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Strategic optimisation of biomass-based energy supply chains for sustainable mobility☆

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ABSTRACT

The identification of alternative and sustainable energy sources has been one of the fundamental research goals of the last two decades, and the transport sector plays a key role in this challenge. Electric cars and biofuel fed vehicles may contribute to tackle this formidable issue. According to this perspective, a multi-echelon supply chain is here investigated considering biomass cultivation, transport, conversion into bioethanol or bioelectricity, distribution, and final usage in alternative bifuel (ethanol and petrol) and electric vehicles. Multiperiod and spatially explicit features are introduced in a Mixed Integer Linear Programming (MILP) modelling framework where economic (in terms of Net Present Value) and environmental (in terms of Greenhouse Gases emissions) objectives are simultaneously taken into account. The first and second generation bioethanol production supply chain is matched with a biopower production supply chain assessing multiple technologies. Both corn grain and stover are considered as biomass sources. In the environmental analysis, the impact on emissions caused by indirect Land Use Change (iLUC) effects is also assessed. Results will show the efficacy of the methodology at providing stakeholders with a quantitative tool to optimise the economic and environmental performance of different supply chain configurations.

1. Introduction

The global energy consumption by transport has grown by 2% per year since 2000 and accounted for 28% of the overall energy consumption in 2012 (IEA, 2015). Considering that the road transport almost totally relies on petroleum derived fuels, diminishing the mobility dependency on fossil fuels may represent not only a strategic decision, but also an environmental necessity. One possibility to reach that goal is the establishment of the production of biofuels and bioelectricity for alternative fuel vehicles (AFVs). On the one hand, biofuels have played a highly significant role in the search for alternatives as they have seemed to many the only feasible approach to replace petroleum-based traditional fuels in the transport sector. On the other hand, the recent introduction of the electric vehicles (EVs) in the private fleet market offers a new possibility to reduce the petroleum dependency.

In regards to both biofuel and bioenergy, many Process Systems Engineering (PSE) approaches focusing on the Supply Chain (SC) design and optimisation through mathematical programming (typically Mixed Integer Linear Programming – MILP) have been recently proposed. With concern to biofuels (in fact, mainly bioethanol), contributions have dealt either with the maximisation of the economic performance (e.g. Dunnett et al., 2008; Zamboni et al., 2009a), also by considering uncertainty effects (e.g. Dal-Mas et al., 2011; Kim et al., 2011), or the interaction between different players (Bai et al., 2012; Yue and You, 2014a,b) or with the minimisation of the environmental impact (Garcia and You, 2015), typically through a multi-objective optimisation approach (e.g. Zamboni et al., 2009b; You and Wang, 2011). For a more comprehensive review, see also Yue et al. (2014c). The design of SCs for bioenergy production has also been optimised in a similar way. Many mathematical models for biomass production centres and conversion facilities location have been carried out (e.g. Fiorese et al., 2005; Freppaz et al., 2004; Voivontas et al., 2001), also combining a detailed energy conversion optimisation with energy/heat transportation costs (Söderman and Pettersson, 2006). For instance, Bruglieri and Liberti (2008) proposed a mathematical programming approach for planning and running an energy production system process based on burning different biomasses. Contributions have

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List of symbols

Sets

$g \in G$	grid squares, $G = \{1,\ldots,60\}$
$g' \in G$	set of square regions different than g
$i \in I$	biomass types, $I = \{\mathit{corn}, \mathit{stover}\}$
$j \in J$	product types, $J = \{\mathit{ethanol}, \mathit{DDGS}, \mathit{power}\}$
$k \in K$	production technologies, $K = \{1,2,3,4,11,22,33\}$
$l \in L$	transport means, $L = \{\mathit{truck}, \mathit{rail}, \mathit{barge}, \mathit{ship}, \mathit{tship}\}$
$p \in P$	discretisation intervals for plant size linearisation, $P = \{1,\ldots,6\}$
$s \in S$	life cycle stages, $S = \{\mathit{bg}, \mathit{bpt}, \mathit{bt}, \mathit{fp}, \mathit{epow}, \mathit{fd}, \mathit{fdist}, \mathit{ebat}, \mathit{ebifuel}, \mathit{ec}\}$
$t \in T$	time periods, $T = \{1,\ldots,5\}$

Subsets

$\mathit{elec}\ (k) \subset K$	subset of pure power production technologies, $\mathit{fratio}\ (k) = \{11, 22, 33\}$

Scalars

δ	conversion factor specific for DDGS, 0.954 $\mathrm{ton_{DDGS}/ton_{EtOH}}$
ϕ	fixed costs % over incomes, 0.15
ψ	emission in battery production, 3046.924 kg of $\mathrm{CO_2}$-eq/EV
ζ	emission in bifuel car driving, 0.005515 kg of $\mathrm{CO_2}$-eq/$\mathrm{km_{bifuel}}$
LHV_e	ethanol lower heating value, 26.952 GJ/$\mathrm{ton_{EtOH}}$
ρ	ethanol density, 0.7891 tonne/l
Γ	MWh to tonne ethanol conversion, 0.133570792 $\mathrm{ton_{ethanol}}$/MWh
χ	MWh/year to number of EVs conversion, 1.896918157 MWh/EV/year
$charg$	domestic electric charger 1.4 kW cost, 59.055 €/newEV
inc	differential EVs purchasing cost, 5000 €/newEV
$\Delta KMcost$	differential EVs driving cost, 0.03 €/$\mathrm{km_{EV}}$
$kmCAR$	average daily trip in Italy, 45 km/day
$\Gamma 2$	conversion of tee to km driven, 64825.42357 km/tonne

Parameters

Φ_g	average ethanol-petrol distribution diameter, km
AD_g	arable land density ($\mathrm{km^2{}_{arable}/km^2{}_{grid\ surface}}$)
$BCD^{max}{}_g$	maximum cultivation density in region g, $\mathrm{km^2{}_{cultivation}/km^2{}_{arable\ land}}$
$dfTCI_t$	discount factor for investments at time t
$dfCF_t$	discount factor for cash flow at time t
$CFdfCAR_t$	discount factor for cash flows at time t for EVs
$etperc_t$	ethanol blending percentage at time t
Θ_t	differential EVs purchasing cost reduction at time t
$gasolTOT_t$	total number of traditional petrol fleet at time t
$renewCAR1_t$	relative number of old EVs to be substituted with new ones at $t = 4$
$renewCAR2_t$	relative number of old EVs to be substituted with new ones at $t = 5$
ω_k	exceeding electricity production specific for each conversion technology k, $\mathrm{kWh_{el}/l_{EtOH}}$
ER_p	ethanol production rate for each plant size p, $\mathrm{ton_{EtOH}}$/month
PR_p	electricity production rate for each plant size p, MWh/month
$\gamma_{i,k}$	conversion factor specific for each biomass type i, $\mathrm{ton_{EtOH}/ton_{biomass}}$
GS_g	grid surface, $\mathrm{km^2}$
MP_j	market price for product j
$BA_{g,i}$	biomass i availability for ethanol production in region g, tonne/time period
$\beta_{i,k}$	fraction of ethanol rate from biomass type i for each technology k
$burn_{i,k}$	fraction of biomass i fed to CHP for each technology k
BY_i	biomass yield of product i in region g, $\mathrm{ton_{biomass}}$/time period/$\mathrm{km^2}$
$CI_{p,k}$	capital investment at each linearisation interval p and for technology k, M€
$c_{k,cc}$	coefficients for the linear regression of production costs for each technology k, slope [€/$\mathrm{ton_{EtOH}}$] and intercept [€]
$fbg_{i,g}$	emission factor for biomass i growth in grid g and biomass, kg $\mathrm{CO_2}$-eq/$\mathrm{ton_{biomass}}$
$fbpt_i$	emission factor for biomass i pre-treatment, kg $\mathrm{CO_2}$-eq/$\mathrm{ton_{biomass}}$
fbt_l	emission factor for biomass supply via mode l, kg $\mathrm{CO_2}$-eq/$\mathrm{ton_{biomass}}$ $\mathrm{km^2}$
ffp_i	emission factor for ethanol production from biomass i, kg $\mathrm{CO_2}$-eq/$\mathrm{ton_{EtOH}}$
$fpp_{i,k}$	emission factor for power production from biomass i, kg $\mathrm{CO_2}$-eq/MWh
ffd_l	emission factor for ethanol distribution via mode l, kg $\mathrm{CO_2}$-eq/$\mathrm{ton_{EtOH}}$ $\mathrm{km^2}$
fec_k	emission credits for each technology k, kg $\mathrm{CO_2}$-eq/$\mathrm{ton_{EtOH}}$
$LD_{g,g'}$	local delivery distance between grids g and g', km
$PC_{p,t}$	production costs linearised for size p and conversion technology k, €/time period
$PCap_p$	plant capacity of size p used for cost linearisation, tonne/time period
r_k	power factor for capital cost estimation for conversion technology k
$\tau_{g,l,g'}$	tortuosity factor of transport mode l between g and g'
$UPC_{i,g}$	unit production costs for biomass type i in grid g, €/$\mathrm{ton_{biomass}}$
$z_{i,k}$	biomass conversion into electricity, MWh/$\mathrm{ton_{biomass}}$

Continuous variables

$bifuelCARS_t$	number of bifuel vehicles at time t
$bifuelKM_t$	total distance travelled by bifuel vehicles at time t, km/month
$CapElec_{i,k,g,t}$	supply of biomass i to plant of technology k in region g at time t, tonne/month
BPC_t	biomass production constant time t, €/time period
CCF	discounted Cumulative Cash Flow, €
CF_t	Cash Flow at time t, €/time period
D_t	Depreciation at time t, €/time period
EPC_t	ethanol production cost at time t, €/time period
$ELtot_{k,g,t}$	energy produced at time t by plant k in region g, MWh/month
$Etot_{g,t}$	ethanol produced at time t, tonne/month
EVm_t	EVs market share at time t
$exCO_t$	extra costs for EVs fleet, €/time period
FCC	discounted facilities capital costs, €
FCC_t	facilities capital costs at time t, €/time period
$FixC_t$	fixed cost at time t, €/time period
$Impacts_{s,t}$	impact for life cycle stage s at time t, kg $\mathrm{CO_2}$-eq/time period
Inc_t	gross earnings at time t, €/time period