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Total footprints-based multi-criteria optimisation of regional biomass energy supply chains

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ABSTRACT

This paper presents a MCO (multi-criteria optimisation) of regional biomass supply chains for the conversion of biomass to energy through the simultaneous maximisation of economic performance and minimisation of the environmental and social FPs (footprints). The energy supply-chain model contains agricultural, pre-processing, processing, and distribution layers. An integrated model, previously developed by the authors, for regional biomass energy network optimisation is used as a basis, and now extended for simultaneous assessment of the supply-chain performance based on LCA (Life cycle assessment). Several total FPs are introduced for “cradle” to “grave” evaluation, which, besides direct, comprises also indirect effects caused by products’ substitutions. In the MCO approach, the annual profit is maximised against each FP generating different sets of Pareto optimal solutions, one for each FP. With this approach the aggregation of different environmental and/or social pressures is thus avoided. The results indicate that total FPs enable the obtaining of more realistic solutions, than in those cases when only direct FPs are considered. More profitable and less environmentally harmful solutions can be gained with significant reduction in total carbon and total energy FPs.

1. Introduction

Currently a lot of research is being performed on the topics of alternative power/fuel generation [1–3]. Examples include fuel cells as a technology [4], the utilisation of solar energy [5], wind [6], geothermal [7], or tidal energy [8], as well as biomass energy applications (bioalcohols [9,10], biodiesel [11], and biohydrogen, biogas, bioheat and bioelectricity as well [12–17]). It is important that energy systems should be as sustainable as possible [18] and based on low carbon thermal processing.

When considering biomass utilisation, there are important issues for ensuring sustainable agriculture, as well as the optimisation of entire bioenergy supply chains [19]. Some of these important issues are obtaining energy by thermal conversion, water, and chemicals’ usage, the economic situation, the world’s growing population, climate change, and biodiversity. The distributed availability of biomass resources, their low density and high moisture content, could result in extensive requirements for transportation and pre-treatment, and therefore have a significant influence on logistics [16,20,21]. Another key issue to be considered in relation to exploiting biomass for energy generation is the competition with food production.

Several papers dealing with the optimisation and environmental assessment of biomass energy supply chains have been published. For example Zamboni et al. [22] developed a supply-chain optimisation model including environmental issues along with the economic one, illustrated by a case study of corn-based ethanol production system of northern Italy. Mele et al. [23,24] developed modelling framework for the design of supply chains for sugar and bioethanol production and illustrated it on a case study of co-production of sugar and bioethanol from sugar cane in Argentina. Gerber et al. [25] presented a methodology to integrate LCA (life cycle assessment) in thermo-economic models, illustrated by an application of combined synthetic natural gas and electricity production from lignocellulosic biomass.

However, by our knowledge until now no contribution appeared that describes general regional biomass and bioenergy supply-chain model and incorporates different environmental and/or social issues along with the economic one avoiding subjective aggregation of different environmental and/or social pressures, and besides that includes direct and indirect effects on the environment. The aim of this contribution was the development of the regional supply chains that include important environmental and

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social FPs (footprints), based on direct and total FPs. For optimisation, the previously developed mathematical model [16] is used as a basis, and has been now upgraded for the simultaneous assessment of FPs. Previous work by authors [16] mainly considered CFP (carbon footprint) as an environmental performance indicator. CFP stands for a certain amount of gaseous emissions relevant to climate change, and is associated with human production and consumption activities [26]. Although the synonyms “climate footprint” [26] and “GHG (greenhouse gas) footprint” [27] are perhaps more appropriate, the term “CFP” is used in this paper, mainly due to its broader acceptance so far. “CFP” is usually defined based on the amount of CO_2 and other GHGs emitted over the full life cycle of a process or product, and expressed in mass unit per functional unit [28,29].

Besides GHG emissions, several other negative impacts may result from biomass production and use for bioenergy generation – water pollution and shortage, as well as food and land scarcity, to name a few.

Therefore, other environmental FPs should also be considered:

- Energy footprint – EFP. One of its definitions is that it represents the demand for non-renewable energy resources [30], expressed in energy unit per functional unit;
- Water footprint – WFP, defined as the total volume of direct and indirect freshwater used, consumed and/or polluted [31], expressed in volume unit per functional unit;
- Agricultural land footprint – LFP, the agricultural land area used for growing biomass for both food and energy [32], expressed in area unit per functional unit;
- Water pollution footprint – WPFP, the amount of substances emitted to water in the environment, expressed in mass unit per functional unit [33].

It should be noted, that environmental FPs are usually considered to be measured in units of area. However the data expressed in units of area show high variability and the high possible inaccuracy in results since they would have to be based on a variety of different assumptions (see e.g., Ref. [26]). Converting some of the FPs to an area units can prove to be problematic, especially for processes that are not primarily area-based such as chemical processes [34], therefore more appropriate unit for each of considered FP is used.

Food versus fuel competition for biomass utilisation is another very important issue relating to the usage of biomass for fuels (first generation biofuels), which should be considered. This problem is emphasised by the Nestlé chief executive: “*If, as predicted, we look to use biofuels to satisfy 20% of the growing demand for oil products, there will be nothing left to eat*” [35]. Another problem related to the biofuel industry is the global increase of food prices as a result of using more crops and land for energy purposes [36,37]. For this reason, a FEFP (food-to-energy footprint) should also be included as a special social FP in this study. It is defined as a mass-flow rate of food-intended crops converted into energy, expressed in mass unit per functional unit.

On the other hand, when considering the direct effects that different FPs have on the environment, this may result in misleading solutions. A much broader picture, leading to more complete estimates, can be obtained if the indirect effects caused by product substitution are considered, too. For instance, although the production of biofuels can cause a possibly significant direct burden on the environment, this effect is more than balanced out by the fact that biofuels substitute equivalent amounts of more harmful fossil-based fuels. Therefore, it is important that FPs account for both direct and indirect effects. The concept of total FPs is now introduced and applied to the biomass and bioenergy supply chain.

2. Implementation of sustainable criteria through total FPs

Biomass and bioenergy supply chains involve harvesting, storage, pre-treatment, conversion steps, distribution and usage of products, and transport amongst their activities. The superstructure of the considered supply chains is presented in Fig. 1.

It contains several layers dedicated to key activities:

(i) “Harvesting and supply” layer (layer 1 – L1) dedicated to raw material supplies
(ii) “Collection and pre-processing” layer (layer 2 – L2) for the pre-treatment of biomass when obtaining intermediates directly suitable for energy generation
(iii) “Main processing” layer (layer 3 – L3) comprising the core processes for energy and other bio-products’ generation
(iv) “Use” layer (layer 4 – L4) comprising the usages of the energy products.

The transportation activities have no dedicated layer. Rather, they are embedded in the communication arrows between the layers.

The bioenergy supply-chain model, which consists of mass balances, production and conversion constraints, cost functions, profit objective function, and CFP calculation [16,17] has been extended to include the consideration of various environmental FPs. In addition to these, a FEFP is defined in order to evaluate the risk of diverting farmland for the production of fuel rather than food [38]. As a result, the mathematical model employs important direct, indirect, and total FPs (the sum of direct and indirect FPs)

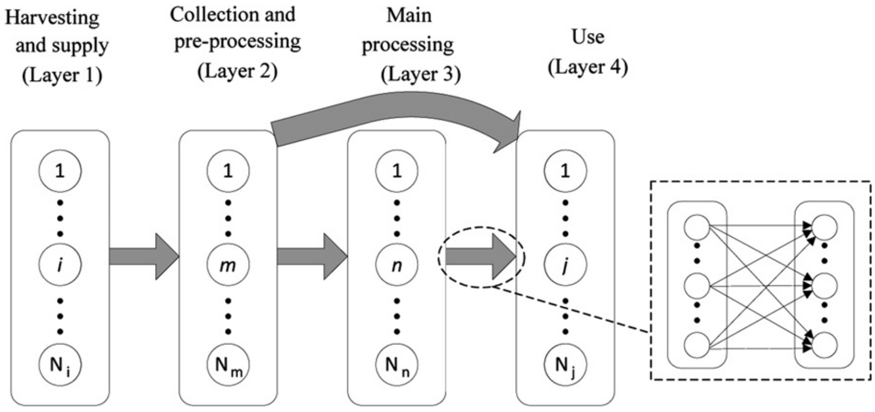

Fig. 1. The superstructure of the biomass and bioenergy supply chains (after Ref. [16]).