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Environmental performance of crop residues as an energy source for electricity production: The case of wheat straw in Denmark

Thu Lan T. Nguyen *, John E. Hermansen, Lisbeth Mogensen

Department of Agroecology, Aarhus University, Tjele, Denmark

HIGHLIGHTS

- This paper assesses the environmental performance of wheat straw as an energy source.
- Coal and natural gas (NG) are selected as references for comparison with straw.
- Straw has a better performance than coal and NG in some midpoint impact categories.
- The single score results show that straw is better than coal but worse than NG.
- Potential improvements lie in reducing NO_x emissions and increasing power output.

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ABSTRACT

This paper aims to address the question, "What is the environmental performance of crop residues as an alternative energy source to fossil fuels, and whether and how can it be improved?". In order to address the issue, we compare electricity production from wheat straw to that from coal and natural gas. The results on the environmental performance of straw for energy utilization and the two fossil fuel references are displayed first for different midpoint categories and then aggregated into a single score. The midpoint impact assessment shows that substitution of straw either for coal or for natural gas reduces global warming, non-renewable energy use, human toxicity and ecotoxicity, but increases eutrophication, respiratory inorganics, acidification and photochemical ozone. The results at the aggregate level show that the use of straw biomass for conversion to energy scores better than that of coal but worse than natural gas. In order to investigate the question of whether and how a reduction in the single score per kW h of electricity produced from straw is feasible, we perform a scenario analysis where we consider two approaches. The first one is a potential significant reduction in emissions of nitrogen oxides (NO_x) by implementing selective catalytic reduction technology and the second is a potential increase in power generation efficiency. The results of the scenario analysis show that both approaches are effective in enhancing the competitiveness of straw as an alternative energy source, though the second approach "increasing efficiency" is somewhat less attractive than the first "reducing NO_x emissions".

1. Introduction

Fossil fuel use for electricity and heat production is facing serious problems related to resource depletion and environmental degradation, notably climate change. Biomass fuels (e.g. wood waste, crop residues, energy crops), in contrast, are considered renewable and carbon neutral. Unlike fossil fuels that take millions of years to be available as an energy source, biomass can be regenerated relatively quickly through photosynthesis where sunlight is captured to convert atmospheric CO_2 and water into organic matter. Biomass burning for energy releases CO_2 back to the atmosphere but this biogenic CO_2, considered to be part of the natural carbon cycle, is not counted as contributing to global warming.

Apart from other biomass fuels, crop residues have recently received large attention as a potentially considerable source of renewable energy. On a global scale, crop residues of 3758×10^6 Mg/year, which is equivalent to 11×10^{15} kcal, are estimated to be available [1]. Out of this available amount, approx. three fourths are made up of cereal residues [1]. A clear advantage of using crop residues as an energy source is that it minimizes the impacts of land use changes since no additional agricultural land is taken into production [2]. In keeping with the cradle-to-grave concept of life cycle assessment (LCA), the upstream impacts of converting biomass to energy, i.e. in this case, the impacts associated with the removal of crop residues as well as the collecting,

* Corresponding author. Tel.: +45 8715 7689; fax: +45 8999 1200.
E-mail address: ThuLan.ThiNguyen@agrsci.dk (T.L.T. Nguyen).

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pre-processing and delivering of the biomass resource, however, need to be taken into account. There is an on-going discussion about the environmental implications of removing cereal straw from traditional cropping systems for energy purposes [3,4]. Another issue is that although biomass fuels generally have superior performance to fossil fuels in global warming and non-renewable energy, they may have inferior performance in other environmental impacts.

Considering the above, we believe that a need exists for a thorough and comprehensive analysis to assess the sustainability of converting crop residues to energy. In this paper, we present as a case study the results of a life cycle analysis of the environmental performance of electricity generation from wheat straw in comparison with coal and natural gas. We also investigate the potential to improve the environmental performance of this biomass resource as an alternative energy source based on the findings of our hotspot analysis. The case study is supposed to take place in Denmark, where biomass fuelled combined heat and power plants have for many years been a common part of the national electricity and district heating supply [5]. The total amount of biomass resources available in Denmark – including lignocellulosic biomass (e.g. wood and straw), manure, grass and waste – has been estimated elsewhere at 182.3 PJ [6].

To achieve the objectives of the study, we aim to address the following questions: (1) What are the upstream impacts of converting crop residues to energy and what if they are included in the full chain analysis?; (2) In addition to global warming and non-renewable energy, what about other impact categories which are relevant for evaluating biomass as an alternative energy source, like acidification, eutrophication, respiratory inorganics, ecotoxicity, human toxicity, and photochemical smog; and (3) How to account for "trade-offs" among different impact categories? In relation to the last two questions, we find that it is not only necessary to take into account a set of relevant impact categories, but also to perform the analysis at a more aggregated level, i.e., translating environmental impacts in different midpoint categories into a single unit so that they can be weighted and added together to give a single score value.

2. Materials and methods

2.1. System boundary definition, process description and basic assumptions

The LCA system boundary for straw-fired electricity generation is presented in Fig. 1, with a focus on the study area (Denmark). It includes three main system processes: straw removal, straw collection and pre-processing, and straw combustion at power plants. Briefly described, by the time of cereal crop harvest, straw is removed (instead of being ploughed into the soil), pre-processed and delivered to power plants where it is burned to produce electricity as the main product and heat as a co-product. The burning also produces bottom ash (or slag) and fly ash. The bottom ash is to be returned to natural ecosystems, as appropriate, to save fertilizers and to implement nutrient recycling. The value of fly ash as a resource, in contrast, has not been realized due to the presence of heavy metals in relatively high concentrations [7]. In many places, fly ash recycling is not acceptable but rather disposing in landfills [8,9].

Using a life cycle approach, apart from the impacts associated with the process of straw conversion to energy, we consider the upstream impacts associated with the removal, collection and pre-processing (including transportation) of the biomass resource. The logic behind basic assumptions for each of these upstream and downstream processes, straw removal, straw collection and pre-processing, and straw combustion is discussed below.

2.1.1. Straw removal

Incorporation of straw into the soil builds up soil carbon as well as soil nitrogen, and returns valuable nutrients to the ecosystem. The removal of straw therefore loses the build-up of soil C and N and has to account for the environmental impacts resulting from the need for an extra input of mineral fertilizers to compensate for the nutrients removed with straw.

Petersen and Knudsen [10] analyzed the effects of straw removal on carbon sequestration in agricultural soils under Danish climatic conditions. They found that the incorporation of 1 t of straw carbon into the soil would correspond to a carbon sequestration rate of 198 kg C (i.e. 19.8%) for loamy sand soil, in a 20-year perspective. The choice of the time perspective, 20 years, is based on the 2006 IPCC guidelines for estimating soil carbon changes [11]. The build up of organic nitrogen is assumed to follow carbon in the ratio of 1:10 [12]. Such build-up of soil C and N will not take place if the straw is removed from the soil.

The removal of straw also results in the removal of nutrients which is assumed to be compensated by an additional input of mineral fertilizers. In order to estimate the amount of extra fertilizer inputs, it is necessary to determine the mineral fertilizer equivalent (MFE) of macronutrients in straw, nitrogen, phosphorus and potassium. In relation to nitrogen, only a portion of the nutrient removed with the straw is considered to be available for crop uptake if returned to the soil. Straw has a very high C/N ratio, which means that when it is incorporated into the soil, N will be immobilized instead of being mineralized to benefit the following crop at least for the first couple of years. Of course, the immobilized N will again be released, but the release (mineralization) occurs slowly over a period of several years. According to Petersen [13], about 30% of N in straw is available to crops (i.e., valued as

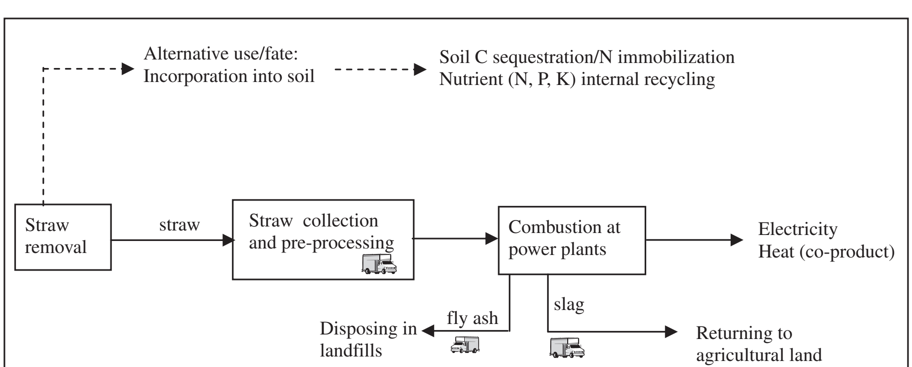

Fig. 1. LCA system boundary for straw-fired electricity generation.