Economic and environmental impact marginal analysis of biorefinery products for policy targets

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ABSTRACT. A simple biofuel production system can be first examined for its policy compliance in terms of GHG emission reduction target relative to fossil-based counterparts. More integrated and optimised biorefinery systems with polygeneration can then be evolved with the aid of graphical analysis of marginal emission savings vs. additional economic margins. This bottom-up approach helps to achieve greater GHG emission cut by integrated systems design and thereby setting a more stringent benchmark to support policies towards achieving climate change mitigation goals. The combined Economic Value and Environmental Impact analysis is a multi-level methodology that can be used to represent biorefinery system performances as an aggregate of differential economic and environmental impact margins of biorefinery products. The methodology is extended in this paper to support process integration strategies that allow achieving policy compliance of biorefinery products in terms of GHG emission savings. An economic and environmental impact profile of the products is introduced for a graphical visualisation of economic costs and values as well as deficits and surpluses in environmental impact savings. The effectiveness of the extended methodology has been demonstrated using a Jatropha-based biorefinery system converting Jatropha seed into biodiesel, glycerol and cake, as a case study.

The biodiesel produced can achieve 53% emission cut, while glycerol and cake can achieve an emission cut by 57% by displacing similar functionality respective fossil based products.

Keywords: biorefinery process optimisation, value analysis, environmental impact assessment, policy support, LCA

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1 Introduction

The challenge that emerges while selecting a biorefinery system configuration is to find the appropriate processing pathways and products from a biomass feedstock in order to achieve profitability and reduce environmental impact. At the least, a biorefinery must clearly show economic and environmental added value over a fossil-based reference system that needs to be displaced. This requires careful assessment of performances in the early stages of process design (Azapagic, 1999; Bovea and Pérez-Belis, 2012; Poudelet et al., 2012).

As biorefinery configurations become more complex with new process and product developments, integrating process design and sustainability objectives will become very challenging. Tools based on process integration methodologies have been developed for biorefinery design and integration (Ng, 2010; Pham and El-Halwagi, 2012; Tay and Ng, 2012) and other industrial facilities for cleaner production (Dunn and Bush, 2001; Klemeš et al., 2010; Munir et al., 2012). Optimisation frameworks have also been developed for the optimum planning and design of biorefinery systems (Hosseini and Shah, 2011; Ponce-Ortega et al., 2012;

Santibañez-Aguilar et al., 2013). Life cycle assessment (LCA) has also been widely applied to analyse the energy, greenhouse gas (GHG) emissions and other environmental impacts of biofuel (Arvidsson et al., 2012; Ekman et al., 2013; Patrizi et al., 2013) and glucose (Tsiropoulus et al., 2013) production systems. Multicriteria assessment is also becoming prominent for new systems deployment (Myllyviita et al., 2012; Ning et al., 2013, Santibañez-Aguilar et al., 2013). However, unlike relatively stable sectors such as crude oil refining and petrochemical production, biorefining is a highly dynamic sector. For this sector, feedstock supply systems, conversion technologies and product portfolios are fast changing together with environmental policies. Policy targets in the European Union affecting biofuel production currently require 60% of minimum GHG saving from biofuels with respect to fossil fuels by 2020 (European Union, 2009). The average reported GHG emission savings are 30-50% for biofuels from dedicated crops and more than 60% for biofuels from waste (Smyth et al., 2010).

Navigating the wide variation of potential GHG savings requires a methodological approach that is capable of linking every change at the process level to overall performance at the system level and that is conceptually explicit, transparent and consistent with the environmental policy (Jänicke, 2012; Poudelet et al., 2012; Shin et al., 2008). In this sense, multi-level strategies embracing a life cycle philosophy are needed to analyse a biorefinery from process streams to whole systems, such that policies can directly influence process design and vice versa (D'Alessandro et al., 2010; Hildén, 2011; Jänicke, 2012). Such strategies will allow the life cycle economic and environmental impact (EI) assessment to be done in a systematic manner from the smallest element in a biorefinery process network (e.g. material streams and unit operations) to cradle-to-grave systems. The approach must also allow identification and prioritisation of pathways for process integration and optimisation that can be linked with the policy targets. Furthermore, a process-based approach will help process engineers to apply life cycle thinking and adopt it in decision-support systems (Poudelet, 2012).

A conceptual graphical analysis of combined effects for more informed decision analysis can assist process synthesis, integration and optimisation tasks to generate process configurations with minimum environmental impacts (Majozi et al., 2006; Tan et al., 2009; Tjan et al., 2010). A methodology to allow the life cycle economic value and environmental impact (EVEI) assessments of biorefinery systems has been presented in Martinez-Hernandez et al. (2013a). The EVEI methodology is extended in this paper by introducing an economic and environmental impact profile of the biorefinery products. This profile is a graphical visualisation of economic costs and values as well as deficits and surpluses in environmental impact savings. The graphical approach allows a direct comparison with policy targets, and hence allows setting a more stringent benchmark for policy adaptation. The methodology is demonstrated by analysing a biorefinery system with *Jatropha curcas* seeds as feedstock.

2 Methodology

2.1 Concepts of EVEI analysis

The value analysis tool has been developed for differential economic marginal analysis from process streams to networks. It enables evaluation and graphical presentation of a network margin in terms of the cost of production (COP), value on processing (VOP) and margins of individual streams (Sadhukhan et al., 2003, 2008). A stream showing a negative economic margin implies that it would be better (if possible) to purchase that stream from the market rather than produce it within the process.

The evaluation of COP starts from the known market prices of feedstocks and proceeds stream by stream in the forward direction until end products are reached. The COP of a stream is the summation of all associated cost components (i.e. the costs of feedstock, auxiliary raw materials, utilities and annualised capital costs) that have contributed to the production of that stream. This must mean inclusion of only those fractional costs involved with the stream's production.

The calculation of COP and VOP values is illustrated with reference to Figure 1, which shows a biorefinery system producing biodiesel, glycerol and cake from *Jatropha curcas* seeds. In Figure 1, the cost of the feedstock is 296.3 \$ t^{-1} and it enters the process at a rate of 271200 t y^{-1}. The first operation it undergoes is dehusking, which entails total operating and annualised capital costs of 248 166 \$ y^{-1}. Then, the COP of the outlet stream from the dehusking unit going to the oil extraction unit is the result of the sum of total cost of feedstock (271 200×296.3 \$ y^{-1}) and the total costs of the dehusking unit (248 166 \$ y^{-1}) multiplied by an allocation factor α (0.9478) and divided by the mass flow rate of the stream: (271 200×296.3+248166)×0.9478/179800=424.9 \$ t^{-1}. Similar calculations proceed forward for each stream as it travels through the process.

The VOP evaluation proceeds in the backward direction from the end product market prices until the feedstock in a process network is reached. The VOP of a stream at a point within the process is obtained from the prices of products that will ultimately be produced from it, minus the costs of auxiliary raw materials and utilities and the annualised capital cost of equipment that will contribute to its further processing into these final products. For example, in Figure 1, the glycerol product and the stream going to the distillation unit are the outlet streams from the decantation unit, which entails total operating and annualised capital costs of 49 160 $ y^{-1}. Then, the VOP of the inlet stream to the decantation unit is the result of the value of the glycerol product (10 700×881.8 $ y^{-1}) plus the value of stream going to the distillation unit (105 300×637.3 $ y^{-1}) minus the total costs of the decantation unit (49 160 $ y^{-1}) and divided by the mass flow rate of the stream: (10 700×881.8+105 300×637.3−49 160) /116 200=658 $ t^{-1}. Note that the COP of a feedstock to a process and the VOP of an end product correspond to their respective market prices.

Equivalent to the COP and VOP, the environmental impact (EI) cost of production and EI credit from fossil-based product displacement can also be evaluated stream by stream, in order to understand quantitatively the origins of environmental impacts and the opportunities for reduction through modification of process configurations. A stream with a positive environmental impact margin (difference between EI credit and EI cost) would indicate that there are EI benefits from its processing, while a stream with a negative EI margin would indicate that its production generates more EI than the EI credit obtained. This basic concept allows the analysis of the performance of biomass-based products from a biorefinery with respect to counterpart fossil-based products. A stream with a negative EI margin would be better (if possible) bought in from a process that produces it with a positive EI margin. When this is not possible but it has economic value, its production pathway must be improved by process integration and using energy and raw materials with a lower embodied EI.

In a cradle-to-grave life cycle approach (including biomass production system, biorefinery process, transportation and end use of products), the CO_2 captured during photosynthesis, direct wastes and emissions can be taken into account within the EI variables of feedstock and products. The EI cost (GHG as CO_2 equivalents) of feedstock I_f is made up of the CO_2 binding by photosynthesis (B_f), the EI cost from transportation (T_f) and EI cost from production (G_f), shown in Eq. 1. This equation shows that for a biorefinery to be environmentally feasible, B_f must be greater than the EI added to the system by G_f and T_f.

$$I_f = G_f + T_f - B_f \tag{1}$$

In that case, I_f is negative, indicating feasibility of an overall biorefinery system and that the GHG emission is reduced due to CO_2 capture during photosynthesis. When the various crop fractions are utilised in a biorefinery e.g. Jatropha oil for biodiesel and seed husks for combined heat and power, the CO_2 binding may need to be allocated to various products. This is carried out by carbon content of the products shown in Table 3 for cake and husk. The carbon content of biodiesel and glycerol is calculated from compositions resulting from process simulation in section 3.2.

The EI credit value of a biorefinery product is the net avoided emission, shown in Eq. 2. The EI credit value of a biorefinery product (D_p) is made up of the emission from an equivalent product being replaced (I_{peq}), multiplied by a unitless equivalency factor β, minus end use or end of life emissions (I_{end}) and the EI cost from transportation (T_p). Emissions from end use or end of life are, for example, the emissions from combustion of fuel products when used to operate a car or the emissions from product decomposition disposed in landfill. An equivalent product is an existing product that can deliver the same functionality or service as the biorefinery product. β, for example, is the ratio between the heating value of a biofuel produced from a biorefinery (e.g. biodiesel) and that of an equivalent fossil based fuel (e.g. diesel).

$$D_p = \beta \times I_{peq} - T_p - I_{end} \tag{2}$$

This equation shows that for a biorefinery product having environmental advantage over a fossil-based counterpart, D_p must be positive. Analogous to the economic cost of the feedstock, I_f represents the EI 'cost' of the feedstock. Hence, I_f is the starting point for forward calculation of EI cost of the intermediate and product streams in a process network, as further explained in the following section. Analogous to the selling price of a product, D_p represents the environmental impact credit of a stream. Hence, D_p is the starting point for the backward EI credit calculations of intermediate streams and feedstocks in a process network.

2.2 Modelling of streams

Equivalent to streams' economic performance indicators, VOP and COP, their EI indicators are their individual impact Credit Value on Processing (CVP) and Impact Cost of Production (ICP), respectively. As noted above, for a final product, CVP = D_p. For an initial feedstock, ICP = I_f.

VOP and CVP of streams. Since VOP and CVP of a biorefinery end product are known from reported market prices and embodied EI of an existing product being replaced, respectively, the calculation proceeds backwards from the end products towards the feedstock. Consider $\overline{V}$ as a vector containing VOP and CVP of a feed stream f to a process unit k (excluding auxiliary raw materials to avoid double accounting in Eq. 3). The vector of values of the feeds (i.e. the inlet streams) can be calculated from the known vector of values of the products (i.e. the outlet streams) p minus the total costs $\overline{O}_k$ of process unit k through Eq. 3:

$$\overline{V}_f = \left[\sum_{p=1}^{q} \overline{V}_p P_p - \overline{O}_k\right] \Big/ \sum_{f=1}^{g} F_f \tag{3}$$

P_p and F_f corresponds to the mass flow rates of product (outlet stream) and feed (inlet stream), respectively.

COP and ICP of streams. The ICP of an outlet or product stream from a process unit represents the EI incurred from its production. To evaluate the ICP of a product or outlet stream from a process unit, the operating and construction EI costs of the process unit are added to the total ICP of the feed and divided by the product mass flow rate. The COP of a product stream is evaluated in the same way using the corresponding economic variables. $\overline{C}$ in Eq. 4 is a vector containing the costs (COP and ICP*)* of a product (outlet stream) p from a process unit k (excluding emission and waste streams to avoid double accounting in Eq. 4). $\overline{C}$ can be predicted for a product p (outlet stream) with allocation factor α from the known vector of costs of the feeds (inlet streams) and total costs of process unit k:

$$\overline{C}_p = \left[\sum_{f=1}^{g} \overline{C}_f F_f + \overline{O}_k\right] \alpha \Big/ P_p \tag{4}$$

The economic operating costs (O_k) of a process unit consist of the costs of utilities, auxiliary raw materials and the disposal or treatment cost of any emission/waste stream produced. The analogous operating EI cost is indicated by IO_k. The capital cost can be estimated from equipment sizing and annualised using a capital charge determined from the net present value, internal return rate and discounted cash flow calculations (Sadhukhan et al., 2008). The total impact from construction can be also estimated from equipment sizing and the type of materials and their EI, and then annualised using the life time of a facility. The annualised economic capital cost and EI costs of constriction are fixed costs that can be added to the operating costs to determine the total costs of a unit as shown in Eq. 5.

$$\bar{O}_k = \begin{bmatrix} O_k \\ IO_k \end{bmatrix} = \begin{bmatrix} \bar{C}_{a,k} \\ \bar{I}_{a,k} \end{bmatrix} \times \bar{A}_k + \begin{bmatrix} \bar{C}_{u,k} \\ \bar{I}_{u,k} \end{bmatrix} \times \bar{U}_k + \begin{bmatrix} \bar{C}_{m,k} \\ \bar{I}_{m,k} \end{bmatrix} \times \bar{M}_k + \begin{bmatrix} CC_k \\ CI_k \end{bmatrix} \qquad (5)$$

$\bar{O}_k$ denotes total costs of a process unit as function of process variables.

$\bar{A}_k$, $\bar{U}_k$ and $\bar{M}_k$ represent single column vectors of mass flow rates of auxiliary raw materials, utilities and emissions/wastes, respectively.

$\bar{C}_{a,k}$, $\bar{C}_{u,k}$ and $\bar{C}_{m,k}$ are single row vectors containing economic costs, while $\bar{I}_{a,k}$, $\bar{I}_{u,k}$ and $\bar{I}_{m,k}$ are a one row vector containing the respective EI costs.

CC_k and CI_k are annualised capital cost and annualised EI from construction, respectively.

The inclusion of the costs from emissions and auxiliary raw materials in the total costs allows their allocations amongst process streams and propagation towards end streams in both directions. The allocation factor (α) shown in Equation 4 is determined in case of multi-output process units. For a stream from single output units α=1. Various approaches or methods can be used for the allocation of costs and EI including allocation by mass, energy content, carbon content and economic value (Dalgaard et al., 2008; Heijungs and Frischknecht, 1998; Kim and Dale, 2002). Amongst these methods, mass or carbon content does not indicate energy outputs from various energy products, hence is not effective for the allocation of impacts between energy products. The allocation by economic value using VOP has been adopted here. The reason for this is that VOP allows capturing the interactions between the economic and environmental values. If the trends in the two values can be merged together, such that environmentally sustainable products are also economically profitable products, then the economic value can be regarded as a good indicator for impact allocation.

The difference between $\bar{V}$ and $\bar{C}$ of a stream provides its margins (Δ): economic margin, Δe = VOP−COP, and avoided emission or EI saving, Δi = CVP−ICP. When the aim is to improve the percentage GHG savings, hence addressing policy targets of biorefinery products with reference to fossil-based equivalent products (European Union, 2009; US Congress, 2007) the relative percentage of EI savings (s_p) of a product can be calculated using Eq. 6.

$$s_p = \frac{\Delta i}{(I_{peq} \times \beta)} \times 100 \qquad (6)$$

Built upon the principles of environmentally friendly process design with the most efficient use of energy, raw materials and capital, process integration tools help to identify a network's bottleneck and shift loads (e.g. energy / water / materials / environmental impact) from constrained to unconstrained parts for overall improved performance (Majozi et al., 2006; Ng, 2010, Tan et al., 2009; Tjan et al., 2010). In order to facilitate compliance with existing legislation, it is possible to shift the environmental burden from one product to another following a process integration approach. Consideration of the network connectivity integrates process operations, economic and environmental indicators to policy drivers. The concepts and methodological procedures developed above along with the construction of an EVEI profile, presented in the next section, can be effectively used for the targeting of avoided emissions for future low carbon adaptation under a strict policy scenario.

2.3 EVEI profile of a product

An EVEI profile represents the cumulative economic, environmental impact costs and values and the resulting margins for a biorefinery product. This graphical representation allows identification of the "distance to target" and quantification of any deficit or excess of EI savings with respect to a policy target and also the resulting economic or environmental compromises from any option for performance improvement. A generic EVEI profile is presented in Figure 2, featuring the following:

Figure 2

- *Costs composite curve* is a plot of cumulative EI costs versus economic costs from the feedstock, auxiliary raw materials, utilities, process emissions and fixed costs (annualised capital costs or EI cost from construction) allocated to a particular product. These costs are plotted as in the order given in a plot of EI in the y-axis and economic value (EV) in the x-axis. In Figure 2, a steeper slope of the contributions from utilities and auxiliary raw material compared with feedstock indicate higher EI contribution per $ spent, while a very small slope of process emissions and fixed costs indicates that there is low EI contribution per $ spent.
- *EI cost limiting line* indicates a benchmark for the EI cost target from the production of a biorefinery product established from policy. The limiting line starts at (0,0) and the end point is ($COP_p \times P_p$, $ICP_{p,\,limit} \times P_p$). $ICP_{p,\,limit}$ is determined using Eq. 6 for the percentage EI saving set by the policy target

($s_{p,target}$) and the definition of Δi = CVP−ICP as: $\mathrm{ICP_{limit}}=\mathrm{CVP}-(s_{p,target}\times \mathrm{I_{peq}}\times\beta / 100)$.

- *Value line* is a horizontal line drawn from the EI-axis to the point of total EI credit value ($\mathrm{CVP}_p\times \mathrm{P}_p$) against the total economic value on processing ($\mathrm{VOP}_p\times \mathrm{P}_p$). This line indicates a reference limit to get positive economic and EI saving margins.
- *Product EI saving surplus/deficit* is the distance from the value line to the end of the limiting line indicating the EI saving margin required to meet the policy target. The distance from the end point of the costs composite curve and the limiting line determines the difference between the EI saving margin achieved and the policy target. If the composite curve is below the limiting line, then there is a surplus EI saving and then stricter policy target for GHG emission reduction could be met.

The application of the EVEI methodology developed above and the use of product EVEI profiles to analyse options for accomplishing policy targets is demonstrated in a case study presented in the next section.

3 Case study

The Jatropha-based biorefinery configuration in Figure 1, producing 100 kt y^{-1} of biodiesel and the corresponding amounts of glycerol, seed cake and husk, has been selected as case study. The context is that it is located in Mexico within the radius of a Jatropha plantation in the state of Michoacan. The current 50% GHG emission reduction target set in US policies (as of 2012) for biofuel production (US Congress, 2012) is the reference point used in the analysis for policy compliance and applied to all the products. The seeds are assumed to be produced by non-toxic Jatropha provenances native to Mexico. Therefore, seed cake can be used as animal feed. The various modelling approaches for each biorefinery subsystems are described as follows.

3.1 Feedstock production model

The EI results for Jatropha seeds production system, deduced from the inventory data given in Table 1, are shown in Table 2. Jatropha cultivation model (Martinez-Hernandez et al., 2013b.) shows nitrogen fertilisation as the hot spot of this stage of the Jatropha-based biorefinery system. Since nitrogen fertilisation is a hot spot in the system and an important decision variable, two different fertilisation rates were studied to track the effect of reducing current fertilisation rate. It can be observed that estimated yield from models correlating yield to average annual rainfall and nitrogen fertilisation is not significantly affected by the reduction in fertilisation rate resulting in lower EI cost of production.

Table 1

Table 2

3.2 Biorefinery process model

Models for seed processing were developed in a spreadsheet, while Jatropha oil conversion into biodiesel was simulated in the commercial process simulation software Aspen Plus® (Aspen Technology, 2012). The heating values of Jatropha fruit fractions used for mass and energy balance calculations are shown in **Table 3**. The overall mass balance of the biorefinery process is presented in Figure 1. The process consists of seed dehusking producing husk as a substitution fuel for natural gas. The seed kernels are oil extracted, with seed cake meal co-produced as a protein source substituting soy meal. The oil undergoes transesterification with methanol using heterogeneous catalyst, which allows flexibility on free fatty acid content in the feedstock and high conversion into biodiesel and high purity glycerol. Methanol is recovered by distillation and recycled to the transesterification reactor. Glycerol is separated by decantation and sold to the market, replacing glycerol from fossil resources.

Table 3

The simulation flowsheet of Jatropha oil conversion into biodiesel is shown in Figure 3. Oil was modelled as a mixture of tryglycerides (TG) made up of triolein, tripalmitin, trilinolein and tristearin and free fatty acids (FFA, modelled as oleic acid). Properties of these components and the corresponding fatty acid methyl esters (FAME) were not available in the Aspen Plus database. The basic properties (e.g. molecular weight, density, molecular structure) were introduced and the UNIFAC-Dortmund physical property model was used for predicting remaining properties. The oil composition and process specifications for the simulation model are presented in Martinez-Hernandez et al. (2013b). Table 4 summarises the simulation results.

Figure 3

Table 4

Heat integration was carried out to reduce the utility requirements as shown in Figure 2. Composite curves were used with a minimum temperature difference of 10^{o}C between hot and cold streams in the heat exchangers to carry out heat integration. The following heat integration opportunities identified were also simulated in Aspen Plus as shown by the dashed lines in Figure 3. The reaction mix stream is preheated (from 26°C to 70°C) by the bottom stream of the methanol recovery column (from 167°C to 135°C). The crude biodiesel stream fed to the distillation column can also be preheated (from 25 to 301°C) by the distillate biodiesel stream (at 317°C cooled to 35°C), thus reducing reboiler duty. The heat requirements after heat integration were used for the inventories. The operating inventories and costs are shown in Table 5.

The process models developed by Martinez-Hernandez et al. (2013b) are used to show how a bottom-to-top level analysis can be carried out to comply with and, at the same time, inform the policy targeting in the case study that follows. Note that the previous work uses LCA to assess alternatives for more complex biorefinery schemes by focusing on environmental impact. In the present work, the combined economic and EI analysis was carried out for the biodiesel production process only.

3.3 Other assumptions

From the predicted seed yield of 4213 kg ha^{-1} (Table 2) and the total seed requirement of 271.2 kt y^{-1} (Figure 1), the total land use is 64385 ha y^{-1}. Thus, a transportation distance of 14.3 km is obtained assuming a circular shape of the cultivation land. The same distance is assumed for seed cake and husk being used locally. For transportation of other products and materials, the distance is assumed to be 100 km.

The EI from construction materials was estimated assuming that process equipment is made up of 70% steel and 30% aluminium. The mass of steel was estimated from the preliminary equipment sizing (Turton et al., 2009). Distillation columns were sized using the built-in feature in Aspen Plus® for such purpose. Then, the weight of the vessels was determined using a weight calculator tool (MatWeb LLC, 2012). The weight of dehusking machines was estimated from vendor data. Cost of vessels, pumps and heat exchangers were estimated using the CapCost software tool (Turton et al., 2009). Prices were levelised using the Chemical Engineering Plant Cost Index (CEPCI) reported in the Chemical Engineering Magazine (2012). The cost of transesterification, decantation and distillation units in the biodiesel process includes pumps and heat exchangers around main equipment. The resulting total fixed costs (capital and EI from construction) of the units are summarised in Table 5. To annualise the economic and EI costs of the process units, the operation time of 7920 h y^{-1}, capital interest rate of 10% and plant life time of 15 years were assumed. The resulting annual capital charge ratio was 0.1315.

Table 5

4 Results and discussion

4.1 EVEI results and overall biorefinery performance

The VOP, COP and Δe from the EVEI modelling of the streams are presented in Figure 1. The biodiesel cost of production (COP) was estimated as 627.7 \$ t^{-1} or 0.55 \$ L^{-1} (7.44 MX\$ L^{-1}, 1 \$=13.5 MX\$), which means it has the potential to be competitive with petro-diesel prices in Mexico (10.81 MX\$ L^{-1}, August 2012). The methanol recycle has been considered as a utility stream for units 3 and 4 considering its market price (i.e. 27.2×1000×372.1 = 10,121,120 \$ y^{-1}). For unit 4 (methanol recovery), the total costs are recalculated as O_4' by subtracting the economic value of the methanol recycle. For unit 3 (transesterification), the methanol recycle presents an additional cost. Thus O_3' is calculated by adding the economic value of the methanol recycle to O_3. The total treatment cost of the oily waste is included in the total cost of the biodiesel distillation unit (number 6).

The calculations of EI cost of feedstock and EI credit value of the products are shown in Table 6. These values are required to calculate EI cost of production (ICP) for intermediate streams and end products and EI credit value (CVP) for intermediate streams and feedstock. Calculations for intermediate streams are exemplified in Table 7. CO_2 emissions from the processing and end use (e.g. combustion) were considered as balanced as they originate from the carbon contained in Jatropha seeds. Within this system's boundaries (from seed production to product distribution point), Eq. 1 reduces to $I_f = G_f + T_f$ while Eq. 2 reduces to $D_p = \beta\times I_{peq} - T_p$. These are the equations used to calculate the values shown in Table 6. However, the CO_2 from the carbon atoms added from fossil-based methanol to methyl esters in biodiesel is accounted (0.157 kg CO_2 kg^{-1}) as shown in Table 6. For seed husk, the heating value in Table 3 is used as a factor to convert D_p from kg MJ^{-1} to kg kg^{-1}.

Table 6

The CVP, ICP and Δi are shown in Figure 4. The oil extracted has an ICP (CO_2 equivalent) of 1.497 kg CO_2-eq kg^{-1} based on the ICP of the incoming seed kernel of 0.909 kg CO_2-eq kg^{-1}, to which is added the fractional EI cost of the utilities and equipment construction materials using allocation factor and stream mass flow rates (i.e. (0.909×179800+30572)×0.8079/104700 = 1.497 kg CO_2-eq kg^{-1}). Similarly, working backwards from the end, the CVP of the stream entering the biodiesel distillation is 2.605 kg CO_2-eq kg^{-1}, based on the biodiesel CVP minus the total EI costs of the unit (including EI from oily waste) and the stream flow rates (i.e. (2.779×100000–3652)/105300). Table 7 further exemplifies EVEI calculations.

Figure 4

Table 7

The economic and environmental impact profiles for the biorefinery marketable products are shown in Figure 5a and 5b, respectively. The areas between the values and costs of each product represents its economic margin and potential EI saving. The sum of areas represents the total biorefinery margins. The profiles show that the biorefinery is profitable and that all the products provide EI savings (thus, streams are sustainable according to this criterion).

Figure 5

4.2 Policy compliance and EVEI profiles

Substituting β, I_{peq} and Δi into Eq. 6, the following % EI savings of end products are calculated: Biodiesel with respect to petro-diesel = 32%; Glycerol with respect to fossil-based glycerol = 36% and seed cake with respect to soy meal =31.5%. These values are lower than the minimum GHG emission reduction target of 50%. Thus, improvements in the biorefinery process system are required in order to meet the targets for these two products. The only product that can meet the policy target is seed husk (used as fuel), which achieves 90.5% savings with respect to natural gas, well beyond the required target of 50%. This gives scope to move some of this excess saving to other products, in order that the savings with which these other products are credited can meet policy targets. This is equivalent to shifting heating loads within a heat exchanger network to ease bottlenecks without altering the overall heat recovery of the network. It thus provides a practical approach to meeting targets in biorefineries that might on the surface appear to be incapable of delivering policy targets. It also provides targeted guidance for optimal sources of additional savings if shifting of existing savings is inadequate.

Figure 6

Figure 6 shows the EVEI profile of biorefinery products in the base case system. A composite factor (α'), determined from the product of allocation factors of the outlet streams (α) from each process unit in a product path, is used to calculate the fractional costs for a particular product as shown in Table 8. These factors are used to generate the data points in the EVEI profile of a product as shown for the economic costs allocated to biodiesel in Table 9. The data points for EI costs are determined following a similar approach. The composite factors (α') will change with any change in economic value of the streams as they determine the allocation factors α. The data points for the value and the limiting lines are determined as discussed in Section 2.3.

It can be observed that biodiesel fails to meet the policy target with a deficit in EI saving of 52.3 kt CO_2-eq y^{-1}. Glycerol incurs a deficit by 5.5 kt CO_2-eq y^{-1} while the deficit from seed cake is 10.1 kt CO_2-eq y^{-1}. Husk exhibits EI saving surplus of 38.5 kt CO_2-eq y^{-1}. If the surplus savings of seed husk are shifted to make up for the deficits of biodiesel and glycerol, there is still an overall deficit of about 29 kt CO_2-eq y^{-1}. As the values are interrelated by the EVEI models, the EI saving across the products can be more evenly distributed and improved by integration strategies. In Figure 6, the segment with the highest contribution to EI in the cost composite curve corresponds to the feedstock (labelled as number 1) for all the products. The segments corresponding to utilities and auxiliary raw materials are also important contributors to the EI value for the composite curve of biodiesel and glycerol. Contribution of utilities is not significant for cake production, while only feedstock EI is relevant for husk EI. These results provide insights into the utilisation of waste and by-product streams for low impact utility generation.

Table 8

Table 9

4.3 Process integration and policy support

Streams with potential as fuels for utility supply were ranked from the lowest to the highest EI saving (Δ*e*) in order to sequentially apply process integration strategies: oily waste < husk < seed cake < glycerol. The EVEI analysis results of modifications a-d below are summarised in Table 10.

a. Decrease the nitrogen fertilisation rate from 162 kg ha^{-1} to 100 kg ha^{-1} (Table 2). This modification increased the % saving of all the products. However, the 50% EI saving target for biodiesel, glycerol and cake was not met and thus modifications b and c were required.
b. The heat from oily waste stream can be recovered into steam generation for the methanol and biodiesel distillation columns' reboilers. The total heat in the oily stream (with a heating value of 39.63 MJ kg^{-1}) is 209 266 GJ y^{-1}. Thus, the heat requirements for the distillation units of 148 833 GJ y^{-1} can be supplied at an energy efficiency of 71%. The EI saving margins were increased for all the products and the policy target is only achieved for glycerol (Table 10) but the modification was not enough to achieve the target for biodiesel and cake.
c. Further, a portion of seed husk needs to be used for heat generation for the oil extraction unit. Since any process modifications affect cost of units, the VOP results and allocation factors are also affected. The calculation of amount of husk required to meet biodiesel policy target saving of 50% is iterative. The solver function in Excel was used to estimate the husk requirement. The EI saving deficit of bioethanol (5.7 kt CO_2-eq y^{-1}, after modifications a and b) is divided by total allocation factor of bioethanol (0.6735, after modifications a and

b). This gives an estimate of 8.47 kt CO_2-eq y^{-1} that needs to be saved by replacing steam from natural gas with steam from husk. Then, an estimate for husk requirement to give the same heat duty as the natural gas is calculated. The calculation uses the EI of natural gas (0.06117 kg CO_2-eq MJ^{-1}), heat generation efficiency of natural gas (0.7), heating value of husk (19.86 MJ kg^{-1}) and heat generation efficiency of husk (0.6). The initial value of husk requirement is obtained as follows: $8.47/(0.06117/0.7)/(19.86\times0.6) = 8.1$ kt y^{-1}. The Excel Solver gives the final value of husk requirement of 8.2 kt y^{-1} that replaces 36.5% of the heat demand by the oil extraction unit: The boiler annualised capital cost and revenue losses from the use of husk can be balanced off by the economic cost saving due to natural gas replacement. As shown in Table 10, all the products achieved EI saving equal to or greater than 50% in relation to the corresponding fossil-based product being displaced.

The cost of production of biodiesel was decreased from 627.7 \$ t^{-1} in the initial system to 621.6 \$ t^{-1} after the modifications a-c. This is due to a net saving of about 0.8 M\$ y^{-1} from the integrated use of oily waste and husk for heat generation. The net positive EI saving is 65 kt CO_2-eq y^{-1}. Thus the total biorefinery margin is increased from 7.0 M\$ y^{-1} to about 7.8 M\$ y^{-1} (11% increase) and the EI savings from about 213 kt CO_2-eq y^{-1} to 278 kt CO_2-eq y^{-1} (30% increase) with respect to the initial system.

Figure 7 shows the effect of improvements “a” to “c” in the costs composite curve of all the biorefinery products. The curve for biodiesel (Figure 7a) is shown displaced downwards to the limiting line indicating that policy target can be met. Glycerol, cake and husk display significant surpluses. Note that the value line for husk (Figure 7d) is also displaced downwards and to the left, indicating the revenue loss and reduction of total EI saving due to use of husk within the system. The EI saving from utility supply from husk has been shifted and distributed to the other biorefinery products.

d. Further improvement could be realised by generating the entire heat required by the oil extraction unit using husk. The effect on the performances is analysed as in the case of improvement c and the final results are shown in Table 10 under modification "a to d". It can be observed that EI savings are increased for biodiesel to 53% and for glycerol and cake to 57%. The total biorefinery economic margin remains the same after modifications a-c. The total biorefinery EI savings are 281 kt y^{-1}, a 32% increase with respect to the initial system.

As shown in Table 10, the saving from husk relative to its fossil counterpart remains the same after modifications; this is because the total EI saving from husk replacing natural gas is reduced in the same proportion as the mass flow rate utilised within the process as fuel. In addition, utilisation of husk does not modify performance of the dehusking unit itself as most of the energy generated from husk is used downstream, affecting the performances of the rest of the units and their products. It is this propagation towards all the product pathways that allows achieving the targets for all the products. Thus, improvement implemented at a certain upstream process unit will improve the EI saving of the products derived from that unit and from its downstream process units.

Figure 8 shows the integrated flowsheet after modifications a to c showing the integration of steam generation from oily waste and husk to achieve the 50% GHG emissions reduction target by all products.

Figure 7

Table 10

5 Conclusions

Economic value analysis results can be combined with environmental impact analysis results for more integrated process design and decision making. The EI analysis has been illustrated in the current work using the global warming potential as a criterion. However, in principle, any environmental impact characterisation can be presented in the same way as the global warming potential, alongside the economic assessments. The EVEI tool has proved to be useful to evaluate options for improvement of biorefinery process designs from differential product EV and EI marginal analysis. By using a multi-level strategy, the tool is capable of capturing the effects of process and market variables on the marginal values. Both empirical and fundamental thermodynamic-based models can be integrated, allowing handling of non-linear models in the EI allocation problems.

Integration strategies similar to those used in the case study can be developed for a scenario where the rebalancing of EI to achieve policy targets entails an economic cost – the benefit of meeting the target would then need to be balanced against the economic cost. Simultaneously, holistic process integration can be applied for integrated biorefinery design, since not only can the EI be reduced, but also the emission reduction targets can be increased and a higher biorefinery economic margin can be obtained. For stricter emission reduction policies in the future, conversion of husk into methanol, heat and power for the biodiesel production process could be considered. Analysis including carbon credit trading could also be used to determine the investment incentives for integrated biorefinery systems.

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