Original Research Article

Energy Balance of Hemp (*Cannabis sativa* L.) Grown for Energy Purposes

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Abstract

This article discusses the energy balance of the hemp biomass from the autumn and spring harvest which was used for the production of briquettes. The hemp plant (*Cannabis sativa* L.) used in this work is the variety Bialobrzeskie that was harvested on a trial plot in Prague-Suchdol in 2009 - 2010. Moisture content (MC), gross calorific value (GCV) and other technical parameters were evaluated for samples from the harvest of both periods. The autumn harvest results led to the assumption that the gross energy yield of the culture per superficies was 186.3 GJ ha⁻¹. As compared to the previous results the spring harvest gave a gross energetic output of 161.4 GJ ha⁻¹. The autumn harvest required more energy inputs compared to the spring harvest with values of 22.2 GJ ha⁻¹ and 16.9 GJ ha⁻¹ respectively. The most energy-consuming aspects of the biomass production were fuels (autumn) and the energy linked to the chemicals used (spring). Regardless of the higher net energy yield in autumn it was found that a spring harvest should be preferred because of its Energy Return on Energy Invested (EROEI) is 8.6. This is higher than for the autumn harvest (7.4).

Keywords: autumn harvest; energy input; energy output; EROEI; gross calorific value; solid biofuels; spring harvest.

INTRODUCTION

The efforts of most industrialized countries around the world to use fossil fuels more efficiently as well as to replace them with renewable sources of energy have attracted scientific research towards testing energy crops whose potential can be ranked higher than other renewable sources of energy (Prade et al. 2011). Most of the research published in the available literature focuses primarily on the evaluation of the potential of the energy crop according to the following criteria: energy balance, tonnage value and productivity as well as environmental impact (Prade et al. 2012; Kreuger et al. 2011; Gill et al. 2011).

Hemp (*Cannabis sativa*) is a plant that has been prohibited for years in relation to the psychoactive effect of some of its secondary metabolites – terpenoids (Sladký, 2004). However, it has been experiencing a worldwide revival in the last 10 years (Prade et al. 2011). This crop and most of the industrial situations involving it is currently grown mainly for the production of its very tough fibers that are unique in composition as well (Li et al. 2012). Such a situation is, from an energy point of view, not endowed to many crops. Hemp can also be used as a feedstock for the production of solid biofuels - briquettes and pellets (Prade et al. 2011) as well as a source of biomass for biogas generators (Kreuger et al. 2011a). Prade et al. (2012) evaluated the physical and chemical properties of solid biofuels. They mentioned that these attributes influence suitability and competitiveness among solid biofuels. However, the above mentioned

physical properties (particle size, bulk density, angle of repose and bridging tendency) can be changed by specific treatment processes (grinding, milling or compaction), but its chemical properties (content of major alkali and earth alkali metals) are hard to change once the crop has been harvested (Prade et al. 2011).

Furthermore, because of the high concentration of cellulosic fibers thus glucose, hemp could be a suitable second generation crop for the production of cellulosic ethanol (Kreuger et al. 2011b).

Finally, adding to the potential of hemp on the energy market, seeds can also be used for energy production since the oil they contain could be converted into biodiesel (Gill et al. 2011). Available literature resources mainly discuss the optimization, oil characteristics and fuel property analysis made of these oils and their blends (Gill et al. 2011).

Industrial hemp is well known for its high productivity as well as gross calorific value, which can be compared to wood (Prade et al. 2011). The uniqueness of this plant lies in its ability to yield more than 24 tons of green biomass per hectare (corresponding to 10.9 t ha⁻¹ of dry biomass) within 120 days. The high energy potential of hemp and lack of information about its cultivation, harvest and environmental suitability has led to further research to obtain new information.

The main objective of this work is to do a system analysis – energy effectiveness (EROEI) of hemp biomass from both the autumn and spring harvest for the production of solid biofuel-briquettes.

MATERIALS AND METHODS

A variety of hemp of Polish origin (Białobrzegie) was harvested in the Prague area (Suchdol) in 2009 and 2010 in order to obtain biomass for the energy yield evaluation of the spring and autumn harvests. Its row spacing was 12.5 cm, seeding rate 60 kg ha⁻¹ and sowing depth 3 cm. The fields were located at 50°7'N, 14°22'E and at an altitude of 285 m over sea level. The growing season¹ lasting 184 days (May - October) had precipitation 358 mm during the vegetation period and an average temperature of 15.8 °C. The spring harvest was done in March 2010, with the growing season of 298 days seeing a total precipitation of 389 mm and an average temperature of 7.9 °C during the growing period.

Hemp was grown on a trial plot of 100 m² and the energy yields of the small-scale samples from the spring and autumn harvests were extrapolated to an energy yield per hectare.

Sample analyses

Biomass yields were determined by collecting and weighing all plants. The plants used for sampling were harvested on a 0.5 m × 0.5 m square and hand-cut down to ground level whilst the different plant parts (leaves, stems and grains) were separated. Samples for MC analysis were dried at a temperature of 105 °C for 8 hours in an automatic hot air dryer until they reached a constant weight.

The MC (the quantity of water in raw material) was determined by formula 1

$$MC = \frac{(m_v - m_0)}{m_v} \cdot 100 [\%] \quad 1$$

Where: m_v – mass of moist sample [kg]
 m_0 – mass of dry sample [kg]

The laboratory measurement of the gross calorific values in MJ kg⁻¹ was carried out in an adiabatic calorimeter type MS 10A from LAGET, Ltd. All calorimetric measurements were repeated 15 times and the results were statistically processed using ANOVA statistical analysis software.

Biomass energy yield calculation

With use of the MC values the dry matter yield (DM) was calculated by use of the following formula:

$$DM = (100 - w / 100) \cdot BY [t \cdot ha^{-1}] \quad 2$$

Where: w – moisture content [%]
 BY – biomass yield [t ha⁻¹]

¹Growing season – period from sowing till harvesting

The biomass gross energy yield (BEY) per hectare describes the total mass of energy stored in biomass (potential energy yield). It was calculated by multiplying the dry matter (DM) yield by corresponding gross calorific value (GCV), i.e.:

$$BEY = GCV \cdot DM [GJ \cdot ha^{-1}] \quad 3$$

The system boundaries

The system analysis was conducted on the whole range of operations from the soil preparation to biomass briquetting. However, the energy balance does not include: solar energy (participating as photosynthesis) and the efficiency of briquette combustion. It is also worth mentioning that no harvest losses that might occur during harvest at large-scale production were taken into account.

Technological process of hemp cultivation

The energy efficiency was determined by extrapolating the gained results onto a large-scale production technology. The chronological sequences of technological operations (fertilization, soil preparation, sowing, harvesting, transport and field treatment after harvest) as well as the repeatability of operations (how many times the same operations were repeated) and material inputs (material name, unit of measure and quantity per hectare) were provided by the Research Institute of Agricultural Engineering in Prague-Ruzyně (Abraham et al. 2009). All procedures were based on average conditions and intensity of production.

The energy balance calculations

The energy balance calculations were conducted according to the methodology of Preininger (1987) which counts energy outputs (gross potential energy yield – BEY) and energy inputs (EI), both of them in GJ ha⁻¹.

The amount of energy inputs (EI) was determined as the conversion of spent labour and materials (hours of human labour, kWh, kg, etc.) in the energy equivalent or the conversion coefficient (see formula 4). Energy equivalents as well as conversion coefficients were taken from the listed references (see Table 1 and Table 2). Direct energy inputs include that of human labour (E_1) and energy in fuels (E_2). Indirect energy inputs consist of energy embedded in machines (E_3), in seeds (E_4), and in fertilizers (E_5). (For E_1 - E_5 see formulas 5 - 9).

$$EI = E_1 + E_2 + E_3 + E_4 + E_5 [GJ \cdot ha^{-1}] \quad 4$$

$$E_1 = S_{hl} \cdot e_{hl} [GJ \cdot ha^{-1}] \quad 5$$

Where: S_{hl} – spent human labour per hectare (h ha⁻¹)
 e_{hl} – energy equivalent of human labour (MJ h⁻¹)

Table 1: Energy conversion equivalents

Item	Unit	Energy equivalent	Source
Human labour	1 h	2.3 MJ h ⁻¹	Bechnik (2009)
Diesel	1EQF	35.8 MJ l ⁻¹	Špička, Jelínek (2008)
Electricity	1kWh	3.6 MJ (kWh) ⁻¹	Preininger (1987)
Steel	1 kg	25 MJ kg ⁻¹	Hill et al. (2006)
Seeds	1 kg	22.9 MJ kg ⁻¹	Abraham et al.(2009)
<i>Fertilizers</i>			
P (P ₂ O ₅)	1 t	5394 MJ t ⁻¹	Špička, Jelínek (2008)
K (K ₂ O)	1 t	12 100.4 MJ t ⁻¹	Špička, Jelínek (2008)
Ca (CaO)	1 t	2799.5 MJ t ⁻¹	Špička, Jelínek (2008)
N (100%)	1 t	82 500 MJ t ⁻¹	Špička, Jelínek (2008)
Superphosphate (19% of P ₂ O ₅)	1 t	1024.9 MJ t ⁻¹	Own calculation
Limestone (87.5% of CaO)	1 t	2449.6 MJ t ⁻¹	Own calculation
Ammonium sulphate (21% of N)	1 t	17 325 MJ t ⁻¹	Own calculation
Potassium salt (60% of K ₂ O)	1 t	7260 MJ t ⁻¹	Own calculation
Farmyard manure	1 t	463 MJ t ⁻¹	Preininger (1987)

Note: Note: EQF - unit is equal to 1.17 liters of fuel where 0.17 corresponds to the energy for mining, refining and transport of one liter of fuel

Table 2: Energy equivalents for energy inputs embodied in machines and equipments

Tractors	95.7 MJ kg ⁻¹
Ploughing machines and equipment	99.2 MJ kg ⁻¹
Sowing machines and equipment	95.4 MJ kg ⁻¹
Spreaders	95.4 MJ kg ⁻¹
Harvesters, mowing machinery	83.5 MJ kg ⁻¹

Source: Špička and Jelínek (2008)

Where: S_{fe} – fertilizing rate (kg ha⁻¹)
e_{fe} – energy equivalents (MJ kg⁻¹)

Indirect energy in machines and used materials

The operational (working) requirements of each operation as well as the necessary material inputs were determined according to common agricultural practice and recommended for hemp cultivation in the Czech Republic. The recommended operational time for the yearly utilization of the machines and time periods for working operations were calculated according to Kavka (2008). The machinery lifetime was considered as 15 years, reported as the world's average (Hill et al. 2006; Špička and Jelínek 2010). The indirect energy in briquetting press set was taken as the basis of energy needed for steel production plus 50% according to Hill et al. (2006). The mass of the equipment was estimated on the basis of individual components. The lifetime was again considered to be 15 years with an annual use of 350 days/16 hours a day (Hill et al. 2006; Špička and Jelínek 2010).

For both kinds of harvest there were included following items (all per hectare and year): superphosphate 0.25 t, potassium salt 0.1 t, farmyard manure 4.5 t, ammonium sulphate 0.3 t; limestone 0.2 t; stubble treatment, ploughing, seedbed preparation, sowing, rolling, chopping, compressing, loading (2 times), transport to processing. Briquetting lines consisted of separator and crusher; desiccators included for autumn harvest only.

$$E_2 = S_f * e_{ff} + S_e * e_e \text{ [GJ ha}^{-1}\text{]} \quad 6$$

Where: S_f - fuel consumption (l ha⁻¹)
e_{ff} – energy equivalent of fuels (MJ l⁻¹)
S_e – consumed electricity per hectare (kWh ha⁻¹)
e_e - energy equivalent of electricity (MJ kWh⁻¹)

$$E_3 = W * K_e * T_s * K_{rm} / T_{wh} \text{ [GJ ha}^{-1}\text{]} \quad 7$$

Where: W –weight (mass) of machines (kg)
K_e – conversion equivalent (MJ kg⁻¹)
T_s – time spent on operation (h)
K_{rm} – repairing and maintenance coefficient
T_{wh} – total number of working hours per machine's service life (h)

$$E_4 = S_s * e_s \text{ [GJ ha}^{-1}\text{]} \quad 8$$

Where: S_s –seeding rate (kg ha⁻¹)
e_s – energy equivalent (MJ kg⁻¹)

$$E_5 = S_{fe} * e_{fe} \text{ [GJ ha}^{-1}\text{]} \quad 9$$

Energy yields

The energy balance was calculated as the difference between the energy outputs (BEY) and energy inputs (EI).

Energy return on energy invested (EROEI)

The parameter EROEI or energy efficiency is ratio of energy yield and energy inputs:

$$\text{EROEI} = \frac{\text{energy yield (E}_y\text{)}}{\text{energy inputs (E}_i\text{)}} \quad 10$$

RESULTS

Energy outputs

Autumn harvest

It was produced 24.3 t ha⁻¹ of green and 10.9 t ha⁻¹ of dry biomass during the growing season lasting 184 days. The gross calorific value was 17 GJ t⁻¹, which determined the maximum potential energy yield of 186.3 GJ ha⁻¹.

Spring harvest

The spring harvest was 10.3 t ha⁻¹ of biomass yield with a moisture content of 19 % and a GCV of 19.3 GJ t⁻¹ which determined maximum potential biomass energy for this kind of harvest 161.4 GJ ha⁻¹.

The energy output of the Bialobrzeskie variety of hemp from the autumn harvest was significantly higher than that from the spring harvest (difference of 24.9 GJ) due to mass losses during the winter period.

Energy inputs calculated as a sum of partial energy items

Autumn harvest

The energy expenditure for hemp taken from the autumn harvest were 22 154 MJ ha⁻¹ of which fuels (10 957 MJ ha⁻¹), energy in fertilizers (8753 MJ ha⁻¹), seeds (1371 MJ ha⁻¹), machinery (955 MJ ha⁻¹) and human labour (119 MJ ha⁻¹) respectively representing, 49.5 %, 39.5 %, 6.2 %, 4.3 %, and 0.5 %, of the energy inputs. For the autumn harvest the main energy consumption was related to electricity (8288 MJ ha⁻¹), which corresponds to 75.6 % of all the fuel energy consumption. This energy was mainly used in briquetting equipment, including high power inputs for the separator, crusher and desiccators.

Spring harvest

The consumed energy for the spring harvest was 16 849

MJ ha⁻¹ of which fuels (5663 MJ ha⁻¹), energy in fertilizers (8753 MJ ha⁻¹), seeds (1371 MJ ha⁻¹), machinery (960 MJ ha⁻¹) and human labour (104 MJ ha⁻¹) respectively representing, 33.6 %, 52 %, 8.1 %, 5.7 %, and 0.6 %. The spring harvest consumed 2994 MJ ha⁻¹ of electricity and 2669 MJ ha⁻¹ of fossil fuels (mainly diesel) for engines. There is a significant reduction in electricity due to the elimination of desiccators, as this was not a necessity because of low moisture content (19 %).

Generally, the agro-chemicals and organic-fertilizers used (farmyard manure production) represented the largest proportion of the energy inputs. The share of each component in the energy outputs is as follows: Ammonium sulphate (59 %), farmyard manure (24 %), potassium salt (8 %), limestone used for liming (6 %) and superphosphate (3 %).

The total hemp energy inputs per hectare for the autumn harvest are significantly higher than those from the spring harvest due to the higher mass moisture content of the winter harvest and the necessity of drying the biomass.

Energy yields and energy return on energy invested

The difference between energy output and energy inputs has been calculated as 164.1 GJ ha⁻¹ for the autumn harvest and 144.5 GJ ha⁻¹ for the spring harvest. The EROEI was determined to be 8.6 for the spring and 7.4 for the autumn harvests. Regardless of the higher energy yields in autumn compared with spring, it was found that, for the given conditions, the spring harvest should be preferred because of its energy efficiency, which is higher than for the autumn harvest. The considerably lower energy input at the spring harvest causes the EROEI ratio to be more favorable despite a lower mass yield. The difference between the two harvests is significant, and the technology feasibility is better at the spring harvest.

DISCUSSION

The biomass yield and gross calorific value for industrial hemp are the most important output factors affecting the overall better efficiency. The yield can be influenced by several factors including weather conditions (precipitation and temperature), sowing rate, period of sowing, time of harvest and soil fertility. Several authors found that GCV could also be influenced by the time of harvest (Prade, 2011; Stražil, 2005).

The hemp was grown in trials under a temperature sum, which can be considered as the average of the most suitable conditions. Although the temperature was suitable, precipitations and dryness during germination was not ideal for hemp, in terms of growth and biomass yield. None of the

experiments met the requirements as for the recommended 500 mm of precipitation per growing season (Sladký, 2004).

In autumn, the moisture content of the plants was relatively high as was the production of biomass itself. In the spring, yields were lower and the humidity also decreased significantly. The GCV values were lower in the autumn than in spring. All the results obtained during this experimental work were comparable to similar experiments done by Prade et al. (2011) with a significant increase from 17.5 MJ kg⁻¹ in July to an average of 18.4 MJ kg⁻¹ during the period ranging from August to December and a further increase to an average of 19.1 MJ kg⁻¹ during the January - April period.

The industrial hemp grown in Prague provided BEY comparable to Stražil (2005). He mentioned a DM yield of 10.3 t ha⁻¹ for the autumn harvest and 7.1 t ha⁻¹ for the spring harvest. The biomass GCV available in the field according to Swedish research was 148.9 GJ ha⁻¹ for the spring harvest (Prade et al. 2011). These authors also take into account harvestable biomass (which is 75% of potential biomass yield) and losses during combustion (20.5%). Our system analysis did not take into account the already mention losses due to uncertainties in calculations.

Therefore, the depending on the intended biomass use, it is crucial to find a compromise between the date of harvest, moisture content and loss of carbon-related mass. There are some criteria for the raw materials used for solid biofuel production: biomass moisture content should not exceed 20% (this eliminates the final drying stage), high yield, higher gross heating value.

The major share in energy consumption at the autumn harvest was fuel energy, the main share of which was represented by electricity used in briquetting, including high power separator, crusher and desiccators (47 kW). For the biomass with a moisture content over 20%, additional energy inputs must be considered for the drying, which is characterized by high-energy demands. In the case of hemp, the majority of the electricity consumption occurs in the desiccators (2.7 GJ ha⁻¹). This can be reduced by using passive drying (storage under a roof or in a barn) or using different types of desiccators drying in cold air thus consuming less energy.

For the industrial hemp grown for biomass production, the volume of chemical products and organic fertilizers used results in 8.8 GJ ha⁻¹, compared with Stražil (2008) – 10.9 GJ ha⁻¹. It would also be possible to decrease the amount of fertilizer used. As Prade et al. (2012) wrote, nitrogen, which is a major part of energy inputs need not to be a limiting factor for hemp cultivation.

Proportionally, the smallest part of energy inputs is the human labour necessary. However, this part of direct inputs is important for the inventory analysis, by which it is possible to work out the economic balance, where the number of

working hours and the related costs are important. The amount of human labour energy depends on the appropriate energy equivalent. According to Bechnik (2009) this experiment takes into consideration an energy equivalent of 2.3 MJ h⁻¹ which is determined according to the recommended energy consumption per worker (14 MJ per day) plus the energy necessary for its food production in the Czech Republic. Its value mainly depends on the intensity of production using fertilizers and the system of crop rotation. For comparison, this value is 5.6 MJ h⁻¹ in the U.S. (Bechnik, 2009). Preininger (1987) used the value 25.7 MJ ha⁻¹, including both the direct energy expended in the process as well as energy for reproduction of human labour as well.

The EROEI is a method for the evaluation of energy efficiency that could be applied to energy production. The output/input energy ratio is proposed as the most comprehensive factor permitting to assess sustainability. The EROEI compared to other energy crops cultivated under similar conditions based on the high level of mechanization, average conditions, the intensity of production and system of crop rotation is as follows: *Miscanthus* -20.1 (Stražil, 2008), Rapeseed (*Brassica napus*) -6.7 (Stražil, 2008), *Camelina sativa* -8.9 (Stražil, 2008). The lower EROEI is mainly caused by the lower yields and the higher energy inputs for different kind of utilization in the case of biodiesel (rapeseed, camelina). Higher EROEI – *Miscanthus*, which can be processed into briquettes as well, does not require annual energy inputs. For that reason, we can state that industrial hemp can be placed among energy crops with slightly above-average energy crops.

In conclusion, this article tackles an issue largely discussed by researchers but rarely tested. The energy balance and energy efficiency are crucial to solving many problems – they indicate how much energy is produced by the crop per unit of energy input; the energy balance can reveal existing reserves and optimize energy inputs in the manufacturing process. The inventory analysis serves well as a measure of the economic balance as well as the environmental impact evaluation and possibility of CO₂ (greenhouse gases) reduction.

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