Renewable and Sustainable Energy Reviews 43 (2015) 244–263

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Biorefining in the prevailing energy and materials crisis: a review of sustainable pathways for biorefinery value chains and sustainability assessment methodologies

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ARTICLE INFO

Article history:
Received 31 January 2014
Received in revised form
20 August 2014
Accepted 1 November 2014

Keywords:
Biorefinery
Biomass feedstock
Sustainability
Biobased product
Environmental performances
Economic performances
Life Cycle Assessment

ABSTRACT

The aim of the current paper is to discuss the sustainability aspect of biorefinery systems with focus on biomass supply chains, processing of biomass feedstocks in biorefinery platforms and sustainability assessment methodologies. From the stand point of sustainability, it is important to optimize the agricultural production system and minimize the related environmental impacts at the farming system level. These impacts are primarily related to agri-chemical inputs and the related undesired environmental emissions and to the repercussions from biomass production. At the same time, the biorefineries need a year-round supply of biomass and about 40–60% of the total operating cost of a typical biorefinery is related to the feedstocks chosen, and thus highlights on the careful prioritization of feedstocks mainly based on their economic and environmental loadings. Regarding the processing in biorefinery platforms, chemical composition of biomasses is important. Biomasses with higher concentrations of cellulose and hemicelluloses compared to lignin are preferred for bioethanol production in the lignocellulosic biorefinery, since the biodegradability of cellulose is higher than lignin. A green biorefinery platform enables the extraction of protein from grasses, producing an important alternative to importing protein sources for food products and animal feed, while also allowing processing of residues to deliver bioethanol. Currently, there are several approaches to integrate biorefinery platforms, which are aimed to enhance their economic and environmental sustainability. Regarding sustainability assessment, the complexities related to the material flows in a biorefinery and the delivery of alternative biobased products means dealing with multiple indicators in the decision-making process to enable comparisons of alternatives. Life Cycle Assessment is regarded as one of the most relevant tools to assess the environmental hotspots in the biomass supply chains, at processing stages and also to support in the prioritization of any specific biobased products and the alternatives delivered from biorefineries.

Contents

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http://dx.doi.org/10.1016/j.rser.2014.11.041
1364-0321/

1. Introduction

The societal need of energy and materials is predicted to reach a crisis point in the near future [1]. This is because of the coupling between escalating demand and cost of fossil fuels upon which the production of chemicals, materials and energy conversions still depend. The high energy intensity in material production has sustainability impacts on the energy sector, environment and economy [2]. Currently fossil fuels contribute about 80% of the global energy demand, and even if the current political commitments and strategies to tackle the issues of climate change and energy insecurity, as envisioned by different countries are in place, the global energy demand in 2035 is still projected to rise by 40% with fossil fuels contributing 75% [3]. The consequences of such dependency of fossil fuels in the agriculture system has resulted hikes in the prices of the raw ingredients for food and feedstuffs [4,5], since fossil fuel is one of the principal raw material in the modern agriculture [6].

Amid concerns about the sustainability of the energy sector initiatives, the production of biofuel is gaining ground in various economic regions, ranging from developing countries [7] to more developed economies [8]. Currently, there are regulations in Europe on the substitution of non-renewable sources with biofuels for transportation. The European Commission [9] has also focused on biofuels such as bioethanol, biodiesel, biogas, biomethanol, synthetic biofuels, biohydrogen and pure vegetable oil [10] to promote greener transportation fuel. Despite biomass being important source of bioenergy sources issues concerning their environmental impacts, security and stability and diversification of their uses also exist [11–13]. Regarding the debates on biofuels, they are primarily based on the advantages and disadvantages of the classified biofuels, i.e., 1st versus 2nd or 3rd generation fuels. Biofuel production chains based on starch and sugar from corn and sugarcane respectively, and including the liquid fuels derived from animal and vegetable fat using conventional technologies are regarded as 1st generation biofuels [14]. Biofuels based on lignocellulosic feedstock (e.g. straw, grasses, willow) [15] are classified under the 2nd generation types. Algae and advanced processing of the 2nd generation biofuels have been defined as 3rd generation biofuels [16]. The main advantage of the 1st generation biofuel production is primarily the high sugar or oil content in the raw material and the conversion process to energy is relatively easy [17]. Regarding the environmental performances of biofuel production chains, studies including Refs. [18–21] have made the comparisons of the environmental differences of them with the corresponding fossil fuels. For instance, a reduction in the global warming potential (GWP) and increase in fossil fuel savings could be achieved if the most common transportation biofuels (bioethanol and biodiesel) replaces conventional diesel and gasoline. One of the crucial issues related to the 1st generation biofuel production is the belief that it accelerates the competition among the food and feed industries for agricultural land. Furthermore, issues related to indirect landuse changes (iLUC) are also increasingly included in the studies related to sustainable agro-ecological management and aiming to assess the negative impacts on Greenhouse gas (GHG) emissions, biodiversity loss and socio-economic impacts [22]. In this context, a wider range of innovations, including the biorefinery, is now emerging to create new ways of generating bioenergy and explore entirely new types of products in new value chains [23]. Biorefining is regarded as a sustainable processing of a biomass or a combination of different types of biomasses [24] to produce a spectrum of marketable products and energy [17] at a potentially better economic return [24–26]. Nevertheless, it is important to ensure the sustainable supply of biomass without compromising the prevailing land use, soil nutrient loss and the wider environmental and economic sustainability [27,28]. This demands a comprehensive analysis of biorefinery value chains; covering the entire flows of material inputs and also including the sustainability features of agriculture system upon which production of biorefinery feedstocks are connected.

The current study undertakes a review of fundamental aspects of sustainable biorefining pathways, concentrating on three major areas: (i) introduction to the processes and platforms of biorefinery, potential biobased products markets, (ii) discussion of key sustainability parameters, such as relevance of considering potential influences of the input materials (energy and non-energy) at the farming system level and at the stages of biorefining processes, as discussed in Sections 2 and 3, and (iii) outlining possible methodological considerations for the sustainability assessment of biorefining processes, as discussed in Section 4. Based on these reviews, the current study also outlines research perspectives in the specific context of Danish agricultural and energy systems, which is discussed in Section 5.

2. Biorefinery processes

2.1. Biorefinery platforms

In the current era, the biorefinery concept is aimed at replacing the 'petroleum refineries' [29] and to reduce the fossil fuel intensity in different production areas [30]. The replacement of