Energy Efficiency of ethanol production from cellulosic feedstock

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Abstract

Biofuel can be a potential supplement to fossil fuel and help in meeting increasing energy demand of the USA as well as rest of the world. However, it is important for the biofuel to be economically competitive and energy efficient to be established as a promising energy source. There has always been an argument about energy efficiency of biofuel production. Some studies have claimed that it requires more energy to produce ethanol than it actually produces as an output.

The objective of the study is to determine energy efficiency of growing two potential cellulosic feedstock; switchgrass and *Miscanthus* and conversion them in to cellulosic ethanol. Energy efficiency was determined by calculating Net Energy Value (NEV), the difference between output energy obtained by ethanol and input energy used in producing ethanol. Input energy consisted of energy required to produce the cellulosic biomass, transporting it to the ethanol processing facility and processing cellulosic biomass in to ethanol. The analysis showed positive The NEV for both switchgrass and *Miscanthus*. NEV for *Miscanthus* (12.41 MJ/L of ethanol) was higher in compared to the switchgrass (7.90 MJ/l of ethanol). Monetary benefits of energy savings were also estimated to determine the impact of energy saving on the society. Results from this research showed both switchgrass and *Miscanthus* as potential biomass feedstock for cellulosic ethanol production.

Keyword: *biofuel; ethanol; Miscanthus; net energy value; switchgrass*

Introduction

Energy is the most important factor of production in economy around the globe, and 90% of energy being produced commercially, comes from the non-renewable sources [1]. The growing concern with rising oil prices and global warming and its consequences are the immediate justification for reducing dependence on fossil fuels [2]. Also, predicted shortage of fossil fuel in future has encouraged researchers to look in to alternatives of petroleum derivatives [3]. Biofuel can be promising alternative of fossil fuel as the energy from the sun is converted in to biomass by the process of photosynthesis. Energy is then obtained from biomass by combustion. In general biofuel can be considered as any liquid or gaseous fuel obtained from biomass substrates and can be used as a partial substitute to fossil fuel.

Global use of energy is increasing by rate of 2-3% per year and bioenergy currently accounts only 13.4% and that too mainly in Africa and other developing countries where biomass is mainly used for cooking and heating. There is a great potential of supplementing growing energy demand in developed economies [4].

There have been different crops being used for biofuel production. For example, sugarcane is the leading crop in Brazil and corn in North America [5, 6]. Brazil has set up an example in biofuel production as it has replaced half of the gasoline requirement in the country [7].

Ethanol produced from corn starch still remains the most significant biofuel, accounting 94 percent of total biofuel production in the USA [8]. However, increased production of corn to meet the biofuel demand caused upward pressure in corn prices [9]. Increasing corn prices are also likely to result in large widespread conversions of non-cropland to cropland, as well as substantial increases in continuous corn production. These changes in land use will lead to

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4 significant increases in nitrate water pollution, soil erosion and loss of soil carbon [10]. Also,
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6 increased use of corn to produce ethanol might raise the concerns about food safety. Raw
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8 materials that do not compete with food stocks can be promising in meeting energy needs by
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10 biofuel production [11].
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14 The other promising biofuel source can be cellulosic ethanol. There has been an
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16 increasing interest in the use of perennial grasses as energy crops in the US and Europe. The
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18 characteristics which make perennial grasses attractive for biomass production are its high yield
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20 potential, the high contents of lignin and cellulose and generally anticipated positive
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22 environmental impacts [12]. Also, a number of studies have suggested recently that marginal and
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24 abandoned lands could potentially be converted to cellulosic feedstock production which would
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26 avoid a large scale conversion of current crop land to biofuel feedstock production [13,14].
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31 To qualify as a viable supplement to fossil fuel, an alternative fuel should not only have
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33 superior environmental and economic benefits and potential of high production but also has
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35 energy gains over the energy sources used to produce it [15]. Net energy production has been
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37 constantly used to determine energy efficiency of ethanol production from cellulosic as well as
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39 grain crops such as corn [16]. In order to qualify for a promising alternative to fossil fuel, it is
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41 necessary for the biofuel to have a potential of offsetting cost of extracting and burning fossil
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43 fuel. The net energy benefit of replacing the fossil fuel will be determined by not only energy
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45 contained in biomass but also energy required to grow the biomass feedstock and convert in to
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47 usable form of energy [17]. Among the tools available for determining energy efficiency of
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49 ethanol production, Net Energy Value (NEV) is an important tool. NEV for ethanol production
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51 can be defined as the difference between output energy obtained from ethanol production and
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53 energy required to produce ethanol [18].
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4 Some of the previous studies have shown net energy gain from producing ethanol from
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7 cellulosic feedstock such as switchgrass as much as 343% [17]. Recent studies in modeling net
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10 energy continue to establish energy efficiency of cellulosic ethanol production. For example,
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12 Ferrell et al. [19] used Energy and Resource Group (ERG) Biofuel Analysis Meta Model
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14 (EBAMM). The study reported approximate 23 MJ/l of ethanol energy gain in cellulosic ethanol
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17 production. Other studies such as Schmer et al. [18] have reported the NEV in the similar range.
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19 Schmer et al. [18] studied 10 switchgrass farms established on marginal croplands ranging from
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22 3 to 9 ha with NEV of 21.5 MJ/L of ethanol. Swana et al. [20] compared the energy yield from
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25 lignocellulosic ethanol with corn-derived bioethanol and corn-derived biobutanol using Life
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28 Cycle Assessment (LCA). According to study findings, the energy gain was significantly higher
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30 in cellulosic ethanol (15.9 MJ/l for lignocellulosic ethanol).

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32 The variation in the net energy gains among different studies could partially be explained
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35 by the difference in the biomass yield. Biomass yield of both switchgrass and Miscanthus is
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38 sensitive to environmental factors such as temperature and rainfall, thus, could vary significantly
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41 from region to region. However, Miscanthus has found to have constantly higher biomass yield
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44 in compare to switchgrass (see for example; [21-23]. The net primary production of Switchgrass
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47 and Miscanthus is found to be highly sensitive to temperature [24] thus has higher productivity
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50 in temperate regions [25]. Also, the incremental biomass losses during harvest and storage can
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53 decrease effective yield at refinery gate. These losses will result in increased input used to
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56 produce per unit of ethanol [26].

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59 However, few studies i.e. [3,27] have reported a negative net energy or an energy loss for
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62 ethanol production from both grain crops and cellulosic feedstocks. These studies have further
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4 been criticized by other authors for using obsolete data, and incorrectly ignoring some important
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6 co-products [19].
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Methodology and Data Sources

To calculate Net Energy Value (NEV), both direct and indirect energy were considered. Direct energy in agriculture production is the energy that is used directly on farm (i.e fuel for operating machines, electricity and labor etc.). On the other hand, indirect energy is that embodied in inputs to a process. Energy embodied in a process is direct energy required in manufacturing of a particular input to that process plus energy embodied in inputs required in manufacturing that particular input [28]. For example, indirect energy in agricultural production is energy embodied in farm inputs such as machinery, fertilizer etc. Energy embodied in fertilizer is that required directly in fertilizer manufacturing and energy embodied in inputs to that process.

Therefore, NEV for biofuel can be described as:

$$NEV = \text{Total energy derived from biofuel} - \text{total energy used in biofuel production}$$

Energy input can be further segregated as follows (see [29] for details).

Total energy used in biofuel production (input energy)

$$E_{In} = E_S + E_I + E_M + E_F + E_{La} + E_T + E_P \quad (1)$$

Where:

E_L = Energy used in land preparation (MJ/ha)

E_S = Energy embodied in seeds (MJ/ha)

E_I = Energy embodied in applied inputs (fertilizers and herbicide) (MJ/ha)

E_M = Energy embodied in machinery (MJ/ha)

E_F = Energy embodied in fuel used By farm machinery (MJ/ha)

E_{La} = Energy embodied in farm labor (MJ/ha)

E_T = Energy used in transporting feedstock from farm to processing facility (MJ/ha)

E_P = Energy used in processing cellulose in to ethanol (MJ/ha)

a. Energy used in applied inputs

Energy used in applied input can be further divided in to energy used in solid input (fertilizer) and liquid input (pesticides).

$$E_I = E_s + E_l \quad (2)$$

Where:

E_s = *Energy of solid inputs* (MJ/ha)

E_l = *Energy of liquid inputs* (MJ/ha)

Energy in solid input can be derived as follows:

$$E_s = Q \times E_c \quad (3)$$

Where:

Q = *Quantity applied* (kg)

E_c = *Energy embodied per unit of fertilizer* (MJ/kg)

Embodied energy in fertilizer has been reported in table 1. All values were converted to the same unit of measurement for comparison purpose.

Table 1 here

Among the above mentioned studies, Bhat et al. [30] provides with detailed explanation of embodied energy calculations for fertilizers however the analysis was based on fertilizer production technologies in 1987. Their study reports total energy requirements for different nitrogen and phosphorus fertilizers and provides with the weighted average energy requirement of nitrogen and phosphorus nutrient. Shapouri et al. [31] used embodied energy in fertilizers based on an estimate done by Keith Stokes, President of the Stokes Engineering Company and fertilizer expert. However, in his later study [32] the data of manufacturing fertilizers and pesticides were based on Argonne's Green House Gases Regulated Emissions and energy use in transportation (GREET) model.

In this study, embodied energy calculations in fertilizers were based on FAO [33], Fertilizer input requirements for switchgrass and Miscanthus was based on [34,35] respectively. Herbicide requirement for both crops was based on [33]. Table 2 and 3 shows the embodied energy in fertilizer calculations for switchgrass and Miscanthus respectively.

Table 2 & 3 here

Energy in liquid inputs can be classified as:

$$E_l = (E_{CI} * \text{active ingredient} * VP * Q) / Va \quad (4)$$

Where:

E_{CI} = Energy embodied in pesticide per unit

V_P = Used volume (l)

Q = Application flow (l/second)

V_a = Volume to be applied (l)

b. Energy consumed by labor

Energy consumed by labor can be calculated by using following equation

$$E_L = (W * F_L) / A_W \quad (5)$$

Where:

W = Work hours per man (h/ha)

F_L = Energy consumed per person (MJ)

A_W = Area worked (ha)

c. Energy embodied in fuel consumed by farm machinery

Embodied energy in fuel was based on the per hectare fuel consumption for growing and harvesting feedstock.

$$\text{Tractor hour required} = \frac{\text{Distance travelled by tractor (meters)}}{\text{Tractor speed } (\frac{\text{meters}}{\text{hour}})} \quad (6)$$

$$\text{Average Fuel Consumption} = \text{Tractor HP} * \text{Diesel or gasolin consumption factor 3.25}$$

Diesel consumption factor = 0.04

Gasoline consumption factor = 0.06

$$\text{Fuel consumed} = \text{Tractor hour required} * \text{Average fuel consumption} \quad (7)$$

Accordingly,

$$E_f = TFC \times E \quad (8)$$

Where:

TFC = Total fuel consumption (g/ha)

E = 114,000 Btu/g

d. Energy embodied in seeds

d. Energy embodied in planting materials

Switchgrass is propagated through pure live seed (PLS). Energy embodied in switchgrass seed/hectare was calculated using equation below

$$E_s = \text{quantity of seed (Kg)} \times \text{Energy embodied/kg of seed} \quad (9)$$

Energy embodied/kg of seed was based on Schmer et al. [18].

Miscanthus is sterile plant and the most common method of propagation is by rhizome. Energy embodied in *Miscanthus* rhizome/hectare was calculated by estimating total number of rhizomes required per hectare (Table 4).

Number of rhizomes required to get density of 10,000 plants = 16,000 [36].

Number of rhizomes required to plant one hectare of land (i.e 19,768 plants) = 31,629

Total rhizome production per hectare was calculated by multiplying total plant population per hectare and rhizome yield/plant. Accordingly, 105,019 rhizomes will be sufficient to plant 5.31 ha. Total energy required to produce *Miscanthus* is 142,026 MJ/ha. This area will yield in rhizomes sufficient to plant 5.31 ha. So the energy required to produce rhizomes needed to plant one hectare would be $142,025.98 / 5.31 = 26,734.30$ MJ/ha

Table 4 here

e. Energy used for transportation and processing

Energy used in transporting bales from field to processing facility and conversion to ethanol was based on Schmer et al. [18]. These values were based on GREET (see [37]), Meta model [38] and Pimental et al. [3].

Accordingly, energy required for processing can be estimated as:

$$E_p = E_{ds} + E_{pc} + E_{pw} + E_{se} \quad 10$$

Where:

E_p = Energy of diesel use (MJ/ha)
 E_p = Energy of plant capitol and equipment (MJ/ha)
 E_p = Energy of processing water (MJ/ha)
 E_p = Energy of sewage effluent (MJ/ha)

f. Energy embodied in farm machinery

Energy embodied in machinery was calculated by using economic input-output life cycle assessment (EIO-LCA) model of Carnegie Mellon University (CMU). This model estimates the materials and energy resources required for, and the environmental emissions resulting from, activities in our economy (GDI-CMU). However the model does not provide with embodied energy in specific farm machinery for example tractors and harvesters. Model uses North American Industry Classification System (NAICS) 2002 and groups all farm machinery in to one sector “Farm Machinery and Input Manufacturing”. NAICS 2002 code for this sector is 333111.

Energy embodied in machinery was estimated using EIO-LCA model. Accordingly, energy embodied in machinery required for switchgrass (Table 5) and miscanthus (Table 6) production is 16,693 and 17,310 MJ/ha respectively.

Table 5 and 6 here

g. Energy embodied in labor:

Energy embodied in labor for cellulosic feedstock production was based on Pimental et al. [3]. Accordingly, the calculation for embodied energy in labor was based on the assumption that an average labor of 2,000 hr/yr and utilizes 1,934 MJ energy. The labor hours required per ha/yr are 12 hence the energy utilized by labor/(ha x yr) would be 0.20 MJ/ha.

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4 ***h. Energy embodied in farm buildings:***
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6 This study does not account energy embodied in farm buildings since previous studies have
7 suggested that embodied energy calculations for farm buildings are not necessary as they will be
8 used for several years and energy embodied will be distributed over those years hence energy
9 embodied in farm buildings per year will not be significant [32].
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Result and Discussion

Net energy value of ethanol production from switchgrass and *Miscanthus* are given in Table 7 and Table 8. Accordingly, estimated NEV for *Miscanthus* is higher compared to switchgrass because of higher biomass yield of *Miscanthus*. Total dry matter yield of *Miscanthus* per hectare is significantly higher in compare to switchgrass. This results in higher ethanol production and higher energy output per hectare for *Miscanthus*.

Table 7 and 8 here

For both switchgrass and *Miscanthus*, most energy intensive categories were farm machinery, fuel and fertilizers. Among the fertilizers, nitrogenous fertilizer is found to have higher contribution in GHG emission due to N₂O emissions [42]. Proper management of nitrogenous fertilizer and use the natural alternatives such as legume intercropping can significantly reduce its negative environmental impacts [43].

Both switchgrass and *Miscanthus* showed positive net energy value when used as feedstock for cellulosic ethanol production. Therefore, producing ethanol from both feedstocks would require less energy than it produces as an output. Positive NEV establishes switchgrass and *Miscanthus* as a promising biofuel feedstock. To determine the monitory benefits of energy saving to the society, value of net energy savings from switchgrass and *Miscanthus* were converted in to monetary values (Table 9). Accordingly, net returns ranged between \$426 and \$1,348 for switchgrass and *Miscanthus* respectively.

Table 9 here

Conclusion and Recommendations

The main objective of this study was to analyze environmental feasibility of production of switchgrass and *Miscanthus* accounting net energy balance. Large scale feedstock development project would cause physical, environmental and socio-economic impacts which are inter-related. Physical changes for example include landscape changes including groundcover, soil and water resources. Soil compaction due to daily running of truckloads of bulky feedstock from production sites and processing plants would account as regional impacts. Physical changes may affect use of resources hence environmental changes are partly due to physical changes which include loss of biodiversity, ground water pollution, issues of soil acidity and salinity and waste of biofuel production. There will be on-site effects as well as off-site effects. Net energy balance and carbon balance are two important areas to be considered when studying the impact of cellulosic feedstock to the environment. The prime reason for investigating biofuel as an alternative to fossil fuel is saving non-renewable energy with lesser negative impact on environment. A positive net energy value (NEV) is an indicator of net energy gain in the whole process. In case of cellulosic ethanol production, a positive NEV shows that energy output is greater than energy input. On the other hand, a negative value will imply unsustainability of a production process.

In this analysis, NEV for both switchgrass and *Miscanthus* was positive. However, NEV for *Miscanthus* was higher (11.99 MJ/l of ethanol) in compared to switchgrass (8.80 MJ/l of ethanol). A positive NEV also establishes both switchgrass and *Miscanthus* as potential biofuel feedstock. To determine benefits of energy savings to the society, net energy gains from switchgrass *Miscanthus* were converted in to monetary terms. Net energy gains were found to be in the range of \$426 and \$1,348/ha for switchgrass and *Miscanthus* respectively.

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4 According to Ethanol Across America [44], energy consumption in ethanol plants has been on a
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6 steady and remarkable decline. For example, total energy use for fossil energy and electricity has
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8 decreased by 21.8% and 7.2% for dry and wet mills respectively based on survey data analyzed
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10 by the Center for Transportation Research at Argonne National Laboratory. As the ethanol
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12 industry has grown, efficiency has increased dramatically. Modern ethanol plants are spaced age
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14 compared to the first generation plants and this must be kept in mind when understanding the
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16 true net energy of ethanol.
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21 As mentioned by Ethanol Across America [44], a frequently overlooked area in the ethanol
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23 energy balance is that of ethanol co-products such as carbon dioxide used in the food and
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25 beverage industry as well as industrial uses. Ethanol plants are producing products that are in
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27 demand worldwide. This means that the energy used in the production of these products must be
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29 factored in as energy credits when quantifying the ethanol energy balance. It is common sense: if
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31 everything coming out of the process is not ethanol, then all the energy going in cannot be
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33 attributed to ethanol production [44].
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38 Our analysis include energy required to produce machinery, farm equipment, conversion
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40 facilities, and other related capital factors which have been omitted in some related studies [45].
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42 The analysis included input data in recent recommendation hence estimated are current. The
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44 model variables and detailed estimation procedures were clearly stated as a reference for similar
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46 studies. Energy embodied in plant materials is not common in literature. For example, we have
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48 accounted energy embodied in Miscanthus rhizomes and switchgrass seeds in our analysis.
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57 funding this research.
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Table 1: Estimated embodied energy in Nitrogen, Phosphorus and Potassium

Source	Unit	Nitrogen	Phosphorus	Potassium
[33]	MJ/kg	65	9	6
[3]	MJ/kg	67	17.39	13.68
[31]	MJ/kg	56.84	9.2	6.96
[30]	MJ/kg	55.48	4.52	4.80
[32]	MJ/kg	42.71	2.17	12.45

Table 2: Energy embodied in fertilizers for switchgrass production:

Fertilizer and herbicide quantity needed/ha			Energy embodied/kg of fertilizer and herbicide		Energy required (MJ/ha)
Category	Quantity (kg/ha)	Source	Value (MJ/kg)	Source	
Nitrogen	68.03	[34]	65	[33]	4421.63
P ₂ O ₅	45.35		9		408.15
K ₂ O	90.70		6		544.20
Herbicide	12.5	[33]	240		3,000
				Total	8,373.98

Table 3: Energy embodied in fertilizers for Miscanthus production

Fertilizer and herbicide quantity needed/ha			Energy embodie/kg of fertilizer and herbicide		Energy required (MJ/ha)
Category	Quantity (kg/ha)	Source	Value (MJ/Kg)	Source	
Nitrogen	146.51	[35]	65	[33]	9523.07
P ₂ O ₅	24.42		9		219.76
K ₂ O	130.23		6		781.38
Herbicide	12.50	[33]	240		3,000
Total					13,524.21

Table 4: Energy required for *Miscanthus* rhizome production

Category	Unit	Amount	Source
Rhizomes Required	ha	19768.41304	[36]
Rhizome Yield	plant	8.50	[46]
Plant population	ha	12,355.25	[46]
Rhizome production	ha	105,019.69	
Hectares can be planted from 42,500 rhizomes	ha	5.31	
Energy Required to produce <i>Miscanthus</i> plants/hectare	MJ/ha	142,025.97	
Energy required to produce rhizome needed per hectare	MJ/ha	26,734.30	

Table 5: Machinery used for switchgrass production

Machinery name	Specification	Cost of new equipment		Life in hours	Hours required/ha
		Value (\$)	Source		
Farm tractor	160 HP	146,000	[39]	4,000	
Mini till planter	12 raw, 9.1 m	85,000		1,000	1.96
Tandem disk	6.4 m rigid	36,500		1,000	1.38
Boom sprayer	27.4 m	43,000		200	0.46
Rotary mower	3.0 m	20,000	[40]	2,500	4.13
Rake, twin wheel	3.0 m	6,000		2,500	4.12
Large square baler	(1.2X1.2X2.4) m	67,000		3,000	10.31
Total cost		403,500	Total hrs/ha		22.36

Table 6: Machinery used for Miscanthus production

Machinery name	Specification	Cost of new equipment		Life in hours	Hours required/ha
		Value (\$)	Source		
Farm tractor	160 HP	146,000	[39]	4,000	
Potato planter (4 rows)	3.6 m	55,000	[41]	1,000	0.57
Tandem disk	6.4 m rigid	36,500	[39]	3,000	1.38
Boom sprayer	27.4 m	43,000		200	0.46
Forage harvester	315 HP SP forage harvester base unit	200,000		2,500	4.13
Rake, twin wheel	3.0 m	6,000	[40]	2,500	4.12
Large square baler	(1.2X1.2X2.4) m	67,000		3,000	10.31
Total cost		559,500	Total hrs/ha		21.55

Table 7: Net Energy Value of ethanol production from switchgrass

Input Category	Energy (MJ/ha yr ⁻¹)	Energy (MJ/l of ethanol)
Fertilizer and herbicides	8,277	2.12
Machinery	16,693	4.28
Diesel	12,262	3.15
Gasoline	4,533	1.16
Labor	0.20	-
Seed	294	0.08
Transporting feedstock	2,456	0.63
Processing	4,210	1.08
Total energy input	48,728	12.50
Total energy output	8,3031	21.30
NEV	3,430	8.80

Table 8: Net Energy Value of ethanol production from *Miscanthus*

Input category	Energy (MJ/ha yr ⁻¹)	MJ/l of ethanol
Fertilizer	13,367	1.48
Machinery	17,309	1.91
Diesel	7,363	0.81
Gasoline	3,954	0.44
Labor	0.21	0.00
Rhizome	26,734	2.95
Transporting feedstock	5,703	0.63
Processing	9,776	1.08
Total energy input	84,210	9.30
Total energy output	192,785	21.30
NEV	108,575	11.99

Table 9: Economic benefits of energy savings

Category	Unit	Feedstock	
		Switchgrass	Miscanthus
Net returns	\$/ha	2,958	4,514
Average Ethanol Yield	gal/ha	1031	2,395
Energy yield	Btu/ha	78,698,998	182,725,685
Net Energy Value	Btu/ha	32,512,973	102,909,812
Value of energy savings	\$/ha	426	1,348