Applied Energy 111 (2013) 862–870

Contents lists available at SciVerse ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Energy and climate benefits of bioelectricity from low-input short rotation woody crops on agricultural land over a two-year rotation ☆

S. Njakou Djomo [a,*], O. El Kasmioui [a], T. De Groote [a,b], L.S. Broeckx [a], M.S. Verlinden [a], G. Berhongaray [a], R. Fichot [a], D. Zona [a], S.Y. Dillen [a], J.S. King [c], I.A. Janssens [a], R. Ceulemans [a]

[a] University of Antwerp, Department of Biology, Research Group of Plant and Vegetation Ecology, Universiteitsplein 1, B-2610 Wilrijk, Belgium
[b] VITO, Unit Environmental Modelling, Boeretang 200, B-2400 Mol, Belgium
[c] North Carolina State University, Department of Forestry and Environmental Resources, Raleigh, NC 27695, USA

HIGHLIGHTS

- A full energy and GHG balance of bioelectricity from SRWC was performed.
- Bioelectricity was efficient; it reduced GHG by 52–54% relative to the EU non-renewable grid mix.
- Bioelectricity required 1.1 m^2 of land kWh^{-1}; land conversion released 2.8 ± 0.2 t CO_{2e} ha^{-1}.
- SRWC reduced GHG emission when producing electricity during the 1st rotation period.

ARTICLE INFO

Article history:
Received 5 November 2012
Received in revised form 4 May 2013
Accepted 7 May 2013

Keywords:
Direct land use change
Eddy fluxes
Life cycle assessment
Energy ratio
GHG emissions

ABSTRACT

Short-rotation woody crops (SRWCs) are a promising means to enhance the EU renewable energy sources while mitigating greenhouse gas (GHG) emissions. However, there are concerns that the GHG mitigation potential of bioelectricity may be nullified due to GHG emissions from direct land use changes (dLUCs). In order to evaluate quantitatively the GHG mitigation potential of bioelectricity from SRWC we managed an operational SRWC plantation (18.4 ha) for bioelectricity production on a former agricultural land without supplemental irrigation or fertilization. We traced back to the primary energy level all farm labor, materials, and fossil fuel inputs to the bioelectricity production. We also sampled soil carbon and monitored fluxes of GHGs between the SRWC plantation and the atmosphere. We found that bioelectricity from SRWCs was energy efficient and yielded 200–227% more energy than required to produce it over a two-year rotation. The associated land requirement was 0.9 m^2 kWh_e^{-1} for the gasification and 1.1 m^2 kWh_e^{-1} for the combustion technology. Converting agricultural land into the SRWC plantation released 2.8 ± 0.2 t CO_{2e} ha^{-1}, which represented ~89% of the total GHG emissions (256–272 g CO_{2e} kWh_e^{-1}) of bioelectricity production. Despite its high share of the total GHG emissions, dLUC did not negate the GHG benefits of bioelectricity. Indeed, the GHG savings of bioelectricity relative to the EU non-renewable grid mix power ranged between 52% and 54%. SRWC on agricultural lands with low soil organic carbon stocks are encouraging prospects for sustainable production of renewable energy with significant climate benefits.

1. Introduction

Renewable electricity represented 19.6% of the European Union (EU) grid mix power generation in 2009 [1]. Limited in natural resources, the EU imports large quantities of non-renewable fuels for its electricity production. Shifting electricity production away from non-renewable fuels towards renewable energy sources could increase the diversity of the generation mix, reduce the import bills, and help to mitigate climate change [2,3].

Biomass has the potential to provide non-intermittent renewable base-load electricity and thus could contribute to meeting the EU's renewable energy targets in 2020 [4–6]. Within the biomass portfolio, short-rotation woody crops (SRWCs) with e.g. poplar (*Populus*) or willow (*Salix*) are candidates for large-scale application [7,8]. Compared to food crops SRWCs require low agrichemical inputs and less fertile land. Wood chips from SRWC can be burned, gasified, or co-fired with coal to produce electricity. In

* Corresponding author. Tel.: +32 3 2652827; fax: +32 3 2652271.
E-mail address: sylvestre.njakoudjomo@ua.ac.be (S. Njakou Djomo).

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http://dx.doi.org/10.1016/j.apenergy.2013.05.017

addition to the non-renewable electricity offsets, SRWC may also store carbon in agricultural soils [9,10], thus helping to reach the EU climate and renewable energy policy targets, whilst maintaining a reliable electricity system.

The greenhouse gas (GHG) performance of bioelectricity from SRWCs can also be affected by carbon stock changes due to land conversion from the previous land use. Converting agricultural lands to SRWC plantations may lead to losses of soil organic carbon (SOC) within the first two years following soil disturbance, although these changes are seldom statistically significant due to the high background variability in soil carbon stocks [10–12]. Such losses of carbon due to land use changes can compromise or even cancel the GHG saving benefits of bioenergy [13,14]. Also, biogenic methane (CH_4) and nitrous oxide (N_2O) emitted during crop production may outweigh the GHG benefits of SRWC-based bioelectricity [15]. Thus, an analysis of bioenergy impacts should consider its full life-cycle costs and benefits before policies aiming at large scale commercialization are adopted and implemented.

Much of the existing science on the energy and GHG performance of bioenergy has focused on liquid biofuels [16,17] with fewer studies investigating the energy and GHG balances of bioelectricity from SRWC [18–22]. The majority of these studies in turn have concentrated on CO_2 emissions from fossil fuel combustion during management activities rather than biogenic GHG emissions from land use change. Direct land use change (dLUC) emissions have been particularly neglected [23], even though the initial loss in soil organic carbon (SOC) as well as emissions of CH_4 and N_2O from agricultural soils may be substantial [24]. Moreover, the accounting of farm labor inputs, and land requirement are missing in earlier studies. Furthermore, the lack of reliable measurements of GHG fluxes (CO_2, CH_4, and N_2O) during the SRWC production increases the degree of uncertainty of previous estimates.

Here we report and document quantitative data on the land requirement, energy yield and GHG offsets of bioelectricity production from SRWCs on former agricultural land. In order to obtain quantitative data on the land requirement, energy yield, and GHG offsets of bioelectricity from SRWC, we managed an industrial-sized SRWC plantation for bioelectricity production without supplemental irrigation or fertilization for two years. We included all energy and GHG emissions incurred during the production and conversion of biomass from SRWCs to bioelectricity.

2. Materials and methods

2.1. Site location, soil carbon, and plant material

An operational SRWC plantation was installed in Lochristi, Belgium (51°06′N, 3°51′E, 6.25 m asl). The long-term mean annual temperature was 9.5 °C and the average rainfall was 726 mm a^{-1} [25]. The soil texture in the top 30 cm was 86.8% sand, 11.4% clay, and 1.8% silt with a mean pH of 5.51 (Table S1). The region of the site is considered to be a sandy region with a poor drainage [26]. Historically, the site was cleared of the original forest in the early 20th century and has since been under agricultural land use, regularly plowed and fertilized at 200 kg N ha^{-1} for production of cereals (wheat and maize) and tuberous (potatoes) crops. Prior to deep plowing, we carried out detailed soil survey in March 2010 by analyzing soil samples taken at 110 locations, uniformly distributed over the agricultural land. Soils were sampled to a depth of 15 cm using core sampling. The conversion of the agricultural land

Table 1
General inventory data for the production of short rotation woody crops. The columns from left to right denote the field activities, the implement used, tractor used, the operating rate, total fuel consumption, the area covered, and the material inputs.

Activities	Implement used		Tractor used			Operating rate ($h\ ha^{-1}$)	Total fuel consumption (l)	Total lubricant consumption (l)	Coverage (%)	Input rates (unit ha^{-1})
	Type	Weight (kg)	Type	Weight (kg)	Power (kW)					
Chemical treatment	HBS	800	Fendt V 415	7000	119	0.43	42	0.3	32	3.5 l
Deep plowing	PF	820	Fendt V820	9000	157	0.95	105	2.1	32	–
Plowing	CP	820	Fendt V820	9000	157	0.93	285	5.0	100	–
Flattening	R	716	Fendt V415	7000	119	0.72	242	4.4	100	–
Planting	LP	600	Massey F6480	5000	97	3.44	302	5.2	78	8000 cuttings
Application of PPEH	HBS	800	Fendt V415	7000	119	0.21	54	0.9	78	0.3 l AZ500
Application of PEH	CBS	200	Iseki TU 165	400	12	2.52	32	0.1	33	1 l Tomahawk
Application of PEH	CBS	200	Iseki TU 165	400	12	2.52	32	0.1	38	1 l Matrigon
Application of PEH	HBS	800	Fendt V415	7000	119	0.36	45	0.8	78	2.5 l Aramo
Mechanical weeding	ST	500	Fendt V712	5000	97	2.76	120	1.7	78	–
Mechanical weeding	GS	–	GS. FS 400	8	1.9	17.36	28	–	62	–
Mechanical weeding	GM	–	GM Rapid euro	237	14.6	6.11	45	–	62	–
Mechanical weeding	HDM	–	HDM	78	3.2	1.24	28	–	62	–
Manual weeding	–	–	–	–	–	–	–	–	78	49.1 h
Harvesting	E-harvester	7000	JD 6920T	14000	110	1.66	710	1.0	78	–

The data were collected on-site. HBS, hardy bomb sprayer; HDM, heavy duty machine; GM, grass mulcher; CBS, custum build sprayer; LP, leek planter; R, roller; PF, plow 4 furrow; GS, grass strimmer; E-harvester, energy harvester; CP, chilser plow; ST, steketee; JD, John Deere; PPEH, pre-emergent herbice; PEH, post emergent herbicide. Deep plowing, plowing and flattening have been grouped into land preparation.

to SRWC plantation began on the 26th March 2010 with the application of glyphosate (3.5 l ha^{-1}) to the soil, followed by deep plowing (up to 70 cm depth), and flattening before planting (Table 1). In April 2010, the SRWC plantation was established on 18.4 ha of this former agricultural land (Fig. S1). Twelve poplar and three willow genotypes representing different species and hybrids of *Populus deltoides*, *P. maximowiczii*, *P. nigra* and *P. trichocarpa* and *Salix viminalis*, *S. dasyclados*, *S. alba* or *S. schwerinii* were planted at a density of 8000 cuttings ha^{-1}. During the first months after planting, chemical, mechanical, and manual weed controls were performed as SRWCs are exposed to weed competition during the first growing season. No irrigation or fertilization was applied in this SRWC plantation. Before harvesting in 2012, we resampled the soil to 15 cm depth at 16 sampling points, with each point located less than 40 m from one of the eight selected sampling points of the initial soil survey of March 2010 [27]. All soil samples were oven-dried at 60 °C for 72 h and analyzed for soil carbon concentration in an elemental analyzer (Carlo Erba Instruments, Italy). The SOC stock was estimated by multiplying the SOC content of the first 15 cm by the bulk density of that soil layer (Table 2).

2.2. GHG flux data

Greenhouse gas flux measurements were carried out from June 2010 to December 2011 using the eddy covariance (EC) method. The EC system consists of a 3-D sonic anemometer, a closed-path CO_2/H_2O analyzer (Li-700, Li-Cor Inc.), and closed-path N_2O/CO (Los Gatos-908, Los Gatos Research), and CH_4 (Los Gatos DLT-100, Los Gatos Research) analyzers mounted on a 5.8 m high micrometeorological flux tower, in the plantation (Fig. S1). Raw data were recorded at a 10 Hz sampling rate; momentum, energy, CO_2, N_2O, and CH_4 fluxes were derived. The CO_2, N_2O and CH_4 fluxes were then converted to densities using a CR5000 data logger. Data processing was done following the generally accepted EC protocols [28] including among other a 2D coordinate rotations of wind components. The EC fluxes were calculated as the mean covariance between CO_2, N_2O, and CH_4 concentrations and fluctuations in the vertical wind speed over 30 min after removing spikes in raw data and corrections for air density fluctuations [29]. Individual data points were removed when the following criteria were met: (i) for CO_2 and for the wind velocity components (u, v and w) when the standard deviation of the 30 min mean was higher than 10, for N_2O when it was higher than 8, for H_2O when it was higher than 1, for CH_4 when it was higher than 0.3; (ii) when CH_4 and N_2O minimum concentrations were less than zero, and (iii) when data points came from outside of the footprint of interest (wind direction between 50 °C and 250 °C) [30,31]. Gaps in data were filled using different techniques. For CO_2 data the method of Reichstein et al. [32] was applied. As no standard gap-filling method exists for CH_4 and N_2O, fluxes of CH_4 and N_2O were linearly interpolated in periods with similar emission rates [33]. An overall annual GHG budget was computed by cumulating the net ecosystem exchange (NEE), N_2O, and CH_4 over each year of the study. CO_2, CH_4 and N_2O were converted to CO_2 equivalent using the IPCC conversion factors [34]. A more detailed description of EC flux calculations can be found in Zona et al. [35].

2.3. Life cycle assessment

To identify and compare the GHG emissions of the investigated bioelectricity system to those of the EU non-renewable grid mix electricity generation (reference system), a life cycle assessment (LCA) was performed. In this analysis, the functional unit was 1 kWh_e of bioelectricity. We included all relevant processes of bioelectricity production – from agrichemicals production, land preparation, planting, weeding, harvest and chipping, to the final conversion of chips to electricity – and all transportation needed within the system boundary (Fig. 1). Capital equipment was also included. Since irrigation and fertilization were not applied in this plantation, the unit processes of irrigation and fertilizer production and application were excluded from the system boundary. Moreover, the agricultural land in this study was not in conservation tillage; therefore, carbon was not being stored in the soil prior to its conversion to SRWC plantation. The foregone carbon sequestration (i.e., the ongoing carbon storage that is given up by devoting the agricultural land in this study to the production of SRWC for bioelectricity) was zero and therefore not included in the system boundary.

The system boundary of the EU non-renewable grid mix electricity generation included the extraction, transport, refining, storage, and conversion of non-renewable fuels to electricity (Fig. 1). Environmental impacts were based on the Impact 2002 + method [36], and were limited only to land requirement, energy balance, and GHG emissions of the bioelectricity production. LCA modeling was performed in Simapro 7.1 [37]. Furthermore, the energy ratio and GHG savings of the system were assessed.

2.3.1. Management input data

We inventoried all activities of the SRWC biomass production in the field (Fig. 1). Using a book keeping method we measured the amount of diesel and lubricant consumed to carry out each activity (e.g., plowing, weeding, planting, and harvesting). We also quantified the types and amount of chemicals used for weeding, as well as the amount of cuttings used in SRWC biomass production. Besides, we collected data on the lifespan, weight of implements and tractors used, and operation-time for each farming activity (Table 1). In addition, we collected data on the production of cuttings (Table 3). We also gathered data on vehicle types (truck or van), weights carried, and the distance traveled to transport farm materials (e.g. chemicals and cuttings) and tractors from the regional storage facilities to the SRWC plantation (Table S2). We further assumed the trucks or vans returned empty. Solar energy, which drives the build-up of SRWC biomass, was excluded from the system boundary. However, unlike in most studies, the human labor input for manual weeding was considered. To estimate the human energy input, we quantified the amount of person-hours of labor for manual weeding (Table 1), and multiplied it by the energy expended (1.9 MJ h^{-1} [38]) by a male worker to carry out manual weeding. No attempt was made to include the human labor associated with manufacturing of farm equipment and agrichemicals. All agricultural input data were collected in the field and referred to the 2010–2012 operations.

Table 2
Soil carbon stocks at depth of 15 cm and change in carbon stock due to land conversion from agricultural land to SRWC plantation. The positive value of the relative change in SOC stock denotes a loss (significant at $p < 0.001$) in carbon.

Land use type	Sampling depth (cm)	Bulk density (kg m^{-3})	Carbon conc. (kg C kg^{-1} soil)	Total carbon (t C ha^{-1})	$\Delta SOC_{2010-2012}$ (t C ha^{-1})
Agricultural (2010) (n = 8)	0–15	1298 ± 169	0.015 ± 0.004	28.38 ± 7.07	
SRWC plantation (2012) (n = 16)	0–15	1519 ± 59	0.009 ± 0.002	20.79 ± 3.33	7.59 ± 7.81

SOC, soil organic carbon; SRWCs, short-rotation woody crops; $\Delta SOC_{2010-2012}$, change in soil organic carbon; n, number of samples.

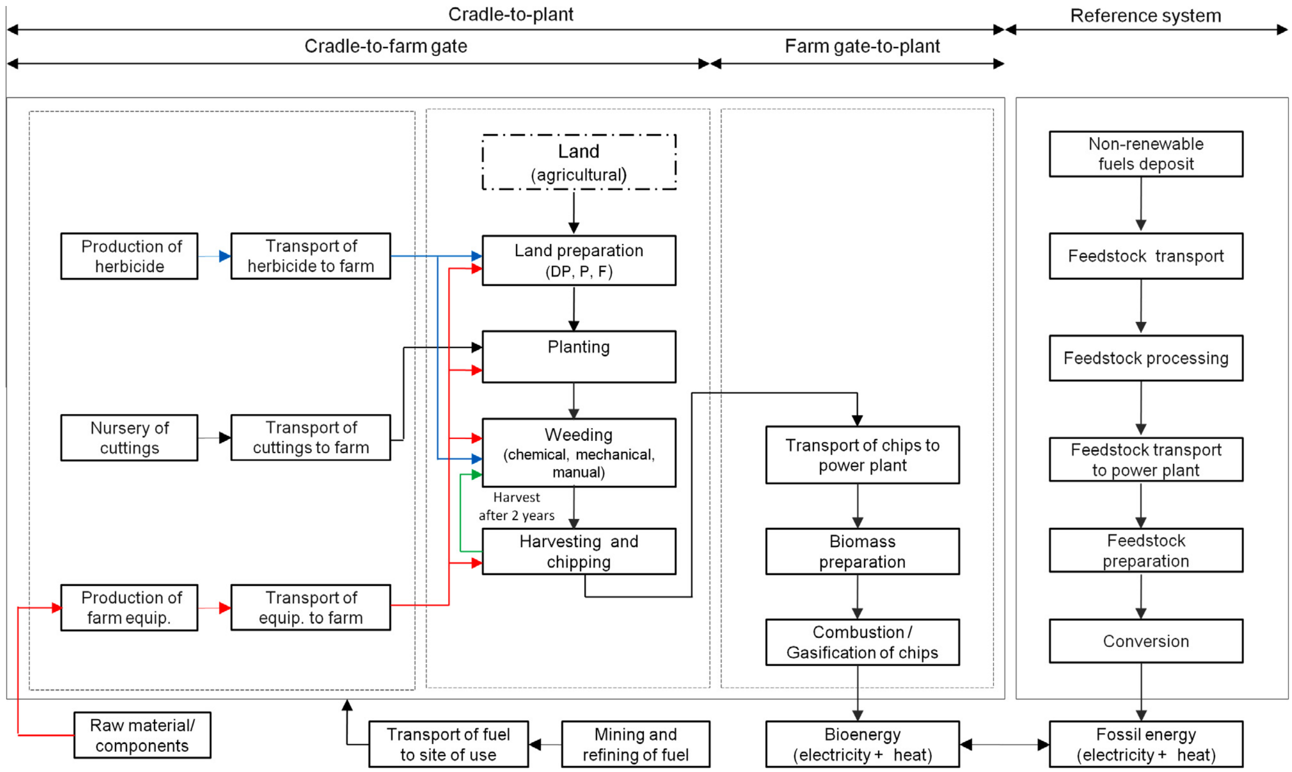

Fig. 1. System boundary of the bioelectricity production as well as of the EU non-renewable grid mix electricity used in this study. The boxes represent unit processes (or activities) and the arrows refer to material and energy flows. The solid lines represent the system boundary. Land preparation includes: deep plowing (DP), plowing (P), and flattening (F).

Table 3
Inputs for the production of SRWC cuttings. The column from left to right denote the field activities, the implement used, tractor used, the operating rate, total fuel consumption. These data are based on 1 ha land use and 15,000 plants at the nursery. The annual average production of cuttings (only three harvests) is 153,300 cuttings per hectare.

Activities	Implement used		Tractor used			Operating rate (h ha^{-1})	Total fuel consumption (l)	Input rates (unit ha^{-1})
	Types	Weight (kg)	Types	Weight (kg)	Power (kW)			
Plowing	4 Furrow	1800	Fendt	6000	104	2	24	–
Flattening	Roller	1200	Fendt	6000	104	1.5	18	–
Fertilising	Sprayer	100	Lamborghini	1150	31	1	7	80 kg N
Fertilising	Sprayer	100	Lamborghini	1150	31	1	7	100 kg P
Fertilising	Sprayer	100	Lamborghini	1150	31	1	7	60 kg K
Fertilising	Sprayer	1000	Fendt	6000	104	1	11	1000 kg $CaCO_3$
Chemical weeding	Sprayer	100	Lamborghini	1150	31	1	7	1 l AZ 500
Chemical weeding	Sprayer	100	Lamborghini	1150	31	1	7	1 l Kerb50
Chemical weeding	Sprayer	100	Lamborghini	1150	31	1	7	1 l Basta
Mechanical weeding	–	130	Deutz Agrocompacts	2150	45	2.5	20	–
Manual weeding	–	–	–	–	–	–	–	65 h

Note: The data were obtained from the Research Institute for Nature and Forest (INBO). SRWCs, short-rotation woody crops.

2.3.2. Data on energy conversion technologies and allocation method

We assumed that woody biomass chips were used in combined heat and power (CHP) plants. Two existing CHP plants were modeled for converting SRWC chips to bioelectricity: (i) a gasification plant which gasified 35.5 kton a^{-1} of dried SRWC chips at 30% moisture to produce 40.2 GWh_e a^{-1} at 27.5% efficiency and (ii) a combustion plant that burned 31.3 kton a^{-1} of dried SRWC chips at 30% moisture to produce 25.9 GWh_e a^{-1} at 22% efficiency (Table S3). Bioheat is also produced during power generation in CHP plants (Table S3). Since bioheat has a positive economic value and displaces heat that would otherwise be supplied from other sources, inputs (e.g. land and energy use) and outputs (GHG emissions) need to be allocated between bioelectricity and bioheat. We used the exergy-based allocation to partition inputs/outputs between bioelectricity and bioheat. First, we assumed an ambient temperature of 10 °C (283 K) and a steam temperature of 120 °C (393 K) for both the gasification and combustion. Next, we estimated the Carnot factor as indicated in Table S4, and then calculated the bioheat exergy by multiplying this Carnot factor (i.e. 0.27) by the annual amount of bioheat produced by the gasification (83.9 GW h) and combustion (82.3 GW h) technologies, respectively. For bioelectricity, we assumed the exergy is equal to its energy content and thus the share of bioelectricity of the total delivered exergy (Table S4).

2.3.3. Energy balance and GHG savings

All the collected data were normalized to the functional unit (i.e., 1 kWh_e), entered into Simapro 7.1, and modeled into environmental inputs and outputs. Simulation results were then exported from Simapro 7.1 to an Excel spreadsheet where calculations of the energy balance and GHG savings were performed. We calculated the energy ratio by dividing the energy content of bioelectricity output (i.e., 1 kWh_e = 3.6 MJ_e) by the sum of all fossil energy inputs needed to produce one unit of bioelectricity. To estimate the GHG emission savings, we first multiplied the emission factors of electricity from natural gas, coal, uranium, and oil derived from Ecoinvent [39] by the fraction of natural gas fired (29%), coal burning (32%), nuclear (35%), and oil fired power (4%) making up the EU non-renewable grid mix electricity in 2009 [40]. We then summed-up these products to obtain the GHG emission rates for the EU non-renewable grid mix electricity in 2009 (Table S5). Finally, we estimated the GHG emission savings by comparing the GHG emission rates for the SRWC-bioelectricity chain to that for the grid mix electricity in the EU in 2009.

3. Results

3.1. Biomass yield

The mean yield after two years of growth was 4 ton ha^{-1} a^{-1}. Considerable tree mortality (~18%) was observed in the establishment year [41]. Because tree mortality was evenly distributed across the plantation, and established trees occupied the vacant spaces, no large gaps occurred. At the end of two years of growth, about 114 tons of biomass were harvested from 14.2 ha and transported to the bioelectricity plant. The chemical composition and the measured heating value (19.5 MJ kg^{-1}) of the harvested SRWC chips from our plantation are summarized in Table S6.

3.2. Energy requirement and energy ratio

The total energy input to produce one unit of bioelectricity was 1.1 MJ kWh_e^{-1} for the gasification and 1.2 MJ kWh_e^{-1} for the combustion technology. The breakdown of the total energy input across the different components of the bioelectricity production is shown in Fig. 2. Land preparation was the activity that consumed the most energy (24%), followed in decreasing order by harvesting (20%), production of cuttings (18%), weeding (17%) and planting (10%). The contribution of cutting production to the total energy input was high because the production of SRWC cuttings covered only three harvests. Facility construction and transport were the activities that consumed the least amount of energy (Fig. 2). For both conversion technologies (gasification and combustion), the energy output was much higher than the total energy inputs to produce 1 kWh_e of bioelectricity. The energy ratio (ratio of the energy content of 1 kWh_e = 3.6 MJ_e of bioelectricity over the total energy input for its production) was 3 for the combustion and 3.3 for the gasification technology (Fig. 2). Thus, the bioelectricity from SRWC yielded 200–227% more energy than the energy invested in its production.

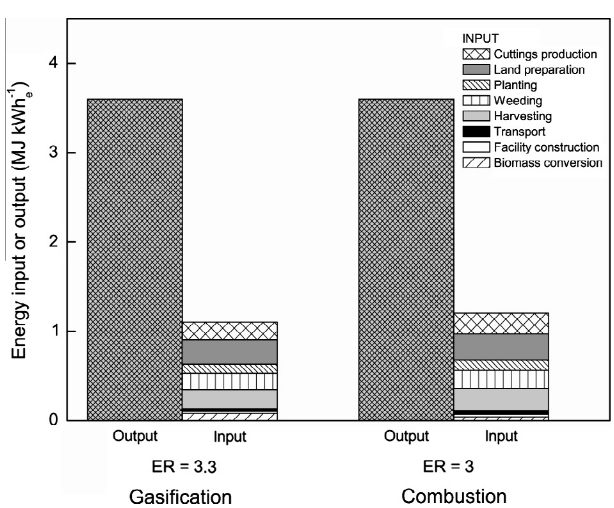

Fig. 2. Energy balance of the biomass gasification (left) and biomass combustion (right) technology investigated in this study. The black bars represent the energy output whereas the stacked bars represent the energy input items of each biomass conversion technology. *Land preparation includes: deep plowing, plowing, and flattening.* ER: energy ratio (output-input ratio). Data presented are based on a biomass yield of 4 odt ha^{-1} a^{-1}, and a single two-year rotation which includes only one harvest.

3.3. Cumulative dLUC emissions

Conversion of agricultural land to an SRWC plantation resulted in a loss of SOC of ~27.8 ± 9.6 ton CO_{2e} ha^{-1} in the top 15 cm of soil over the two-year period (Table 2). The cumulative NEE measured by eddy covariance is shown in Fig. 3. High amounts of CO_2 were released after the plantation establishment in 2010 and during the autumn–winter period, whereas much of the CO_2 uptake by the SRWC canopy occurred during the growing season. Integrated over the measuring period, the cumulative NEE which also includes the loss of SOC was −0.8 ± 0.6 ton CO_{2e} ha^{-1} (Fig. 3). This suggests that the SRWC plantation was a sink of CO_2 despite the initial loss in SOC. No seasonal trends in N_2O and CH_4 fluxes were observed in this study during the entire measurement period. Most of the N_2O emissions occurred in July–August 2010, and the cumulative amount changed very little thereafter. CH_4 fluxes were very small throughout the measurement period (Fig. 3). The cumulative N_2O and CH_4 emissions were 2.39 ± 0.52 ton CO_{2e} ha^{-1} and 1.12 ± 0.07 ton CO_{2e} ha^{-1}, respectively (Fig. 3). These positive cumulative fluxes more than offset the CO_2 uptake, and turned the SRWC plantation from a net CO_2 sink into a small source of GHGs. At the end of the study period, the cumulative dLUC GHG emissions, taking into account the CO_2, N_2O and CH_4 fluxes, amounted to 2.8 ± 0.2 ton CO_{2e} ha^{-1} (Fig. 3). This indicates that N_2O and CH_4 played an important role in GHG emissions associated with dLUC at our site. Thus, the soil N_2O and CH_4 fluxes may reduce the potential sink strength of SRWC plantations during the first two years of culture.

3.4. GHG emissions and savings of bioelectricity

The combustion of SRWC chips in an existing biomass-fired power station resulted in a total GHG emission of about 272 g CO_{2e} kWh_e^{-1}. The gasification of these chips showed a lower total GHG emission of ~256 g CO_{2e} kWh_e^{-1} (Fig. 4). For both the gasification and the combustion technology, dLUC accounted for 89% of the total GHG emissions, while the emissions from all the other processes associated with bioelectricity production made-up the remaining fraction (11%) (Fig. 4). The GHG emission reduction compared to the EU non-renewable grid mix electricity was 52% for the combustion and 54% for the gasification technologies. The GHG savings even reached 67% and 69% for the combustion and gasification technologies, respectively, when the EU fossil fuels grid mix electricity (i.e., excluding nuclear power) was considered as a baseline (Fig. 4). Therefore, converting agricultural land into a low-input SRWC plantation did not negate the GHG emission benefits of bioelectricity production regardless of the conversion technology chosen and of the EU grid mix electricity displaced.

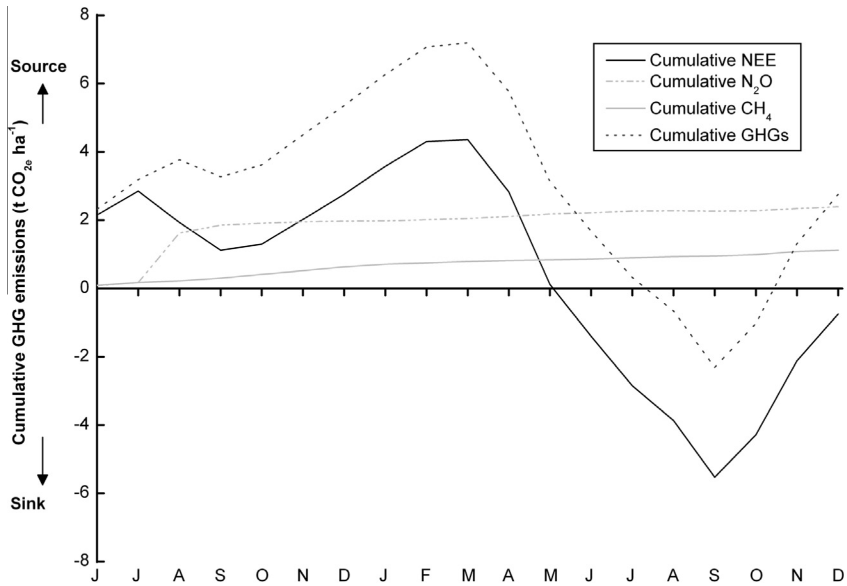

Fig. 3. Cumulative GHG fluxes over the measuring period (2010–2011). The NEE is represented by the black line, N_2O fluxes by the dash-dot grey line, CH_4 fluxes by the light grey, whereas the cumulative GHGs is represented by the dotted grey line. Positive values denote the loss from ecosystem and negative values denote uptake. GHGs: greenhouse gases, NEE: net ecosystem exchange, N_2O: nitrous oxide, CH_4: methane.

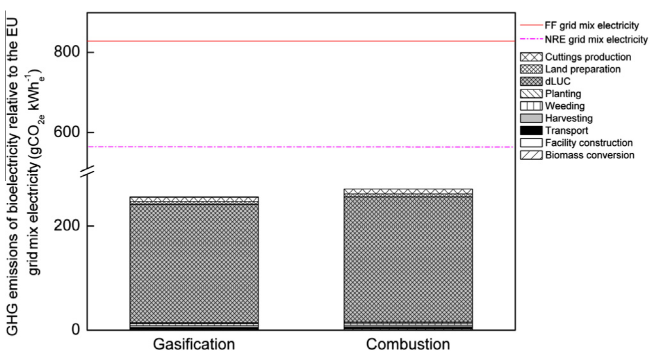

Fig. 4. Greenhouse gas emissions relative to the EU non-renewable and fossil fuels grid mix electricity. The bars represent the total GHG emission of each bioelectricity production technology whereas the dotted- and solid lines above the bars represent the GHG emission of the EU non-renewable as well as fossil fuels (i.e., excluding nuclear power) grid mix electricity production respectively. *Land preparation includes*: *deep plowing, plowing, and flattening.* Data presented are based on a biomass yield of 4 odt ha^{-1} a^{-1}, and a single two-year rotation which includes only one harvest.

3.5. Land requirement

The total land requirement for bioelectricity production was 1 m^2 kWh_e^{-1} for the combustion and 0.9 m^2 kWh_e^{-1} for the gasification technology (Fig. S2). For both the combustion and the gasification technology, the land requirement of the SRWC chips accounted for 95% of the total land requirement while the land needed for the production of cuttings used in the site establishment accounted for only 5% of the total land requirement (Fig. S2). Because of its high electrical efficiency, gasification reduced the total land requirement by 10% compared to combustion technology. This reduction suggests that conversion efficiency played a considerable effect on the land requirement.

4. Discussion

The biomass yield was 50–60% lower than the average attainable yield in Europe (8–10 ton ha^{-1} a^{-1}) [42], which may be explained by the young age of the plantation, the soil type, the low planting density, and possibly other factors such as weather, and weed pressure. It has been shown that SRWC stands invest more in their root systems and less in aboveground growth early in stand development [43,44]. Moreover, unlike in most European studies, neither fertilizer nor irrigation was used at our site. Given that the number of shoots per stool and stem diameter usually increase between the first and subsequent harvests [45], an increase in yield is likely in the second harvest of our SRWC plantation.

Our bioelectricity production systems yielded 200–227% more energy than required for its production, which implies that bioelectricity from SRWCs grown on agricultural land is a valuable energy substitute, and producing more bioelectricity from SRWCs could displace non-renewable fuel imports, which would increase energy security. The high net energy yield of bioelectricity from SRWC in this study was attributable to the low inputs (no fertilization and no irrigation) during the feedstock production phase and the use of bioheat as a co-product of bioelectricity production. All recent studies showed that bioelectricity from SRWCs has a positive energy balance, and reported energy ratios ranged from 3 to 16 [46]. Our results, even though they are for a single two-year rotation with only one harvest, are consistent with other studies that show that bioelectricity has a positive energy balance. However, our estimated energy ratio (3–3.3) was at the lower end of this range. The main reason for the low energy ratio estimate is the low biomass yield during the first two years of tree growth.

The loss of SOC from the SRWC plantation may be attributed either to decreased organic inputs to the soil relative to decomposition early in the SRWC establishment [47] or to the effect of tillage during site preparation which renders more SOC vulnerable to decomposition and thus triggered the release of SOC [48]. Carbon dioxide fluxes showed high seasonal variability, driven primarily by the SRWC response to seasonal changes in temperature and soil moisture (Fig. 3). Nitrous oxide fluxes were high, in which a peak emission of ~60% of the annual N_2O flux occurred after a single rainfall event in August 2010 (Fig. 3). The high N_2O emissions were contrary to what we expected given that our SRWC plantation was unfertilized. A likely explanation is that decades of intensive fertilization and very high atmospheric N deposition – due to high ammonia and nitrogen oxides from dense livestock and traffic, respectively, in Flanders – led to a high N content of the soils (9.3 ton N ha^{-1}) some of which could not be fixed by plants and was converted to N_2O during nitrification and denitrification processes. The observed fluxes also showed that our SRWC plantation was a source of CH_4. These CH_4 fluxes could be attributed to a high water table and low atmospheric evaporative demand at our site in winter, causing soil saturation, favoring methanogenesis and restricting the oxidation of CH_4 by methanotrophs.

The cumulative dLUC GHG emissions occurring during the two-year rotation was 2.8 ± 0.2 ton CO_{2e} ha^{-1} (Fig. 3), indicating that the SRWC plantation was a net source of GHGs due to low biomass yield, and low input from leaf litter and root turnover relative to soil carbon loss. However, it is likely that our SRWC plantation may become a net sink of GHGs in the longer term. In fact, Arevalo et al. [11] showed that at least four years were necessary for a SRWC plantation on croplands to reach its pre-plantation carbon level and become a net sink of GHGs. Our estimate of dLUC GHG emissions was much lower than that for conversion of grassland to a corn plantation (~12 ton CO_{2e} ha^{-1}) [49], and for establishment of fertilized SRWC on pastureland (7–11 ton CO_{2e} ha^{-1}) [50], and lower than for conversion of abandoned cropland to prairie biomass (~6 ton CO_{2e} ha^{-1}) [13]. Our estimate of dLUC GHG emissions was low because the SRWC plantation was established on agricultural land that contained depleted SOC pools due to repeated tillage. Thus, our dLUC estimate was limited only to emissions from soil disturbance during land preparation. The total GHG emissions of bioelectricity production (256–272 g CO_{2e} kWh_e^{-1}) in this study were well above the maximum value (39–132 g CO_{2e} kWh_e^{-1}) reported in [46] because of the inclusion of dLUC GHG emissions in our system boundary. Also, differences in SRWC yields, assumptions about efficiencies of conversion technologies, as well as the allocation method used in this study partly explained the differences with previous analyses. When leaving out the contribution of dLUC (~89% of total GHG emissions), our estimate of GHG emissions from bioelectricity fell to 29–31 g CO_{2e} kWh_e^{-1}. This latter range compared well with estimates reported in [46] since dLUC emissions were ignored in all articles reviewed in that study. On a kWh_e basis, bioelectricity from SRWC on agricultural lands reduced emissions by at least 52–54% compared to the current EU non-renewable grid mix power (Fig. 4). Thus, despite entailing dLUC GHG emissions (Fig. 4), bioelectricity still provided immediate GHG benefits because SRWC were grown on agricultural lands and were converted to electricity using efficient technologies.

The EU has committed to producing 20% of consumed energy from renewable energy sources by 2020 [4]. To meet this target, it has been projected that about 232 TWh_e would come from biomass [51]. Considering that it takes about ~1 m^2 kWh_e^{-1} electricity (Fig. S2), and assuming that electricity from cultivated woody biomass represents 15% of the projected amount [52], about 34,800 km^2 of land (~2% of the EU's total utilized agricultural area) would be required to meet the EU 2020 bioelectricity target from cultivated woody biomass. Unless yield of food crops is increased on existing croplands to meet the growing food and feed demand, it may be difficult to devote ~2% of EU's utilized agricultural land to SRWC. However, yield increase in the future years has the potential to decrease the land requirement for SRWC [53,54].

A number of sensitivity analyses were carried out to assess the influence of some key inputs variables and assumptions and the robustness of the obtained results. The elasticity method (i.e., the ratio of the change in the results to the change in data) was used to perform the sensitivity analysis. When the biomass yield (4 ton ha^{-1} a^{-1}) in this study was doubled, we found that the energy demand and GHG emissions of bioelectricity production were reduced significantly (Table 4). A sensitivity analysis on initial SOC content revealed that, even if SRWCs were grown on an agricultural land containing 20% more SOC than at our site, the overall GHG reduction would still be 44–47% relative to the current EU non-renewable grid mix power (Table 4). We also hypothesized a case where the electrical conversion efficiencies of both the gasification and combustion were reduced by 20%. In that scenario, we found that the land requirement would increase by 10% while the energy ratio and the GHG saving would decrease by a similar percentage. But bioelectricity would still provide energy and GHG benefits (Table 4). Finally, when the energy-based allocation method was adopted, the land requirement, energy demand, and GHG emissions of bioelectricity were strongly reduced for both conversion technologies (Table 4).

4.1. Limitations and cautions to the interpretation of results of this study

One limitation of the current study is that it only addresses the dLUC GHG emissions of bioelectricity. However, growing SRWC on agricultural lands for bioelectricity may trigger land conversion elsewhere in the world, releasing GHGs through indirect land use (iLUC) [14,55–57]. Therefore, a complete assessment needs to include both dLUC and iLUC. Another limitation is that this study considers only SRWC from tilled agricultural land. Grassland, non-tilled agricultural land as well as set-aside lands are currently a sink of GHGs [58,59]. Consequently, converting these lands to SRWC plantations would result in significant dLUC GHG emissions,

Table 4
Sensitivity analysis of key parameters on results.

Parameters	Scenario	Gasification			Combustion		
		Land requirement (m^2 kWh_e^{-1})	Energy demand (MJ kWh_e^{-1})	GHG emissions (gCO_2 kWh_e^{-1})	Land requirement (m^2 kWh_e^{-1})	Energy demand (MJ kWh_e^{-1})	GHG emissions (gCO_2 kWh_e^{-1})
Yield	Increase +100%	0.452	0.575	130.2	0.481	0.622	140.6
Electrical conversion efficiency	Increase +20%	0.8	0.9	213.3	0.8	0.9	227.1
	Decrease −20%	1.1	1.4	298.2	1.2	1.4	316.8
Initial carbon stock	Increase +20%	na	na	300.0	na	na	318.2
	Decrease −20%	na	na	211.9	na	na	225.4
Allocation method	Energy approach	0.5	0.6	128.1	0.4	0.5	121.4

NB, 100% decrease in yield makes no sense and was therefore not considered in sensitivity analysis; na, not applicable.

which in turn would result to little or no GHG savings. Thus, our study likely understates the disadvantage of bioelectricity production relative to facilities that would obtain SRWCs from set-aside or grasslands. Finally, our study assesses the life-cycle of existing bioelectricity technologies that currently have low to medium electrical efficiency. The adoption of advanced gasification/combustion technologies (i.e. $\eta_e \geqslant 35$) changes the results of this analysis. Thus, the land requirement, energy demand, and GHG emissions reported here reflect today's average technologies. Despite these limitations, our study suggests that (i) in areas where SRWCs can be grown sustainably, even with low yields and one two-year rotation, there is a positive energy balance; and (ii) bioelectricity would contribute to GHG mitigation in the power sector if appropriate lands, feedstocks, and the correct conversion technologies were used, and if the SRWC plantation was maintained as a low-input system.

5. Conclusion

By combining field measurements and LCA approach we showed that low input SRWC plantations on agricultural lands for bioelectricity production resulted in immediate GHG savings relative to grid mix electricity. Consequently SRWCs that come from agricultural land with low carbon stocks are an encouraging prospect for sustainable production of renewable energy with significant climate benefits.

Acknowledgements

This research has received funding from the European Research Council as ERC Grant Agreement Nr. 233366 (POPFULL) and from a Marie Curie International Re-integration Grant (MIRG) as Grant Agreement Nr. 268257 under the EC 7th Framework Programme (FP7/2007-2013). Further funding was provided by the Flemish government through the Hercules Foundation as Infrastructure Contract ZW09-06 and through the Methusalem Program. OEK and SYD were researchers from the Flemish Research Foundation (FWO), and TDG received a grant from FWO and the Flemish VITO Institute. GB held a grant from the Erasmus-Mundus Consortium EADIC (Lot 16) financed by the European Union Mobility Programme (2009-1655/001-001). JSK was supported at UA by the International Francqui Foundation and by the Fulbright Program of the Commission for International Exchange. We gratefully acknowledge the excellent technical support of Joris Cools and the logistic support of Kristof Mouton at the field site. Finally, we thank Dr. Florian Gahbauer for correcting English language, and the two anonymous reviewers for their constructive comments and valuable suggestions on an earlier version of the manuscript.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.apenergy.2013.05.017.

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