CHEMICAL ENGINEERING TRANSACTIONS Volume 24, 2011
Editor Sauro Pierucci
Copyright © 2011, AIDIC Servizi S.r.l., ISBN 978-88-95608-15-0 ISSN 1974-9791
DOI: 10.3303/CET1124043

Supply Chain Design and Capacity Planning: from First to Second Generation Biofuel Systems

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Supply Chain optimisation tools may help managing the oncoming transition from first to second generation bioethanol productions. A multi-objective Mixed Integer Linear Programming is developed to design bioethanol supply chains where both corn grain and stover are considered as suitable biomass. Environmental and financial performance are simultaneously taken as design drivers and alternative process design options are considered, too. Northern Italy is taken as geographical benchmark to assess a real-world case study. Results show how the design transition from first to second generation bioethanol systems substantially depends on the specific trade-off between environmental and financial objectives.

1. Introduction

In the ambitious attempt to relieve the world economy from oil dependency, renewable energy has been gaining ever greater attention as a realistic alternative to conventional supply sources. The EU Commission (Directive 2009/28/EC) has been promoting biofuels as a key stone of its energy agenda setting specific targets in terms of both fuel share (5.75% of energy from renewable sources by 2010, up to 10% by 2020) and sustainability levels (35% of minimum Greenhouse Gas - GHG - reduction from 2009, 50% from 2017 and 60% from 2018 onwards). Initially indicated as the most suitable option within the transport sector, bioethanol from first generation productions is now incurring increasing discredits (e.g. conflict with food industry, concerns on environmental degradation and economic sustainability) asking for the identification of more sustainable production technologies (Londo et al., 2010). Second generation production might be the keystone to overcome such drawbacks, despite the high capital expenditures and production costs. In particular, corn stover is considered a very promising raw material to bridge the gap between first and second generation technologies (Petrolia, 2008) allowing for a well-advised transition between them (USDA, 2005).

Supply Chain (SC) optimisation is a critical aspect of modern enterprises development. Decision makers should be provided with tools for analysing the overall network and assessing the economic and environmental pros and cons. According to this, Mixed Integer Linear Programming (moMILP) models represent one of the most suitable tools in steering decision making tasks when conflicting targets are aimed at, as happens for defining the most convenient strategies to design biofuels systems.

Please cite this article as: Giarola S., Zamboni A. and Bezzo F., 2011, Supply chain design and capacity planning: from first to second generation biofuel systems, Chemical Engineering Transactions, 24, 253-258
DOI: 10.3303/CET1124043

Up to date, several research works have been directed towards the enhancement of the economic and environmental performance of second generation bioethanol systems (Petrolia, 2008; ANL, 2006). Only a few efforts have been devoted to the optimisation of the entire SC of lignocellulosic ethanol production (Dunnett et al., 2008).

Here a moMILP approach is adopted to design first and second generation corn-based bioethanol SCs considering alternative production technologies as well as optimising the biofuel system according to both economic and environmental criteria. This work aims at delivering an environmentally conscious decision-making tool for the design of hybrid corn grain- and stover-based bioethanol production systems. It is based on a multi-period moMILP modelling framework for the design and the optimisation of bioethanol SCs. Production technologies are assessed according to their economic and environmental performance over the long term. Technological alternatives are characterised by varying biomass mix between corn grain and stover for bioethanol production. In addition, valuable by-products (i.e. DDGS, Distiller's Dried Grains with Solubles) and stover use to produce energy are investigated as suitable options to improve the environmental performance of the system.

2. Assumptions and Methods

The core task of this work is the development of a design tool to steer decisions on general biofuel SC over the long term. This is performed through an optimisation problem driven by both profit maximisation and impact minimisation criteria. The objective is to determine the optimal system configuration which maximises the financial profitability while minimising the GHG emissions. Therefore, key variables to be optimised deal with the best bioethanol SC design in terms of *i.* feedstock mix, *ii.* plant capacity and conversion technology, *iii.* by-products end-use options, *iv.* financial performance of the system over the long term and *v.* system impact on global warming.

The problem refers to a single bioethanol production plant which is supplied with the necessary biomass (corn, stover or both) cultivating a hypothetical land surface of limited, although flexible, extension. The financial analysis is assessed through a multi-period modelling pattern for the NPV index implementation, supporting an environmentally conscious investment planning over a 20-years time horizon.

Referring to fuel production, ten technologies were taken into account (Table 1): first generation from corn (dry-grind process, DGP) (Zamboni et al., 2009), second generation from stover (lignocellulosic process, LCEP) (USDA, 2005), and integrated technologies (Hybrid, characterised through purpose-designed Aspen models), where the feedstock mix describes three decreasing corn to stover ratios (1:1,1:2,1:3). Finally, the use of by-products (i.e. DDGS, Distiller's Dried Grains with Solubles) and stover as alternative fuels to natural gas (NG) for the combined heat and power station (CHP) were investigated.

The whole SC analysis has been limited to the upstream biofuel production involving biomass cultivation and delivery as well as fuel production sites. Impact assessment over the biofuel life cycle refers to the standard Lifecycle Assessment (ISO 14040) and has been limited to the WTT (Well-to-Tank) approach (Zamboni et al., 2009). Each network node considered (i.e. SC or life cycle stage) has been characterised tailoring actual economic and environmental data to the case study under assessment. The SCA and LCA approaches proposed by (Zamboni et al., 2009) for corn-based bioethanol production in Northern Italy have been adopted to evaluate the specific modelling parameters. The environmental and economic assessments of the stover-to-ethanol pathway have followed the approaches by (ANL, 2006; Luo et al., 2009) and the work by (USDA, 2005).

Table 1. Conversion technologies assessed in the study for ethanol production.

Process (*k*)	Biomass-to-ethanol		Fuel to CHP			Output		
	Corn	Stover	NG	DDGS	Stover	Ethanol	CHP	DDGS
DGP	•		•			•		•
DGP-CHP	•			•		•	•	
DGP-Stover	•				•	•	•	•
LCEP		•				•	•	
Hybrid[†]	•	•			•	•	•	•
Hybrid-CHP[†]	•	•		•	•	•	•	

[†]Each Hybrid technology comprises three instances at varying biomass mix.

3. Mathematical Features

The problem is formulated as a moMILP model based on the mathematical approaches commonly adopted in the strategic design of multi-echelon SCs (Tsiakis et al., 2001). It also embodies different features to address the capacity planning and technology selection (Liu et al., 2007) of fuel systems design at the strategic level. The environmental frame as well as the moMILP solution algorithm are approached as in (Zamboni et al., 2009).

The first objective function concerns the NPV (Net Present Value) maximisation (Obj_{NPV} [€]) of the business to be established. This imposes the maximisation of profit-related indexes. It is calculated by summing up the discounted annual cash flows minus the capital investment when a production facility is established. The economic objective function is stated as follows:

$$Obj_{NPV} = NPV = \sum_k \left(\left(\sum_t CF_{k,t} \cdot df_t \right) - TCI_k \right) \tag{1}$$

where $CF_{k,t}$ [€/y] represents the annual cash flow; TCI_k [€] stands for the capital investment related to the establishment of a production facility of technology k; and df_t is the discount factor related to each year t. The second objective is to minimise the total GHG impact (Obj_{ENV} [kg of CO_2-eq]) resulting from the operation of the biofuel SC over the 20 years horizon. This is estimated by summing up the annual impact $TI_{k,t}$ [kg of CO_2-eq/y] resulting from the operation of the production chain for each year t and when a conversion technology of type k is chosen. The definition of $TI_{k,t}$ needs considering each life cycle stage s contribution to the overall GHG impact as well as the effect of emission credits coming from by-products allocation. Accordingly:

$$Obj_{ENV} = \sum_{k,t} TI_{k,t} = \sum_{k,t} \left(CRD_{k,t} + \sum_{s} Imp_{s,k,t} \right) \qquad (2)$$

where $Imp_{s,k,t}$ [kg of CO_2-eq/y] is the GHG emission rate resulting from the operation of each single stage s at time t when a technology k is chosen, whereas $CRD_{k,t}$ [kg of CO_2-eq/y] represents the emissions discount for technology k at time t. The GHG emission rate is defined as follows:

$$Imp_{s,k,t} = \sum_{i} f_{s,i} \cdot F_{s,i,k,t} \;, \quad \forall\, s,k,t \qquad (3)$$

where the reference flow $F_{s,i,k,t}$ [units/y], specific for each life cycle stage s, biomass i and technology k is multiplied by a global emission factor, $f_{s,i}$ [kg of CO_2-eq/unit], representing the carbon dioxide emissions equivalent at stage s for treating biomass i per unit of reference flow.

The emissions discount is given by:

$$CRD_{k,t} = -c_k \cdot P_{'ethanol',k,t} \;, \quad \forall\, k,t \qquad (4)$$

where c_k [kg of CO_2-eq/t] represents the emission credits assigned to cattle feed and/or energy displacement per unit of ethanol rate, $P_{'ethanol',k,t}$ [t/y], produced through technology k at time t. This formulation imposes that the primary product has to be charged of the total GHG emissions, minus the emission credits derived from the displacement of alternative goods with by-products. With concerns to the corn-based bioethanol system, DDGS is the main by-product, which could be a valuable substitute for cattle feed and may also be used as a fuel for CHP generation. On the other hand, stover-based processes deliver electricity as main by-product, generated from the valorisation of stover lignin in a CHP system.

4. Results and Discussion

The two objectives problem was solved through the CPLEX solver in the GAMS® modelling tool (Rosenthal, 2006). Figure 1 shows the resulting trade-off set of Pareto non-inferior solutions.

The economic optimum (point A in Figure 1) involves the selection of the standard DGP technology in which DDGS is sold as animal fodder. This option allows for more revenues coming from the by-product business and results in a normalised NPV of about 1.61 €/$GJ_{ethanol}$. The environmental outcomes show an overall GHG emission of 78.03 kg CO_2-eq/$GJ_{ethanol}$ (about 9% less than the conventional gasoline pathway) which are insufficient for eligibility for public incentives (asking for at least 35% of GHG reduction with respect to conventional fuels, according to Directive 2009/28/EC).

Moving down towards better performance in terms of environmental impact mitigation and still keeping high financial levels, a suitable technological option is represented by the Pareto non-inferior point B of Figure 1: this would involve the establishment of a production facility exploiting the technology *k* = DGP-CHP and operating at maximum capacity (*p* = 276 kt/y). This option, however, takes advantage of burning DDGS in the power station thus leading to a global decrease in ethanol production costs due to the heavy effect of energy supply savings (the normalised NPV is now 1.52 €/$GJ_{ethanol}$). This process design also entails substantial emission savings due to the emission credits coming from the alternative use of by-products. Thus, the overall GHG emissions decrease down to about 56% lower with respect to gasoline, thus matching the EU requirements for 2017 (i.e. 50% savings).

If the 2018 emission target (i.e. 60% savings) has to be reached, solution C (Figure 1) is suggested: this supply chain configuration may provide very positive effects on global warming mitigation leading to an overall GHG savings of about 84%. This performance is achieved by operating the Hybrid technology with a corn/stover ratio of 1/3, at the maximum capacity (*p* = 276kt/y). However, the high investment required to establish such technologies entails a consistent worsening on the economic performance: the solution indicates a normalised NPV of 1.21 €/$GJ_{ethanol}$ (about 20% worse than solution B).

The environmental optimum is reached with configuration D (Figure 1): it involves the establishment of a full second generation facility (technology *k* = LCEP) operating at minimum capacity (*p* = 96 kt/y) and with an impact on global warming reduced down to 1.8 kg CO_2-eq/$GJ_{ethanol}$ (about 97% less than gasoline). This is mainly due to the lower emissions resulting from stover production and conversion to ethanol when compared to conventional first generation biomass. This solution is not economically feasible, though: the normalised NPV drops down to -6.20 €/$GJ_{ethanol}$, which clearly shows the scarce competitiveness of such a business due to the consistent capital costs.

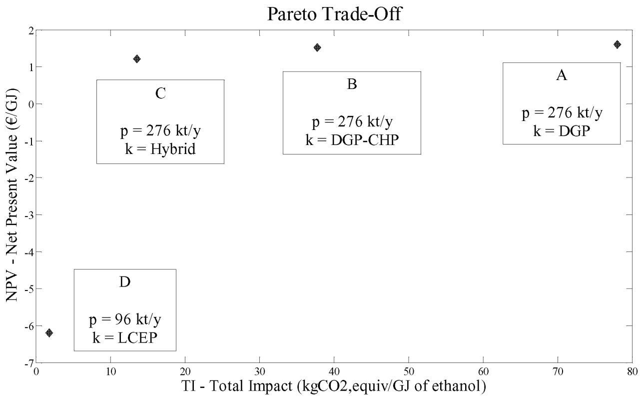

Figure 1: Pareto set of solutions: NPV maximisation and GHG emissions minimisation (p=plant scale; k=production technology).

5. Final Remarks

A moMILP modelling framework for the strategic design of biofuel systems has been presented and discussed. The aim of the study was to build a general modelling tool that might be helpful to steer the transition towards more sustainable second generation productions under both economic and environmental criteria. Results show how first generation technologies, although more competitive within the conventional fuel market, are not a sustainable answer to the energy supply question, particularly if the EU legislation is taken into account. Although current stand-alone cellulosic technologies are not viable on economical terms, integrated corn grain and stover technologies may allow for a significant reduction of GHG emissions (abiding by the EU emission limits) and still deliver a profitable business.

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