthus* is a genus of highly resistant plants countering disadvantageous ecological factors. Its evolution in regions of the world with wide temperature fluctuations between seasons has led to characteristics that make the plant resistant to heat, frost, drought and flood, though its biomass yield may vary under different conditions [4]. Alhough temperatures below 12 °C limit productivity of C_4 crops, *Miscanthus* is an exception to this rule by remaining productive and with high CO_2 assimilation efficiency [5]. Even though the crop prefers warmer climates, it can be grown throughout Europe in reasonable yields.

Various studies have reported the efficiency of *Miscanthus* as an energy crop. Angelini *et al.* [6] found a mean net energy yield of 467 $GJ \cdot ha^{-1} \cdot y^{-1}$ for a twelve-year cycle period of *Miscanthus*. Mantineo *et al.* [7] have reported an efficiency of energy (EoE), that is the energy output/input ratio, of

11.5 and a yearly net energy yield amounting to 221 GJ· ha^{-1}· y^{-1} for the first three years of production. Ercoli *et al.* [8] have evaluated the energy input for irrigated and rain-fed *Miscanthus* crops for different nitrogen levels. For irrigated crop (4 year crop cycle) with 50 kg· ha^{-1} nitrogen fertilization, the energy input was approximately 17 GJ· ha^{-1} for the first year and approximately 8.5 GJ· ha^{-1} for the following years.

In general, the reports on the energy requirements (or efficient of energy index) of *Miscanthus* production and its use as an energy crop show that there is a considerable spread in the estimated values. This is a result of the multiparametric nature of agricultural production systems. There are numerous factors that can significantly affect input requirements and the output of a biomass production system as well [9,10]. For example, different distances between the field and the storage/processing facilities, variations in the machinery systems, and material input dosages can lead to different energy input requirements for each individual field. Although the outcomes of estimating task times based on average norms are useful for providing a general picture that can be valuable for strategic planning decisions, the task of designing a specific production system (e.g., a bioenergy plant and the allocated field area around the plant) require tools that provide individualized results [11,12]. To that effect, in this paper a computational tool is presented for the estimation of the energy requirements of *Miscanthus* on individual fields and including a detailed analysis and accounting of the involved in-field and transport operations.

2. Materials and Methods

2.1. System Boundary

The system boundary of the presented approach is shown in Figure 1. The system regards the in-field operations and the corresponding field-farm transports of the machinery and the materials applied in the field, and the biomass field-storage transportation. The storage of biomass (or any further processing of the biomass) is not taken into account in this approach. The indirect inputs in the system regard the embodied energy of machinery performing the field operations, the materials applied in the field, and the fuels.

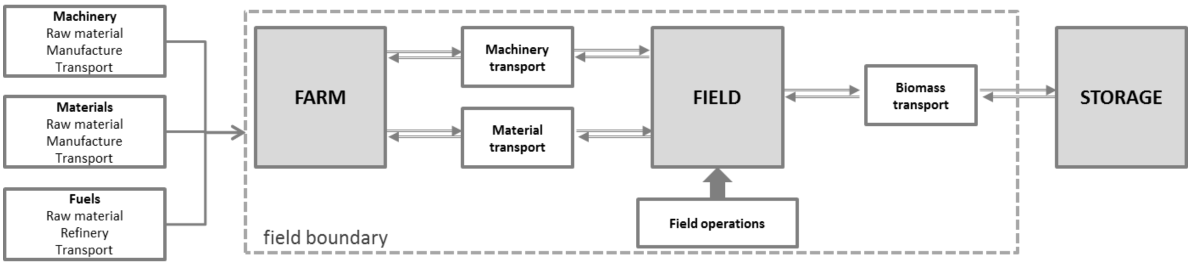


Figure 1. System boundaries of the energy inputs.

2.2. Inputs

The input parameters for the estimation process (Figure 2) can be categorized in the following sets:

- Production-related input parameters. This set includes the field features (e.g., field area, field-farm distance, and field-storage distance), and the crop features (e.g., yield, bulk density, moisture content of the harvested crop, and rhizome density),
- Machinery-related input parameters. This set includes the tractors features (e.g., type of tractor, machine power, mass, and repair and maintenance coefficients), equipment features (e.g., operating width and equipment mass),
- Operation-related input parameters. This set includes operational information (list of operations and years that each operation is performed, assignment of tractor to equipment for each

operation) and parameters related to the execution of the operation (e.g., operating speed, and field efficiency),

- Material-related input parameters. This set includes the parameters for agrochemicals, fertilizers, and the propagation means, as it regards the corresponding dosages and the energy content coefficients of any type these inputs.

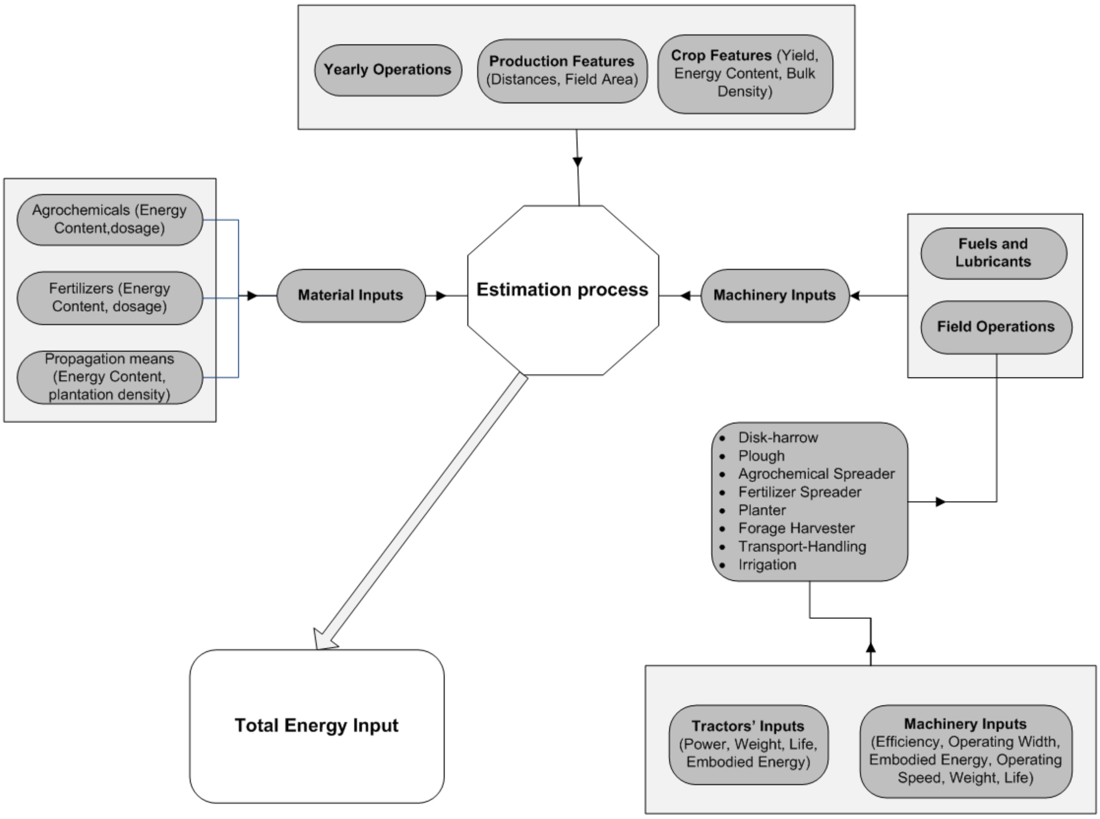


Figure 2. The general inputs for the input energy estimation process.

2.3. Operations

Field operations can be separated into three types, namely, neutral material flow (NMF) operations—(where there is no material flow during the operation—e.g., tillage, and ploughing); input material flow (IMF) operations (e.g., fertilizing and spraying); and output material flow (OMF) operations (*i.e.*, harvesting) [13]. In order to accommodate these types, three modules have been developed in the tool.

- The first module refers to the in-field part of the operations (this module is involved in all of the three types of operations defined above),
- The second module refers to the field-farm transport (this module is involved in all of the three types of operations defined above),
- The third module refers to the biomass transport (this module is only involved in the OMF type).

The estimation of the energy requirements for each one of the three modules are presented in the following sections.

2.3.1. In-Field Operation Part Module

This module calculates the energy requirements for the execution of the in-field part of each operation. As mentioned previously, this operation part regards all types of field operations. In all cases, the estimated input energy elements constitute the fuel (and lubricant) energy and the machinery embodied energy, while in the case of IMF operations the applied material energy is also estimated (Figure 3).

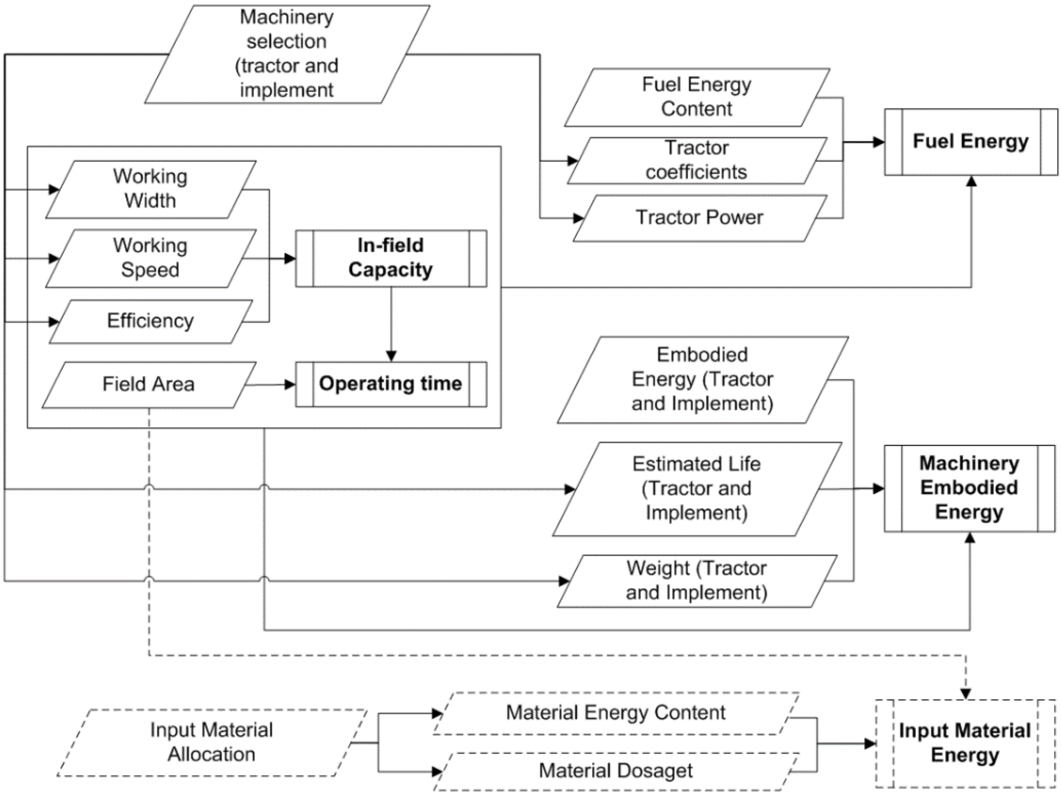


Figure 3. Estimation process of energy elements for the in-field part of an operation (the dotted lines correspond to input material flow (IMF) operations).

As a first step, the in-field capacity (h· ha^{-1}) is estimated for the specific machinery system based on the working speed, the working width, and the field efficiency of the specific system. The field capacity provides the in-field task time of the specific operation in a given field area. The in-field task time of an operation includes the effective in-field operation time (the time that a machine produces work) and the non-effective time (that includes times for loading/unloading—in the case of the material-handling operations, machinery adjustments and time that is allocated for headland turns). The relation between the effective and non-effective time is described by the term of "time efficiency", e_t, which represents the ratio of the time a machine is effectively operating to the total time the machine is committed to the operation [14]. Based on the time efficiency the field capacity (C) is calculated by:

$$C = s \cdot w \cdot e_t \cdot c \tag{1}$$

where s is the operating speed (km· h^{-1}), w is the rated width of the implement (m, the product $s \cdot w$ expresses the theoretical capacity), and c is a unit conversion factor.

For the calculation of field capacity data from ASABE standards for the field efficiency for each operation and the average operational speed are used [15]. Based on the field area, a (ha), the total task time for a field operation is estimated for the particular field:

$$t = a \cdot C^{-1} \tag{2}$$

For the fuel consumption estimation, the specific volumetric fuel consumption equation given in the American Society of Agricultural and Biological Engineers (ASABE) standard [16] is used:

$$Q = (2.64X + 3.91 - 0.203\sqrt{738X + 173}) \cdot X \cdot P_{\mathrm{pto}} \tag{3}$$

where, Q is the fuel consumption (for a diesel engine) at partial load for operation (in $\mathrm{L \cdot h^{-1}}$), $X = P/P_{\mathrm{rated}}$ is the ratio of equivalent PTO (power-take-off) power (P) in a specific operation to the rated PTO power (P_{rated}) that is normally considered as the 83% of the gross flywheel.

The equivalent PTO power is given by:

$$P = P_{\mathrm{db}}/(E_{\mathrm{m}}E_{\mathrm{t}}) + P_{\mathrm{pto}} \tag{4}$$

where E_{m} is the mechanical efficiency of the transmission and power train, typically 0.86 for tractors with gear transmission. E_{t} is the tractive efficiency, that depends on the tractor type and tractive condition (e.g., E_{t} is 0.75 for a 4WD tractor on a tilled soil surface, from Figure 1 of the ASABE standards [17], P_{pto} and P_{db} are the PTO and drawbar power (kW), respectively, required by the implement.

The PTO power requirement is given by:

$$P_{\mathrm{pto}} = a + b \cdot w + cF \tag{5}$$

where *a,b,c* are machine-specific parameters ([16], w the working width, and F is the material feed rate ($\mathrm{t \cdot h^{-1}}$), while the drawbar power requirement is given by:

$$P_{\mathrm{db}} = D \cdot s/3.6 \tag{6}$$

where D is the implement draft given by:

$$D = Wor_i \left[A + Bs + Cs^2\right] \cdot w \cdot de \tag{7}$$

where parameters *A,B,C* are machine-specific parameters given in ASABE D497 standards [16], and de is the tillage depth.

Lubricant consumption ($\mathrm{L \cdot h^{-1}}$), is given by:

$$L = 0.00059 \cdot P + 0.02169 \tag{8}$$

where P (kW) is the machine power as presented in ASABE D497 [16].

Farm machinery contributes to the energy input, not only directly through the fuel and lubricant consumption, but also through the embodied energy of each machinery, implement or tractor. This energy includes the energy of raw materials that are used in the manufacture of farm machinery, the energy for transport to the final consumer, and the energy for repair and maintenance of machinery. A number of studies in the literature [18,19] have estimated the calculation of the total embodied energy of an agricultural machine (tractor, implement, self-propelled machine) which is allocated to the whole life time of the machine and usually are expressed as $\mathrm{MJ \cdot kg^{-1}}$ of embodied energy for various types of machinery. For the estimation of the portion of the embodied energy corresponding to an operation, the lifetime of the machine [16] and the task time for a particular field were taken into account.

In the case of IMF operations, where input material handling is involved, and in addition to the energy inputs mentioned above, the material energy input (*i.e.*, propagation means, fertilizers, and agrochemicals) should be calculated also. Regarding the propagation means, the planting density is taken into account, while in the case of the fertilizers, the yearly dosage is taken into account. Irrigation has also been considered as a field operation (although it does not directly involve an agricultural machine). From the relevant literature, for the calculation of consumed energy regarding irrigation, the mathematical equation adapted from Ercoli *et al.* [8]:

$$E_{\mathrm{ir}} = 550 \cdot L \cdot A \tag{9}$$

where E_{ir} is the irrigation energy in $\mathrm{MJ \cdot ha^{-1}}$, L is the lift (m) and A is the amount of pumped water in $\mathrm{m \cdot ha^{-1}}$. It was also assumed that water is delivered to the field with a 20% loss due to transport and application [8].

2.3.2. Farm-Field Transportation Module

The machinery (and material in IMF operations) transport cycle farm-field-farm is taken into account in every field operation considered. The calculation of energy consumed for this transport cycle varies if the field operation includes material application or not, since in the former case a number of trips might be required. For IMF operations (Figure 4), and the associated fuel energy input estimation, the required number of trips, the fuel consumption per trip, the maximum wagon volume (in case of planting) and the maximum tanker weight (in case of fertilization and agrochemicals' spreading) are taken into account. For the embodied energy input estimation of the tractor and the wagon/tanker, the estimated lifetime, the weight, the number of trips, the farm-field distance, and the average road speed is taken into account.

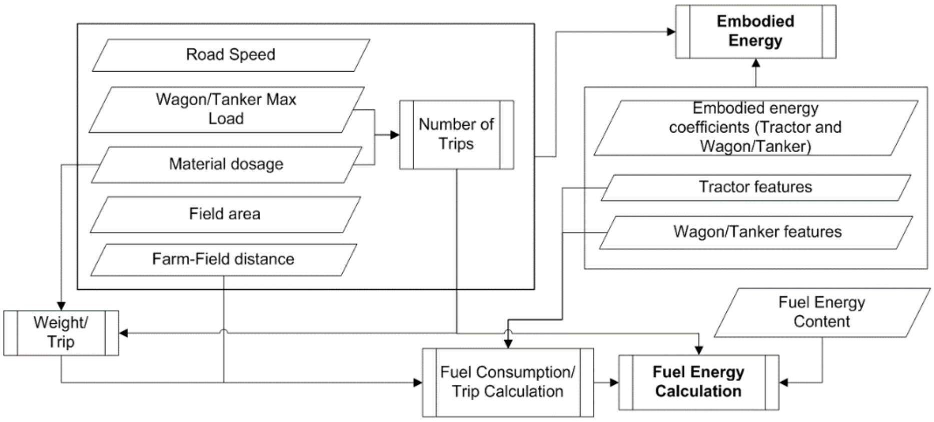


Figure 4. Farm-field material transport operations.

For the estimation of the fuels consumption during the farm-field-farm routing, the same approach as in the in-field operations is followed with the difference [20] that the implement draft force is given now by:

$$D = R_{\mathrm{sc}} + MR \tag{10}$$

where R_{sc} is the road surface resistance and MR the total motion resistance. For these transportations the hard soil coefficient is considered.

The total implement motion resistance is given by:

$$MR = \sum R_{\mathrm{M}} \tag{11}$$

as the summation of each individual wheel of the implement. It has been assumed that:

$$R_{\mathrm{M}} = 0.55m \tag{12}$$

where m is the dynamic wheel load and the 0.55 coefficient has been considered as an assumption for a concrete surface [16].

2.4. Biomass Transport

The energy inputs of the biomass transport consider the transport of the harvested product from field to biomass storage-processing facilities. Logistics field-storage operations (Figure 5) also include the same categories of energy inputs, fuels and embodied energy. For the energy input calculation the same approach as described previously for the material farm-field transport was applied. The approach is divided into a pre-processing stage where the required trips are estimated (Figure 5). In order to avoid any idle times for the harvester during execution, the number of transport carts that are allocated for supporting the operation was estimated as a function of the cycle time for travel from the field to the storage facility, unloading, and drive back to the field, the carrying capacity of the wagon and the in-field capacity of the harvester (processed biomass per unit time).

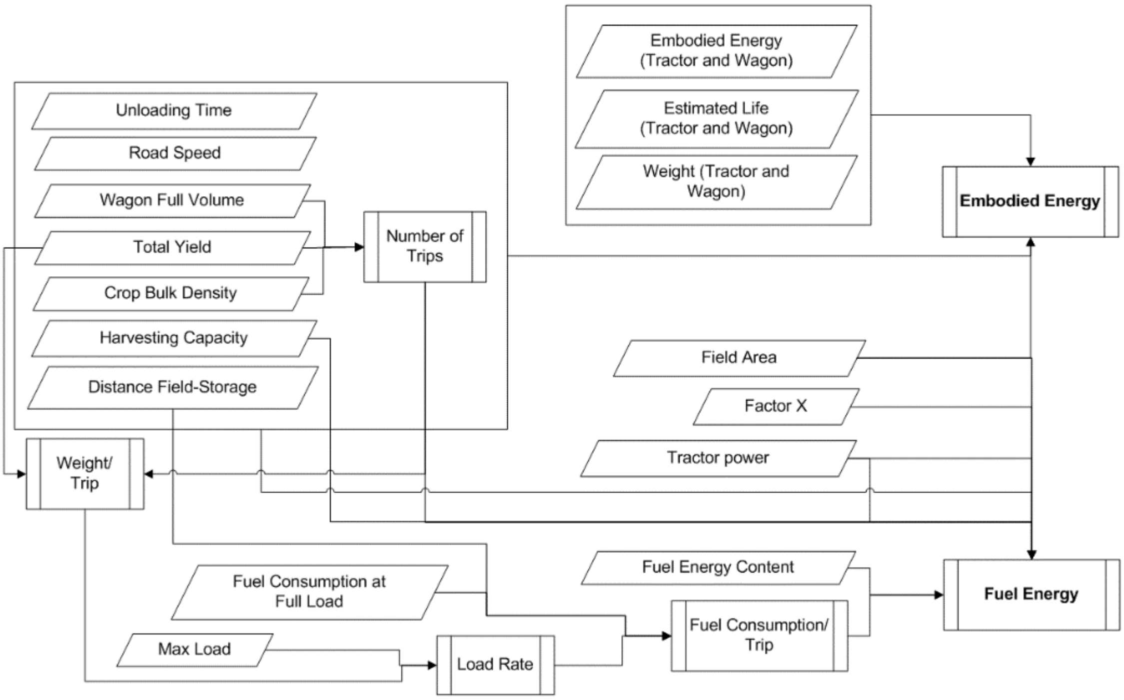


Figure 5. Field-storage biomass transport operations.

3. Results

3.1. Production Scenario

The presented production scenario is based on the *Miscanthus* production practices followed by various farmers in Italy. All followed practices and prevailing cultivation conditions were derived from interviews with farmers and machinery contractors. Based on the interviews, the various parameters of the production scenario (e.g., average field area and distances, agrochemicals and fertilizers dosages, field operations, machinery selection, *etc.*) were determined in a way that the scenario represents a realistic *Miscanthus* production case. In the presented study, a ten-year production period has been considering for the demonstration of the model. The operations performed during this period and for each individual year are listed in Table 1.

Concerning the field preparation, *Miscanthus* cultivation requires limited soil management [6]. Thus, plowing up to 20 cm depth was considered as a first preparation of the soil and afterwards a disk-harrowing. Before the establishment of the crop and after soil preparation it is very important to thoroughly control perennial weeds that can affect competitively on the new-established *Miscanthus* plants. However, after the early growth the crop has the ability to protect itself from the weeds. In the presented production scenario one herbicide application has been considered as a pre-planting weed control in the first year.

Table 1. Field operations for the ten-year period.

Field Operations	Year									
	1	2	3	4	5	6	7	8	9	10
Plowing	√	-	-	-	-	-	-	-	-	-
Disk-harrowing	√	-	-	-	-	-	-	-	-	-
Pre-planting herbicide spreading	√	-	-	-	-	-	-	-	-	-
Planting	√	-	-	-	-	-	-	-	-	-
Fertilization	√	√	√	√	√	√	√	√	√	√
Harvesting	-	√	√	√	√	√	√	√	√	√
Biomass Transport	-	√	√	√	√	√	√	√	√	√
Irrigation	√	√	√	√	√	√	√	√	√	√

For the planting operation, the case of a row crop planter similar to the one implemented for planting seed potatoes was adopted. The desired final plant population should be approximately between 10,000 and 12,000 plants per ha [21], and since large rhizome survival usually averages 60%–70% [21,22], approximately 15,000 to 17,000 rhizomes per ha are needed to reach the final recommended stand density. In the presented scenario, 16,000 rhizomes per ha has been considered (app. 0.8 m × 0.8 m inter-row and intra-row spacing).

After planting, the irrigation of the newly planted *Miscanthus* plants during the first growing season improves establishment rates [23]. Irrigation is applied every year in order to cover water requirements in parallel with rainfall and ensure considerable yields.

Generally, *Miscanthus* has low nutrient requirements because the soil is able to supply much of the needed nutrients to the crop. However, the addition of nitrogen, phosphorus and potassium might be necessary depending on the specific nutrient soil conditions. It has been reported that 50 kg N, 21 kg P_2O_5, and 45 kg K_2O per ha per year are sufficient to support adequate yields [24]. This nutrient allocation was assumed in the presented study, also.

Harvesting of the crop usually occurs every year from the second year on. At the end of the growing season, *Miscanthus* usually drops most of its leaves as it senesces, and the senesced stems are typically harvested during the period from November until late March [5]. Harvesting is usually carried out using conventional forage harvesters for cutting and chipping the biomass supported by transport carts (usually a tractor-wagon combination) moving in parallel to the harvester for unloading the processed material. The yield of the crop was considered as 21.87 $t\cdot ha^{-1}$ corresponding to an energy content of the harvested biomass of 16.4 $MJ\cdot kg^{-1}$ of dry matter [7].

3.2. Input Parameters

As mentioned in the production scenario description, the yearly application of 50 kg N, 21 kg P_2O_5, and 45 kg K_2O per ha was adopted. According to these requirements, urea, single superphosphate, and potassium chloride, were selected as fertilization means. Specifically, the application of 108 $kg\cdot ha^{-1}$ urea, 116 $kg\cdot ha^{-1}$ single superphosphate, and 112 $kg\cdot ha^{-1}$ potassium chloride was considered. The same amount of fertilizer was assumed for each individual year of the production.

The energy requirement of *Miscanthus* rhizomes in the presented study was based on the approach presented in [7] and corresponded to 0.0862 $MJ\cdot kg^{-1}$ of rhizomes, given that each rhizome weighs approximately 50 g.

Finally, the weed control was selected to be implemented with a pre-planting herbicide application Glyphosate was adopted as an appropriate commercially available, environmentally friendly herbicide with many benefits for our crop. The embodied energy of this herbicide was adopted from [18].

Table 2 summarizes the values of the energy input parameters for the selected case study. The material input elements are summarized in Table 3.

Table 2. Inputs per farm operation.

Inputs	Plough	Disk-Harrow	Harvest	Agrochemical Spreading	Fertilization	Planting	Transport	Irrigation
Operating width (1) (m)	2	4.5	1.83	14.4	14.4	2	-	-
Operating speed (2) ($km\cdot h^{-1}$)	7	10	5	11	11	9	-	-
Field efficiency (2)	0.85	0.80	0.70	0.70	0.70	0.65	-	-
Irrigation lift (m)	-	-	-	-	-	-	-	10
Water amount ($m\cdot ha^{-1}$) (3)	-	-	-	-	-	-	-	0.20
Tractor embodied energy (4) ($MJ\cdot kg^{-1}$)	138	138	138	138	138	138	-	-
Implement embodied energy (4) ($MJ\cdot kg^{-1}$)	180	149	116	129	129	133	-	-
Tractor weight (5) (10^3 kg)	6.94	6.94	6.94	3.93	3.93	6.94	6.94	-
Implement weight (1) (10^3 kg)	2.30	1.80	0.90	3.35	3.35	1.20	-	-
Tractor estimated life (2) (10^3 h)	16	16	16	12	12	12	-	-
Implement estimated life (2) (10^3 h)	2.00	2.00	2.50	1.20	1.20	1.50	-	-
Average road speed ($km\cdot h^{-1}$)	20	20	20	20	20	20	20	-
Tanker/wagon weight (kg)	-	-	-	1500	1500	1500	4000	-
Tanker/wagon embodied energy ($MJ\cdot kg^{-1}$)	-	-	108	108	108	108	108	-
Tanker/wagon estimated life (2) (10^3 h)	-	-	3	3	3	3	3	-
Fuel energy content (5),(6) ($MJ\cdot L^{-1}$)	41.20	41.20	41.20	41.20	41.20	41.20	41.20	-
Tractor power (kW)	120	120	120	50	50	50	120	-
Lubricants energy content (7) ($MJ\ L^{-1}$)	46	46	46	46	46	46	46	-
Crop bulk density ($kg\cdot m^{-3}$)	-	-	-	-	-	-	240	-
Wagon full volume (1) (m^3)	-	-	-	-	-	-	40	-

(1) Commercial Values; (2) [16]; (3) [23]; (4) [18]; (5) [19]; (6) [25]; (7) [26].

Table 3. Energy content per unit mass and dosage for the input materials.

Input Material	Energy Content (MJ· kg^{-1})	Dosage (kg· ha^{-1})
Herbicide (Glyphosate)	454 * (1)	20
Propagation means	0.0862 (2)	800
Nitrogen fertilizer	78.1 (3)	50 (1)
Phosphorus fertilizer	17.4 (3)	21 (1)
Potassium fertilizer	13.7 (3)	45 (1)

* (MJ· kg^{-1} of active ingredient); (1) [18]; (2) [7]; (3) [24].

3.3. Demonstration of the Method

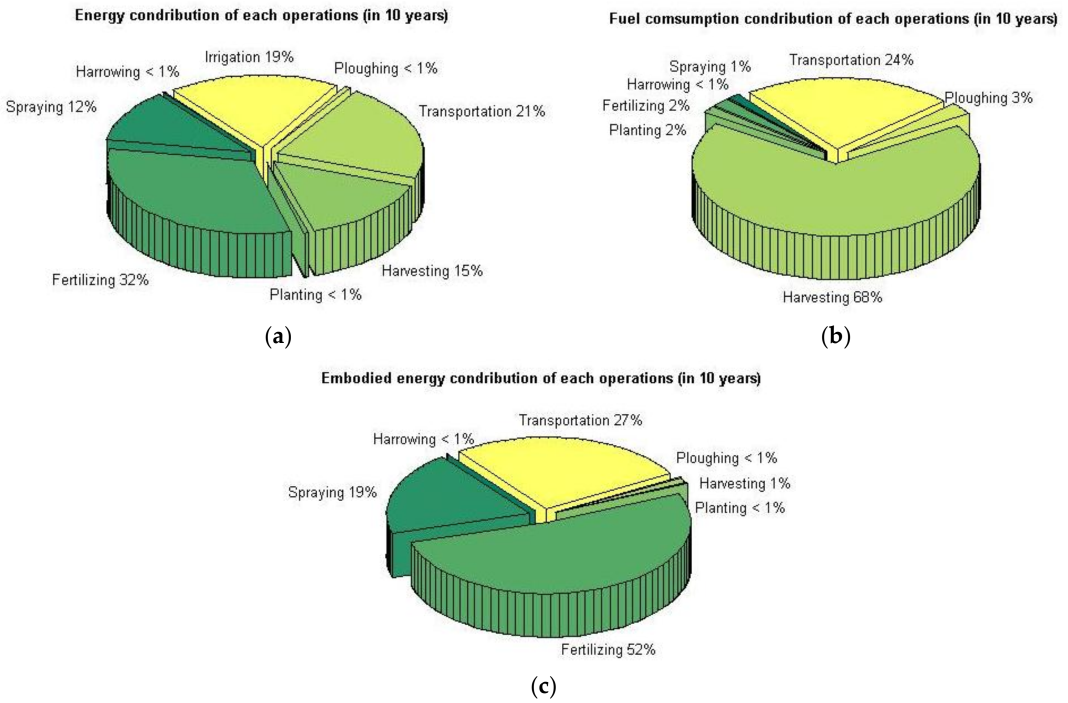
3.3.1. Basic Scenario Analysis

A field area unit of 5 ha located 5 km from the farm and 10 km from the biomass storage-processing facilities is selected as the basic scenario for the demonstration and analysis of the approach. By taking into account all the energy inputs for the *Miscanthus* crop, the consumed energy per farm operation has been extracted and is presented in Table 4.

Table 4. Energy requirements for each operation in the basic scenario.

Operation	Stage	Energy (MJ· ha^{-1})			
		Fuel	Embodied	Material	Total
Ploughing	In-field Farm-field	882 8	138 25	- -	1053
Cultivation	In-field Farm-field	272 8	20 11	- -	311
Disc-harrowing	In-field Farm-field	437 8	49 18	- -	512
Spraying	In-field Farm-field	52 4	21 6	18,160 -	18,243
Fertilizing	In-field Farm-field	520 120	210 350	48,870 -	50,070
Planting	In-field Farm-field	534 16	76 23	69 -	718
Harvesting	In-field Farm-field	24,590 80	1270 80	- -	26,020
Irrigation	-	-	-	-	29,700
Transport	In-field Field-storage	2460 7380	730 22,960	- -	33,530

For the basic scenario, the total energy input requirements amounted to 14.8 GJ· ha^{-1}· y^{-1}, the total energy output amounted to 322.9 GJ· ha^{-1}· y^{-1}, resulting in a net energy amount of 308.1 GJ· ha^{-1}· y^{-1} and an efficiency of energy of 21.2. Figure 6a presents the distribution of the energy input in the various operations for the ten-year period of the considered production. Figure 6b presents the distribution of the energy corresponding to the fuels (and lubricants) consumption of the machinery in the various operations. Finally, Figure 6c presents the contribution of the embodied energy in the various operations for the whole production period which includes the embodied energy for both machinery and input materials.

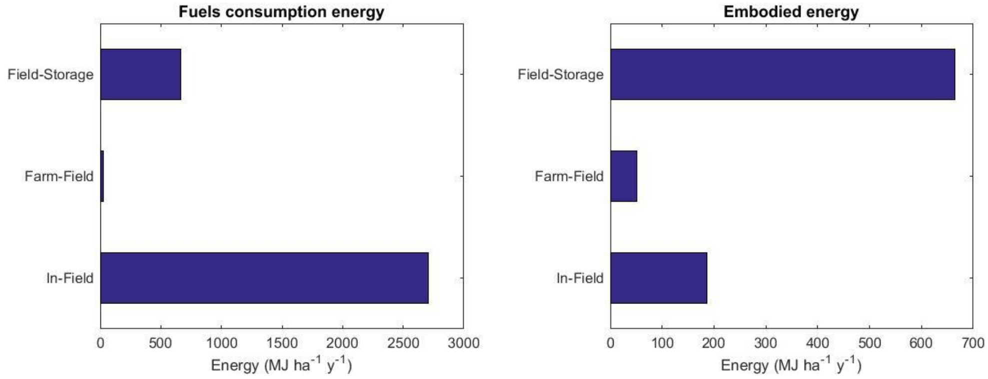


(**a**) (**b**)

(**c**)

Figure 6. Distribution of the total energy input (**a**), fuel consumption (**b**), and embodied energy (**c**) to the various operations for the basic scenario.

As mentioned previously, three activity types have been considered, namely, in-field operations, farm-field transportation, and field-storage transportation. In Figure 7, the amount of energy contributed by each of the activities is presented for the fuels consumption and the embedded energy categories.



(**a**) (**b**)

Figure 7. Energy input from fuels (**a**) and embodied energy (**b**) for in-field, farm-field and field-storage activities.

The energy inputs for the field operations are detailed in Figure 8 where it can be seen that the harvesting operation is the most energy demanding operation. Note that in the input material operations only the machinery originated energy requirements (direct and indirect) are included (not the embedded energy of the input material).

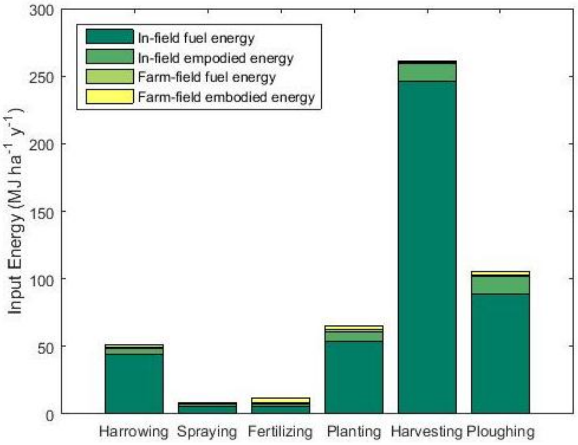


Figure 8. Energy contribution for the various field operations.

3.3.2. Variability of the Energy Requirements on Field Area and Field-Storage Distance

The energy requirements, and subsequently, the EoE of the studied crop are affected from the field-storage distance and the field area. The EoE for field areas ranging from 1 to 30 ha and for field-storage distances ranging from 1 to 30 km are shown in Figure 9 as a surface graph. It is clear that the major effect on the energy requirements derives from the distance variations and less from the variations due to the field area. For the selected variations of field-storage distances and field areas the EoE varies from a minimum of 15.8 (for the case of 1 ha field area and 30 km field-storage distance) to a maximum of 23.7 (for the case of 30 ha field area and 1 km field-storage distance). For these two marginal cases the input energy accounts to 20.4 GJ$\cdot$ ha$^{-1}\cdot$ y^{-1} and 13.6 GJ$\cdot$ ha$^{-1}\cdot$ y^{-1}, respectively for the minimum and maximum EoE case, while the range of the net energy between the minimum and maximum is 6.8 GJ$\cdot$ ha$^{-1}\cdot$ y^{-1} (302.5 GJ$\cdot$ ha$^{-1}\cdot$ y^{-1} and 309.3 GJ$\cdot$ ha$^{-1}\cdot$ y^{-1}, respectively). This difference is mainly a result of the increased travelled distance for the biomass transportation. This can be elaborated in Figure 10 which shows the contribution of the transport energy in the total energy requirements for various distances starting form 15% for a distance of 5 km and increasing to 33% for the distance of 30 km.

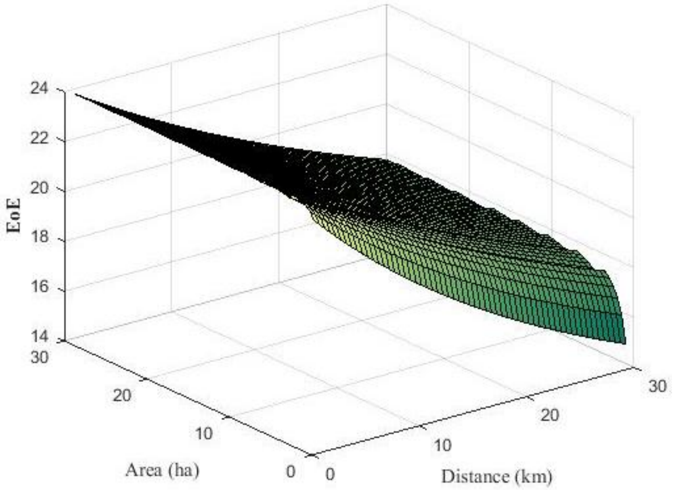


Figure 9. Efficiency of energy (EoE) surface for various field-to-storage distances and field areas.

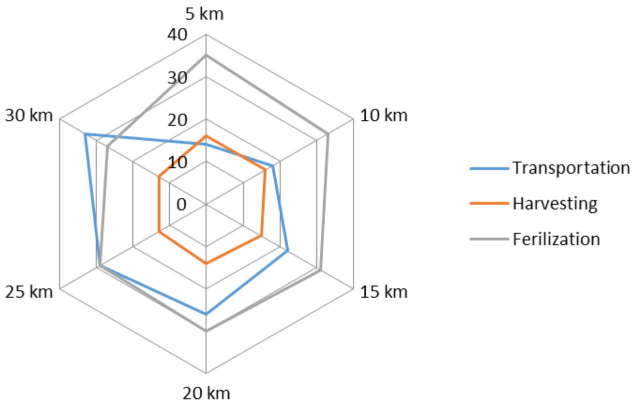


Figure 10. The contribution of the transportation, harvesting, and fertilization operations in the total energy input for various filed-to-storage distances (field area: 10 ha, farm-field distance: 5 km).

Is has to be further noted that the transportation system also highly affects the energy requirements since it affects the number of trips (and the number of transport units used), the waiting times, and the level of utilization of each unit. Figure 11 shows the biomass transport energy requirements for three different wagon capacities and field-storage distances ranging from 1 km to 30 km and field areas ranging from 1 ha to 30 ha. The variations in the energy requirements for the biomass transportation lead to considerable variation in the EoE indices of the production systems. For the middle case (15 ha field area; 15 km field-storage distance) the EoE amounts to 17.5, 15.6, and 12.9 for the cases of 40 m^3, 20 m^3, and 10^3 wagons capacity, respectively. For the case of basic scenario (5 ha field area, 10 km field-storage distance) the EoE amounts to 21.2, 20.0, and 18.0 for the cases of 40 m^3, 20 m^3, and 10 m^3 wagons capacity, respectively.

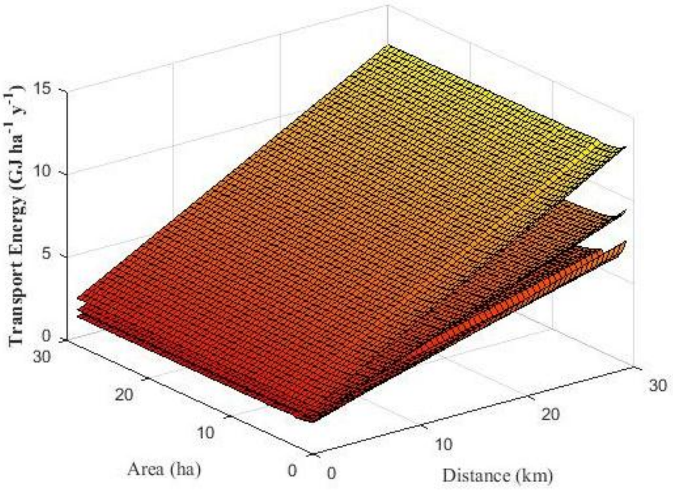


Figure 11. The biomass transport energy requirements for three sizes of wagons, higher surface: 10 m^3 capacity; middle surface: 20 m^3 capacity; lower surface: 40 m^3 capacity.

4. Discussion

A computational tool for the estimation of the energy requirements in biomass production was presented using as a case study the *Miscanthus* crop. The tool takes into account all the individual involved in-field and transport operations and provides a detailed analysis on the energy requirements of the components that contribute to the energy input.

A basic scenario was implemented to demonstrate the capabilities of the tool. Furthermore, the variability of the energy requirements in field area and field-storage distance changes was also demonstrated. The field-storage distance highly affects the energy requirements resulting to a variation in the EoE form 15.84 up to 23.74 for the examined cases. 302.5 $\text{GJ}\cdot\text{ha}^{-1}\cdot\text{y}^{-1}$ and 309.3 $\text{GJ}\cdot\text{ha}^{-1}\cdot\text{y}^{-1}$, respectively, As compared to other studies on *Miscanthus* as an energy crop, the resulting EoE for the examined cases is higher than the one reported in Mantineo *et al.* [7] (*i.e.*, EoE of 11.5 and yearly net energy of 221 $\text{GJ}\cdot\text{ha}^{-1}\cdot\text{y}^{-1}$). However, the later corresponds to the first three years of production where input requirements are higher (e.g., soil preparation, planting, and spraying operations) while the harvested yield is reduced. The opposite stands for the case reported in Angelini *et al.* [6] where a mean net energy yield of 467 $\text{GJ}\cdot\text{ha}^{-1}\cdot\text{y}^{-1}$ was found since it refers to a twelve-year production period which compared to the ten-year production period the total energy output is increased while the energy input for the first year (which is the most intensive in terms of energy input requirements) remains the same.

Not only the field-distance highly affects the energy requirements but also the biomass transportation system. Based on the presented example, for different transportation systems and keeping the same configuration of the production system the variation in the EoE was between 12.87 and 17.52. Regarding the field area, it affects only slightly the energy requirements. However, this is not a proven result since in the presented modelling the actual field shape and the in-field operation execution practice were not taken into account. Of course, the user can change the field efficiency factor to roughly cope with this issue, but this cannot provide accurate results nor is it a recognized standard way of comparison. The connection in the tool of models that take into account the detailed features that affect field efficiency (e.g., [27,28]) as well as of models for various harvesting and transportation chains (e.g., [29–31]), is an issue of further research.

The presented tool provides individualized results that can be used for the processes of designing or evaluating a specific production system since the outcomes are not based on average norms. The tool can be used as a decision support system for the evaluation of different agronomical practices that can apply in the same crop (e.g., different levels of irrigation, fertilizing, and spraying, and also different levels of output production). Furthermore, different crops for bioenergy production can be compared on their feasibility and performance for energy production. Finally, the individual field-specific output of the tool makes it feasible for its implementation in an optimization process for the solution of the crop allocation problem in geographical dispersed fields (e.g., around a bioenergy production plant) under the criterion of the maximization of the net-energy production.

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Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

EoE	Efficiency of energy
IMF	Input material flow operation
NMF	Neutral material flow operation
OMF	Output material flow operation
PTO	Power take off

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