Renewable Energy 93 (2016) 383–403

Contents lists available at ScienceDirect

Renewable Energy

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

Biodiesel supply chain optimization via a hybrid system dynamics-mathematical programming approach

Ali Azadeh*, Hamed Vafa Arani

School of Industrial Engineering, Center of Excellence for Intelligent Based Experimental Mechanic and Department of Engineering Optimization Research, College of Engineering, University of Tehran, Iran

A R T I C L E I N F O

Article history:
Received 19 September 2014
Received in revised form
8 January 2016
Accepted 21 February 2016
Available online 10 March 2016

Keywords:
Biodiesel supply chain
Optimization
System dynamics
Stochastic mixed-integer programming
Renewable energy

A B S T R A C T

Development of biofuels causes reduction of environmental pollution, but certain limitations affect their production. In this research, a hybrid system dynamics-mathematical programming approach is developed to design and plan a biodiesel supply chain from biomass fields to consumption markets. The supply chain faces limitations in biodiesel production. Water resource limitations for biodiesel production, land limitations for biomass procurement, and technological issues are the most important limitations considered in the system dynamics model. In addition, competition between fossil fuels and biodiesel is taken into account. The proposed methodology, firstly, estimates the most important parameters in biodiesel supply chain in a given planning horizon. Then, estimated parameters are used as inputs of the mathematical model and the optimal supply chain decisions are made by means of a stochastic mixed-integer programming model. Besides, a scenario-based approach is used to model the disruption risks for links and biomass fields. Finally, a numerical experiment is presented to show the applicability of the methodology according to some interviews with experts in Iran. Results demonstrate the potential appropriate market of biodiesel in Iran while several resource and technology limitations and environmental pollution avoid growth of biodiesel market. Moreover, a sensitivity analysis is performed on risk preferences of decision makers and government policies adopted to improve the biodiesel market.

1. Introduction

Energy is one of the most important shaping factors of socio-economic strength. Economic, social and environmental effects of energy are undeniable facts in all societies. A remarkable proportion of required energy in most of the countries is fossil fuels, which are procured from oil. In this situation, energy dependence reduces the political power of countries, especially in developed and industrial countries. Therefore, countries without sufficient oil resources have to develop other energy resources and infrastructures to avoid dependency on oil exporter countries. Renewable energies are the best options for all the countries to reduce oil dependency along with the reduction of environmental pollution. Increasing the share of renewable energy has a high preference on the policy agenda of countries around the world. Several governments have set ambitious targets and have started to implement support schemes aimed at facilitating market implementation [3]. Developed countries such as the United States are developing renewable energy infrastructures in spite of sufficient oil resources because of finitude of non-renewable energies. In addition to energy dependency reduction, environmental pollution associated with fossil fuels is another issue that causes renewable energy introduction in several forms. CO_2 emissions associated with consumption of fossil fuels in the global transportation are a remarkable share of global CO_2 emissions. Three main reasons have been mentioned for suitability of biofuels as substitutes of fossil fuels. First, increase in energy price due to an increase in energy demand and risks of supply [39]. Second, climate change mitigation [39]. Third, potential to foster rural economic development [27]. The biofuels are produced from several biomasses including plants, animal fats, and urban wastes. Biomasses from several fields and cities are transported to the biorefineries to refine and converse to several types of biofuel. A primary scheme of biomass-to-biorefinery supply chain is presented in Fig. 1. Smith [42] investigated the plans of bioenergy infrastructure development in the United States. They addressed three categories for evaluation of biofuel supply chains. The impact

* Corresponding author.
E-mail address: aazadeh@ut.ac.ir (A. Azadeh).

http://dx.doi.org/10.1016/j.renene.2016.02.070
0960-1481/

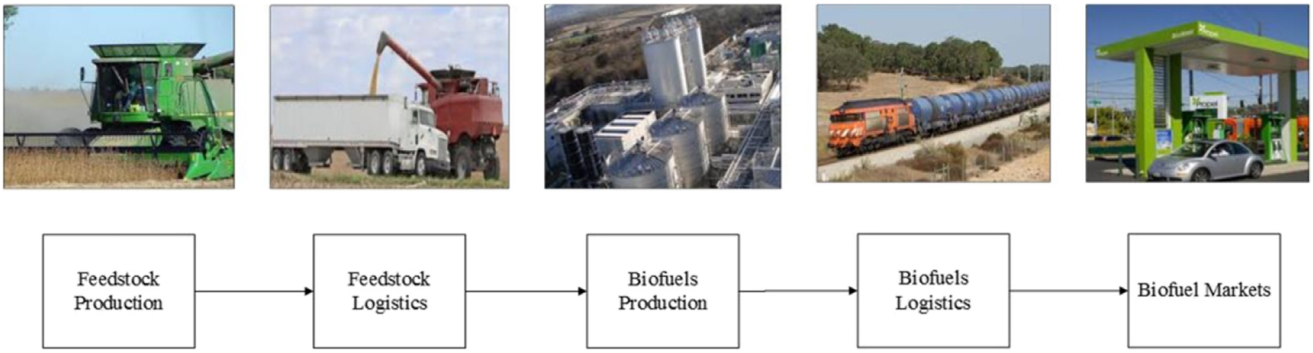

Fig. 1. Biomass-to-biorefinery supply chain.

category was reduction of greenhouse gases, the indicator group was the amount of yield for biofuel crops, and the sustainability metric was the energy ratio. Energy ratio is defined as usable energy acquired divided by the energy expended to produce that energy.

Supply chain management of biofuels, from biomass procurement fields to consumption markets is a critical issue because of complex and uncertain environment of the problem. For instance, biomasses for biofuel production have an uncertain environment for following reasons. Firstly, as they are agricultural products, weather conditions, insect populations, plant diseases, and farmers planting decisions affect the biomass supply. Secondly, land limitation is another reason which may increase biomasses price. Third, high logistic costs including high inventory costs because of seasonality of biomasses, high transportation costs because of being bulky and geographically dispersion. Recent studies have considered agricultural residues, forest residues, municipal solid waste, and perennial grasses to produce bioenergy which they are known as lignocellulosic biomasses [17]. In addition to uncertain environment of biomass production, biofuel market has a number of uncertain variables. Competition between fossil fuels and biofuels forms a non-deterministic problem for decision makers. A number of factors which affect market share and demand of biofuels in competition with fossil fuels include air pollution and CO_2 emission, price of biofuels in comparison with fossil fuels and technological limitations. Besides, the number of automobiles that use biofuels as the main fuel is another factor that changes the market share of biofuels.

Abovementioned complexities and high level of uncertainties need an appropriate approach to handle this situation. In addition to complex relationship between different variables in biofuel market and biomass production supply system, a number of feedback relationships exist between different variables in the biofuel supply chain. For example, social effects of air pollution associated with fossil fuels reduce their demand and increase the demand of biofuels. Water resource limitations, water resource destruction as well as land limitations for biomass production reduce or stop the increasing trend of biofuel supply. Such a system of variables, which includes complex relationship between variables, feedback loops, and delays, could be modeled via several approaches. In this study, system dynamics as one of the most effective approaches is used in this regard. System dynamics shows the behavior of the system with considering complex relations, feedback loops, and delays. Simulation of several variables and causal relationships between different environments in a given planning horizon provides a larger insight to the decision makers to manage the biofuel supply chain.

This study aims at providing a supply chain planning framework in a tactical decision level in which effects of the macro variables of biofuel market have been considered. To do so, a hybrid decision making framework is introduced. This framework includes following steps. Firstly, a system dynamics model is developed to simulate the key parameters of the biodiesel supply chain. Biodiesel production capacity, biodiesel demand, biodiesel market price, biomass production capacity, and biomass price are the main outputs of the system dynamics model. Some resource limitations such as water and land are taken into consideration in the biodiesel supply chain. Biodiesel production and market, biomass production and market, and fossil fuels market are subsystems of the system dynamics model. Secondly, a stochastic programming approach is proposed to optimize the decision variables of the biodiesel supply chain in four scenarios. In this regard, a stochastic linear programming model is developed. The addressed supply chain includes biomass production fields, biorefineries, and consumption markets. Some key parameters of the mathematical model are simulated with the system dynamics model over the planning horizon. Then, the estimated parameters are inserted to the mathematical model. Finally, optimal values of the decision variables of the supply chain are obtained using the mathematical model, which aims at maximization of the profit of the biorefineries, as the focal firms. Biodiesel production quantity, location of biorefineries, biomass production quantity, inventory and shortage of biodiesel in each market, and allocation of biomass fields and biorefineries as well as allocation of biorefineries to markets are outputs of the mathematical model. A robust optimization approach has been chosen to reduce the variability of the model in the stated stochastic environment. Briefly, the developed framework provides a macro view for the decision makers through the system dynamics model and a micro view through the mathematical model.

Remainder of this paper is organized as follows. In the second section, a comprehensive review of the literature in the field of biofuel supply chain management is presented. In the third part, the addressed problem and its assumptions are presented. Fourth section includes the system dynamics model for estimation of mathematical model parameters. Section five presents the proposed mathematical model and robust reformulations. Sixth section includes numerical experiments for both system dynamics and mathematical models. The last section consists of concluding remarks and future research directions.

2. Literature review

There are several studies in the field of biofuel supply chain because of focus of governments on development of renewable energies. Several modeling approaches have been used by previous studies. Tactical level decisions in the supply chain usually have been made through mathematical programming models.