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Environmental assessment of chemical products from a Norwegian biorefinery

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ABSTRACT

To mitigate climate change and to ensure energy security, society is searching for alternatives to fossil fuels. Biomass is an interesting renewable resource, because it can be used both as energy and as feedstock for material and chemical production. The aim of this article is to present the environmental impacts associated with products from a biorefinery in Norway (Borregaard). More specifically, the article shows results from studies on the products ethanol 96%, ethanol 99%, cellulose, liquid lignin, lignin powder and vanillin, and identifies the processes which contribute most in each impact category and product. Comparative emissions are also shown for at least one product alternative. The study has been carried out using the life cycle assessment method from "cradle to gate". The functional unit is 1 tonne product for cellulose, lignin and vanillin and 1 m^3 product for ethanol. All of the products are based on the same raw materials (timber and wood chips). The infrastructure of the biorefinery has been included. The study has, as far as possible, avoided allocation by analysing and modelling the processes at a detailed level. Where necessary, energy allocation, using dry weight energy content, has been applied. Climate change, acidification, eutrophication, photochemical ozone creation, ozone depletion and cumulative energy demand have been selected as environmental impact categories. Different processes relating to the biorefinery have significance for the various environmental impact categories. This has made it difficult to single out the processes to be studied further. Oil combustion is the most important process in relation to climate change. Infrastructure is not important for either impact category. The global warming potential for bioethanol from Borregaard is in the lower range when compared with earlier studies. To conclude, this article demonstrates that the biofuel under study is, even at worst, comparable to that produced using other bioethanol production processes. The other products are also substitutes for fossil derived chemicals, but as the available literature lacks data for such chemicals, the environmental profiles for these have not been compared.

1. Introduction

In recent years, the search for alternatives to fossil fuels as energy sources has become a priority (IPCC, 2014). The reasons for this are linked to endeavours to mitigate climate change and to ensure energy security for countries with limited access to fossil fuels. In this context, renewable energy is a valuable choice. Within the wide range of alternative energy sources, biomass as "material of biological origin excluding material embedded in geological formations and transformed to fossil" (CEN, 2004) is a raw material which is immediately available and exploitable. In order to become a real alternative to fossil-based materials, however, biomass should offer more than being merely a source of energy. Although society depends on the everyday consumption of petroleum derivatives, biomass can be a useful feedstock in the production of chemicals and fuels (Fernando et al., 2006; Fiorentio et al., 2014). Moncada et al. (2014) concludes that not only biofuels, but also bio-based materials, are important products when coproduction is considered. This leads one to the basic idea of a biorefinery, which is a facility that is equipped for the integration of conversion processes to produce fuels, power, and chemicals from biomass (NREL, 2012). The biorefinery concept is analogous to that of petroleum refineries, where multi-products and fuels are produced simultaneously from the same raw material. Cherubini (2010) highlights three key elements for a biorefinery: 1) It should produce at least one high value chemical/material product, in addition to low-grade

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and high-volume products such as animal feed and fertilisers. 2) It should produce at least one energy product as well as heat and electricity. The production of at least one biofuel (liquid, solid or gaseous) is then required, and 3) it should aim to operate sustainably.

In this paper, the term biorefinery is defined in accordance with the International Energy Agency's definition (Cherubini et al., 2012) as “the sustainable processing of biomass into a spectrum of marketable products and energy”. More specifically, the biorefinery investigated would be coined a forest-based biorefinery according to a classification system developed by Cherubini et al. (2009).

Bio-based products are produced from a variety of feedstocks. At present, the main feedstock being used for first generation products is edible biomass from, for example, oil plants or sugar-starch rich crops, while residual non-food parts of current crops or other non-food sources such as lignocellulosic biomass are high potential feedstock for second generation products (King, 2010). It is more difficult to convert lignocellulosic biomass than to convert edible biomass (Wettstein et al., 2012). This is due to the high amount of energy required in the case of the former, to break down the protective shield of hemicelluloses and lignin surrounding the cellulose.

The IEA Bioenergy Task 42 regarding Biorefineries (Cherubini et al., 2012) lists the most important existing biorefineries and non-conventional biomass industries now running in the task countries (Austria, Canada, Denmark, France, Germany, Ireland and the Netherlands). The list comprises 23 facilities, of which only a few can be characterised as biorefineries according to the strict IEA definition. Several studies have been carried out on products from ‘biorefineries’, for example Fahd et al. (2012) on fuel (biodiesel), chemicals and heat, González-García et al. (2010), Zhu and Zhuang (2012) and Patrizi et al. (2014) on fuel (bioethanol), and Martinez-Hernandez et al. (2014) on fuel (biodiesel), chemical (glycerol) and energy. The facilities scrutinised do not, however, produce a spectrum of products, but rather focus on one or two material products, or one energy product in addition to heat and/or electricity. Bio-based material e.g. are scrutinized by Weiss et al. (2012, 2007) through a review of LCA (life cycle assessment) studies in regards to environmental impacts for production. Gironi and Piemonte (2011) instead focus more on the impact assessment for bioplastic production. Zhu and Zhuang (2012) claim that there is a lack of comprehensive information regarding energy data for promising process technologies in the field of biorefining of lignocellulosic biomass. Ahlgren et al. (2013) made a review of twelve selected scientific papers with case studies of biorefinery systems, and found that there are methodological inconsistencies in existing case studies, making comparability among studies difficult. Ahlgren et al. (2013) also claim that there is a lack of proper documentation of assumptions regarding data and methodological choices in many case studies of biorefineries, and that there is a need for further research on these topics. In a review of 340 papers, of which 238 were published after 2011, Kajaste (2014) claims that the assessment of chemicals produced from biomass seems to be practically absent in LCAs, and that there is a need for future research on both carbon efficiency and economics of biorefinery production chains.

One example of a biorefinery which accords with the IEA definition, comes from Norway. Borregaard is a company located in Sarpsborg in the Southeast of Norway. It owns and operates a highly advanced biorefinery which has been producing biochemicals, biomaterials and bioethanol using lignocellulosic feedstock, for more than 40 years (Rødsrud et al., 2012). Cellulose, ethanols, lignins, vanisperse, vanillin, sodium hypochlorite, hydrochloric acid, chlorine and steam are the principal products manufactured at Borregaard, and all are based on hemicellulose from Norwegian spruce.

An LCA was performed, and environmental product declarations (EPDs) generated, in order to document the environmental properties of products manufactured simultaneously at the Borregaard facility. The current study focuses on ethanol 96%, ethanol 99%,[1] cellulose, liquid lignin, lignin powder and vanillin. These products are used in pharmaceuticals, chemical and technical applications, building materials, feed, food, textiles, and biofuel. The aim is to present the environmental impacts associated with the aforementioned products and highlight the most significant environmental impacts and the most important life cycle stages for each. There is currently a lack of transparent and well-documented LCA data on second generation biofuel production and on sophisticated biorefineries, which the paper aims to remedy.

2. Methods

The study has been carried out using life cycle assessment (LCA) based on the ISO-standards 14025 and 14044/48 (ISO, 2006a,b, 2002). Life cycle assessment of a product can be defined as a systematic mapping and evaluation of environmental and resource impacts throughout its entire life cycle, i.e. from ‘cradle to grave’, although this study has, in fact, a narrower scope as it stops at the factory gate. The analysis thus spans the processes from “cradle to gate” (see Fig. 1). As such it includes all upstream processes and processes taking place at the biorefinery and excludes the product's use. In order to develop EPDs, however, a transportation distance of 100 km, weighted according to the actual means of outbound transport from the facility, has been chosen for products delivered to customers, as required by the product category rules (PCR) for chemical products (The International EPD®system, 2000).

The analysis has been based on a *product system*, and has considered the environmental and resource impacts in relation to a defined *functional unit*, describing the performance of the product in relation to the particular needs of the user. Because the products are used in several applications, the functional unit has been chosen to be based purely on mass and volume. The functional unit is 1 tonne of the product for cellulose, lignin and vanillin and 1 m^3 of the product for ethanol. The analysis has been performed on a dry basis, meaning that it has been carried out per tonne dry matter (DM) of the various products. In the case of ethanol, this means that the environmental impacts refer only to the amount of ethanol in the product (water contents are 0.1% and 4% respectively). The study is attributional (accounting LCA), and specific data are used for the biorefinery processes.

At the Borregaard facility, there are many different factories and process plants, and the raw materials are processed in several installations before ending up as finalised products. All products are based on the same raw materials (timber and wood chips from Norwegian forests) and are mutually dependent due to the internal use of co-products and energy in the loops. Generic data and processes are used for most of the chemicals (Ecoinvent 2.2 database (Ecoinvent Centre, 2010)). The complexity of the process and the interconnection of the products are evident in the principle model, shown in Fig. 2.

Wiloso et al. (2012) affirm that a clearer guidance is necessary for the methodological aspects of the production of bioethanol based on lignocellulosic biomass. According to Cherubini et al. (2011a) there is no one and standard technique for assessing biorefineries, and thus LCA practitioners must choose the method most appropriate to the objective of the study. This study has, however, as far as possible avoided allocation by analysing and modelling the processes of the biorefinery at a detailed level. Outlet

[1] The product is called ‘Ethanol (99%)’ while the actual ethanol content is 99.9%.

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