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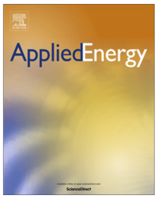

Impact of feedstock, land use change, and soil organic carbon on energy and greenhouse gas performance of biomass cogeneration technologies

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HIGHLIGHTS

- Comparison of 40 bioenergy pathways to a fossil-fuel based CHP system.
- Not all energy efficient pathways led to lower GHG emissions.
- iLUC through intensification increased the total energy input and GHG emissions.
- Fluidized bed technologies maximize the energy and GHG benefits of all pathways.
- Perennial crops are in some cases better than residues on GHG emissions criteria.

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ABSTRACT

Bioenergy (i.e., bioheat and bioelectricity) could simultaneously address energy insecurity and climate change. However, bioenergy's impact on climate change remains incomplete when land use changes (LUC), soil organic carbon (SOC) changes, and the auxiliary energy consumption are not accounted for in the life cycle. Using data collected from Belgian farmers, combined heat and power (CHP) operators, and a life cycle approach, we compared 40 bioenergy pathways to a fossil-fuel CHP system. Bioenergy required between 0.024 and 0.204 MJ $(0.86\ \mathrm{MJ_{th}} + 0.14\ \mathrm{MJ_{el}})^{-1}$, and the estimated energy ratio (energy output-to-input ratio) ranged from 5 to 42. SOC loss increased the greenhouse gas (GHG) emissions of residue based bioenergy. On average, the iLUC represented ~67% of the total GHG emissions of bioenergy from perennial energy crops. However, the net LUC (i.e., dLUC + iLUC) effects substantially reduced the GHG emissions incurred during all phases of bioenergy production from perennial crops, turning most pathways based on energy crops to GHG sinks. Relative to fossil-fuel based CHP all bioenergy pathways reduced GHG emissions by 8–114%. Fluidized bed technologies maximize the energy and the GHG benefits of all pathways. The size and the power-to-heat ratio for a given CHP influenced the energy and GHG performance of these bioenergy pathways. Even with the inclusion of LUC, perennial crops had better GHG performance than agricultural and forest residues. Perennial crops have a high potential in the multidimensional approach to increase energy security and to mitigate climate change. The full impacts of bioenergy from these perennial energy crops must, however, be assessed before they can be deployed on a large scale.

1. Introduction

By 2020 Belgium's final energy consumption must be 13% renewable [1], and greenhouse gas (GHG) emissions must be reduced by 15% from 2005 levels [2]. To meet the renewable energy target the share of bioenergy (i.e. bioheat and bioelectricity) in the final energy consumption must be increased from 811 ktoe in 2005 to 2748 ktoe in 2020 [3]. Perennial energy crops such as miscanthus, short rotation woody crops, and forest and agricultural (e.g. corn stover, wheat straw) residues are potential biomass feedstocks for bioenergy production in Belgium. These feedstocks could supply about 782 ktoe a^{-1} gross energy by 2015 [4] with about 47% of this amount coming from agricultural residues, 31% from forest residues, and 22% from perennial energy crops [4].

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Fixed and fluidized bed combined heat and power (CHP) technologies are used to convert biomass to bioenergy via a number of pathways. Pathways using fixed and fluidized bed boilers directly burn biomass to produce bioenergy whereas those based on fixed and fluidized bed gasifiers convert biomass into synthesis gases that in turn are used to produce bioenergy. Bioenergy is viewed as 'carbon neutral' because the CO_2 emitted at the CHP facilities comes from the CO_2 that was taken-up during the growth of the biomass crop [5]. The carbon neutrality of bioenergy is a highly debated topic due to the extreme complexity of the agricultural and forest ecosystems, the wide variety of feedstock and conversion technologies. Quantifying the greenhouse gas (GHG) benefits of bioenergy requires well defined criteria that capture the changes in soil carbon stock, the flux of CO_2, N_2O, and CH_4 due to land use changes (LUC), the energy conversion efficiency, as well as the defined fossil reference system [6].

Most studies have focused on liquid biofuels [7–10], and on gaseous biofuels such as biogas [11–14] and biohydrogen [15]. Among the bioenergy sources, agricultural and forest residues are the most energy efficient and climate friendly feedstocks for heat and/or electricity production [16,17]. This is because their management is less energy intensive, than that of perennial energy crops, and because they do not compete with food production [18]. Nearly all studies on bioenergy concluded that bioenergy systems reduce GHG emissions through the substitution of fossil energy [10]. In estimating the GHG balances of bioenergy systems, most previous studies did not include emissions from SOC, or from direct (dLUC) and indirect (iLUC) land use change [19]. If emissions from SOC, dLUC and iLUC are accounted for, the total CO_2 emissions of bioenergy chains can more than offset the savings incurred by the displacement of fossil energy with bioenergy [20–22].

The removal of residues and the conversion of land to the production of energy crops influence the soil organic carbon (SOC) stock [23,24]. Residues remaining in the forest or on the agricultural soils are direct inputs into the SOC stocks [25,26]. The removal of these residues diminishes the carbon flow to the soil, thus decreasing SOC stocks [26,27]. In contrast, the conversion of croplands to perennial crop plantations increases the SOC [28,29]. But in that case, the displaced food crops need to be produced elsewhere: either by converting uncultivated lands to new croplands or by intensifying the food production on existing croplands [30]. Both scenarios have major implications for GHG savings. Worldwide, the sustainable intensification of agriculture is seen as an important solution to iLUC of bioenergy [31]. Until now, only the iLUC GHG emissions due to land conversion (i.e., expansion) have been studied [21]. The iLUC GHG emissions due to intensification of existing croplands as result of devoting a piece of cropland to energy crops production has never been assessed. In this study, we couple multiple biomass feedstocks to CHP technologies to: (i) assess impacts of SOC, dLUC and iLUC on energy and GHG performance of bioenergy systems, (ii) identify the CHP technology that optimizes the energy and GHG balances, and (iii) compare the sustainability of land and non-land based bioenergy production.

2. Materials and methods

We analyzed 40 bioenergy production pathways (cf. Supplementary Information (SI), Fig. S1, Table S1) and a reference system using a life cycle assessment (LCA) method [32]. The decision to include a given pathway in the study was based on the following criteria: (i) feedstock availability and flexibility; (ii) potential national impact; (iii) data availability across the full pathway; and (iv) near-, mid-, and long-term techno-economic potential. All investigated pathways were related to Belgium as the place of production and end use, and they simultaneously produced bioheat and bioelectricity. The functional unit was defined as a package of "$0.86\ MJ_{th} + 0.14\ MJ_{el}$" at the factory gate for different end uses.

We considered the entire life cycle of each bioenergy pathway: (i) production/collection of the biomass feedstock; (ii) transport; (iii) processing and conversion of biomass to bioheat and bioelectricity; and (iv) the recycling/disposal of ash. Processes of extracting, refining, processing, and transporting diesel, lubricants, and agrochemicals used in the farming activities were all included in the analysis. N_2O emissions related to the application of fertilizers during the production of perennial energy crops were also considered, as were the avoided N_2O emissions from residue removal, using the IPCC method [33]. Carbon sequestration in the soil during growth of the biomass crop, CO_2 lost to the atmosphere due to land conversion, as well as CH_4 and N_2O emissions during the combustion/gasification of biomass were also considered. The unit process of the ash disposal was included in all bioenergy production pathways, as the ash content varied substantially for different feedstocks. In perennial cropping systems, leaf litter accumulates on the surface where it decomposes aerobically [34]. Given that N_2O emissions from leaf litter are usually very low [35], they were considered negligible, and thus excluded from the assessment. Finally, the manual labor energy input required to produce and/or to collect each type of biomass feedstock was not included as it is negligible [36].

The system boundary of the different bioenergy pathways analyzed in this study is shown in Fig. S1. The fossil reference system includes the processes of extraction, transport, storage and conversion of light fuel oil, as well as of natural gas in condensing boilers operated for CHP production. Primary data were gathered from farmers, forest managers, and biomass CHP plant operators in Belgium via personal interviews and questionnaires. Secondary material and energy data were derived from the Ecoinvent database [37] supplemented by observations from the literature. Investigated impacts were global warming (with a 100-year time frame) and the consumption of non-renewable energy, which were assessed using the IMPACT 2002+ method [38] as this method very well incorporates the environmental impacts assessed in this study. All modeling was performed in Simapro 7.1 [39]. We finally calculated the energy ratio by dividing the total energy output by the total primary non-renewable energy consumed to produce a unit package of ($0.86\ MJ_{th} + 0.14\ MJ_{el}$).

2.1. Feedstock production

Cultivation of perennial energy crops under different microclimates and soil conditions results in highly varying yields in Belgium. The culture of miscanthus and of short rotation woody crops requires a number of inputs such as rhizomes/cuttings, pesticides, herbicides, fertilizers, tractors, land and fuel, which we considered, along with the energy inputs for manufacturing farm tractors and agrochemicals (Table S2).

Agricultural residues were assumed to dry in the field prior to collection. Energy inputs and GHG emissions were considered for harvesting (i.e., collecting), baling, and moving agricultural residues to the edge of the field. The supply of forest residues involved the harvesting (i.e., collection), chipping, and forwarding of the residues along the roadside. We included the energy inputs for the harvesting and forwarding of the residues (Table S3). However, since the standard practice in Belgium considers residues as waste, the energy inputs for cultivating the crops/trees were allocated to the main products (i.e., grain/trees). The yield of each feedstock, the chemical composition, and the heating value are presented in Table S4.

2.2. dLUC of perennial crops

To estimate the dLUC GHG emissions associated with farming of perennial energy crops, the IPCC Tier 1 approach was used [40]. The initial soil organic carbon content was considered to be 87 tC ha^{-1} for croplands [41], and the assumed carbon sequestration rates were 0.09 tC ha^{-1} a^{-1} for short rotation woody crops [42], and 0.62 tC ha^{-1} a^{-1} for miscanthus [42]. We then applied the IPCC Tier 1 land use, management regime, and input factors [40] to compute the resulting gain in soil organic carbon (SOC) from switching from croplands to perennial crop production [40]. Thereafter, we assessed the annual carbon accumulation rates by dividing the resulting gain in SOC by 20 yr. Finally, the annual carbon accumulation rates were multiplied by 3.66 to convert it to CO_2 (see SI).

2.3. SOC change of residues

The IPCC Tier 1 methodology [40] for SOC losses due to biomass harvest was adapted and used to quantify the GHG emissions associated with the removal of agricultural and forest residues. We considered the initial soil carbon contents to be 87 tC ha^{-1} for croplands [41] and 91 tC ha^{-1} for forest lands [43]. We also considered the nitrogen contents of agricultural and forest residues (Table S4) as well as the IPCC stock change factors related to management, inputs, land use, forest types, and disturbance regimes [40]. We computed the GHG emissions due to residue removal as the sum of the loss of SOC and the decrease in N_2O emissions from the soil due to residue removal (see SI).

2.4. iLUC of perennial crops

To estimate the iLUC energy and GHG emissions due to the devotion of 1 ha of cropland to perennial energy crop production, we assumed that the displaced food crops are most likely compensated for by intensified production on existing cropland in Belgium. We also assumed that not all soils in Belgium are saturated [44] and that additional fertilizer (i.e. N/P/K) inputs increase yields [45]. From the FAOSTAT database [46] we obtained agricultural data on major food crops (i.e. those occupying an area $\geqslant$ 1% of total croplands) in Belgium for the year 2012. We calculated the amount of land required to meet the 2020 bioenergy target from perennial crops in Belgium (i.e. 172 ktoe, Table S5) and assigned the land required by each perennial crop to different major food crops on the basis of their share of the total cropland in production in 2012. Next, we calculated the remaining area for each food crop by subtracting the assigned land required from the initial land area.

For each food crop, the yield (i.e., the new yield) required to maintain the current level of food production was calculated by dividing the current food production by the remaining cropland area. A yield ratio for each food crop was then estimated by dividing their new yield by their current yield (Table S6). To calculate the amounts of fertilizers required to maintain food production within the remaining cropland area, an average yield ratio Yr was determined by compounding the yield ratios of individual crops across all major food crops in Belgium. We considered that no extra inputs were required for P and K fertilizers since the relationship of these inputs to yields per hectare was considered to be linear [47,48]. Therefore, achieving a yield increase per hectare of Yr% amounts to increasing the input rates by the same ratio, which leads to a constant overall amount of P and K fertilizer inputs, since the new cropland area is reduced by the same percentage. The case was different for N fertilization: we used a non-linear relationship [49], with the efficiency of additional N fertilizer decreasing as the yield increased. This means that to increase yield by Yr%, the current fertilizer application rates in Belgium [50] had to be increased by more than Yr%. On a hectare basis, the increase translated to 30.7 kg N ha^{-1} (Table S7). Finally we estimated the iLUC energy of devoting 1 ha of cropland to the production of perennial crops by multiplying the additional fertilizer required, by the energy needed to produce a given amount of fertilizer. We also multiplied the additional amount of fertilizer by the sum of GHG emissions from the production and application of the fertilizer to estimate the iLUC GHG emissions of devoting 1 ha of cropland to perennial crop production (see SI).

2.5. Feedstock transport

Feedstocks are transported to the biomass CHP plants by trucks. An average distance of 30 km (round-trip) was assumed for both perennial energy crops and residues, based on information provided by CHP plant operators in Belgium and by earlier studies [51].

2.6. Feedstock conversion

Different biomass combustion and gasification CHP technologies were considered. Among the combustion systems were fixed bed boilers (stoker boilers (SB), grate firings (GB)) and fluidized bed boilers which may be bubbling (FFBB) or circulating (CFBB). An alternative to combustion is gasification, which may be accomplished by updraft (UDBG) and downdraft gasifiers (DDBG), as well as fluidized bed gasifiers, which may also be bubbling (BFBG) or circulating (CFBG). The mechanisms of fixed and fluidized bed combustion and gasification are described in SI. Technical data for bioenergy production using combustion and gasification technologies are presented in Tables S8 and S9 respectively.

2.7. Recycling/disposal of ash

Bottom and fly ashes are generated as by-products of biomass combustion/gasification. About 40% of the total ashes (i.e., bottom and fly ashes) generated can be recycled [52]. We assumed that all the generated bottom ash is landfilled, since the Belgian law does not allow its use in agriculture. In contrast, fly ashes are used as a substitute for Portland cement in concrete manufacturing. Given that the proportion of bottom and fly ashes generated also depends on the conversion technology, we assumed that fly and bottom ashes represent respectively 30% and 70% of the total ashes generated in fixed bed burners/gasifiers [53]. For the fluidized bed burners/gasifiers a fly ash fraction of 80% of the total ashes generated and a bottom ash fraction of 20% were assumed. Considering a displacement ratio of 60% [54], we computed the quantity of Portland cement displaced by multiplying the total ashes generated, with the product of the replacement ratio, the fraction of ash recycled, the feedstock's ash content, and the fraction of fly ash (see SI). The energy and GHG benefits of using fly ash are equivalent to the energy and GHG emissions associated with the manufacturing of Portland cement displaced by fly ash, minus the energy and GHG emissions associated with transporting the ash to a concrete manufacturing facility, located 20 km from the CHP plants. We credited the energy and GHG benefits to bioenergy. Similarly, we calculated the energy and GHG emissions associated with the disposal of the remaining ashes by multiplying the quantity of ashes to be disposed of (i.e., all bottom ash and the remaining fly ash) with the transport distance between CHP plants and the waste disposal site (30 km).

2.8. Sensitivity analyses

We varied the base case biomass yield, initial SOC content, and ash recycling rate by 20%, the conversion efficiencies by 5%, and we doubled the transport distance in order to understand their influences on the outcome of the study. We also carried out a sensitivity estimate by allocating 12% of impacts of the agricultural phase to residues (e.g., corn stover) based on the value generated by corn production. Finally, to identify the sensitivity of the impact assessment method used (i.e., IMPACT 2002+) we also applied the CML1992 method for comparison [55].

3. Results

3.1. Energy inputs of bioenergy from residues

Corn stover pathways [0.024–0.042 MJ $(0.86\ \mathrm{MJ_{th}} + 0.14\ \mathrm{MJ_{el}})^{-1}$] were the least energy consuming pathways, followed by wheat straw pathways [0.05–0.09 MJ $(0.86\ \mathrm{MJ_{th}} + 0.14\ \mathrm{MJ_{el}})^{-1}$] (Fig. 1c and d). Forest residue pathways required 2.5 times more energy than wheat straw pathways, and up to 5 times more energy than pathways based on corn stover when the same CHP technology was employed to produce bioheat and bioelectricty. The large amount of energy inputs of forest residue pathways relative to their agricultural residue counterparts was mainly due to the amount of diesel consumed and to the size of the equipment used to collect forest residues (Table S3). For agricultural residues, the largest contributors to the total energy inputs were baling, harvesting, and transport. The process with the largest energy use across the forest residue pathways was harvesting, followed by forwarding and transport. Averaged over all residues and CHP technologies, baling/forwarding accounted for 37.1% of the total energy input, followed by harvesting (36.7%) and transport (16%). These results suggested that fossil fuel consumption was the main energy input driver representing ~90% of total energy inputs across all residue-based pathways. On average, the conversion of feedstock to bioheat and bioelectricity accounted for 12% of the total energy inputs whereas the recycling of ashes represented −6% of the total energy inputs, because it obviates the need for fuel consumption in the production of competing products such as Portland cement. The analysis suggested a net life cycle energy input of 0.024–0.204 MJ $(0.86\ \mathrm{MJ_{th}} + 0.14\ \mathrm{MJ_{el}})^{-1}$ for residues based bioenergy (Fig. 1c and d).

3.2. Energy inputs of bioenergy from perennial energy crops

The total energy inputs for pathways based on perennial energy crops varied from 0.054 to 0.14 MJ $(0.86\ \mathrm{MJ_{th}} + 0.14\ \mathrm{MJ_{el}})^{-1}$ (Fig. 2c and d). Miscanthus-based pathways required the lowest amount of energy [0.054–0.09 MJ $(0.86\ \mathrm{MJ_{th}} + 0.14\ \mathrm{MJ_{el}})^{-1}$] for bioenergy production because miscanthus has a high biomass yield and consumes less fertilizer than short rotation woody crops (Fig. 2c and d). Activities that were performed more than once in the lifetime of perennial crops (e.g., fertilizing, harvesting,

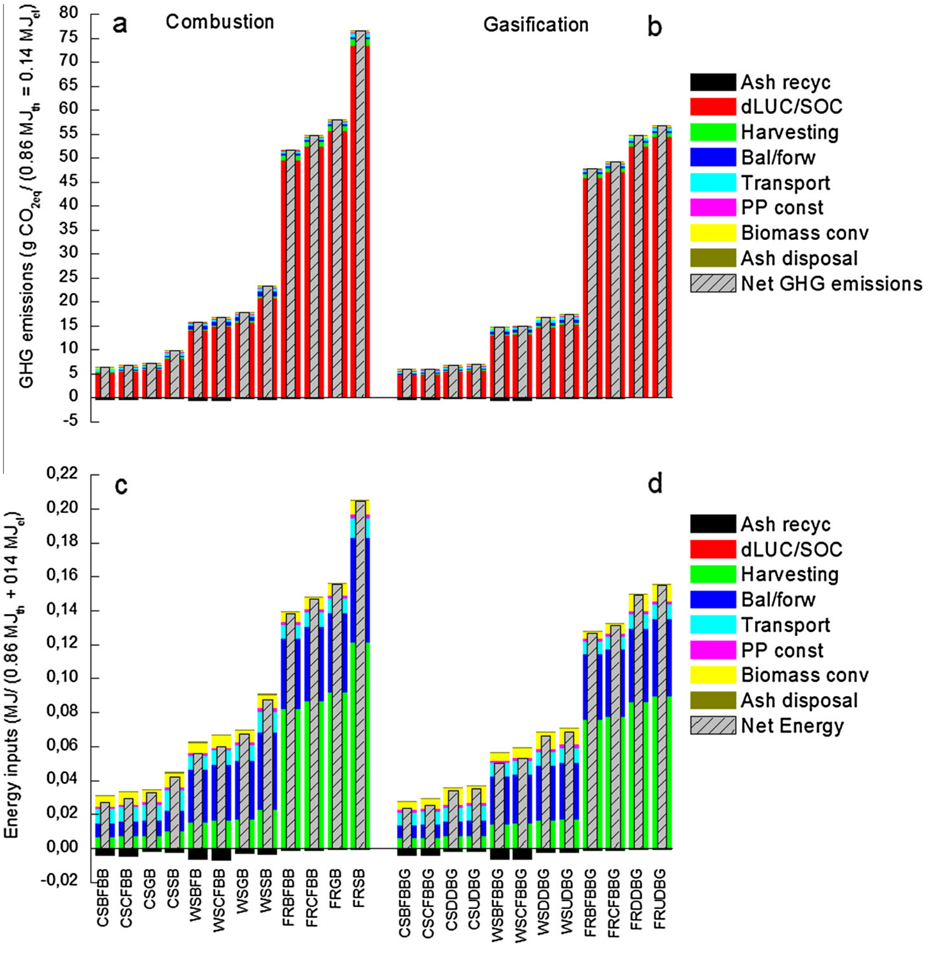

Fig. 1. Energy requirement (c and d) and greenhouse gas emissions (a and b) of residue based bioenergy production pathways. Left panels: combustion; right panels: gasification. dLUC: direct land use change; SOC: soil organic carbon stock; Bal/forw: baling or forwarding; PP const: power plant construction; CS: corn stover; FR: forest residues; WS: wheat straw; BFBB: bubbling fluidized bed boiler; CFBB: circulating fluidized bed boiler; GB: grate boiler; SB: stocker boiler; BFBG: bubbling fluidized bed gasifier; CFBG: circulating fluidized bed gasifier; DDBG: downdraft gasifier; UPBG: updraft gasifier. A combination of a given feedstock and conversion technology (e.g., CSCFBB or CSCFBG) represents a pathway.

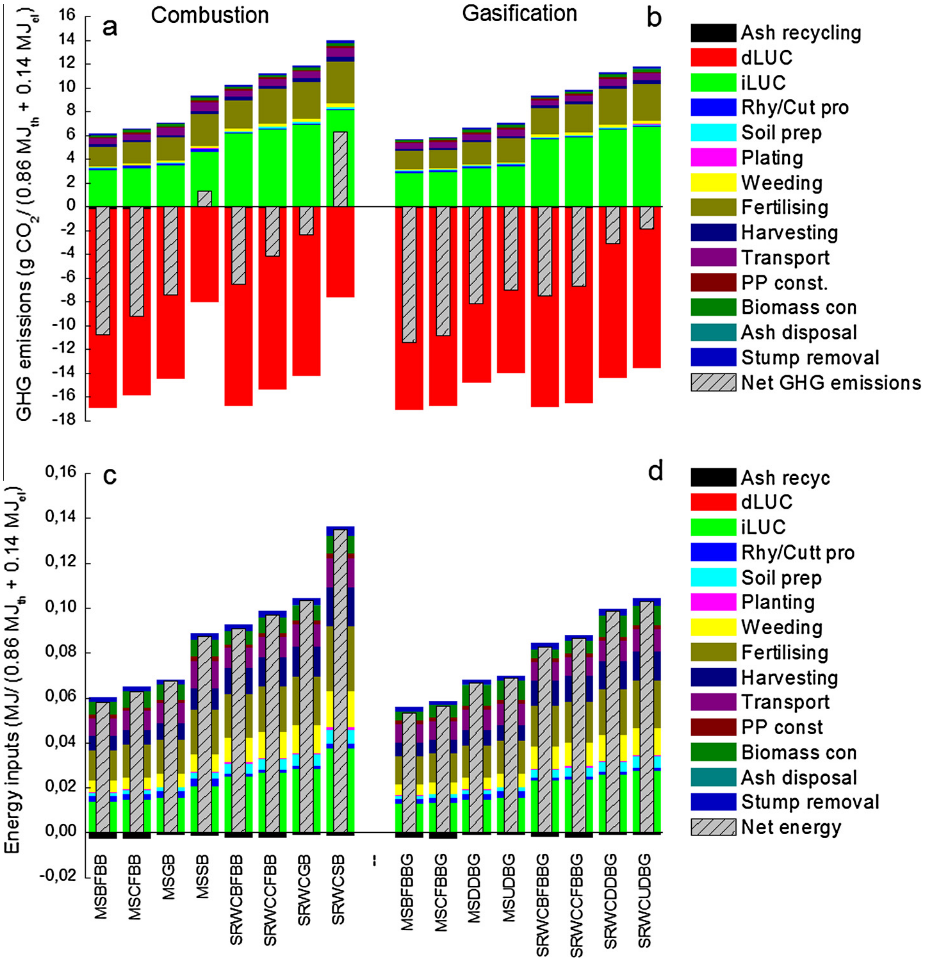

Fig. 2. Energy requirement (c and d) and greenhouse gas emissions (a and b) of perennial crop based bioenergy production pathways. Left panels: combustion; right panels: gasification. dLUC: direct land use change; iLUC: indirect land use change; Rhy/cutt: rhizomes or cuttings; Soil pre: soil preparation; PP const: power plant construction; Stump rem: stump removal; MS: miscanthus; SRWC: short rotation woody crops; BFBB: bubbling fluidized bed boiler; CFBB: circulating fluidized bed boiler; GB: grate boiler; SB: stocker boiler; BFBG: bubbling fluidized bed gasifier; CFBG: circulating fluidized bed gasifier; DDBG: downdraft gasifier; UPBG: updraft gasifier. A combination of a given feedstock and conversion technology (e.g., MSBFBB or MSBFBG) represents a pathway.

transport, and weeding) and the iLUC due to additional fertilizer consumption were the largest contributors to the total energy inputs. Averaged over all perennial energy crops and CHP technologies, iLUC (∼26%), fertilizing (22%), harvesting (13%), transport (12%), and weeding (10%), represented together about 83% of the total energy inputs for the production of bioheat and bioelectricity. This indicated that the fossil fuel consumption and the use of agrochemicals were the main energy drivers across the bioenergy production pathways based on perennial crops. The conversion of perennial crops to bioheat and bioelectricity accounted for ∼9% of the total energy inputs while the recycling of ashes contributed about-2% to the total energy inputs, reflecting the lower ash content of perennial crops (Table S2).

3.3. GHG emissions of bioenergy from residues

The GHG emissions of residues based bioenergy ranged from 5.8 to 76.5 g CO_{2e} $(0.86\ MJ_{th} + 0.14\ MJ_{el})^{-1}$ (Fig. 1a and b). Pathways based on corn stover were the lowest GHG emitting bioenergy pathways [5.8–9.8 g CO_{2e} $(0.86\ MJ_{th} + 0.14\ MJ_{el})^{-1}$], followed by wheat straw based bioenergy pathways [14.7–23.3 g CO_{2e} $(0.86\ MJ_{th} + 0.14\ MJ_{el})^{-1}$], and forest residues [47.9–76.5 g CO_{2e} $(0.86\ MJ_{th} + 0.14\ MJ_{el})^{-1}$] (Fig. 1a and b). Across all residue based bioenergy pathways, the single largest contributor to the total GHG emissions was SOC change. The GHG emissions due to the changes in SOC of forest residues were 4 times those of wheat straw and 9 times those of corn stover (Fig. 1a and b). The low yield of forest residues and high carbon stock of forest soils explained the high SOC induced GHG emissions of bioenergy based on forest residues relative to bioenergy based on agricultural residues (Table S2). When averaged over all feedstock and CHP technologies, SOC changes contributed ∼91% of the total GHG emissions of residue based bioenergy production, followed by transport (4%), baling/forwarding (3%), harvesting (2%), residue conversion (1.5%), power plant construction (1%), and to a lesser extent ash disposal which contributed <1% (Fig. 1a and b). The substitution of Portland cement with ashes from bioenergy production resulted in a significant reduction (−2.1%) of GHG emissions when averaged over residue based bioenergy production pathways (Fig. 1a and b).

3.4. GHG emissions of bioenergy from perennial crops

The GHG emissions from perennial energy crop based bioenergy varied between −11.4 and 6.3 g CO_{2e} $(0.86\ MJ_{th} + 0.14\ MJ_{el})^{-1}$ depending on the pathways chosen (Fig. 2a and b). Pathways based on miscanthus maximized carbon sequestration (Fig. 2a and b), so their net GHG emissions were ∼0.7–4.8 times lower than those of pathways based on short rotation woody crops, which ranged from

-7.5 to 6.3 g CO_{2e} $(0.86\ MJ_{th} + 0.14\ MJ_{el})^{-1}$ (Fig. 2a and b). These results were consistent with the higher biomass yield and the higher carbon sequestration rate of miscanthus relative to short rotation woody crops (Table S2). Regardless of the CHP technology used, dLUC was the largest contributor to GHG emission benefits, while other processes, such as fertilization, iLUC, transport and harvesting, contributed to GHG emission costs in the perennial crop based bioenergy (Fig. 2a and b). Averaged over all perennial crops and conversion technologies, dLUC accounted for −210% of the total GHG emissions whereas iLUC (67%), fertilization (28%), transport (5%), harvesting (4%), weeding (3%) and the production of cuttings (1%) made up the remaining fraction. The GHG costs from the biomass conversion stage offset the GHG benefits (−2%) from the recycling of ashes, but they were lower than the GHG costs from the biomass production stage. Consequently, the feedstock production was the key phase contributing to the GHG emissions of bioenergy from perennial energy crops.

3.5. Effects of power to heat ratio on energy inputs and GHG emissions

Converting a given biomass feedstock to bioenergy using larger and more efficient combustion technologies with a high bioelectricity to bioheat ratio (α) required less energy and emitted fewer GHGs than using smaller, inefficient burners with a low α. For example, when corn stover was converted to bioenergy using either CFBB or BFBB, it required 31–37% less energy and emitted 32–36% less GHGs than when a SB was chosen as the conversion technology (Fig. 1a–c). Likewise, converting miscanthus employing either CFBB or BFBB resulted in 29–34% less energy inputs and 610–725% less GHGs than when using a SB (Fig. 2a–c). This was due to both the large thermal capacities and the high overall efficiencies of the CFBB ($C = 20\ MW_{th}$; $\eta = 88\%$) and BFBB ($C = 48\ MW_{th}$; $\eta = 93\%$) compared to the thermal capacity and the overall efficiency of the SB ($C = 20\ MW_{th}$; $\eta = 63\%$). In addition, the lower α of the SB ($\alpha = 0.16$) relative to those of CFBB ($\alpha = 0.37$) and BFBB ($\alpha = 0.50$) necessitates an additional stand-alone power plant to cover the electricity deficit. CFBB and BFBB outperformed GB on both energy and GHG balances for the same reason above. Similar conclusions were drawn regarding fluidized bed gasification technologies relative to their fixed bed counterparts (Figs. 1b–d and 2b–d). Consequently, fluidized bed combustion and gasification technologies improved the energy and GHG performances of these feedstocks.

3.6. Energy and GHG balances of bioenergy pathways

For all biomass feedstocks and all conversion technologies together, the energy efficiency (i.e., the ratio of energy output to energy input) ranged from 5 to 42 (Fig. 3). Thus, for every unit of energy invested to produce bioheat and bioelectricity, about 4 to 41 net units of energy were gained. The five investigated feedstocks could be unambiguously ranked by energy efficiency in descending order: corn stover > wheat straw ⩾ miscanthus > short rotation woody crops > forest residues. However, not all energy efficient pathways led to lower GHG emissions (Fig. 3). For a given conversion technology bioenergy pathways based on agricultural residues were more energy efficient than those based on perennial crops. Surprisingly, in some cases they emitted more GHGs than pathways based on perennial crops because the net SOC changes increased the emissions of GHGs. The low yield of forest residues and the high carbon stock of forest soils relative to agricultural soils (see SI) explained the higher GHG emissions of forest residues compared to agricultural residues and perennial energy crops. In the case of perennial crops, the net LUC effects of perennial crops significantly reduced the GHG emissions incurred during all phases of crop production and conversion to bioenergy (Figs. 1a–b and 2a–b).

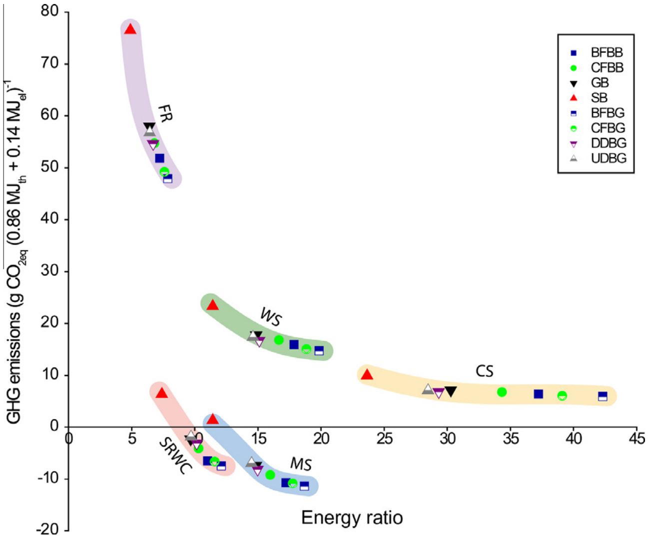

Fig. 3. Energy ratios vs. greenhouse gas (GHG) emissions of bioenergy production using combustion and gasification technologies. Each symbol (circle, triangle, and rectangle) represents one specific combustion or gasification technology. CS: corn stover; FR: forest residues; MS: miscanthus; SRWC: short rotation woody crops; WS: wheat straw; BFBB: bubbling fluidized bed boiler; CFBB: circulating fluidized bed boiler; GB: grate boiler; SB: stocker boiler; BFBG: bubbling fluidized bed gasifier; CFBG: circulating fluidized bed gasifier; DDBG: downdraft gasifier; UPBG: updraft gasifier.

A small reduction in GHG emissions may be achieved by switching to more efficient conversion technologies (Fig. 3). However, a considerable reduction in GHG emissions was achieved either by switching within a group of feedstocks from low to high yielding residues or perennial energy crops, or between feedstocks from residues to perennial crops. Thus, the choice of the feedstock is a decisive factor in the GHG performance of a bioenergy production pathway. The results are only valid if the food formerly produced on the agricultural lands now used for perennial energy crops can be produced on the remaining croplands in Belgium by assuming an intensification of existing management. If yields of major food crops in Belgium remain constant because they have reached a plateau despite such an intensification, the iLUC would change dramatically. This scenario then would influence the overall results a lot more than the present evaluation suggests.

3.7. Comparison of bioenergy to a reference system, and sensitivity analyses

Compared to a reference CHP system (i.e., heat and electricity from oil and natural gas fired CHP in Belgium: Table S10), all 40 bioenergy pathways assessed in this study represented real GHG sinks. Indeed, between 8% and 93% of GHG emissions were saved yearly when residues were used for bioenergy production (Fig. 4). The savings increased to between 92% and ∼114% when perennial energy crops were deployed for bioenergy (Fig. 4).

Sensitivity analyses showed that increasing the biomass yield and the ash recycling rate by 20% increased the energy ratio by 11% and the GHG savings by 1.6%. When the initial SOC was increased by 20% the GHG savings decreased by 1.7% whereas the energy ratio remained unchanged (Table S11). The energy ratio increased by 6% and the GHG savings by 0.8% when the conversion efficiency was increased by 5%. Doubling the transport distance reduced the energy ratio by 23% and the GHG savings by 0.2%. The lowest energy ratio and GHG savings were found when some fractions of field based impacts were allocated to residues. In all cases, the ranking of the bioenergy pathways remained unchanged

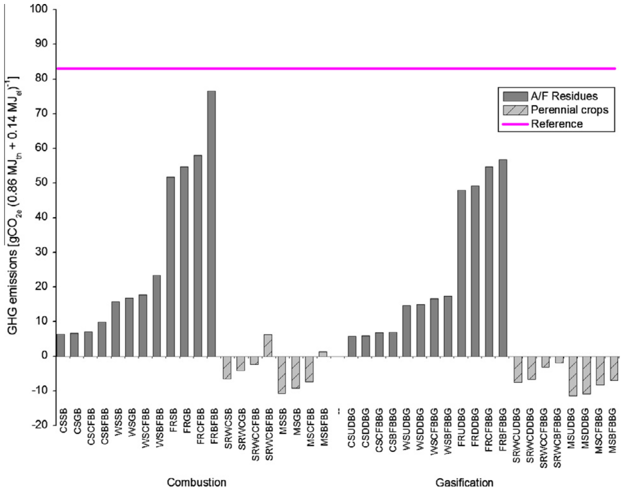

Fig. 4. Greenhouse gas (GHG) emissions of bioenergy (i.e. bioheat and bioelectricity) compared to fossil fuel based combined heat and power (CHP) systems. The bars represent the total emissions of each bioenergy production pathway whereas the solid line above the bars represents the GHG emissions of the fossil fuel based CHP system.

when these parameters were altered. Choosing only heat or only electricity as the main energy product reduced the energy ratio and GHG savings. Finally, using the CML1992 method [55] showed very similar results as the IMPACT2002+ [38] (Table S11).

4. Discussion

Biomass CHP systems remain underutilized in Belgium although they could help to achieve the 2020 energy and climate targets faster than competing technologies. Reasons for this underutilization include the economic advantages of fossil fuel fed CHP systems [56] and the lack of district heating systems in Belgium. The use of fly ash to replace Portland cement in the manufacturing of concrete reduced the energy inputs and the GHG emissions of bioenergy production, and so these reductions are sensitive to the demand for fly ash in Portland cement production [57]. While fly ash is reused in cement industries, the recycling of bottom ash in agriculture is banned in Belgium because of its heavy metal (Cd, Ni) content [58]. But depending on the quality of the bottom ash, such a practice is allowed in other EU countries (e.g., Germany, and The Netherlands) since heavy metals can be removed or reduced at the source during the ash burning and granulation phase [59]. The most important benefit of bottom ash recycling would be the reduced phosphorus import. Phosphorus is highly limited, non-renewable, and its large scale import is unsustainable [60,61]. Although no negative environmental side-effects are to be expected according to bottom ash composition, it nevertheless raises the pH of the soils and, increases microbial populations and the potential mineralization of nitrogen [62,63]. Consequently, it is necessary to conduct further ecotoxicological studies to ensure that the use of bottom ash is safe for agricultural soils in Belgium.

Our observations corroborate the idea that biomass CHPs reduce GHG emissions relative to fossil fuel based CHPs (with 8–93% for residues, and 92% to ~114% for perennial energy crops) even when SOC and LUC impacts are considered in the assessment. For residues, the estimates of GHG emission reductions agree with those of a CHP production study based on agricultural residues in Austria [64]. Using a functional unit and system boundary similar to ours, these authors [64] quantified GHG reductions between 88% and 92% for straw. Also, our estimates of GHG benefits for perennial crops are slightly higher than those of miscanthus (72–82%) and poplar (79–87%) reported by Jungmeier and Spitzer [64]. In the Austrian study the sequestration triggered by LUC could not fully compensate for the GHG emissions incurred during the production and the conversion of perennial crops to bioheat and bioelectricity unlike in our study.

The impact of forest residue removal on SOC had been demonstrated earlier but was not considered an issue as long as these removal practices enable forests to continue functioning as carbon sinks [65–67]. However, the intensified removal of forest residues may decrease the sink potential of forests. Likewise, the increased removal of agricultural residues may increase the size of the source, export nutrients from sites, and expose agricultural lands to erosion and soil compaction [68]. Consequently, if the removal of agricultural and forest residues in Belgium intensifies, criteria addressing nutrient management as well as regarding other environmental impacts are required. This might include setting limits to the extraction of residues and the need to balance nutrient extractions according to specific site conditions. The adoption of forest management practices such as prolonged rotation, continuous forest cover, increased thinning, and crop management like no-till plus cover crops, animal manure, and biochar could replace SOC loss after the removal of forest and agricultural residues. Further investigations on effects of these management options under different residue removal practices need to ensure SOC stocks are maintained where forest and agricultural residues are removed.

The potential for production of perennial crops in Belgium is very limited because of its low ratio of agricultural land per capita (0.13 ha cap^{-1}). However, perennial crops also grow well on degraded lands where food/feed crop production is not optimal because of contamination [69] or other limiting factors. In Belgium ~ 504.4 kha of degraded lands [70] (i.e., ~88% of the total cropland in 2012) could be used for perennial energy crops cultivation. This would increase the potential of biomass production for bioenergy, reduce competition for land with food/feed production and thus the risk of iLUC. Decisions to bring these lands into production depend on local circumstances such as ownership of the land, access, productivity, size of the plot, and available political incentives.

This study used the IPCC Tier 1 approach to estimate the dLUC and SOC stock changes due to perennial crop production and residue removal. A comprehensive and regionally specific approach which captures soil moisture and crop types would yield better estimates of dLUC and SOC stock changes than the IPCC method. Also, a better understanding of the carbon sequestration rates of perennial energy crops, as well as the relationship between fertilizer inputs and yield can reduce uncertainties associated with estimates of GHG emissions due to LUC and SOC changes. Despite these limitations, the results presented here are useful as they demonstrate the differences in various bioenergy pathways and provide new data for bioenergy policy formulation.

5. Conclusion

Perennial energy crops are in some cases better than residues on both energy and GHG balance criteria. However, their broader impacts such as water usage, should be assessed before a further large-scale deployment can be developed. Fluidized bed technologies improved the performances of bioenergy pathways. The choice of feedstock has, however, a larger influence on the energy and GHG performances of a pathway than the conversion technology, and it thus represents the decisive factor in the deployment of bioenergy. Given that emissions from dLUC, iLUC, and SOC changes were considerable, they need to be included in future assessments to avoid potentially large errors in the estimates of GHG emissions of bioenergy pathways. Improvement in management practices and in conversion efficiencies of biomass CHPs will further increase the potential of bioenergy for mitigating climate change.

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Appendix A. Supplementary material

Additional information on method, technology description, reference system, sensitivity analysis, graphical illustration of the system boundary, data tables, and references. Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.apenergy.2015.04.097.

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