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A mathematical model formulation for the design of an integrated biodiesel-petroleum diesel blends system

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ABSTRACT

This paper addresses the strategic planning of an IBSC (integrated biofuel supply chain) using total annualized cost and total life cycle GHG (green house gas) emissions as economic and environmental criteria respectively. The IBSC for an extended planning horizon *H* (e.g. 10 years) is considered and horizon *H* is further subdivided into a set of discrete time intervals. For each of these subintervals the diesel and the biodiesel fuel consumption can be varied according to a predetermined value. A mixed-integer linear programming model of biodiesel production that takes into account infrastructure compatibility, demand distribution, size and location of biorefineries using the available biomass and carbon tax data is proposed. An important aspect of the proposed model is the inclusion of crop rotation conditions to assure the supply of biological feedstock. The price of biodiesel and any byproducts produced are included in the model. Inputs to the model are the quantity of biological feedstock, the cost of biomass transportation, as well as inventory and processing costs. The proposed model is illustrated in Part 2 of this work with an example of Bulgarian economy for planning period 2010 to 2020 when the objectives of the Renewable Energy Directive 28/2009/EC will be achieved.

1. Introduction

The European Commission encourages increasing the production of biofuels because, as well as reducing net atmospheric carbon emissions, it leads to increased energy independence and stability of supply and creates sustainable employment in rural areas. One of the ways to reduce global warming as a result of human activity is the use of biofuels in the transport sector. It is accepted that the combustion of biofuels is carbon neutral, which means that there is no net release of carbon into the air because the raw material for the production of biofuels is carbon dioxide removed from the air by photosynthesis. It is nevertheless necessary carry out a detailed life cycle analysis of greenhouse gas emissions from biofuel production especially in the context of a first generation technology. In particular the fuel required for production, processing and distribution of the feedstock crops must be taken into account. The aim of the present work is to use a life cycle analysis of the complete supply and distribution chain for the production of biofuel to determine the best configuration of the individual elements. The geographical distribution of feedstock production and biofuel refineries in relation to biofuel demand, transport infrastructure and environmental impact need to be determined so that the efficiency of the entire system can be ensured. It is necessary to bear in mind at the design and management system stages that the demand for fuel as well as environmental load will change in time for each geographical location.

Both the spatial and the temporal dimensions are taken into consideration in the operational strategy of [1] for the optimization of the overall system. The spatial dimension is primarily the geographical distribution of feedstock, fuel needs and manufacturing and transport infrastructure in each region. The proposed model takes into account the interdependence between the cost of biomass, biofuel production, and transport. In the presence of large size refineries the production costs can be reduced through increased economies of scale, but the costs for raw materials procurement and distribution of fuels will be higher. Although, as noted in the work of [2] the performance of the entire supply chain of biofuels in space and time need be taken into account in supply chain models a systematic approach is not widely accepted in the literature on planning of energy from renewable sources [3]. Timing is a key element in a strategic planning system

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especially when the conditions of supply in response to growing demand are considered over extended time periods and the effectiveness of the planning system will depend on its ability to take into account the dynamics of such an evolving process. The conventional independent method used in previous studies is insufficient as noted [4], while in Ref. [5] a stochastic programming approach towards optimization of biofuel supply chain is proposed.

The design of any BSC (biofuel supply chain) affects the overall structure of the networks for biofuel production, the amount of capital investment required, the choice of appropriate production technologies and the geographical location of refineries. Logistics and management of contracts for biomass and distribution of final products usually include medium and short-term solutions. Models have been developed for decision making concerned with expanding the BSC's in uncertain conditions with emphasis on the environmental and economic performance. In Ref. [6] stochastic linear programming model for the production planning of a multi-product biofuel supply chain have been developed. In it the target products' demands are represented as normal distribution functions where mean and standard deviations are known. The latter has shown better performance than used before deterministic model based on simulation analysis. In order to deal with uncertainties in it, a sensitivity analysis has been carried out. The model can be applied for any type of biomass resources. In addition, the study has been extended with considerations related to the disruptions arisen in the biomass supply or the jumps in the prices of the target products. In Ref. [7], grid design and optimal allocation of wind and biomass resources for renewable electricity supply chains under uncertainties have been studied. The study [8] has proposed a model for optimization of the life cycle cost of biofuel supply chain under uncertainties. It involves a number of agriculture zones, transportation modes for the transport of grain and biofuel, biofuel plants, and market centers. Moreover, the price of the resources, the yield of grain and the market demands have been presented in it as variables changing within certain boundaries rather than constants. In Ref. [9] a method for solution of interval linear programming problem has been proposed which taking into account the uncertainties in the design of bidirectional biodiesel supply chain.

Recently, much attention has been paid to the problems of integration of the sustainability into the design and planning of supply chains activities. Authors of [10] have proposed a generic multi-objective optimization model for design and planning of supply chains, incorporating as economic, as well as environmental and social considerations. In it for the first time a LCA (Life Cycle Assessment) methodology for solution of defined in such a way problem has been represented. Involved in the problem social assessment accounts the impact of the facility location on the economic performance of the company, as well as the level of municipal economic incentives which should compensate relocating.

In Ref. [11] an optimization problem for sustainability improvement of all activities of the supply chain network where the three aspects are unified by one goal has been formulated. This framework has been approved on a real case with real test data produced by the Dow Chemical businesses.

The objective which is placed in the work [12] is to achieve maximum sustainable viable use of resources by considering the competition between fuel and food production.

The article [13] has presented the relevant contributions on the optimization models for second-generation biofuel SCs. This study summarizes the common characteristics and tendencies of the applied models in the literature, identifying similar decision variables, economic-based objective functions, crop residuals as a common feedstock, the domestic market as the final destination. Limited sensitivity analysis and several input data sets based on previous estimation as the main features of the optimization models. The proposed model in this research addresses these characteristics.

In Ref. [14] a multi-period MILP model for the design and planning of an advanced hydrocarbon biofuel supply chain integrated with existing petroleum refinery infrastructure has been proposed for the first time. The optimization model integrates decision making along with multiple temporal and spatial scales and simultaneously predicts the optimal network design, integration strategy, facility location, technology selection, capital investment, production operations, and logistics management decisions. Compared to the traditional biofuel supply chain without integration, insertion points into petroleum refineries significantly contributes to the capital cost reduction, and the utilization of the existing distribution network in petroleum system reduces transportation costs.

One type of model is focused on the elements of the biomass supply. A model for decision support was developed [15] for dynamic integrated analysis of the supply and logistics of biomass. This model is designed to simulate the collection, storage and transport operations for the supply of agricultural biomass. The problem of combining a number of circuits for the supply of biomass in order to reduce the space requirement for storage has been addressed by Ref. [16].

GIS (Geographical information systems) can be used for the precise estimation of transport distances from the biomass sources to biorefineries and from the biorefinery to end users. A GIS-based decision support system for selecting least-cost bio energy locations when there is a significant variability in biomass farm gate price and more than one bioenergy plant with a fixed capacity in the region is described in Ref. [17]. Another GIS based methodology focused on logistics and transport strategies that describes a procedure for achieving an optimal use of agricultural biomass has been used to locate a network of biorefineries in a given region [18].

In addition to model of the of the biomass supply component, models of the production component that converts the biomass into liquid fuels have been developed. Such models often include a calibration using data collected from specific geographical areas. A combined production and logistics model by Ref. [19] investigated cost-optimal configurations for a range of technological, system scale, biomass supply and ethanol demand distribution scenarios specific to European agricultural land and population densities. In the USA a model for mathematical programming of the design and management of biorefinery logistics to determine the number, size and location of bio-refineries for the production of biofuels from biomass in the state of Mississippi has been developed [20]. A MILP (mixed linear programming) model to determine the optimal geographical location and capacity of methanol plants in Austria was developed by Ref. [21].

Such static models using regional data have been expanded to address the issues of planning and management over extended time periods. Authors of [22] have shown that the mathematical programming approaches are widely applied in the scientific literature. A great part of developed mathematical programming models used for design and management of biomass-for-bioenergy supply chains are related to structures of the supply chain network where the nodes represent facility locations and the arcs represent product flows and transport operations. However, the developed mathematical models refer to certain hierarchical decision level considering specific operations from the supply chain. In addition, most of the developed approaches have considered the optimization problems in bioenergy producer's terms, which is incomprehensibly due to the fact that the energy producer makes long-term investment decisions. The optimization of the upstream biomass