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Climate effect of an integrated wheat production and bioenergy system with Low Temperature Circulating Fluidized Bed gasifier

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HIGHLIGHTS

- Wheat straw removal from agricultural system has considerable GWP effect.
- Changing the carbon conv. in the gasifier to 0.8–0.86 mitigates those effects.
- Considerable difference is between sequestration potential of straw and biochar.
- Lowering the carbon conversion improves GWP, but depends on subst. technology.

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ABSTRACT

When removing biomass residues from the agriculture for bioenergy utilization, the nutrients and carbon stored within these "residual resources" are removed as-well. To mitigate these issues the energy industry must try to conserve and not destroy the nutrients. The paper analyses a novel integration between the agricultural system and the energy system through the Low Temperature Circulating Fluidized Bed (LT-CFB) gasifier from the perspective of wheat grain production and electricity generation using wheat straw, where the effects of removing the straw from the agricultural system are assessed along with the effects of recycling the nutrients and carbon back to the agricultural system. The methods used to assess the integration was Life Cycle Assessment (LCA) with IPCC's 2013 100 year global warming potential (GWP) as impact assessment method. The boundary was set from cradle to gate with two different functional units, kg grain and kW h electricity produced in Zealand, Denmark. Two cases were used in the analysis: 1. nutrient balances are regulated by mineral fertilization and 2. the nutrient balances are regulated by yield. The analysis compare three scenarios of gasifier operation based on carbon conversion to two references, no straw removal and straw combustion. The results show that the climate effect of removing the straws are mitigated by the carbon soil sequestration with biochar, and electricity and district heat substitution. Maximum biochar production outperforms maximum heat and power generation for most substituted electricity and district heating scenarios. Irrespective of the substituted technologies, the carbon conversion needs to be 80–86% to fully mitigate the effects of removing the straws from the agricultural system. This concludes that compromising on energy efficiency for biochar production can be beneficial in terms of climate change effect of an integrated wheat production and bioenergy system.

1. Introduction

Climate change, security of supply and depletion of fossil fuels have become increasingly well-known issues, and the combination of the three has instigated a worldwide attention on finding pathways for sustainable energy supply [1,2]. Increased use of biomass feedstock for transport, power and heat generation are generally perceived as relevant methods to mitigate these concerns. However parallel to these before-mentioned issues are problems associated with food supply, population growth, land use, essential mineral depletion and soil degradation. All of which contribute to the increasing awareness of biomass as both an energy and food resource.

Moving from a fossil fueled energy system towards greater reliance on renewables, requires cautiously designed allocation of

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the obtainable resources and a highly flexible system [3]. In this perspective, gasification of biomass has proven its potential. A Low Temperature Circulating Fluidized Bed gasifier (LT-CFB), currently termed *Pyroneer*, was developed to be able to operate on biomass feedstock with high ash content that has proven difficult to use in other systems, e.g. straw, manure fibers, sewage sludge, organic waste etc. [3].

Biomass residues from the agricultural industry are normally taken to be readily available to the energy sector, and obvious to exploit for producing power, heat and fuels. However, what is not so obviously seen from the energy system's perspective is the fact that together with the removal of biomass residues from the agricultural sector, the nutrients and carbon within them are also removed. This entails the need to add nutrients and possibly carbon to the agricultural fields in order to maintain soil fertility and soil carbon content. This has been highlighted with recent environmental impacts studies on bioenergy. Djomo et al. [4] report the change in soil organic carbon for perennial energy crops to be climate change mitigating, conversely Sastre et al. [5] show that loss of carbon of soil carbon is the greatest contributor to the climate change effect of a bioenergy system utilizing wheat straw. It is also one of the conclusions of Yang et al. [6] and Parajuli et al. [7] that carbon loss from agricultural residue removal is an important contributor to climate change in a bioenergy system. Two latter papers discuss the impact of atmospheric carbon load due to biogenic carbon emissions, Parajuli et al. [7] uses the approach of Petersen et al. [8], which is very similar to the work of Guest et al. [9,10] for forestry systems.

Kuligowski et al. [11] concluded from a field study that ash derived from a low-temperature gasification of the fiber fraction from anaerobically digested pig slurry has the potential to be used to maintain phosphorus levels in agricultural soils. Müller-Stöwer et al. [12] further concluded that ash from low temperature gasification of biomass can replace mineral fertilizer. Moreover, in addition to the recycling of valuable nutrients, the use of ash containing recalcitrant carbon fractions could maintain or even increase soil organic carbon stocks and thus contribute to carbon sequestration as suggested by Brandao et al. [13]. Recently Veronika et al. [14] contributed to this discussion by experimental results indicate that gasification biochar is very stable in soil and has good potential for a longterm carbon sequestration in soil.

Realizing this, and integrating it into a bioenergy concept, can create the foundation of a flexible and sustainable use of biomass resources, and make such a bioenergy system a genuinely climate neutral or even climate mitigating source of energy. Nguyen et al. [15,16] used Life Cycle Assessment (LCA) to assess the environmental concerns of using wheat straw in the energy system and applying the ash back to the field using both combustion and gasification technologies. However, it was noted that more research was required on the issue to conclude on those results. This article is meant to shine a light on those issue and by further analyzing the carbon conversion (CC) in a polygeneration energy system producing; electricity, district heat and carbon rich "fertilizer" (named GBC in the article or gasification biochar). The system will be analyzed for three operational scenarios in the gasifier, i.e. maximum product gas production, maximum biochar production and a climate neutral scenario. These scenarios are compared with two reference scenarios, one where the straws are not harvested and thus no heat or power are generated, another with straw removal and combustion instead of gasification in the energy system.

Moreover, it is of interest to include in the analysis the total wheat production at a specific location in Denmark and to analyze more closely the consequences of the changes in soil nitrogen dynamics. This is done by computing a novel inter-connected model of the agricultural system and the energy system. Which combines carbon in soil simulation in C-TOOL [17,18], energy system simulation with Dynamic Network Analysis (DNA) [19], Life Cycle Inventory and Impact Assessment processing with Brightway2 [20], along with substance flow calculations and atmospheric carbon decay simulation.

2. Methods

2.1. System description

Energy system utilizing wheat straw for heat and power generation is analyzed. Ashes and biochar (GBC) are recycled back to the agricultural system, GBC is considered the third product of the energy system. Three scenarios (S1–S3) and two reference cases (RA and RB) are modeled.

2.1.1. Scenarios

- *RA: Straw not harvested.* Straws are not removed from the field and thus no electricity and heat production.
- *RB: Straw direct combustion.* Straws are removed from the field and combusted. Bottom ash is recycled back to the field and fly ash is landfilled.
- *S1: Maximum heat and power generation.* Straws are removed from the field and gasified with carbon conversion[1] (CC) of 95%, gas produced is combusted in an conventional combined heat and power (CHP) steam cycle and the GBC is returned to the field.
- *S2: Climate neutral.* Like High CC, but with a carbon conversion adjusted to make the mitigating effect of carbon soil sequestration equal to the impact of removing and utilizing the straw in the energy system.
- *S3: Maximum biochar production.* Like High CC, but the lowest possible carbon conversion is found from system simulation.

A simple schematic of the complete system including the agriculture and energy conversion is presented in Fig. 1. Grain yield per hectare is an input to the model and was assumed to be 8.0 tonnes.The harvestable residues, i.e., *straw* are calculated based on the residue harvest index (0.42), i.e. ratio between total residues and total harvest, while the straw part of the total residues was estimated to be 65%. The residues left on the field (referred to as *residues*) are equal to the total residues for RA, and equal to the difference between the total residues and the straw for RB and S1–S3. Ultimate analysis of the residues and straw was taken from Vassilev et al. [21] and the lower heating value (LHV) from Nguyen et al. [15]. Straw is then transported 20 km to the energy system where it is either directly combusted for heat and power generation or gasified at specific carbon conversion before the product gas can be combusted, the GBC or bottom ash is transported back to the same agricultural field 20 km away from the energy system.

2.2. Analytical approach

The analysis follows the framework of consequential LCA. The fertilization and field emissions were modeled by a nutrient balance based on inputs, what is harvested and the emissions that occur as a consequence. Other factors in the LCA, except for transportation between the field and the gasifier, were modeled with the aid of the Ecoinvent 3.1 database [22], i.e. the work processes, pesticides input, farm transport and seeds input. The Ecoinvent database was also used for all upstream processes. The analysis was made from cradle to gate for two functional units.

[1] Carbon conversion in the gasifier is the carbon ratio between fuel input and product gas out of the gasifier, the rest leaves the gasifier as biochar.