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A comprehensive approach to the design of ethanol supply chains including carbon trading effects

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ABSTRACT

The optimal design of biofuels production systems is a key component in the analysis of the environmental and economic performance of new sustainable transport systems. In this paper a general mixed integer linear programming modelling framework is developed to assess the design and planning of a multi-period and multi-echelon bioethanol upstream supply chain under market uncertainty. The optimisation design process of biofuels production systems aims at selecting the best biomass and technologies options among several alternatives according to economic and environmental (global warming potential) performance. A key feature in the proposed approach is the acknowledgement of an economic value to the overall GHG emissions, which is implemented through an emissions allowances trading scheme. The future Italian biomass-based ethanol production is adopted as a case study. Results show the effectiveness of the model as a decision making-tool to steer long-term decisions and investments.

1. Introduction

In view of making the current transport system more secure and sustainable, the EU Directive (EC, 2009) has been instrumental towards reaching the goal of increasing biofuels market penetration, and the ambitious target of 10% share of energy from renewable sources by 2020 has been set for all the EU Members. Sustainability requirements have been also established: e.g., GHG (greenhouse gas) emissions reduction should reach a minimum threshold of 35% from 2009, 50% from 2017 and 60% from 2018 onwards. Bioethanol has been assuming a leading position among biofuels and the earlier impulse came from first generation technologies, whose potential environmental drawbacks and social perception have unveiled the need of a more sustainable conversion processing. Second generation technologies might overcome such issues but high costs are currently hindering the establishment of cellulosic ethanol infrastructures. However, extensive market-based tools, such as emissions trading integrated with regulation targets, might play a key role for managing high costs related to the transition to biofuels (Turk et al., 2010) and delivering a sustainable transport systems at lower costs (Skinner et al., 2010). Even if the road transport sector is currently excluded from the EU Emissions Trading System (EU ETS) several institutions have adopted market-based tools addressing the issue of biofuels sustainability to help accelerating the implementation of new technologies. The Californian 'Low Carbon Fuel standard' (CGA, 2009) set a target on GHG emissions over biofuels life cycle, representing the baseline with respect to which tradable credits may be generated.

A new approach in the biofuels-based transport system is also required to face ever-changing energy markets, and uncertainty has been recognised as one of the most challenging aspect for modern enterprises development (Guillén-Gosàlbez and Grossmann, 2009). Goods and raw materials prices volatility needs to be carefully addressed within a thorough financial evaluation of bioenergy systems.

In light of this multi-faceted situation, decision making on ethanol investments should be supported by quantitative design tools assessing both financial and environmental performance of biofuels production in a holistic approach along the entire supply chain (SC) over the long-term. Mixed integer linear programming (MILP) represents an effective tool in steering decision making about completely undetermined infrastructures particularly when complex optimisation tasks involve uncertainty of exogenous factors.

Abbreviations: CHP, combined heat and power; DAP, dilute acid hydrolysis process; DDGS, distiller's dried grains with solubles; DGP, dry-grind process; DGP-CHP, dry-grind process with a DDGS fuelled CHP station; EU ETS, European Union emissions trading scheme; GBP, gasification biosynthesis process; GHG, greenhouse gas; LCA, life cycle assessment; MILP, mixed integer linear programming; eNPV, expected net present value; SC, supply chain; SCA, supply chain analysis; SEP, steam explosion process; SOC, soil organic carbon; WTT, well-to-tank.

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Nomenclature

Sets

$c \in C$ set of production costs regression coefficients C = {*slope*, *intercept*}
$i \in I$ set of biomass typology, I = {*corn*, *poplar*, *willow*, *miscanthus*, *corn stover*, *wheat straw*, *barley straw*, *switchgrass*}
$j \in J$ set of product, J = {*ethanol*, *DDGS*, *power*}
$k \in K$ set of conversion technologies, K = {*DGP*, *DGP-CHP*, *DAP*, *SEP*, *GBP*}
$p \in P$ set of plant scale index, $P = \{1, \ldots, 6\}$
$s \in S$ set of life cycle stages, S = {*bp*, *bpt*, *bt*, *fp*, *ec*}
$sc \in Sc$ set of scenario probability, $Sc = \{1, \ldots, NS\}$
$t \in T$ set of time intervals (years), $T = \{1, \ldots, 20\}$

Scalars

ζ interest rate
GHG_r GHG emissions savings required to biofuels
LA land surface availability [ha]
M maximum profit value [€], s.t. $M \gg PBT$
PM_{EtOH} ethanol molecular weight
ρ ethanol density [kg/L]
Trate taxation rate
UpperLimit allowable ethanol production variation [t/y]

Parameters

α feedstock intermediate compounds involved in ethanol production
$a_{i,k}$ coefficient for capital cost estimation for conversion technology k and biomass i
$BA_{i,t}$ biomass i available for ethanol production at time t [t/y] $BA_{i,t} = LA \cdot BY_{i,t} \cdot q_i$
$BN_{i,k,p}$ biomass i needs for technology k at each linearisation interval p [t/y]
$BY_{i,t}$ cultivation yields for each biomass i at time t [t/ha]
$CapMax_{i,k}$ maximum capacity in terms of biomass i for conversion technology k [t/y]
$CapMin_{i,k}$ minimum capacity in terms of biomass i for conversion technology k [t/y]
$CI_{i,k,p}$ capital investment at each linearisation interval p for the conversion technology k and biomass i [M€]
$coef_{i,k,c}$ coefficients (slope [€/$t_{ethanol}$], intercept [€/y]) for linear regression of production costs for technology k and biomass i
df_t discount factor at time t
dk_t depreciation charge at time t
φ_α concentration of the intermediate compound α in the feedstock
$f_{i,k,s,t}$ emission factors for life cycle stage s time t technology k and biomass i [kg CO_2 equiv./t_{ref}]
$\gamma_{i,j,k}$ conversion of biomass i to product j through technology k [$t_{ethanol}$/$t_{biomass}$] or [kWh/$L_{ethanol}$]
$\eta_{r,k}$ recovery efficiency for technology k
$MP_{j,t}$ market price of product j at time t [€/t] or [€/MWh]
$MP\_All_{sc,t}$ market price for traded emissions at scenario sc and time t [€/kg CO_2 equiv.]
π_{sc} probability related to scenario sc
q_i maximum quota of collectable biomass i for ethanol production
r_k power factor for capital cost estimation for conversion technology k
$S_{\alpha/fuel,k}$ selectivity of reactant α for technology k
$UPC_{i,sc,t}$ unit purchase cost for biomass i at scenario sc and time t [€/t]
UTC_i unit transport cost for biomass i [€/t]
$\chi_{\alpha/fuel,k}$ conversion of reactant α for technology k

Continuous variables

$BPC_{i,k,sc,t}$ biomass purchase cost for biomass i technology k scenario sc at time t [€/y]
$Cap_{i,k,sc,t}$ biomass i rate for technology k scenario sc at time t [t/y]
$CF_{i,k,sc,t}$ cash flow for biomass i technology k scenario sc at time t [€/y]
$D_{i,k,t}$ depreciation charge for biomass i technology k at time t [€/y]
$D\_Cap_{i,k,sc,t}$ inlet of biomass i decrease for facility k at time $t \geqslant 2$ [t/y]
eNPV expected net present value [€]
$EPC_{i,k,sc,t}$ ethanol production cost for biomass i technology k scenario sc at time t [€/y]
$F_{i,k,s,sc,t}$ reference flow for life cycle stage s, biomass i, technology k and time t [units/y]
$I_{i,k,s,sc,t}$ impact for life cycle stage s for biomass i technology k scenario sc at time t [kg CO_2 equiv./y]
$I\_Cap_{i,k,sc,t}$ inlet of biomass i increase for facility k at time $t \geqslant 2$ [t/y]
$In\_Cap_{i,k}$ initial inlet of biomass i for facility k at time $t = 1$ [t/y]
$Incomes_{i,k,sc,t}$ gross earnings for biomass i technology k scenario sc at time t [€/y]
$\lambda_{i,k,p}$ linearisation variables for TCI for biomass i at interval p and for technology k
$MaxCO2_{i,k,sc,t}$ emissions cap for biomass i technology k scenario sc at time t [kg CO_2 equiv./y]
NPV_{sc} net present value of scenario sc [€]
Obj_{eco} economic objective function [€]
$OpCosts_{i,k,sc,t}$ variable costs for biomass i technology k scenario sc at time t [€/y]
$P\_All_{i,k,sc,t}$ purchased permit for biomass i technology k scenario sc at time t [kg CO_2 equiv./y]
$PBT_{i,k,sc,t}$ profit before taxes for biomass i technology k scenario sc at time t [€/y]
$P^T_{i,j,k,sc,t}$ total production rate for product j from biomass i technology k scenario sc at time t [t/y]
$S\_All_{i,k,sc,t}$ sold permits for biomass i technology k scenario sc at time t [kg CO_2 equiv./y]
$TAX_{i,k,sc,t}$ tax amount for biomass i technology k scenario sc at time t [€/y]
$TC_{i,k,sc,t}$ transport cost for biomass i technology k scenario sc at time t [€/y]
$TCI_{i,k}$ total capital investment for biomass i and technology k [€]
$TI_{i,k,sc,t}$ total impact for biomass i technology k scenario sc at time t [kg CO_2 equiv./y]
$TI^*_{i,k,sc,t}$ gasoline total impact equivalent to biofuels pathway for biomass i technology k scenario sc at time t [kg CO_2 equiv./y]
W_e bioethanol rate in the black-box model [t/y]
W_f feedstock rate in the black-box model [t/y]

Binary variables

$V_{i,k,sc,t}$ 1 if taxation has not to be applied for facility k biomass i at time t, 0 otherwise
$Y_{i,k}$ 1 if a production facility k treating biomass i is to be established, 0 otherwise
$y_{i,k,p}$ supporting variable for linearisation of plant scale
$Z_{i,k,sc,t}$ 1 if a facility of technology k with biomass i at scenario sc and time t, has to be enlarged, 0 otherwise