Applied Energy 204 (2017) 66–77

Contents lists available at ScienceDirect

Applied Energy

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

Integrated design and sustainable assessment of innovative biomass supply chains: A case-study on miscanthus in France

Aurelie Perrin [a,*], Julie Wohlfahrt [b], Fabiana Morandi [c], Hanne Østergård [c], Truls Flatberg [d], Cristina De La Rua [e], Thor Bjørkvoll [c], Benoit Gabrielle [a]

[a] INRA – AgroParisTech, Université Paris-Saclay, UMR EcoSys, Thiverval-Grignon, France
[b] INRA, UR SAD-ASTER, Mirecourt, France
[c] DTU, Department of Chemical and Biochemical Engineering, Lyngby, Denmark
[d] SINTEF Technology and Society, Department of Applied Economics, Trondheim, Norway
[e] CIEMAT, Department of Energy, Madrid, Spain

HIGHLIGHTS

- Optimum sizes of biomass supply chain from economic and environmental standpoints differ.
- Expanding biomass supply did not impact the profitability, which remained around 20 €/t DM.
- Expanding the biomass supply led to higher environmental impacts due to scattered crop production.
- Low-cost densification options such as decentralized briquetting emerge as the optimal choice.
- Autumn harvesting increases profitability when biomass storage is limited or costly.

ARTICLE INFO

Article history:
Received 20 December 2016
Received in revised form 20 June 2017
Accepted 28 June 2017

Keywords:
Miscanthus
Economic optimization
Emergy assessment
Multi-regional input-output analysis
Life-cycle assessment
Logistics

ABSTRACT

Cost-efficient, environmental-friendly and socially sustainable biomass supply chains are urgently needed to achieve the 2020 targets of the Strategic Energy Technologies-Plan of the European Union. This paper investigated technical, social, economic, and environmental barriers to the development and innovation of supply chains, taking into account a large range of parameters influencing the performances of biomass systems at supply chain scale. An assessment framework was developed that combined economic optimization of a supply chain with a holistic and integrated sustainability assessment. The framework was applied to a case-study involving miscanthus biomass in the Burgundy region (Eastern France) to compare alternative biomass supply chain scenarios with different annual biomass demand, crop yield, harvest timing and densification technologies. These biomass supply chain scenarios were first economically optimized across the whole supply chain (from field to plant gate) by considering potential feedstock production (from a high-resolution map), costs, logistical constraints and product prices. Then sustainability assessment was conducted by combining recognized methodologies: economic analysis, multi-regional input-output analysis, emergy assessment, and life-cycle assessment. The analysis of the case study scenarios found that expanding biomass supply from 6,000 to 30,000 tons of dry matter per year did not impact the profitability, which remained around 20€ per ton of biomass procured. Regarding environmental impacts, the scenario with the lowest feedstock supply area had the lowest impact per ton due to low economies of scale. Mobile briquetting proved to be also a viable economic option, especially in situations with a considerable scattering of the crop production and expensive transportation logistics. By highlighting hot-spots in terms of economic, environmental and social impacts of biomass supply systems, this study provides guidance in the supply chain optimization and the design of technological solutions tailored to economic operators as well as other stakeholders, such as policy makers.

---

* Corresponding author at: INRA Centre Angers-Nantes, USC GRAPPE, Campus du Végétal, 42 rue Georges Morel, 49 071 Beaucouzé, France.
E-mail address: aurelie.perrin@inra.fr (A. Perrin).

http://dx.doi.org/10.1016/j.apenergy.2017.06.093

1. Introduction

Two recent pieces of legislation in Europe, the Renewable Energy Directive [1] and the Fuel Quality Directive [2], will have considerable impacts on the deployment of bio-energy in Europe over the next decade. These directives set targets for the renewable content and the greenhouse gas (GHG) abatement of transport fuels, which were communicated in 2009 by the European Commission [3] and its subsequent updates. A rapid 'transformation of our entire energy system' and the development of competitive and affordable low-carbon technologies are warranted, according to the SET-plan. In this policy document, biomass was ascribed an overall 14% share for the energy mix of the EU by 2020, an increase from 6% in 2010. This implies a more than two-fold increase within a very short timeframe, creating a unique opportunity to develop bioenergy while also posing a formidable challenge in terms of feedstock supply. Biomass production and supply are the key components of the economic and environmental performance of bio-based value chains [4]. Accordingly, the SET-plan puts an emphasis on sustainability assessment for current and upcoming feedstock sources, and calls for the development of technologies that broaden the feedstock base and maximize the economic and environmental efficiency of the entire biomass supply chains. It also flags the need to manage and develop human and social capital, to increase the sustainability and facilitate a continuous improvement of these chains. Innovative techniques for crop management, biomass harvesting, storage and transport offer a prime avenue to increase biomass supply while keeping costs down and minimizing adverse environmental impacts [5].

Dedicated energy crops are projected to provide a large proportion of the biomass feedstock needed to fuel bioenergy development in the coming decades [6]. Among such crops, the perennial C4 grass miscanthus is a promising candidate due to its high yield potential and low requirements for soil tillage, weed control, and fertilization, combined with a long cultivation period [7,8]. It is currently primarily used as a solid fuel for combustion, on a relatively small scale (i.e. annual biomass supply under 10 kt year^{-1}). Some case-studies of miscanthus production at plot or farm scale have been described, but mostly focus the agricultural production phase and ignore the downstream logistics, which can be complex. The aspects of the miscanthus production that have been studied include, cultivation methods [9], the socio-economic or environmental performance of the production system [10,11], and the environment life cycle assessment of hypothetical supply chains to produce energy from miscanthus biomass[12,13]. In contrast, larger-scale bioenergy pathways, such as those on 2nd generation, lignocellulosic feedstock, have only been studied hypothetically, considering aspects such as logistical challenges [14,15]. Environmental assessment of large-scale of several feedstock have considered the impact of land-use or greenhouse gases emissions reductions policies [4,15], or trade-offs and competition between biofuel and food production [16,17] using ecosystem and/or economic modeling. Such studies have aimed to estimate the land requirements, energy yields and associated economic and environmental impacts of new bioenergy pathways [18]. However, such large-scale analyses have large source of uncertainties, mainly due to the diversity of cultivation technologies, large variations in yields, and different transport contributions [19,20]. These factors vary greatly between cases and largely influence the sustainability of biomass supply chains. Thus, it appears necessary to examine on a case by case basis how supply chains can be optimized and their sustainability assessed, but using an integrated assessment framework.

In addition to the economic optimization of the bio-based value chain, its impact on the regional economy may be assessed in a Multi-Regional Input-Output (MRIO) analysis. It generates information about socio-economic impacts of biomass supply chains, such as economic value added, and job creation, directly and indirectly related to the activities involved in a system [21]. Using the same kind of input data, not expressed in monetary units but in biophysical units, the environmental assessment can be conducted under the same framework. Life-cycle assessment (LCA) is commonly used as a flexible tool to answer a wide variety of different policy-relevant questions [22]. It considers both direct and indirect use of resources throughout the supply chain, and emissions to the environment. It outputs a set of indicators representative for the diverse range of environmental issues relevant to bioenergy pathways. However, LCA draws system boundaries around anthropogenic processes (resource extraction, refining, transportation, etc.) and does not consider the energy provided by natural phenomena and, usually, human labour. These latter aspects can be considered by Emergy assessment (EmA) [23]. Both methods are largely based on the same type of inventory data (i.e., accounting for energy and material flows), but apply different theories of values and system boundaries since their scopes differ. In EmA, in fact, all forms of energy, materials and human labour that contribute, directly or indirectly, to a production process are evaluated using a common unit. EmA is particularly suited for assessing agricultural systems since the method accounts for the use of freely available natural resources (sun, rain, wind and geothermal heat), as well as marketable goods and services.

Sustainability assessment of biomass supply chains should address economic, social and environmental aspects. However, these three dimensions are seldom combined and there is a need for models and methodologies, which integrate the main factors that influence biomass supply chains performances and sustainability in a consistent and comprehensive manner [24]. A recent study on wood-based value chains proposed such a multi-criteria analysis [25], but only partially integrated the various dimensions of sustainability. Here, we have combined the above methodologies into an integrated framework for sustainability assessment, encompassing economic, environmental and social criteria in relation to a bioenergy project. The development and test of a new 4-step framework was the overreaching objective of this manuscript. The framework was applied to optimize and assess a currently-operating supply chain in Burgundy, as well as potential, innovative variants involving an expansion of biomass demand based on supply area or crop yield, or alternative harvesting dates and biomass densification technologies. All scenarios are defined based on economic optimization of transportation and storage.

2. Materials and methods

2.1. The existing miscanthus supply chain at Bourgogne pellet

Bourgogne Pellets (BP) is a farmers' cooperative comprising about 350 members based in the municipality of Aiserey in the Burgundy region of Eastern France. In 2015, the supply area of BP covered 400 ha of miscanthus, scattered across arable land in an approximately 70 km radius around Aiserey. The supply chain operated by BP includes six stages, namely agricultural production, harvest, handling, transport, storage and processing, and produces biomass feedstock products in a range of forms – chips, bales and pellets. Each year, the scale of production and type of product vary in response to the miscanthus yields and demand for different products.

Miscanthus is a perennial crop with a life span of about 15 years thanks to rhizomes, which store starch, proteins, and other nutrients during winter, allowing for a regrowth in spring. From year 2 to year 15, the plantation is mature and the above-ground