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Research paper

Supply chain optimization of residual forestry biomass for bioenergy production: The case study of Portugal

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ABSTRACT

Within a large set of renewable energies being explored to tackle energy sourcing problems, bioenergy can represent an attractive solution if effectively managed. The supply chain design supported by mathematical programming can be used as a decision support tool to the successful bioenergy production systems establishment. This strategic decision problem is addressed in this paper where we intent to study the design of the residual forestry biomass to bioelectricity production in the Portuguese context. In order to contribute to attain better solutions a mixed integer linear programming (MILP) model is developed and applied in order to optimize the design and planning of the bioenergy supply chain. While minimizing the total supply chain cost the production energy facilities capacity and location are defined. The model also includes the optimal selection of biomass amounts and sources, the transportation modes selection, and links that must be established for biomass transportation and products delivers to markets. Results illustrate the positive contribution of the mathematical programming approach to achieve viable economic solutions. Sensitivity analysis on the most uncertain parameters was performed: biomass availability, transportation costs, fixed operating costs and investment costs.

1. Introduction

The energy issues are still on debate on global agendas. In order to respond to the increasing demand for energy, energy security vulnerability and environmental concerns renewable energies are presented as promising alternatives to the traditional fossil resources [1]. Being aware that the best strategy is not to become dependent on a single source of supply, efforts have been made towards the diversification and construction of an energy mix using all available renewable sources to produce the different energy products [2]. In order to promote the development of renewable energy systems, bioenergy - the energy that comes from the transformation of biomass, is considered a key option [3]. However, bioenergy is not yet economical competitive when compared with fossil resources. Technological development and bioenergy supply chain design and management improvements can certainly contribute to enhance this bioenergy weakness [4]. Most researchers agree that bioenergy can help us reaching sustainability however some point out that not all are benefits. Some debate still remains regarding biomass usage to energy production as several economic sectors compete for limited biomass resources and consequently some uncertainty can arise on the net availability and market prices [5]. Promoting the use of residual biomass material, by-products and wastes generated in agriculture, forestry and human activities allows at the same time expanding the capacity of bioenergy and reduce the amount of waste that constitutes a huge environmental problem to the modern society. Residues that are available and that often have a negative value can be converted into a source of revenues and simultaneously solve the waste management problem [6]. Many challenges then exist to assess the feasibility of bioenergy systems. Certainly that the expansion of bioenergy systems is dependent on many different issues, ranging from political and legislative areas to the developments on technical aspects related with the development of technology and processes to produce bioenergy with higher efficiency being economically competitive. Nevertheless one of the most important and challenging aspects of bioenergy systems is the design and operation of the associated supply chain network [7]. The characteristics of biomass represent a major challenge with regard to the definition of supply chains for bioenergy production. The seasonality of supply

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Nomenclature

Sets

B	set of biomass type denoted by index b
I	set of biomass locations denoted by index i
K	set of energy production facilities location denoted by index k
Q	set of energy production facilities capacity denoted by index q
R	set of biomass transportation mode denoted by index r
P	set of energy products denoted by index p
V	set of markets location denoted by index v
T	set of time periods denoted by index t

Parameters

BA_{bit}	amount of available biomass b at location i at time t (t)
BigM	big number
CB_{bit}	biomass acquisition cost of biomass type b at location i at time t (€/t)
CP_{bpqt}	unitary production cost to produce product p from biomass type b at power plant with capacity q at time t (€/t)
DIK_{ik}	distance between biomass location i and power plant location k (km)
DKV_{kv}	distance between power plant location k and market (substation) v (km)
DP_{pvt}	maximum demand of product p in market v at time t (units of product)
IBF_q	power plant capacity q (units product)
ICB_{kq}	annualized investment cost of a power plant at location k and capacity q (€/y)
$MDistC_{ik}$	maximum distance allowed between a biomass collection point i and a power plant location k (km)
$MDistD_{kv}$	maximum distance allowed between a power plant location k and a market v (km)
OP_{qt}	fixed operating cost of a power plant with capacity q at time t (€/y)
$TrCIK_{ikrt}$	transportation cost between biomass location i and a power plant location k with biomass transportation mode r at time t (€/t/km)
$TrCKV_{kvt}$	transportation cost between power plant location k and market v at time t (€/t/km)
TD_{pt}	total demand of product p at time t (units of product)
φ_{bp}	conversion factor of biomass type b in product p (units of product/t)

Continuous non-negative variables

B^C_{bit}	collected biomass b at location i at time t
X_{bikrt}	biomass flow b from collecting site i to power plant k using transport mode r at time t
X^P_{pkqvt}	amount of product p produced at power plant location k of capacity q for market v at time t

Binary variables

Y^B_{kq}	equals 1 if a power plant is located at k with capacity q, equals to 0 otherwise
Y^P_{pkv}	equals 1 if a product p goes from a power plant in location k to market v, equals to 0 otherwise

and geographic distribution with widely dispersed occurrence makes collection, storage and transport complex and expensive operations. Also its physical properties like the high and variable moisture content and low energetic density constrain transport, storage and processing technology selection. Supply chain design and logistics integrated in a whole system perspective can positively contribute to achieve greater performance of bioenergy production systems.

In recent years the literature on bioenergy supply chain has been growing. Many different biomass sources as well as many different energy products were studied. Studies that integrate strategic and/or tactical decisions, long term decisions related with design and sizing of the network components, to more operational decisions that deal with aspects that affect the short term. Elia et al. [8] review paper illustrates the aforementioned. Concerning the specific case of bioelectricity production the model presented by Pérez-Fortes et al. [9] has the ability to define location, technologies, connectivity between entities, biomass storage periods, matter transportation and biomass utilization taking into account three performance metrics with economic, environmental and social concerns. In order to solve the location allocation problem of solid biomass power plants Bojić et al. [10] developed a mathematical model where all biomass sources, potential power plant types, capacities and locations are combined to search for the parameters combination that will result in the minimal electricity generation costs. A case study and consequent results illustrate that the high density of biomass and power plant investment costs have the highest impact to the capacity selection and allocation. Stating that the electricity generation cost from forest biomass is higher than most of the other sources of energy mostly due to several factors such as high transportation cost of a low bulk density material and low efficiency of the system, Shabani and Sowlati [11] proposed an optimization and mathematical modeling to manage and optimize the supply chain. The model considers biomass procurement, storage, energy production and ash management in an integrated framework at the tactical level, using forest biomass in direct combustion power plants to provide a less expensive source of electricity. To increase renewable energy production without major capital investment to electricity generation Roni et al. [12] introduced a framework for the supply chain design for biomass co-firing in coal fired power plants. Using a hub-and-spoke design problem aims to optimize the delivery cost of biomass. Yue et al. [13] work dealt with the design of bioelectricity supply chain network taking into account economic, environmental and social considerations in a cradle-to-gate perspective. The application to a potential bioelectricity supply chain in the state of Illinois illustrates the applicability of the multiobjective mixed-integer linear fractional programming model.

Faced with a real situation where the bioelectricity production is currently a nonprofit activity motivated the present work. Attracting the investment to the not well established bioelectricity market can only be possible if the feasibility of this system is demonstrated. This paper expands the scope of the previous research proposing an in-depth analysis of the Portuguese case regarding bioelectricity production. Due to the high number of stakeholders, the high number of available alternatives in each supply node as well as all the potential the interactions between the bioenergy supply chain nodes, creates the need for a comprehensive approach that considers the entire supply chain as a whole system. A mixed integer linear programing (MILP) model is then proposed that supports the design problem and aims to choose the location and capacity to future biomass power plant sites as well as the best option regarding residual biomass collection namely location and quantities; the definition of biomass transportation