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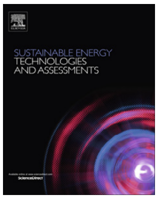

Original Research Article

Stochastic techno-economic considerations in biodiesel production

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ABSTRACT

Biodiesel production, like other engineering projects, involves critical decisions which have to be made under uncertainties stemming from a range of sources such as the inherent variation in operating conditions and market forces featuring inflation, depreciation factors, variations in equipment/production costs, etc. Although the effect of such uncertainties on front end engineering and management decisions was recognised, these have not been considered comprehensively in the literature. In this paper, for the first time, structural reliability principles are applied to determine the prospect of a process plant achieving some performance targets under uncertainties. Considering the published case of a biodiesel production plant, this paper presents a new approach for techno-economic assessment in a stochastic framework. Mean values of the economic indicators obtained through the stochastic analysis are found to be in good agreement with previously published nominal values. The stochastic techno-economic analysis approach combines First Order Reliability Method (FORM) and Monte Carlo Simulation (MCS) to offer additional performance measures which are needed by prospective investors, governments, engineers and other stakeholders to ensure plant safety and cost-efficiency.

Introduction

Biodiesel has a number of advantages over the conventional petrodiesel; it is renewable, biodegradable, non-toxic, carbon neutral, has lower sulphur content, high lubricity and better flash point [1]. Service properties of biodiesel are very similar to those of conventional diesel; this makes it possible to blend the duo in all proportions [1,2]. On the other hand, biodiesel production faces certain technical and economic challenges as well as uncertainties in sustainability and market forces. Some of the concerns associated with biodiesel usage are storage, low-temperature performance characteristics, NO_x exhaust emissions, high breakeven cost, the tendency to compete with food sources and costing 1.5 to 3.0 times the conventional diesel price. Also, in terms of heating value, biodiesel has slightly lower calorific value (42.65 MJ/kg) than petrodiesel (43 MJ/kg) and gasoline (46 MJ/kg), but performs better than coal (32–37 MJ/kg) [3].

Considerable progress in the development of biodiesel production technologies has already been reported. Use of waste cooking oil (WCO) as feedstock for production of biodiesel appears to be a promising way to address issues such as the high breakeven unit price and the fuel-against-food problem [4–6]. Zhang et al. [7] modelled and evaluated four different biodiesel production processes involving both virgin and waste cooking oil; employing both heterogonous and homogenous catalysis. A subsequent economic assessment concluded that none of the four processes was able to result in a net positive after tax rate of return [8]. However, among the four processes, homogenous acid-catalysed process was shown to be potentially viable in terms of both returns and technological requirements. West et al. [9] extended the works of Zhang et al. [7,8] by modifying the design configurations, employing fewer unit operations with smaller capacities and reducing the need for stainless steel (by changing certain reacting conditions including the type of catalyst) and confirmed that acid catalysed process could be a practical biodiesel production pathway. For the same plant capacity (8000 ton/yr), depreciation rate (10%), income tax rate (50%) and other economic conditions, West et al. [9] showed that the capital cost can be cut down from \$2.55M to \$0.63M and the total production cost from \$5.92M to \$4.45M, bringing down the after tax rate of return from −15.63% to +58.76%.

Depending on plant capacity and type of feedstock, among other factors, different techno-economic assessments of biodiesel production processes suggest different breakeven unit prices. For instance, the four processes presented by Zhang et al. [8] indicated that the required selling price for biodiesel ranges from 644 to 884 \$/ton (plant capacity: 8000 tons/yr); Encinar et al. [10]

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Nomenclature

a/b	lower/upper bound of a parametric range
Biod	Biodiesel
C_E^o	Total Delivered Equipment Cost ($)
C_{TCI}	total capital cost ($)
$C_{b,i}$	known equipment (base) cost ($)
CPI	consumer price index (2000–2013)
F_{CEPCI}	equipment cost updating factor (CEPCI)
F_{stup}	factor accounting for start up cost
F_{BM}	bare module factor (stochastic)
F_{BM}^*	deterministic bare module factor
F_{Disc}	average depreciation factor
F_{TCI}	total capital investment factor
F_{TPC}	total production cost factor
$f_{\underline{X}}(.)$	joint probability distribution function
f_{Del}	factor accounting for cost of delivery
$f_{M,i}$	material cost factor
$f_{P,i}/f_{T,i}$	working pressure/temperature cost factor
$G(\underline{X})$	limit state function
HEX	heat exchanger
I_T	total investment cost
m_B	mass flowrate of biodiesel (kg/h)
m_G	mass flowrate of glycerine (kg/h)
$m_{M\text{-}in}$	mass flowrate of methanol feed (kg/h)
m_{UWO}	mass flowrate of unreacted WCO (kg/h)
$m_{WO\text{-}in}$	mass flowrate of WCO (kg/h)
Mthnol	methanol
n	plant life span (yrs)
P_{fB}	probability of exceeding, $U_{B_{max}}^*$
P_{gross}	gross profit (before Tax) ($/yr)
p	production cost inflation rate (%)
P.Stream	process stream
P_{net}	net after tax profit, ($/yr)
$Q_{E,i}$	capacity of new equipment *i*
$Q_{b,i}$	capacity of a known (base) equipment
q_i	equipment specific cost factor
$Q - CL$	quantity of heat removed in the cooler
$Q - RB$	quantity of heat added by the reboiler
R_T	total revenue from products
Rxn	reaction
r	capital/construction cost inflation rate (%)
t	upstream plant time per year, *(h)*
$U_{B_{max}}^*$	target breakeven price $/ton
U_G	unit price of glycerine ($/ton)
U_M	unit price of methanol ($/ton)
U_{WO}	unit price of waste cooking oil ($/ton)
UNRXTD	unreacted
WCO	waste cooking oil
$\underline{X}^*$	most probable design/operation point
x_{in}^M	mass fraction of methanol (%)
x_2^B	mass fraction of biodiesel in P.Stream2 (%)
x_2^{UWO}	mass fraction of unreacted WCO (%)
x_4^G	mass fraction of GLYCERINE P.Stream4 (%)
Greek symbolsα	
	sensitivity index
β	Hasofer–Lind (H–L) reliability index
φ	assessment criteria/threshold

estimated this to be 537$/ton and van Kasteren and Nisworo [11] observed that the biodiesel minimum selling price could be 202 $/ton, 282 $/ton and 623$/ton for plant capacities of 125,000 ton/yr, 80,000 ton/yr and, respectively. Similarly, different figures for investment costs, production costs, etc. were observed; emphasising the need for considering uncertainties in these estimates within a probabilistic framework. Usually, assuming input/output linearity in terms of uncertainty, a fixed error limit is imposed implicitly to account for the effect of such uncertainties. However, such an assumption does not scale or gauge the specific quantities within a given range in terms of likelihood of occurrence. For instance, with reference to the breakeven price range reported in Zhang et al. [8], i.e. 644—884$/ton, it would be beneficial to know the:

- probability of recovering the investment cost when the biodiesel is sold at a target breakeven price of $U_{B_{max}}^*$$/ton;
- confidence level associated with the entire price range; probability that the net after tax profit is greater than or equal to a certain threshold P_{min} throughout the life of the plant;
- most probable design/operational specifications for a plant to achieve a defined performance target; and
- probability distribution of different economic indicators, the sensitivity of selected financial indices to given variables or the reliability associated with certain critical investment decisions.

To provide such deep insights, stochastic uncertainty modelling together with reliability analysis is usually recommended [12,13]. The proposed stochastic framework is designed to address these questions.

Uncertainties in the technology and economic forces are among the major sources of concern. There are a number of uncertainty sources in biodiesel production including random input/process variations due to changes in the composition of WCO, which originate from different sources; these can ultimately affect annual plant tonnage in terms of biodiesel and glycerine production. In addition, uncertainties in market forces such as inflation, depreciation factors, variations in the cost of equipment, production costs, etc. are also likely to affect the credibility of the usual deterministic estimates, especially during the early development phase. For instance, Thompson et al. [14] opined that effects of uncertainty on the market of feedstock are very significant and argued that considering them as constant represents over simplification. Other sources of concern include modelling and statistical uncertainties arising from lack of data, simplifications as well as lack of knowledge; these various sources of uncertainties come together and propagate across various project development phases and impact the techno-economic performance estimates.

Being a new venture, potential investors would always desire to understand not only the prospects, but the uncertainties, including the underlying risk. Probabilistic design/economic modelling and analysis could help provide a rational basis for supporting critical decisions by offering various stochastic measures [15,16]. It is seen that research studies discussed so far did not offer these possibilities for biodiesel production. The present work seeks to bridge this gap by proposing an enhanced stochastic modelling approach to consider the techno-economic viability of biodiesel production plants, considering a published case study. This work is an extension of the generic framework for optimising chemical process performance proposed in Abubakar et al. [17]. As the focus of this paper is on stochastic assessment, only a brief reference will be made to traditional deterministic approach, further information on these aspects is available elsewhere [3,9,18,19]. In addition, all the economic indicators considered in this paper are based on a fixed-capacity, heterogonous catalysed biodiesel production