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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 $(0.86\ MJ_{th} + 0.14\ MJ_{el})^{-1}$, 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.