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Possibilities for sustainable biorefineries based on agricultural residues – A case study of potential straw-based ethanol production in Sweden

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HIGHLIGHTS

- ▶ Biorefineries can produce ethanol, biogas, heat and power efficiently with profit.
- ▶ Location of plant is decided by raw material supply in the region.
- ▶ Increased production of high value compounds affects profitability.
- ▶ Energy efficiency is increased by availability of heat sinks.
- ▶ Several locations may be suitable for construction of a biorefinery plant.

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ABSTRACT

This study presents a survey of the most important techno-economic factors for the implementation of biorefineries based on agricultural residues, in the form of straw, and biochemical conversion into ethanol and biogas, together with production of electricity and heat. The paper suggests locations where the necessary conditions can be met in Sweden. The requirements identified are regional availability of feedstock, the possibility to integrate with external heat sinks, appropriate process design and the scale of the plant. The scale of the plant should be adapted to the potential, regional, raw-material supply, but still be large enough to give economies of scale. The integration with heat sinks proved to be most important to achieve high energy-efficiency, but it was of somewhat less importance for the profitability. Development of pentose fermentation, leading to higher ethanol yields, was important to gain high profitability. Promising locations were identified in the county of Östergötland where integration with an existing 1st generation ethanol plant and district heating systems (DHSs) is possible, and in the county of Skåne where both a significant, potential straw supply and integration potential with DHSs are available.

1. Introduction

The debate on sustainability issues concerning biofuels has intensified, especially about the potential conflict between food and fuel production and about increased emissions of greenhouse gases from changes in the use of land [37]. Thus, the great challenge of today is how to produce food, fuel and bioproducts in the best possible way, and minimise the risk of land-use changes and deforestation [23,5].

Despite the concerns with 1st generation biofuels based on sugar and starch crops, the majority of biofuels are still produced in single-product factories from food crops such as corn, sugarcane or wheat. One way to improve both productivity and sustainability is the establishment of integrated biorefineries to generate value from the entire agricultural crop by producing multiple products [8]. The interest in producing 2nd generation biofuels based on lignocellulosic feedstock has increased in recent years due to an increased awareness of the drawbacks of 1st generation biofuels. Straw is a potential raw material for 2nd generation ethanol production. It is a by-product generated from the cultivation of various crops such as grains, oilseeds and rice, which makes it one of the most abundant agricultural by-products worldwide. With a few exceptions, such as its use in animal husbandry, soil improvement and, in some developing countries as a building material and in domestic stoves for cooking and heating, straw is mainly seen as a waste residue [18].

This study presents an example of how sustainable, straw-based biorefinery concepts can be implemented in practice. The study is divided into two parts of which the first gives a short review of environmental and policy issues concerned with biofuels and 2nd generation ethanol. The second part presents a case study

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of straw-based biorefinery concepts developed in Sweden, their energy and economic performance and options for siting based on raw material supply and infrastructure for integration with external heat sinks.

2. Incentives and initiatives for production of 2nd generation ethanol, globally

2.1. Policy drivers

Most countries have adopted policies or other political or financial incentives to increase the production of biofuels, sometimes with special focus on the 2nd generation biofuels [41]. The main drivers behind these policies are climate-change mitigation, the security of energy supply and the stimulation of rural development [8]. In the EU, targets for biofuel consumption are set in the Renewable Energy Directive (RED). According to this directive, 10% of the total energy used for transportation shall originate from renewable sources by 2020 [15]. Since the previous EU directive of 2003 was criticised because the drawbacks of crop-based biofuels had not been considered [13]. The directive of 2009 [15] includes sustainability criteria to prevent increased GHG emissions caused by land-use changes and to protect sensitive and biodiverse areas. The directive states that compared to fossil fuels the reductions of CO_2 emissions of biofuels produced in new plants should be at least 35%, after 2017, 50% and after 2018, then 60% [34,41,15]. To reach these targets, 2nd generation biofuels will be necessary. In order to further stimulate the demand and thereby production of biofuels produced from residues, waste and non-edible crops the contribution of such biofuels should be considered to be twice that of other biofuels [15].

In the US the updated Renewable Fuel Standard (RFS2), adopted in 2010, requires the producers of biofuels to reduce life-cycle emissions of greenhouse gases by at least 50% compared to conventional fuels for advanced biofuels, 60% for cellulosic biofuels and by 20% for 1st generation biofuels [41,34]. In the Energy Independence and Security Act (EISA) absolute targets for the supply of biofuels have been set in which also 2nd generation biofuels are included. For 2010 the target was a production of 6.5 million gallons of cellulosic ethanol. This should be compared with the total ethanol supply of 13 billion gallons, which corresponds to roughly 5% of total gasoline consumption [3].

Brazil introduced its first national alcohol programme in 1975 but in the 1990s the demand for ethanol diminished. With increasing oil prices and concern about global warming, the production of ethanol gained a new impetus in the 2000s [41]. Thanks to favourable conditions for sugarcane production, well-developed technology and a dedicated innovation system, Brazil is also the only country in which ethanol as a vehicle fuel is profitable without subsidies. Thus, an extended production of 2nd generation ethanol in Brazil will most likely be driven by economic rather than political reasons [17,19].

China was previously not taking actions to promote the use and production of biofuels, specifically due to the competition with food production and dependency on imported agricultural products. In recent years however, the fast growing car industry demands increased production of non-food based biofuels [49]. Today only ethanol from non-grain crops is promoted and the government strictly controls the price and production of ethanol [3,41]. China has substantial straw resources and part of these is used for energy purposes, mainly in domestic applications in rural areas [53].

However, despite the various policies adopted around the world, only a few demonstration-scale plants producing 2nd generation ethanol has, until now, been built. In Europe, the most recent investment is the Chemtex plant in Italy that will use straw and in the future energy crops such as Giant Reed (*Arundo donax*) as feedstock. A review of 2nd generation ethanol plants was presented by Menon and Rao [27].

2.2. Environmental performance

Several studies of the environmental impacts of various biofuels have been performed and reviewed, among others, by Cherubini and Strömman [10], Hoefnagels et al. [22] and Singh et al. [39]. Environmental assessments of 2nd generation biofuels in biorefinery concepts are as yet rare, however, a few have been performed by Cherubini and Ulgiati [11], Cherubini and Jungmeier [9], Uihlein and Schebek [46] and others.

From the above-mentioned studies it is seen that factors with high impact on 1st generation biofuels are related to agricultural production and potential land-use changes. For 2nd generation biofuels based on agricultural residues and by-products these negative impacts can be limited since no additional agricultural land is taken into production. There are, however, limits to the amounts of residues that can be harvested. Straw, for example, is a soil conditioner used to maintain the organic matter content, and thereby the long-term productivity of the soil.

Environmental performance of 1st generation ethanol production-systems can be improved by gradually integrating these with 2nd generation ethanol production. One example of this is integrated ethanol production from sugarcane and the by-product bagasse. This would increase profits since more ethanol is produced per unit of biomass. On the other hand, this will reduce the potential of co-generated electricity, and, depending on the reference electricity production system replaced, will have different greenhouse gas (GHG) implications [48,35,36]. Increased efficiency of ethanol plants to reduce energy consumption will also improve the environmental performance.

2.3. Global potentials for supply of agricultural residues

Several studies reviewing the future biomass potentials have been published but there are significant variations in the results. According to a study by Akhurst et al. [2], energy crops grown on marginal land, excess forest production and residues from agriculture (i.e. straw), industry and forestry will all give important contribution to future biomass supply. The amount of straw and other potential biomass raw materials that can be utilised for energy purposes differs among regions due to technical, ecological and socio-economic factors [2].

One frequently cited study of the global potential for ethanol production from agricultural wastes and residues, was performed by Kim and Dale [24]. According to this study, the potential production of ethanol from cereal straw (wheat, barley and oat) is estimated to be 2.83 EJ ethanol globally. Of this, 1.23 EJ is produced in the EU, 0.98 EJ in Asia and 0.42 EJ in North America. From rice straw approximately 4.64 EJ ethanol could be produced, 4.24 EJ in Asia, 0.13 EJ in Africa and 0.15 EJ in South America. Other agricultural residues from which the bioethanol production potentials are significant are corn stover (1.26 EJ globally) and sugarcane bagasse (1.07 EJ globally). As a comparison, the total amount of gasoline and diesel consumed only in Sweden was approximately 0.29 EJ in 2009 of which 87% was diesel and 13% gasoline [42]. For Sweden to fulfil the consumption targets set in the RED and replace 10% of gasoline consumption by ethanol, approximately 3.8 PJ of ethanol (corresponding to about 167,000 m^3 pure ethanol) will be needed. However, if 2nd generation ethanol is used, double counting can be applied and thus the amount could be reduced by 50%, (equal to 1.9 PJ of ethanol) while still achieving the targets for 2020.