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Strategic design and investment capacity planning of the ethanol supply chain under price uncertainty

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ABSTRACT

Fossil fuel depletion and the increase of greenhouse gases emissions has been pushing the search for alternative fuels for automotive transport. The European Union has identified biofuel technology as one option for reducing its dependence on imported energy. Ethanol is a promising biofuel, but great uncertainty on the business profitability has recently determined a slowdown in the industry expansion. In particular, geographical plant location, biomass price fluctuation and fuel demand variability severely constrain the economic viability of new ethanol facilities. In this work a dynamic, spatially explicit and multi-echelon Mixed Integer Linear Program (MILP) modeling framework is presented to help decision-makers and potential investors assessing economic performances and risk on investment of the entire biomass-based ethanol supply chain. A case study concerning the corn-to-ethanol production supply chain in Northern Italy is used to demonstrate the effectiveness of the proposed modeling approach. The mathematical pattern addresses the issue of optimizing the ethanol supply network over a ten years' time period under uncertainty on biomass production cost and product selling price. The model allows optimizing economic performances and minimize financial risk on investment by identifying the best network topology in terms of biomass cultivation site locations, ethanol production plant capacities, location and transport logistics.

1. Introduction

Over the last years there has been a global redefinition of the conventional way to conceive the energy supply question. Alarming (although uncertain) perspectives regarding energy demand [1] and time of peak oil production [2] together with concerns about environmental health [3] as well as geopolitical unpredictability of primary energy suppliers jeopardized the reliance on conventional hydrocarbon-driven energy systems. These issues have been driving a sudden shift of paradigm in outlining a transition toward more sustainable and secure alternatives. Renewable sources (i.e. hydropower, solar, wind, geothermal, and biomass) have been pointed out as the best viable option in facing the challenge. In particular, biomass has been encountering particular interest due to its suitability not only in providing electric, mechanical and thermal energy, but also as primary source to produce liquid biofuels for automotive purposes.

Accordingly, the European Commission (EC) has outlined an ambitious program to promote the market penetration of biomass-derived fuels. For instance, the Directive 2003/30/CE [4] set as mandatory a minimum quota of biofuels content within conventional ones and recently the target has been lift up to 10% by 2020. This has also been reinforced by the

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European Union (EU) in its proposal for the new renewable energy directive [5] by including other commitments like, for instance, a minimum greenhouse gas emissions reduction of 35% compared to fossil fuels [6].

Biomass conversion into suitable fuels would ensure a number of environmental benefits, a gradual release from oil dependence as well as a tangible reduction of the import bill through supplier and technology diversification. Moreover the establishment of a biomass-derived fuel system can lead to a positive effect for the local economy by stabilizing the agricultural sector as well as by offering new development opportunities [7]. However, any biomass-based pathway toward fossil fuels substitution also presents known drawbacks: first generation biofuels production, for instance, has caused a competition for land resources with other biomass-based energy sectors (e.g., biomass for heat and power supply) and, more critically, with the food industry. Moreover, the lay-down of radical new infrastructures might require both great capital expenditures and potentially long time to be established.

Notwithstanding this, biofuels have the unquestioned potential to perform a unique range of services within any future energy-system portfolio [8]. This is undoubtedly proved by the wide diffusion of liquid fuels as a prompt substitute of conventional hydrocarbons. In particular, ethanol from biomass conversion (commonly referred to as bioethanol) has been assuming a leader position within the biofuels market: in 2007, roughly 45 Mt of ethanol have been produced for automotive purposes in the world [9], and customers' demand is expected to more than double in the next 10 years [10].

However, the effective economic feasibility of such a business is tightly related to the geographical location as well as to the technological alternatives which the systems builds on. Recently, Zamboni et al. [11,12] developed a spatially explicit mathematical programming framework to optimize biofuels supply networks under steady state conditions. However, the authors did not consider the dynamic nature of the system as an intrinsic feature within the modeling framework. In fact, building up and planning a new production system would require the assessment of its dynamic behavior over a certain time horizon. Furthermore, a financial-based evaluation is needed to take into account the market volatility in terms of goods and raw materials prices. This is clearly demonstrated by the recent ethanol production history: the industry expansion has been tempered by changing market conditions [13] and, in particular, the high variability of both DDGS and corn prices have been pushing companies through a disinvestment decision trend. Thus, it is of vital importance for decision-makers to consider the market volatility in undertaking a well advised capacity planning process.

In view of the above, it clearly arises the need to provide specific tools capable of properly managing the inherent level of uncertainty characterizing a multi-faceted and dynamic problem such as the design and planning of biofuels systems. These tools should adopt a wider approach which goes beyond the limited company-centric view of the business by extending the scope of the analysis from the functional or hierarchical level to the global system one [14]. Moreover, working within a financial environment, the effectiveness of the analysis relies on the use of appropriate performance indicators [15].

In the past years the process systems engineering community have been putting a lot of efforts to give an answer to the above questions within the general context of process industry [16,17]. Many studies have been hence directed toward addressing the design and planning of entire supply chains (SC) [18–21]; more recently, also the management of novel biomass energy systems have been taken into account [22–24].

However, to the author's knowledge no contribution has appeared so far addressing the assessment of the entire SC by simultaneously incorporating spatially explicit modeling and parameters uncertainty in optimizing the strategic design and investment capacity planning of biofuels systems.

The objective of this work is to provide a design framework based on the approaches applied to the multi-echelon SC optimization under uncertainty [16,19,21]. The problem is formulated as a time dynamic Mixed Integer Linear Program (MILP). It embodies different features for spatially explicit siting of supply networks nodes [25] and capacity planning of strategic fuel systems [20]. A stochastic formulation is implemented to handle the effect of uncertainty [26,27]. With concern to the investment analysis, this has been assessed by formulating the financial criteria in terms of economic indicators such as the expected net present value (eNPV) as formulated by Bagajewicz [28] and the conditional value-at-risk (CVaR) [29]. The emerging Italian corn-based ethanol production is chosen as a case study to demonstrate the model effectiveness. In particular, Northern Italy is considered as geographical benchmark and the dry-grind process was assumed as the standard technology for ethanol production. The model is conceived to maximize the expected profit as well as to minimize financial risk on investment over a ten years time horizon by identifying the best network topology in terms of biomass cultivation site locations, ethanol production plant capacities and location as well as transport logistics. The uncertainty on corn purchase costs and product market prices has been taken into account in formulating the stochastic optimization.

This paper is organized as follows. First, a general description of biofuels SC key issues is presented. The subsequent section introduces the mathematical formulation of the model. The case study is then described. Finally, the results of SC optimization with respect to the eNPV and CVaR indexes are presented and discussed.

2. Problem statement

The problem addressed in this paper deals with the strategic design and planning of a general biofuel SC over a 10-years horizon. The optimization problem aims at the minimization of alternative objectives: (i) the NPV related to a number of scenarios for biofuel price and biomass cost averaged on the corresponding probabilities (eNPV criterion) and (ii) the NPV evaluated on the 10% confidence level of the worst market scenario probabilities (CVaR criterion). The structure of the biofuel SC taken as reference in this work is illustrated in Fig. 1. It can be divided into two main substructures: the former concerns with the upstream fuel production and involves biomass cultivation, biomass delivery, and fuel