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Greenhouse gas mitigation potential of a second generation energy production system from short rotation poplar in Eastern Germany and its accompanied uncertainties

Anja Hansen [a,*], *Andreas Meyer-Aurich* [a], *Annette Prochnow* [a,b]

[a] *Leibniz Institute of Agricultural Engineering Potsdam-Bornim e.V., Max-Eyth-Allee 100, D-14469 Potsdam, Germany*

[b] *Humboldt-University of Berlin, Faculty of Agriculture and Horticulture, Hinter der Reinhardtstr. 8-18, 10115 Berlin, Germany*

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ABSTRACT

This study investigates the variance of the overall greenhouse gas mitigation potential of a complete second generation stationary bio-electricity production system, generated by poplar wood chips (*Populus spec.*) in Germany, using Monte Carlo simulations. We computed the GHG emissions as $E_B = (-0.034 \pm 0.021)\ kg\ CO_{2e}\ MJ^{-1}$ (mean ± SD) and the mitigation factor as $MF_B = (0.274 \pm 0.021)\ kg\ CO_{2e}\ MJ^{-1}$ following a life cycle assessment-based approach. Additionally, avoided nitrous oxide (N_2O) emissions due to land use change were considered in the assessment. The most important factor for the overall mitigation variability was the uncertainty of the organic carbon changes in the soil, followed by the variability of yields. The uncertainty of (i) direct N_2O emissions from the poplar site or (ii) the reference rye site as well as (iii) the uncertainty of heat recovery percentage was of minor importance. Uncertainties in the global warming potentials of nitrous oxide and methane and in the transport distance were found to be irrelevant.

The uncertainty of the GHG mitigation which was associated with this specific electricity generation by poplar wood chips gasification was significantly lower compared to the variability of another common bio-electricity system (biogas). Uncertainty implications seem to be system-specific and therefore should be analysed separately for each bioenergy pathway under consideration.

1. Introduction

Second generation bioenergy is often seen as a means of reaching ambitious carbon dioxide (CO_2) emission reduction-targets in industrialised countries and as a way to simultaneously increase the efficiency of land use [1]. It is frequently defined as energy produced from lignocellulosic biomass from agricultural and forestry plant residues and high-yielding, mainly perennial energy crops [2,3], being specifically of the non-food and non-feed type [4]. The latter characteristic describes the difference between second and first generation starch and oil crops. Second generation conversion

* *Corresponding author*. Tel.: +49 331 5699223; fax: +49 331 5699849.
E-mail addresses: ahansen@atb-potsdam.de (A. Hansen), ameyeraurich@atb-potsdam.de (A. Meyer-Aurich), aprochnow@atb-potsdam.de (A. Prochnow).

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technologies, which are still under development, are typically biochemical and thermo-chemical pathways [5].

The CO_2 emission-reductions, which possibly can be reached via bioenergy pathways, are usually calculated using the concept of mitigation potentials (see for example Refs. [6–8]). In principle, all greenhouse gas (GHG) emissions, including CO_2, methane (CH_4) and nitrous oxide (N_2O) of the complete bioenergy production chain E_B, are counterbalanced against those of a reference system based on energy from fossil and nuclear feedstock E_F. Typically, the emissions from combustion of the biomass are not accounted for, since they are captured by the plants shortly before the combustion process [1].

The mitigation effect E_F–E_B is then expressed as mass (kg carbon dioxide equivalents; CO_{2e}) divided by energy (here: Megajoule electricity generated; MJ). Financial incentives for renewable energies may depend on these mitigation calculations. In Germany for example, the act on granting priority to renewable energy sources (RESA) [9] requires minimum mitigation effects as pre-requisite for its guarantied feed-in tariffs for bioenergy. The conditions are defined in two ordinances [10,11] which implement the sustainability criteria formulated in the European Renewable Energy Directive (RED) [7]. Annex V of RED presents rules for the calculation of the GHG impact of biofuels, bioliquids and their fossil fuel comparators. These European and national regulatory frameworks aim at liquid biomass at the moment as does a draft standard [12]. The European Commission (EC) [13] recommended that member states use the RED sustainability scheme for solid and gaseous biomass accordingly, but proposed no binding methodology for calculating the GHG performance of solid and gaseous biomass. It just explicitly stated to use the life cycle assessment (LCA) method as described in the RED with some extensions. RESA was recently modified and now requires the ordinances to be adapted to include also solid biomass.

Existing approaches to assess the carbon (or GHG, respectively) footprints of products and services [14–17] agree on essential components of GHG inventories. Parameter and system uncertainties and variability are considered important, data quality should be stated, and relevance of values for the outcome of the analysis should be assessed [16]. Standard values for unit processes of supplying and processing biogenic feedstock, in case that no specific data are available, are provided by RED. These standard data are supposed to be conservative assumptions. Nevertheless, the underlying variability of parameters and assumptions is not transparent in published mitigation values. Albeit such frameworks exist, LCA's underlying methodological challenges make the comparison of different studies difficult [18,19]. Among the reasons for that are, for example, the choice of how the by-products are accounted for [20], the choice of the functional unit and the setting of system boundaries [21], the direct and indirect land use change (LUC) effects, the uncertainties regarding soil organic carbon (SOC) development, the choice of the conventional reference system, and the uncertainties in those fossil reference systems themselves [22,23].

Several ways for dealing with uncertainty in LCA have been suggested: (i) the *scientific* way (=do more research), (ii) the *social* way (=discuss and find consensus) and (iii) the *statistical* way, which means using methods from statistical theory and thus incorporating the uncertainty into the analysis [24]. Statistical methods are, for example, Monte Carlo (MC) simulations. These were recently used for the calculation of GHG emissions of the first generation biofuel rapeseed-oil, which displaced fossil diesel [25], and for the comparison of cash flows of two second generation technologies [26].

The majority of the existing studies focus on biomass as feedstock for second generation biofuels in mobile applications [2,5,27–31] and use generic data for the biomass provision. In contrast, we concentrate in this study on the conversion of ligneous biomass in a stationary electricity generation process and use data from an experimental poplar plantation site (*Populus maximowiczii* × *Populus nigra*) as a case study.

The objective is to determine the GHG mitigation potential of a second generation bio-electricity production system from poplar wood chips under German conditions, including reliable ranges, due to the uncertainties of the parameters and the underlying assumptions. The most influential of them, with regard to the overall uncertainty, shall be detected using MC simulations.

2. Methodology

2.1. *Greenhouse gas mitigation of bio-electricity from short rotation poplar*

The GHG mitigation effect of bio-electricity from poplar short rotation coppice (SRC) is expressed as the overall mitigation factor MF_B (kg CO_{2e} MJ^{-1}) with

$$MF_B = E_F - E_B \quad (1)$$

where E_F is the cumulative CO_{2e} emission MJ^{-1} from electricity generation via the country-specific fossil feedstock mix and E_B is the cumulative GHG emission when electricity is generated from poplar wood chips via gasification. E_B was assessed according to the valid national framework [10] and the suggested approach which was presented in Ref. [13]. A modification was made in the way that also N_2O emission savings from changed land management were considered. In the cited frameworks, LUC emissions or savings, respectively, so far only comprise those due to carbon stock changes. Generally, E_B includes GHG emissions from pre-chains, from farming operations of agricultural SRC cultivation and from the transport of the harvested biomass to the conversion site. The processes considered for the respective production chains are presented in Fig. 1. More detailed assumptions and system descriptions for the production chains are given in the following paragraphs. For all processes the absolute amounts of the emitted greenhouse gases were converted to carbon dioxide equivalents with the actual global warming potentials (GWPs) for a 100-yr time horizon ($GWP_{N_2O} = 298, GWP_{CH_4} = 25$ [32]). The functional unit is 1 MJ electric energy generated either via fluidised bed gasification of poplar wood chips or with the reference electric energy supply systems in Germany.

We used the LCA software umberto® [33] to define the overall electricity generation system from short rotation poplar cultivation under East German conditions to calculate the accompanied GHG emissions E_B and to carry out the MC calculations for the parameters under study.