AIChE

Process Synthesis and Optimization of a Sustainable Integrated Biorefinery via Fuzzy Optimization

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DOI 10.1002/aic.14156
Published online July 5, 2013 in Wiley Online Library (wileyonlinelibrary.com)

Over the last decade, utilization of biomasses is highly encouraged to conserve scarce resources, reduce dependency on energy imports as well as protect the environment. Integrated biorefinery emerged as noteworthy concept to integrate several conversion technologies to have more flexibility in product generation with energy self-sustained and reduce the overall cost of the process. Integrated biorefinery is a processing facility that converts biomass feedstocks into a wide range of value added products via multiple technologies. In this work, a systematic approach for the synthesis and optimization of a sustainable integrated biorefinery which considers economic, environmental, inherent safety, and inherent occupational health performances is presented. Fuzzy optimization approach is adapted to solve four parameters simultaneously as they are often conflicting in process synthesis and optimization of an integrated biorefinery. An integrated palm oil-based biorefinery case study is solved to demonstrate the proposed approach. © 2013 American Institute of Chemical Engineers *AIChE J*, 59: 4212–4227, 2013

Keywords: fuzzy optimization, network synthesis, integrated biorefinery, sustainable, palm-based biomass

Introduction

An integrated biorefinery is a processing facility that integrates multiple biomass conversion technologies to produce various biochemicals, biofuels, and bioenergy.[1] In the last decade, various works on systematic screening and selection of technology pathways for integrated biorefineries had been carried out. Systematic frameworks of integrated biorefinery in optimal product allocation and production optimization were developed.[2,3] A hierarchical procedure for the synthesis and screening of potential alternatives for integrated biorefinery was proposed.[4] Meanwhile, computer-aided molecular design (CAMD) and reaction network flux analysis (RNFA) were adapted in integrated design of biofuels production.[5] Besides, Ng[6] extended the use of an optimization-based targeting technique (known as automated targeting), which developed for resource conservation network synthesis[7,8] in integrated biorefinery with maximum economic performance (EP). Later, Tay and Ng[9] further extended the automated targeting approach to handle multiple process parameters. Ponce-Ortega et al.[10] presented a disjunctive programming approach for synthesis of optimal configuration of a biorefinery. Later, Tay et al.[11] presented a robust optimization approach for the synthesis of integrated biorefineries that addresses the uncertainties of supply and demand. Most recently, Ng et al.[12] presented a modular optimization approach for the simultaneous process synthesis, heat, and power integration in a sustainable integrated biorefinery. Other than mathematical optimization approaches, Tay et al.[13] presented a graphical targeting approach for the evaluation of gas phase equilibrium composition of biomass gasification via C—H—O ternary diagram and synthesis of gasification-based biorefinery.

Other than process synthesis and design of integrated biorefinery, various works on thermoeconomic model which combines thermodynamics and economic analysis for integrated biorefineries were also presented.[14–16] In addition, environmental impact assessment with economic analysis were also taken into consideration in synthesizing integrated

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biorefineries.[17–19] Different environmental evaluation methods were presented in synthesizing integrated biorefineries, such as the IChemE Sustainability Metrics,[19,20] Eco-indicator 99[18,21] life cycle assessment (LCA),[22] waste reduction algorithm,[23] etc. Besides, Pokoo-Aikins et al.[24] included safety metrics evaluation alongside process and economic metrics in designing, screening, and analyzing biorefineries. El-Halwagi et al.[25] performed pareto-optimal curves to trade-off both economic factors and risk associated with the biorefinery supply chain. On the other hand, Bernardi et al.[26] presented a spatially explicit multiobjective optimization of both water and carbon footprint for sustainable bioethanol supply chain design.

In addition to integrated biorefinery, Kim and Moon[27] presented hydrogen facilities design with consideration of both total cost and relative risk of the network via optimal pareto solutions. Al-Sharrah et al.[28] performed multiple objectives (i.e., environmental effect, economic gain and operational risk) for petrochemical industry. Gutiérrez-Arriaga et al.[29] considered both economic and environmental aspects simultaneously in regenerative-reheat Rankine power-generation with a two-level optimization algorithm (Genetic Algorithm and linear programming). Most recently, job opportunities have gained a lot of attentions in social aspects. Trade-offs between EP, environment impact and job opportunities in designing sustainable integrated absorption refrigeration systems,[30] process cogeneration system,[31] and biofuel production[21,32] via pareto-optimal analysis had also been presented.

Other than safety aspect and job opportunities, health impacts in process industry should be considered as social issues. Accidents in process industry are not only causing damages to property but also impairing health condition of the employees. Inherent safety concept has been extended to occupational health aspect with the aim to prevent occupational health hazards arise from hazardous chemicals or technologies that may adversely impact workers′ health.[33] According to Hassim and Hurme,[34] inherent hazards assessment should be done early when developing a new process since at early lifecycle stages. This is because the margins for making process modifications are larger yet involving lower costs than at latter stages. Thus, it is essential for process designers to consider economic, environmental, inherent safety, and occupational health assessments into the conceptual design stage.

It is noted that limited research work has been developed in synthesizing sustainable integrated biorefinery by considering four different objective functions (EP, total environmental impact [TEI], total safety impact [TSI] and total health impact [THI]) simultaneously, which is the subject of this work. The optimization objective of the synthesis task is maximizing the EP, while minimizing the environmental, inherent safety and inherent occupational health impacts simultaneously. In order to address the abovementioned synthesis problem, fuzzy multi-objective optimization approach is adapted in this work. This work offers a systematic multiobjective optimization approach for the synthesis of a sustainable integrated biorefinery. The optimized network configuration with the trade-off between four optimization objectives can be determined prior to the detail design. To illustrate the proposed approach, an integrated palm oil-based biorefinery case study is presented in this work.

Fuzzy Optimization

According to Bellman and Zadeh,[35] decision problems can be formulated as fuzzy decision models to determine the favored alternatives in solving an objective function and constraints simultaneously. In fuzzy optimization, a degree of satisfaction (λ) which is a continuous interdependence variable is introduced. Based on "max-min" aggregation, every fuzzy constraint will be satisfied partially at least to λ.[36] Thus, fuzzy optimization approach can integrate the multiple objectives into a single parameter within the model. Fuzzy optimization was extended to linear and nonlinear programming problems with fuzzy constraints and multiple fuzzy objective functions by Zimmermann.[36] Fuzzy multiobjective approach had been widely adapted in synthesis of integrated biorefinery.[19,20,23,37,38] For instance, Tan et al.[37] adapted a fuzzy multiobjective approach for synthesizing a sustainable energy supply system by optimizing biomass production and trade under resource availability and environmental footprint constraints. Later, fuzzy optimization was further extended for synthesis of integrated biorefinery which considers economic and environmental performances simultaneously in kraft pulp and paper industry[23] and palm oil industry.[20] Shabbir et al.[19] also adapted fuzzy optimization in a hybrid optimization for synthesis of gasification-based integrated biorefinery. Most recently, Ubando et al.[38] presented a fuzzy linear programming approach for designing and optimization of an integrated algal biorefinery which considers water footprint, land footprint, and carbon footprint.

As mentioned previously, in order to synthesize a sustainable integrated biorefinery, all objectives (EP, TEI, TSI and THI) should be considered simultaneously. In order to optimize the four objectives simultaneously, a degree of satisfaction (λ) for each objective is introduced. Each flexible target (EP, TEI, TSI, and THI) for all objectives is predefined as fuzzy goals. Note that flexible target can be determined based on investor′s interest (e.g., targeted annual gross profit and payback period) or regulations (e.g., environmental regulations, inherent safety industrial standard, etc.). The fuzzy goal is given by a linear membership function bounded by upper limits (EP^U, TEI^U, TSI^U, and THI^U) and lower limits (EP^L, TEI^L, TSI^L, and THI^L) as visualized in Figure 1. As illustrated in Figure 1, λ approaches 1 as EP approaches the upper limit and vice versa. In contrast, λ shows reverse behavior for TEI, TSI, and THI where λ approaches 1 as TEI, TSI, and THI approaches lower limit. Higher λ indicates higher satisfaction of each objective function in fuzzy optimization. Based on "max-min" aggregation, the optimization objective is set as:

Maximize λ

Problem Statement

The problem definition of this work is stated as follows: Biomass $i \in I$ is produced in existing facilities which can be sent to technologies j and g. In biorefinery, intermediate $k \in K$ is produced from technologies $j \in J$ and then upgraded to green product $q \in Q$ via technology $j' \in J'$. On the other hand, primary energy $e \in E$ and secondary energy $e' \in E'$ can be generated from technologies $g \in G$ and $g' \in G'$ in combined heat and power (CHP). Note that r represents all technologies considered in both biorefinery and CHP ($\forall r \in J \cup J' \cup G \cup G'$). In this work, four objective functions (EP, TEI, TSI and THI) are taken into consideration in synthesizing a sustainable integrated biorefinery. The EP is determined by the net present value (NPV) of an integrated

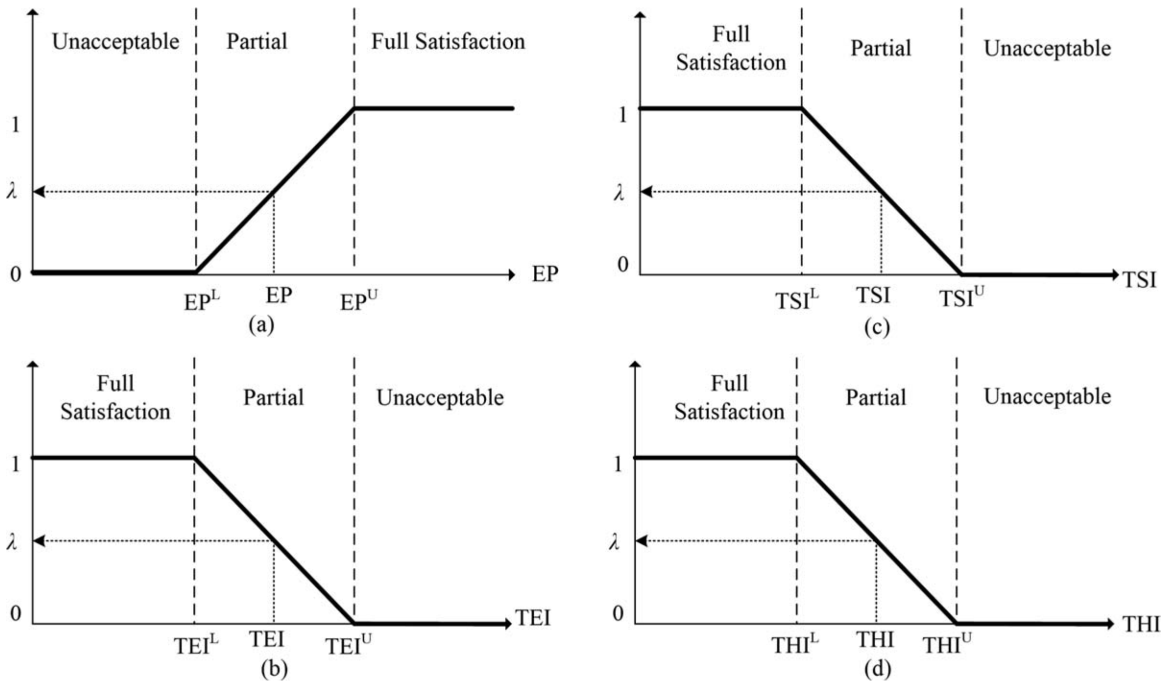

Figure 1. Fuzzy degree of satisfaction (λ) of the inequalities.

(a) Economic performance, EP, (b) total environmental impact, TEI, (c) total safety impact, TSI, and (d) total health impact, THI.

biorefinery. Besides, TEI of an integrated biorefinery is evaluated by the total environmental burden (TEB) which quantifies environmental performance for emission to air and water.[39] While, the TSI and THI of the process are determined using the summation of inherent safety index (ISI) and inherent occupational health index (IOHI) which developed by Heikkilä et al.[40] and Hassim and Hurme,[33] respectively. The major problem is these four objective functions are often contradictory naturally. The objective is to optimize four objective functions simultaneously via fuzzy optimization.

Problem Formulation

Generic superstructure of biorefinery integrated with CHP is developed in Figure 2. As shown, the allocation of biomass i to technology j to produce intermediate k. Then, intermediate k is converted to produce green product q via technology j'. Furthermore, biomass i can also be converted to primary energy e or secondary energy e' via technologies g and g' in CHP, respectively.

Each biomass i with flow rate W_i^{BIO} is split into the potential technology j with the flow rate of W_{ij}^{I} and the potential technology g in CHP with the flow rate of W_{ig}^{I}

$$W_i^{\mathrm{BIO}} = \sum_{j=1}^{J} W_{ij}^{\mathrm{I}} + \sum_{g=1}^{G} W_{ig}^{\mathrm{I}} \quad \forall i \tag{1}$$

Biomass i is converted to intermediate k via technology j at the production rate of W_{jk}^{I}, with the conversion of $\mathrm{X}_{ijk}^{\mathrm{I}}$.

$$W_{jk}^{\mathrm{I}} = \sum_{i=1}^{I} W_{ij}^{\mathrm{I}}\, \mathrm{X}_{ijk}^{\mathrm{I}} \quad \forall j \forall k \tag{2}$$

The total production rate of intermediate k is given as:

$$W_k^{\mathrm{INT}} = \sum_{j=1}^{J} W_{jk}^{\mathrm{I}} \quad \forall k \tag{3}$$

Next, the intermediate k can be distributed to potential technology j' for further process to produce green product q. The splitting constraint of intermediate k is written as:

$$W_k^{\mathrm{INT}} = \sum_{j'=1}^{J'} W_{kj'}^{\mathrm{II}} \quad \forall k \tag{4}$$

Green product $q(W_{j'q}^{\mathrm{II}})$ can be produced by converting intermediate k at the conversion rate of $\mathrm{X}_{kj'q}^{\mathrm{II}}$ via the technology j'.

$$W_{j'q}^{\mathrm{II}} = \sum_{k=1}^{K} W_{kj'}^{\mathrm{II}} \quad \mathrm{X}_{kj'q}^{\mathrm{II}} \quad \forall j' \forall q \tag{5}$$

The total production rate of green product $q(W_q^{\mathrm{PR}})$ is written as:

$$W_q^{\mathrm{PR}} = \sum_{j'=1}^{J'} W_{j'q}^{\mathrm{II}} \quad \forall q \tag{6}$$

Note that biomasses i and intermediate k are allowed to by-pass technologies j or j' via a "blank" technology in the circumstances where no technology is required to produce intermediate k or desired green product q without any conversion. For instance, in palm oil-based biorefinery, palm kernel shell (PKS) is carbonized in carbonization (technology j) to produce PKS charcoal (product q). There is no further conversion (technology j') and, therefore, the material can by-pass technology j'.

In CHP, biomass i is converted to energy e via technology g at the production rate of E_e^{Gen}, with given conversion of $\mathrm{Y}_{ige}^{\mathrm{I}}$. The production rate of energy e is given as:

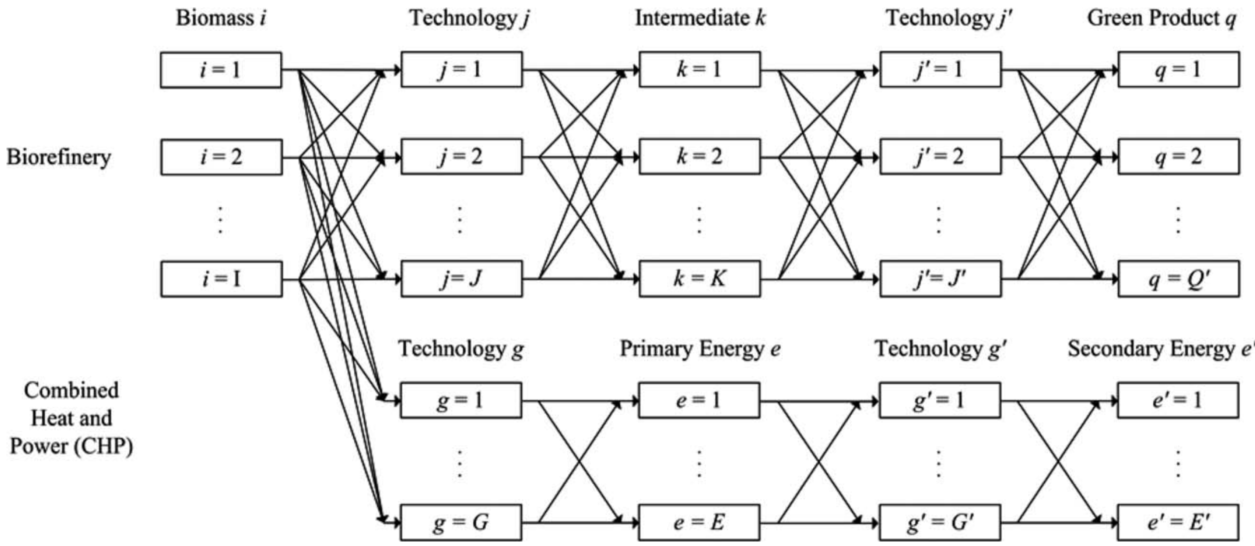

Figure 2. Generic superstructure of biorefinery integrated with CHP.

$$E^{\mathrm{I}}_{ge} = \sum_{i=1}^{I} W^{\mathrm{I}}_{ig}\, \mathrm{Y}^{\mathrm{I}}_{ige} \quad \forall g \forall e \tag{7}$$

$$E^{\mathrm{Gen}}_{e} = \sum_{g=1}^{G} E^{\mathrm{I}}_{ge} \quad \forall e \tag{8}$$

Primary energy e can be further upgraded via technology g' for production of other types of energy (e.g., electricity). Therefore, E^{Gen}_{e} is split and further converted to secondary energy e' via technology g' with conversion of $\mathrm{Y}^{\mathrm{II}}_{eg'e'}$. The splitting constraint of energy e is written as:

$$E^{\mathrm{Gen}}_{e} = \sum_{g'=1}^{G'} E^{\mathrm{Gen}}_{eg'} \quad \forall e \tag{9}$$

The total production rate of secondary energy e' through technology g' is written as

$$E^{\mathrm{II}}_{g'e'} = \sum_{e=1}^{E} E^{\mathrm{Gen}}_{eg'}\, \mathrm{Y}^{\mathrm{II}}_{eg'e'} \quad \forall g' \forall e' \tag{10}$$

$$E^{\mathrm{Gen}}_{e'} = \sum_{g'=1}^{G'} E^{\mathrm{II}}_{g'e'} \quad \forall e' \tag{11}$$

The total energy consumption $E^{\mathrm{Con}}_{e'}$ in biorefinery is determined based on the energy consumed in technologies j and j'. The total energy consumption is determined as

$$E^{\mathrm{Con}}_{e'} = \sum_{k=1}^{K}\sum_{j=1}^{J}\left(W^{\mathrm{I}}_{jk}\mathrm{Y}^{\mathrm{I}}_{e'jk}\right) + \sum_{q=1}^{Q}\sum_{j'=1}^{J'}\left(W^{\mathrm{II}}_{j'q}\,\mathrm{Y}^{\mathrm{II}}_{e'j'q}\right) \quad \forall e' \tag{12}$$

In a sustainable integrated biorefinery, the excess energy $E^{\mathrm{Exp}}_{e'}$ can be sold and exported to any third party plants if the total energy generation exceeds the total energy consumption ($E^{\mathrm{Gen}}_{e'} > E^{\mathrm{Con}}_{e'}$). In contrast, import of external energy $E^{\mathrm{Imp}}_{e'}$ is needed in case where the total energy generated is insufficient to fulfill the total consumption ($E^{\mathrm{Gen}}_{e'} < E^{\mathrm{Con}}_{e'}$). Therefore, the energy correlation can be written as

$$E^{\mathrm{Con}}_{e'} = E^{\mathrm{Gen}}_{e'} + E^{\mathrm{Imp}}_{e'} - E^{\mathrm{Exp}}_{e'} \quad \forall e' \tag{13}$$

Gross profit (GP) of an integrated biorefinery is determined as given in Eq. 14

$$GP = \mathrm{AOT}\left(\begin{array}{l} \sum_{q=1}^{Q} W^{\mathrm{PR}}_{q}\,\mathrm{C}^{\mathrm{PR}}_{q} + \sum_{e'=1}^{E'} E^{\mathrm{Exp}}_{e'}\,\mathrm{C}^{\mathrm{Exp}}_{e'} - \sum_{e'=1}^{E'} E^{\mathrm{Imp}}_{e'}\,\mathrm{C}^{\mathrm{Imp}}_{e'} - \sum_{i=1}^{I} W^{\mathrm{BIO}}_{i}\,\mathrm{C}^{\mathrm{BIO}}_{i} \\ -\sum_{k=1}^{K}\sum_{j=1}^{J} W^{\mathrm{I}}_{jk}\mathrm{C}^{\mathrm{Proc}}_{jk} - \sum_{q=1}^{Q}\sum_{j'=1}^{J'} W^{\mathrm{II}}_{j'q}\mathrm{C}^{\mathrm{Proc}}_{j'q} - \sum_{e=1}^{E}\sum_{g=1}^{G} E^{\mathrm{I}}_{ge}\mathrm{C}^{\mathrm{Proc}}_{ge} \\ -\sum_{g'=1}^{E'}\sum_{g'=1}^{G'} E^{\mathrm{II}}_{g'e'}\mathrm{C}^{\mathrm{Proc}}_{g'e'} \end{array}\right) \tag{14}$$

where AOT is annual operating time, $\mathrm{C}^{\mathrm{PR}}_{q}$ is selling price of green product q, $\mathrm{C}^{\mathrm{Exp}}_{e'}$ is cost of energy e' export, $\mathrm{C}^{\mathrm{Imp}}_{e'}$ is cost of energy e' import as well as $\mathrm{C}^{\mathrm{BIO}}_{i}$ is cost of biomass i. $\mathrm{C}^{\mathrm{Proc}}_{jk}$, $\mathrm{C}^{\mathrm{Proc}}_{j'q}$, $\mathrm{C}^{\mathrm{Proc}}_{ge}$, and $\mathrm{C}^{\mathrm{Proc}}_{g'e'}$ are overall expenses of technology j per unit flow rate of k produced, technology j' per unit flow rate of q produced, technology g per unit energy e

generated and technology g' per unit energy e' generated, respectively. Note that overall expenses cover startup, working capital, maintenance, manpower, installation, bare module costs, etc of each technology.

In this work, EP is evaluated based the NPV of an integrated biorefinery. Additional factors can be considered in NPV (e.g., tax, depreciation costs, incentives or penalties from government, hedging costs, etc.). Thus, NPV is a more robust indicator for economic evaluation than using only gross profit.[23] NPV is expressed in the following equation

$$\mathrm{NPV}=\sum_{t}^{t_{\max}}\frac{[\mathrm{GP}\times(1-\mathrm{TAX})+\mathrm{DEP}\times\mathrm{TAX}-\mathrm{HEDGE}+\mathrm{GOV}]}{(1+\mathrm{ROR})^{t}} \tag{15}$$

where GP is gross profit, TAX and DEP are the marginal tax rate and depreciation rate, respectively. HEDGE and GOV are expenses associated with hedging against catastrophic market actions and net benefits realized through governmental incentives or penalties, respectively, $t_{\max}$ is the operating lifespan and ROR is the expected rate of return.

In addition, payback period (PP) is calculated to determine the length of time required to recover the total investment cost. PP can act as constraint to constrain the extent of the optimization model. PP is expressed as total cost of investment over GP and it is shown in following equation

$$PP=\frac{t_{\max}\times\mathrm{AOT}\left(\begin{array}{l}\sum_{k=1}^{K}\sum_{j=1}^{J}W_{jk}^{\mathrm{I}}C_{jk}^{\mathrm{Cap}}+\sum_{q=1}^{Q}\sum_{j'=1}^{J'}W_{j'q}^{\mathrm{II}}C_{j'q}^{\mathrm{Cap}}\\+\sum_{e=1}^{E}\sum_{g=1}^{G}E_{ge}^{\mathrm{I}}C_{ge}^{\mathrm{Cap}}+\sum_{e'=1}^{E'}\sum_{g'=1}^{G'}E_{g'e'}^{\mathrm{II}}C_{g'e'}^{\mathrm{Cap}}\end{array}\right)+C^{\mathrm{Cap\text{-}Fixed}}}{GP} \tag{16}$$

where C_{jk}^{Cap}, $C_{j'q}^{\mathrm{Cap}}$, C_{ge}^{Cap} and $C_{g'e'}^{\mathrm{Cap}}$ are fixed capital investment of technology j per unit flow rate of k produced, technology j' per unit flow rate of q produced, technology g per unit energy e generated and technology g' per unit energy e' generated, respectively; while $C^{\mathrm{Cap\text{-}Fixed}}$ is miscellaneous fixed capital cost neededs to be invested in integrated biorefinery which includes industrial land, vehicles, building, etc.

On the other hand, TEB is used to evaluate the TEI of all processes in an integrated biorefinery. The IChemE Sustainability Metrics is utilized to evaluate the potency factor (PF) or environmental burden of each pollutant in a sustainable integrated biorefinery.[39] TEB can be determined from the following equation

$$\begin{aligned}\mathrm{TEB}=&\sum_{q=1}^{Q}\sum_{j'=1}^{J'}W_{j'q}^{\mathrm{II}}\mathrm{NPF}_{j'q}^{\mathrm{II}}+\sum_{k=1}^{K}\sum_{j=1}^{J}W_{jk}^{\mathrm{I}}\mathrm{NPF}_{jk}^{\mathrm{I}}\\&-\sum_{e'=1}^{E'}E_{e'}^{\mathrm{Excess}}\mathrm{NPF}_{e'}^{\mathrm{Energy}}-\sum_{i=1}^{I}W_{i}^{\mathrm{BIO}}\mathrm{NPF}_{i}^{\mathrm{BIO}}\end{aligned} \tag{17}$$

where $E_{e'}^{\mathrm{Excess}}$ is excess energy where $E_{e'}^{\mathrm{Exp}}$ minus external import of energy, $E_{e'}^{\mathrm{Imp}}$. $\mathrm{NPF}_{j'q}^{\mathrm{II}}$, $\mathrm{NPF}_{jk}^{\mathrm{I}}$, $\mathrm{NPF}_{g'e'}^{\mathrm{II}}$, $\mathrm{NPF}_{ge}^{\mathrm{I}}$, $\mathrm{NPF}_{e'}^{\mathrm{Energy}}$ and $\mathrm{NPF}_{i}^{\mathrm{Bio}}$ are normalized potential factor of pathway $j'q$, pathway jk, energy e' and biomass i, respectively.

Normalization procedure thresholds value (TV) was introduced by Irabien et al.,[41] as PF of each pollutant has different unit (e.g., ton equivalent per year [t/y]) carbon dioxide per ton of pollutant for global warming and t/y ethylene per ton of pollutant for while photochemical ozone (smog) formation. NPF in Eq. 17 is determined by PF divided by thresholds value on releases of each pollutant to air, water or land which can be specified by E-PRTR Regulation.[41]

$$\mathrm{NPF}=\frac{\mathrm{PF}}{\mathrm{TV}} \tag{18}$$

Binary variable, I_r is used to denote the existence (or absence) of each technology r which includes technologies j, j', g, and g'. I_r is used in determining TSI and THI of all selected technologies and it can be determined by[42]

$$L(1-I_r)<F<UI_r \quad \forall r\in j,j',g,g' \tag{19}$$

where L and U are lower and upper bounds, respectively, F is material flow or energy flow (t/h or MW electricity) which includes intermediate W_k^{INT} ,product W_q^{PR} ,primary energy E_e^{Gen}, and secondary energy $E_{e'}^{\mathrm{Gen}}$.

For process safety perspective, TSI is used to measure the process safety level. TSI can be determined by the summation of ISI of selected technologies in an integrated biorefinery. Note that ISI is the first index developed for inherent safety assessment to select inherent safest reaction pathway.[40] According to Heikkilä et al.,[40] ISI consists of two parameters, which are chemical inherent safety index ($\mathrm{SI}_r^{\mathrm{CI}}$) and process inherent safety index ($\mathrm{SI}_r^{\mathrm{PI}}$). TSI calculations are presented in the following equations

$$\mathrm{TSI}=\sum_{r\in j,j',g,g'}I_r(\mathrm{ISI}_r) \tag{20}$$

$$\mathrm{ISI}_r=\mathrm{SI}_r^{\mathrm{CI}}+\mathrm{SI}_r^{\mathrm{PI}} \quad \forall r\in j,j',g,g' \tag{21}$$

where $\mathrm{SI}_r^{\mathrm{CI}}$ and $\mathrm{SI}_r^{\mathrm{PI}}$ are evaluated for all selected technologies j, j', g, and g'.

$\mathrm{SI}_r^{\mathrm{CI}}$ for all technologies j, j', g, and g' is determined by the maximum penalty approach received by any of the substance s (regarded as the worst chemical) in each subprocess. $\mathrm{SI}_r^{\mathrm{CI}}$ is then calculated by summing up the penalties (representing hazards level) of all the chemical-related parameters as below

$$\begin{aligned}\mathrm{SI}_r^{\mathrm{CI}}=&\max_{\forall s\in i,k,q,e,e'}\left(\mathrm{SI}_s^{\mathrm{RM}}\right)+\max_{\forall s\in i,k,q,e,e'}\left(\mathrm{SI}_s^{\mathrm{RS}}\right)\\&+\max_{\forall s\in i,k,q,e,e'}\left(\mathrm{SI}_s^{\mathrm{INT}}\right)+\max_{\forall s\in i,k,q,e,e'}\left(\mathrm{SI}_s^{\mathrm{FL}}+\mathrm{SI}_s^{\mathrm{EX}}+\mathrm{SI}_s^{\mathrm{TOX}}\right)\\&+\max_{\forall s\in i,k,q,e,e'}\left(\mathrm{SI}_s^{\mathrm{COR}}\right)\quad \forall r\in j,j',g,g'\end{aligned} \tag{22}$$

where $\mathrm{SI}_s^{\mathrm{RM}}$, $\mathrm{SI}_s^{\mathrm{RS}}$, $\mathrm{SI}_s^{\mathrm{INT}}$, $\mathrm{SI}_s^{\mathrm{FL}}$, $\mathrm{SI}_s^{\mathrm{EX}}$, $\mathrm{SI}_s^{\mathrm{TOX}}$, and $\mathrm{SI}_s^{\mathrm{COR}}$ are subindex for heat of main reaction, heat of side reaction, chemical interaction, flammability, explosiveness, toxicity, and corrosiveness, respectively. Note that the parameters of $\mathrm{SI}_s^{\mathrm{FL}}$, $\mathrm{SI}_s^{\mathrm{EX}}$, and $\mathrm{SI}_s^{\mathrm{TOX}}$ are determined separately for each substance s which includes biomass i, intermediate k, green product q, primary energy e, and secondary energy e'.

On the other hand, $\mathrm{SI}_r^{\mathrm{PI}}$ is expressed in the following equation

$$\begin{aligned}\mathrm{SI}_r^{\mathrm{PI}}=&\mathrm{SI}_r^{\mathrm{I}}+\max_{\forall s\in i,k,q,e,e'}\left(\mathrm{SI}_s^{\mathrm{T}}\right)+\max_{\forall s\in i,k,q,e,e'}\left(\mathrm{SI}_s^{\mathrm{P}}\right)+\max_{\forall s\in i,k,q,e,e'}\left(\mathrm{SI}_s^{\mathrm{EQ}}\right)\\&+\max_{\forall s\in i,k,q,e,e'}\left(\mathrm{SI}_s^{\mathrm{ST}}\right)\quad \forall r\in \quad j,j',g,g'\end{aligned} \tag{23}$$

where $\mathrm{SI}_r^{\mathrm{I}}$, $\mathrm{SI}_s^{\mathrm{T}}$,$\mathrm{SI}_s^{\mathrm{P}}$, $\mathrm{SI}_s^{\mathrm{EQ}}$, and $\mathrm{SI}_s^{\mathrm{ST}}$ are subindex for inventory, process temperature, pressure, equipment safety, and process structure, respectively. For more information about

ISI calculation, it can be referred to the original work of Heikkilä et al.[40]

Other that economic, environment and process safety assessments, health impact of the synthesized process is also taken into consideration in this work. For THI, it can be determined by the summation of IOHI values for all technologies j, j', g, and g'. This method was developed by Hassim and Hurme[33] based on the same idea as ISI, but it is focusing on inherent health hazards. Based on Hassim and Hurme,[33] IOHI composes of subindex for physical and process hazards HI_r^{PPH} and subindex for health hazards HI_r^{HH} as shown in the following equation

$$\text{THI} = \sum_{r \in j,j',g,g'} I_r(\text{IOHI}_r) \tag{24}$$

$$\text{IOHI}_r = \text{HI}_r^{\text{PPH}} + \text{HI}_r^{\text{HH}} \quad \forall r \in j, j', g, g' \tag{25}$$

The subindex for physical and process hazards HI_r^{PPH} is calculated by summing up the penalties received by all the six parameters of the subindex. HI_r^{PPH} is given as

$$\text{HI}_r^{\text{PPH}} = \text{HI}_r^{\text{PM}} + \text{HI}_r^{\text{P}} + \text{HI}_r^{\text{T}} + \max_{\forall s \in i,k,q,e,e'} \left(\text{HI}_s^{\text{MS}}\right) + \max_{\forall s \in i,k,q,e,e'} \left(\text{HI}_s^{\text{V}}\right) + \max_{\forall s \in i,k,q,e,e'} \left(\text{HI}_s^{\text{C}}\right) \quad \forall r \in j, j', g, g' \tag{26}$$

where HI_r^{PM}, HI_r^{P}, HI_r^{T}, HI_s^{MS}, HI_s^{V}, and HI_s^{C} are subindex for mode of process, pressure, temperature, material phase, volatility, and corrosiveness of construction material, respectively.

Aside from HI_r^{PM}, HI_r^{P}, and HI_r^{T} all the other parameters are penalized based on the worst (most hazardous/toxic) chemical in the reaction subprocess. This is because, each reaction subprocess normally consists of more than one chemicals. Therefore, any chemical that receives the maximum penalty in the subprocess will be regarded as the worst chemical, and hence its penalty value will be taken to represent the parameter for that particular subprocess. The details of the IOHI index were discussed in Hassim and Hurme.[33]

The subindex for health hazards HI_r^{HH} is then determined by parameters of exposure limit HI_s^{EL} and R-phrase HI_s^{R} of substance s (e.g., biomass i, intermediate k, green product q, primary energy e and secondary energy e'). Since both parameters are related to chemical properties (toxicological), thus, the maximum penalty (worst chemical) based approach is used here in the calculation and HI_r^{HH} is given as

$$\text{HI}_r^{\text{HH}} = \max_{\forall s \in i,k,q,e,e'} \left(\text{HI}_s^{\text{EL}}\right) + \max_{\forall s \in i,k,q,e,e'} \left(\text{HI}_s^{\text{R}}\right) \quad \forall r \in j, j', g, g' \tag{27}$$

As mentioned previously, in order to synthesize a sustainable integrated biorefienery, economic, environment, and social (process safety and health) perspectives should be addressed simultaneously. In this work, fuzzy optimization approach is adapted to address the issue. In order to satisfy the set fuzzy goals of multiple-objectives simultaneously, the optimization objective of λ is to be maximized subject to the predefined upper and lower limits in equations 28–31.

$$\frac{\text{EP-EP}^{\text{L}}}{\text{EP}^{\text{U}}\text{-EP}^{\text{L}}} \geq \lambda \tag{28}$$

$$\frac{\text{TEI}^{\text{U}}\text{-TEI}}{\text{TEI}^{\text{U}}\text{-TEI}^{\text{L}}} \geq \lambda \tag{29}$$

$$\frac{\text{TSI}^{\text{U}}\text{-TSI}}{\text{TSI}^{\text{U}}\text{-TSI}^{\text{L}}} \geq \lambda \tag{30}$$

$$\frac{\text{THI}^{\text{U}}\text{-THI}}{\text{THI}^{\text{U}}\text{-THI}^{\text{L}}} \geq \lambda \tag{31}$$

where EP^{U} and EP^{L} are upper and lower limits of predefined EP, TEI^{U}, and TEI^{L} are upper and lower limits of predefined TEI, TSI^{U}, and TSI^{L} are upper and lower limits of predefined TSI, THI^{U}, and THI^{L} are upper and lower limits of predefined THI. Note that the level of satisfaction (λ) of each objective is highly dependence on the predefined limits. Therefore, in order to obtain the reliable optimization result, it is a need to define the limits systematically.

In this work, in order to determine the fuzzy limits, four scenarios (Scenarios 1–4) are first solved. Based on the minimum and maximum of each objective function from all scenarios, the fuzzy limits are determined. Based on the fuzzy limit, fuzzy optimization is used to synthesize a sustainable integrated biorefinery in Scenario 5. The relationship of each fuzzy goal is showed in Figure 1. As shown, λ achieves 1 when the synthesized integrated biorefinery achieves EP higher or equal to its upper limit; while TSI, TEI and THI lower or equal to their lower limits and vice versa. In cases where λ is targeted between 0 and 1, the optimum solution which satisfies all objectives is obtained by maximizing the least satisfied constraint or goal. Thus, lowest λ would be obtained based on all objectives. To illustrate the proposed approach, an integrated palm oil-based biorefinery case study from Malaysia is solved.

Case Study

According to statistics from Malaysia Palm Oil Board, Malaysia oil palm plantation occupies 5.08 million hectares and a total of 18.79 million tons of crude palm oil (CPO) and 2.16 million tons of crude palm kernel oil (CPKO) had been extracted from the oil palm fruits, which known as fresh fruit bunches (FFBs). FFBs are processed in palm oil mills to extract CPO and CPKO.[43] With the increasing volume of CPO and CPKO productions, large amounts of palm-based biomasses (e.g., empty fruit bunches [EFBs], palm mesocarp fiber [PMF], palm kernel shell [PKS], palm oil mill effluent [POME], etc.) are generated as by-products or waste throughout the palm oil milling process. Palm-based biomasses are projected to increase up to 110 million dry tons by 2020.[44] Integrated palm oil-based biorefinery has been proposed to integrate the multiple biomass processing platforms in palm oil-based biorefinery with CHP.[12,20] Ng and Ng[45] extended palm oil-based biorefinery (POB) and CHP with palm oil mill (POM) as well as palm oil refinery (POR) to form an integrated palm oil processing complex (POPC). Recently, Ng et al.[46] adapted industrial symbiosis concept to synthesize POPC which own by different companies. As shown in the previous work,[46] a systematic approach for synthesis of POPC with multiple owners was presented.

In this case study, an existing palm oil mill with a capacity of 80 t/h of FFB is planning to integrate with biorefinery and CHP. In this case, EFB, PKS, POME, and PMF are identified as the potential biomass feedstock. Note that 1 ton of FFB generated 230 kg EFB, 60 kg PKS, 600 kg POME, and 130 kg PMF.[47] These palm-based biomass can be further processed to produce valuable products (i.e., dried long fiber [DLF], pellet, briquette, char coal, compost, etc.).

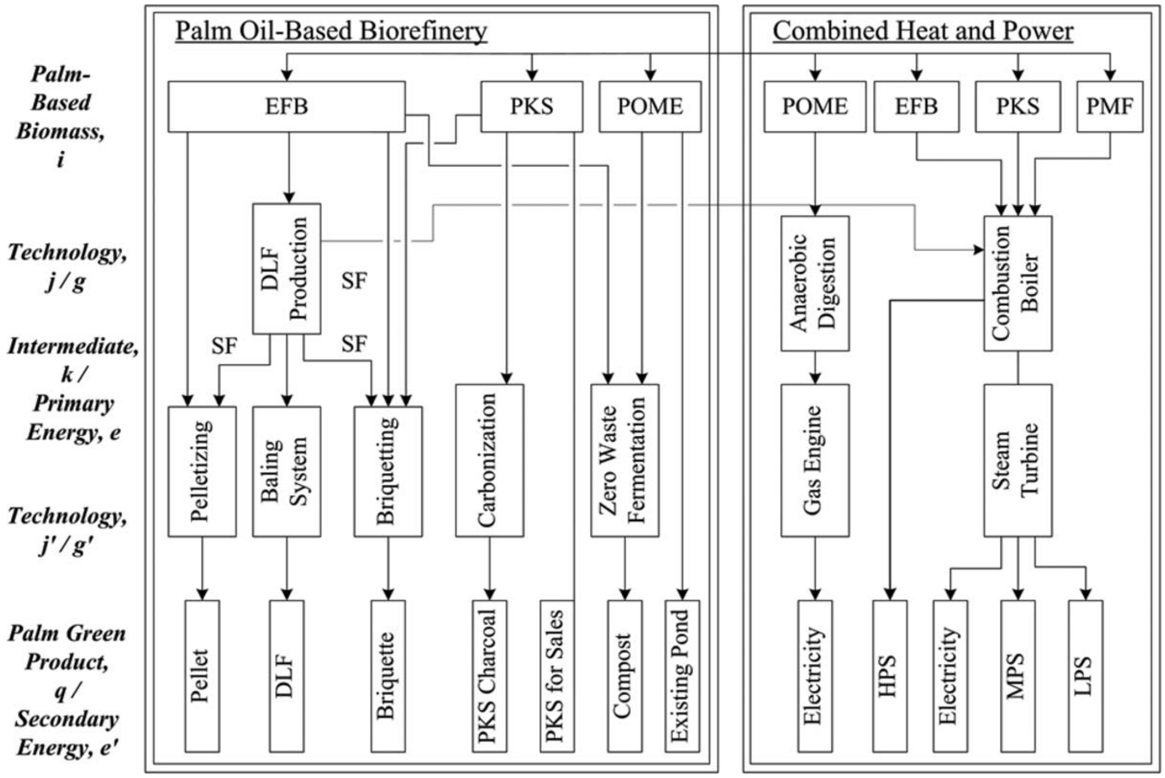

Figure 3. Superstructure of case study.

In order to sustain the palm oil-based biorefinery, energy generated from the given palm-based biomass in CHP is integrated with palm oil-based biorefinery.

Figure 3 shows the superstructure of case study with all the potential pathways for converting palm-based biomass i into palm green product q (pellet, DLF, briquette, PKS charcoal, and compost) and energy e' (steam and electricity). Note that throughout the processing of EFB into DLF, short fiber (SF) is produced. SF can be further processed to valuable products through pelletizing, briquetting, or combustion processes. Meanwhile, PKS can be sent to carbonization to produce PKS-charcoal as final product. POME can be fermented with EFB to produce compost or sent to anaerobic digester for biogas production. Unutilized POME has to be treated in existing pond system before discharge into environment and remaining PKS can be sold directly to market. On the other hand, palm-based biomass i can also be converted into high-pressure steam (HPS) at 40 bar, 400°C or biogas via boiler and anaerobic digestion (technology g), respectively, and sent to steam turbine or gas engine (technology g') for production of electricity and medium pressure steam (MPS) at 12 bar, 250°C or low-pressure steam (LPS) 4 bar, 145°C. Excess MPS or LPS can be sent to palm oil mill for heating purpose.

In this study, it is assumed that the AOT is given as 8000 h, ROR is given as 15%. and the processing facility is designed based on an operating life-span of 15 years. In case where ROR is lower than 15%, the stakeholder will not be interested in investing the project. Table 1 shows the price of raw materials, palm green products, and energy. Meanwhile, Table 2 shows the mass conversion factor, economic data (including fixed capital and general expenses) and energy consumption (electricity and steam) for each technology. Note that information given in Tables 1 and 2 are collected based on interview with industrial partner. Note also that the conversion factor is determined based on input-output model in which the overall separation and efficiency conversion have been considered. It is assumed that the main factor of EP is based on GP, thus, terms of TAX, DEP, HEDGE, and GOV are neglected in Eq. 15. The miscellaneous fixed capital cost $\left(C^{\text{Cap-Fixed}}\right)$ is assumed as USD 700,000. Note that miscellaneous fixed capital cost is assumed based on industrial land price, construction, and vehicle costs in Malaysia. Based on feedback given by industrial partner, the stakeholder will not investing this project if payback period more than 5 years. In this scenario, payback period is assumed to be less or equal 5 years. The constraint of payback period is

Table 1. Price of Palm Green Products, Palm-Based Biomass and Energy

Item	Price (USD)
Palm-based Biomass, i	
EFB	6/t
PKS	50/t
PMF	22/t
Green Product, q	
Pellet	140/t
DLF	210/t
Briquette	120/t
Charcoal	380/t
Compost	100/t
Energy, e'	
Electricity (Import)	140/MWh
Electricity (Export)	90/MWh
HPS (Import)	26/t
MPS (Import)	17/t
LPS (Import)	12/t

Table 2. Operating Condition, Conversion Factor, General Expenses, Fixed Capital Cost and Energy Consumption for Each Technology

Palm Oil-Based Biorefinery	
Pellet production	Operating Condition = Separation (35°C, 1 bar), Drying (200°C, 1 bar), Pelletizing (40°C, 13.8 bar) Conversion = 0.3846 pellet/(EFB + SF) General Expenses = USD 34.00/(1 t/h pellet) Fixed Capital Cost = USD 450,000/(2 t/h pellet) Steam Consumption = 3.5 t/h MPS/(1 t/h pellet) Electricity Consumption = 0.25 MW/(1 t/h pellet)
DLF production + baling system	Operating Condition = Separation (35°C, 1 bar), Primary Sieving (35°C, 1 bar), Drying (200°C, 1 bar), Secondary Sieving (40°C, 1 bar), Baling (40°C,172 bar) Primary Sieving Conversion = 0.6695 LF/EFB Secondary Sieving Conversion = 0.2400 SF/EFB Drying Conversion = 0.5580 DLF/LF Baling Conversion = 1 Baled DLF/DLF General Expenses = USD 44.00/(1 t/h DLF) Fixed Capital Cost = USD 550,000/(1 t/h DLF) Steam Consumption = 3.5 t/h MPS/(1 t/h DLF) Electricity Consumption = 0.30 MW/(t/h DLF)
Briquette production	Operating Condition = Separation (35°C, 1 bar), Drying (200°C, 1 bar), Briquetting (40°C, 13.8 bar) Conversion = 0.3846 briquette/(EFB + PKS +SF) [*Ratio of EFB+SF : PKS = 80 : 20] General Expenses = 32.00/(1 t/h briquette) Fixed Capital Cost = USD 680,000/(3 t/h briquette) Steam Consumption = 3.5 t/h MPS/(1 t/h briquette) Electricity Consumption = 0.21 MW/(1 t/h briquette)
PKS charcoal production	Operating Condition = Carbonization (700°C, 1 bar) Conversion = 0.3333 charcoal/PKS General Expenses =USD 60.00/(1 t/h charcoal) Fixed Capital Cost = USD 450,000/(1 t/h charcoal) Steam Consumption = 0 Electricity Consumption = 0
Compost production	Operating Condition = Fermentation (50°C, 1 bar) Conversion = 0.1758 compost/(EFB + POME) [*Ratio of EFB : POME = 22 : 60] General Expenses = USD 55.00/(1 t/h compost) Fixed Capital Cost = USD 800,000/(1 t/h compost) Steam Consumption = 3.5 t/h LPS/(1 t/h compost) Electricity Consumption = 0
Combined Heat and Power	
Anaerobic digestion + electricity generation	Operating Condition = Anaerobic Digestion (55°C, 1 bar), Biogas to Electricity (350°C, 12 bar) Biogas Conversion = 0.2781 biogas/POME Electricity Conversion = 0.026 MW electricity/t/h biogas General Expenses = USD 105.00/(1 MW electricity) Fixed Capital Cost = USD 1,400,000/(1 MW electricity)
Combustion + steam and electricity generation	Operating Condition = Boiler Combustion (400°C, 40 bar), Steam Turbine Conversion (400°C, 40 bar) EFB (Moisture Content, MC = 67%, Calorific Value, CV = 18838 kJ/kg)[48] PKS (Moisture Content, MC = 12 %, Calorific Value, CV = 20108 kJ/kg)[48] PMF (Moisture Content, MC = 37%, Calorific Value, CV = 19068 kJ/kg)[48] MPS Conversion = 0.40 MPS/HPS LPS Conversion = 0.60 LPS/HPS Electricity Conversion = 0.089 MW electricity/t/h HPS General Expenses = USD 100.00/(5 MW electricity) Fixed Capital Cost = USD 2,500,000/(5 MW electricity)

introduced in order to constrain the extent of the optimization model. Thus, Eq. 16 is modified and given as

$$5\times GP \ \geq t_{\max}\times \mathrm{AOT}\left(\begin{array}{c}\sum_{k=1}^{K}\sum_{j=1}^{J}W_{jk}^{\mathrm{I}}C_{jk}^{\mathrm{Cap}}+\sum_{q=1}^{Q}\sum_{j'=1}^{J'}W_{j'q}^{\mathrm{II}}C_{j'q}^{\mathrm{Cap}}\\ +\sum_{e=1}^{E}\sum_{g=1}^{G}E_{ge}^{\mathrm{I}}C_{ge}^{\mathrm{Cap}}+\sum_{e'=1}^{E'}\sum_{g'=1}^{G'}E_{g'e'}^{\mathrm{II}}C_{g'e'}^{\mathrm{Cap}}\end{array}\right)+C^{\text{Cap-Fixed}} \tag{32}$$

Based on the collected information from the industry, production capacity of each technology is rounded to the nearest integer of the production rate.[12] Meanwhile, total fixed capital cost of technology in Table 2 is also normalized based on production capacity of each technology. In addition, total moisture content of palm-based biomasses which feeds into boiler is assumed to be less than 40% as shown in equation below.[12]

$$0.4\times\sum_{i=1}^{\mathrm{I}}W_{ig}^{\mathrm{I}} \ \geq \sum_{i=1}^{\mathrm{I}}\mathrm{MC}_{i}W_{ig}^{\mathrm{I}} \quad g=2 \tag{33}$$

where MC_i is moisture content of each palm-based biomass i. Note that values of MC_i in this case study can be referred in Table 2.

The amount of HPS boiler in CHP can be determined in following equations

$$E_{\mathrm{HPS}}^{\mathrm{Gen-CHP}}=\frac{\eta_{\mathrm{boiler}}\times\sum_{i=1}^{\mathrm{I}}\left(1-\mathrm{MC}_{i}\right)\left(W_{ig}^{\mathrm{I}}\right)\mathrm{CV}_{i}}{H_{\mathrm{T=400^{\circ}C,P=40bar}}-H_{\mathrm{T=100^{\circ}C,P=1bar}}} \quad g=2 \tag{34}$$

where nominator term is boiler efficiency η_{boiler} multiplies with calorific value of dry biomass mixtures fed into boiler; while denominator term is enthalpy H of HPS in CHP or

Table 3. Potency Factor of each Pollutant, Emission of Pollutant and Normalisation Procedure

Pollutants	CO_2	CO	CH_4	NO_X	SO_X	VOC
Potency factor (PF) each pollutant per t[39]						
Global Warming	1	3	21	40	-	11
Photochemical Ozone (smog) Formation	-	0.027	0.034	0.028	0.048	-
Eutrophication	-	-	-	0.13	-	-
Emission of pollutant per t of palm green production or kW of electricity generation[20]						
Electricity Generation	519.363	0.726	-	0.562	0.014	0.014
EFB Production	0.51	-	-	-	-	-
PKS Production	0.55	-	-	-	-	-
PMF Production	0.54	-	-	-	-	-
POME Production	0.28	-	-	-	-	-
	Unit of Penalty Factor			Reporting threshold, t	Normalised Penalty Factor (NPF)	
Normalisation Procedure[41]						
Global Warming	te/y carbon dioxide per tonne of pollutant			100000	PF/100,000	
Photochemical Ozone (smog) Formation	te/y ethylene per tonne of pollutant			1	PF/1	
Eutrophication	per tonne of pollutant			5	PF/5	

MPS in POM subtract the enthalpy H of feed water at 1 bar, 100°C. Based on the collected industry data, the boiler efficiency of palm-based biomass boiler is given as 55%.

In order to reduce the complexity of model, all energy correlation in this case study focuses on secondary energy e'. In case where primary energy e (e.g., HPS) is required in palm oil-based biorefinery, primary energy e is allowed to by-pass technology g' via a "blank" process where no conversion occurs. Thus, primary energy e is equal to secondary energy e'.

The potential factor (PF) of pollutants are adapted from the IChemE Sustainability Metrics and tabulated in Table 3.[39] Note that the unit of PF of global warming, photochemical ozone (smog) formation, and eutrophication are given as ton equivalent per year (t/y) carbon dioxide per ton of pollutant, t/y ethylene per ton of pollutant, and t/y phosphate per ton of pollutant, respectively. As mentioned earlier, each PF has different unit, normalization procedure[41] is adapted in this work to normalize PF into NPF, as shown in Table 3. Note that the unit of NPF is given as per ton of pollutant. By applying Eqs. 17 and 18, dimensionless TEB can be calculated to evaluate TEI of the integrated palm oil-based biorefinery. It is assumed that in this case study, TEB only considers releases of pollutants to relevant medium (air, water, and land).

As mentioned earlier, ISI and IOHI are adapted to evaluate inherent safety impact and inherent occupational health performances of each subprocess of technology, respectively. Note that in both ISI and IOHI calculation, the allocation of penalties is based on the degree of potential safety or health hazards; the higher the probability of safety or health hazards, the higher the penalty. Based on Supporting Information, Tables S1 and S2 tabulated the penalty scores to determine SI_r^{CI} and SI_r^{PI}. For IOHI, the parameters and associated penalties for both physical and process hazards, HI_r^{PPH} and health hazard, HI_r^{HH} are summarized in Supporting Information Tables S3 and S4, respectively.

In this study, the penalties of ISI and IOHI assigned to each subprocess of technology are summarized in Tables 4

Table 4. Summary of ISI Calculations for All Technologies

	SI_s^I		SI_s^T	SI_s^P	SI_s^{EQ}	SI_s^{ST}	SI_s^{RM}	SI_s^{RS}	SI_s^{INT}	SI_s^{FL}	SI_s^{EX}	SI_s^{TOX}	SI_s^{COR}	ISI
Pellet production	1	Separation	0	0	0	3	0	0	0	0	0	0	0	
		Drying	3	0	1	3	0	0	0	0	0	0	0	**17**
		Pelletizing	0	1	2	3	0	0	0	0	0	0	0	
DLF production + baling system		Separation	0	0	0	3	0	0	0	0	0	0	0	
	1	Primary sieving	0	0	0	3	0	0	0	0	0	0	0	**17**
		Drying	3	0	1	3	0	0	0	0	0	0	0	
		Secondary sieving	0	0	0	3	0	0	0	0	0	0	0	
	1	Baling system	0	3	0	3	0	0	0	0	0	0	0	**7**
Briquette production		Separation	0	0	0	3	0	0	0	0	0	0	0	
	1	Drying	3	0	1	3	0	0	0	0	0	0	0	**17**
		Briquetting	0	1	2	3	0	0	0	0	0	0	0	
PKS charcoal production	1	Carbonization	5	0	4	2	0	0	4	0	0	0	0	**16**
Compost production	2	Fermentation	0	0	0	3	0	0	0	0	0	0	0	**5**
Anaerobic digestion + electricity generation	2	Anaerobic digestion	0	0	2	3	0	0	0	4	1	0	0	**12**
	2	Gas engine	3	1	3	3	4	0	3	4	1	0	0	**24**
Combustion + steam and electricity generation	2	Boiler	3	3	4	3	4	0	4	1	0	0	0	**24**
	3	Steam turbine	3	2	3	3	0	0	3	0	0	0	0	**17**

Table 5. Summary of IOHI Calculations for All Technologies

		HI_s^{PM}	HI_s^{MS}	HI_s^{V}	HI_s^{P}	HI_s^{C}	HI_s^{T}	HI_s^{EL}	HI_s^{R}	**IOHI**
Pellet production	Separation	2	3	1	0	0	0	0	0	
	Drying	2	3	3	0	0	3	0	0	**24**
	Pelletizing	2	3	1	1	0	0	0	0	
DLF production	Separation	2	3	1	0	0	0	0	0	
	Primary sieving	2	3	3	0	0	0	0	0	**33**
	Drying	2	3	3	0	0	3	0	0	
	Secondary sieving	2	3	3	0	0	0	0	0	
	Baling system	2	3	3	2	0	0	0	0	**10**
Briquette production	Separation	2	3	1	0	0	0	0	0	
	Drying	2	3	3	0	0	3	0	0	**24**
	Briquetting	2	3	1	1	0	0	0	0	
PKS charcoal production	Carbonization	3	3	3	0	0	3	0	0	**12**
Compost production	Fermentation	3	3	3	0	0	0	0	0	**9**
Anaerobic digestion + electricity generation	Anaerobic digestion	3	3	3	0	0	0	0	0	**9**
	Gas engine	3	1	3	3	0	1	0	0	**11**
Combustion + steam and electricity generation	Boiler	1	3	3	1	0	3	0	0	**11**
	Steam turbine	1	1	1	1	0	3	0	0	**7**

and 5, respectively. Penalty of each subprocess is assessed based on chemical properties and operating conditions of corresponding subprocess via Eqs. 21–23 and 25–27. For example, there are four subprocesses in DLF production which include separation, primary sieving, drying, and secondary sieving. Total score of ISI and IOHI for the DLF production is determined as 17 and 33, respectively. These scores are obtained by summing up the index value of all the four subprocesses in the DLF production, as shown in Tables 4 and 5. Later, DLF is then compressed into compact DLF bales via baling system for transportation purpose. Similarly, ISI and IOHI values of the DLF baling system are calculated and they are 7 and 10, respectively. Note that based on this additive-based approach (in which the index of the whole production technology is calculated by summing up the scores of the individual subprocess), technology with more subprocesses will normally results in higher ISI and IOHI. From inherent safety and health perspectives, a more complex process is potentially more hazardous than a simpler process, due to the involvement of more chemical substances, unit operations, piping, plant structure, etc. To provide better understanding on the proposed approach, a sample calculation is provided in appendix. Further details on the additive-based approach for safety and health index calculations can be found in Heikkilä et al.[40] and Hassim and Hurme.[33]

In this case study, five scenarios are taken into consideration; design for maximum EP, design for minimum TEI, design for minimum TSI, design for minimum THI, and design with multiobjectives optimization via fuzzy optimization. As mentioned previously, first four scenarios are presented to determine the upper and lower limits of each objective function. Based on the result, highest and lowest values of each objective function in first four scenarios are taken as upper limits (EP^U, TEI^U, TSI^U, and THI^U) and lower limits (EP^L, TEI^L, TSI^L, and THI^L). Last scenario is performed to trade off four objective functions within predefined upper and lower limits. The presented MILP model in different scenarios is solved via LINGO v13.0 in HP Compaq 6200 Elite Small Form Factor with Intel® Core^{TM} i5–2400 Processor (3.10 GHz) and 4GB DDR3 RAM. The summary and detailed optimization results for these five scenarios are summarized in Table 6.

Scenario 1: Design for Maximum EP

In this scenario, maximum EP of an integrated palm oil-based biorefinery with CHP is targeted. A MILP model for Scenario 1 is solved by maximizing EP with the constraints in Eqs. 1–15, 17–20, 24, 32–34 and data tabulated in Tables 1–5.

Maximize EP

Based on the optimized result, the maximum EP in Scenario 1 is determined as USD 29.52 million over its operational lifespan (15 years) with TEI, TSI, and THI of −25.43,

Table 6. Summary of Case Study

		Scenario				
Description	Unit	1	2	3	4	5
Economic performance (EP)	USD million	29.52	12.59	7.81	7.81	18.47
Total environmental impact (TEI)	–	−25.43	−34.90	−28.80	−28.80	−30.08
Total safety impact (TSI)	–	65	123	58	58	65
Total health impact (THI)	–	72	114	53	53	72
Payback period (PP)	Year	1.94	4.16	5.00	5.00	3.58

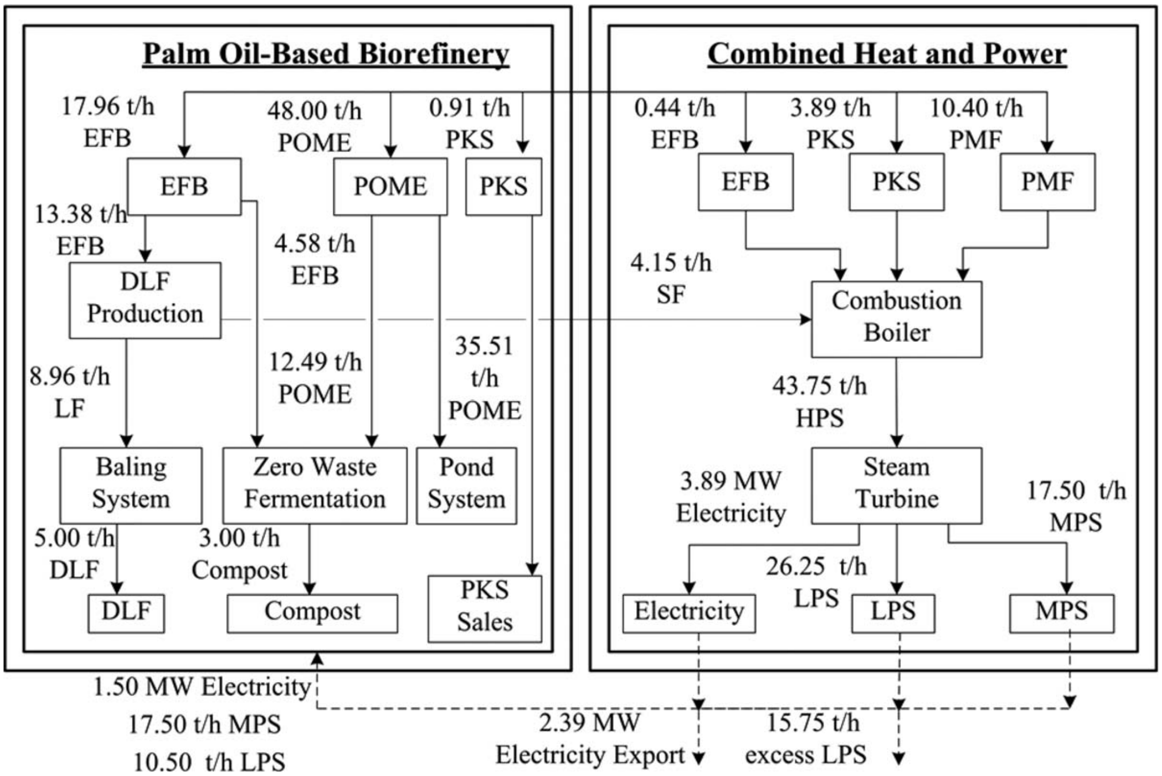

Figure 4. Optimized allocation for Scenario 1.

65, and 72, respectively. Figure 4 shows the optimum network configuration of this scenario. It is noted that in this scenario, 80 t/h FFB is fed into the POM, which produced 18.40 t/h EFB, 4.80 PKS, 48.00 t/h POME, and 10.40 t/h PMF. As shown in the result (Table 6), technologies of DLF and compost are selected. Note that, 17.96 t/h fresh EFB and 12.48 t/h fresh POME are utilized to produce 5.00 t/h DLF and 3.00 t/h compost. Besides, 0.91 t/h PKS is sold to biomass boiler owner to use as feedstock of combustion boiler. The remaining 35.51 t/h unutilized POME is sent to existing pond system for further treatment.

In CHP, all collected SF from DLF production is fully utilized for combustion in combustion boiler. Besides, 10.40 t/h PMF is mixed with 0.44 t/h EFB, 4.15 t/h SF, and 3.89 t/h PKS to meet the moisture content requirement before feeding to the boiler for generation of 43.75 t/h HPS. The pressure of HPS is then reduced via steam turbine to generate 3.89 MW of electricity. At the same time, 17.50 t/h MPS and 26.25 t/h LPS are produced. It is noted that 1.50 MW of electricity is used for self-consumption within the entire POB. Since there is excess of electricity, additional electricity generated from biogas through gas engine is not required. The excess of 2.39 MW of electricity can then be exported for any external demands or feed into the national grid system, while excess MPS and LPS can be sent to sterilization process in palm oil mill for heating purpose.

Scenario 2: Design for Minimum TEI

The objective of this scenario is set to minimize TEI of entire integrated palm oil-based biorefinery with CHP. Objective function is solved in this scenario with the constraints in Eqs. 1–15, 17–20, 24, 32–34 and data tabulated in Tables 1–5.

Minimize TEI

According to the optimization result which tabulated in Table 6, the minimum TEI is targeted as −34.90 with EP of USD 12.59 million, TSI of 123 and THI of 114. In this scenario, pellet, DLF, and compost production pathways are selected as shown in Figure 5. 9.57 t/h, 2.68 t/h and 3.10 t/h of EFB are sent to pellet production, DLF production, and combustion boiler, respectively. Meanwhile, the rest of EFB (3.05 t/h) is mixed with 8.32 t/h of POME to produce 2 t/h compost. All PKS and PMF are mixed with EFB and fed into boiler to generate HPS (45.11 t/h), electricity (4.01 MW), MPS (18.04 t/h), and LPS (27.07 t/h). Most of the POME (38.66 t/h) is fully utilized and treated in anaerobic digester to produce biogas. Biogas is sent to gas engine and 1 MW of electricity is generated. The remaining POME (1.01 t/h) is then treated in existing pond system before discharging to the environment. It is noted that higher general expenses is required on biogas production and gas turbine system, thus results in lower net profit in this scenario. Meanwhile, TSI and THI are higher as additional pellet production and biogas engine pathways included in this scenario. On the other hand, palm oil-based biorefinery requires 1.30 MW of electricity and, therefore, 3.71 MW of excess electricity can be exported.

Scenario 3: Design for Minimum TSI

Design for integrated palm oil-based biorefinery and CHP based on for minimum TSI is presented in this scenario. In order to determine the process pathway with the minimum TSI, the optimization objective is solved, subjected to the

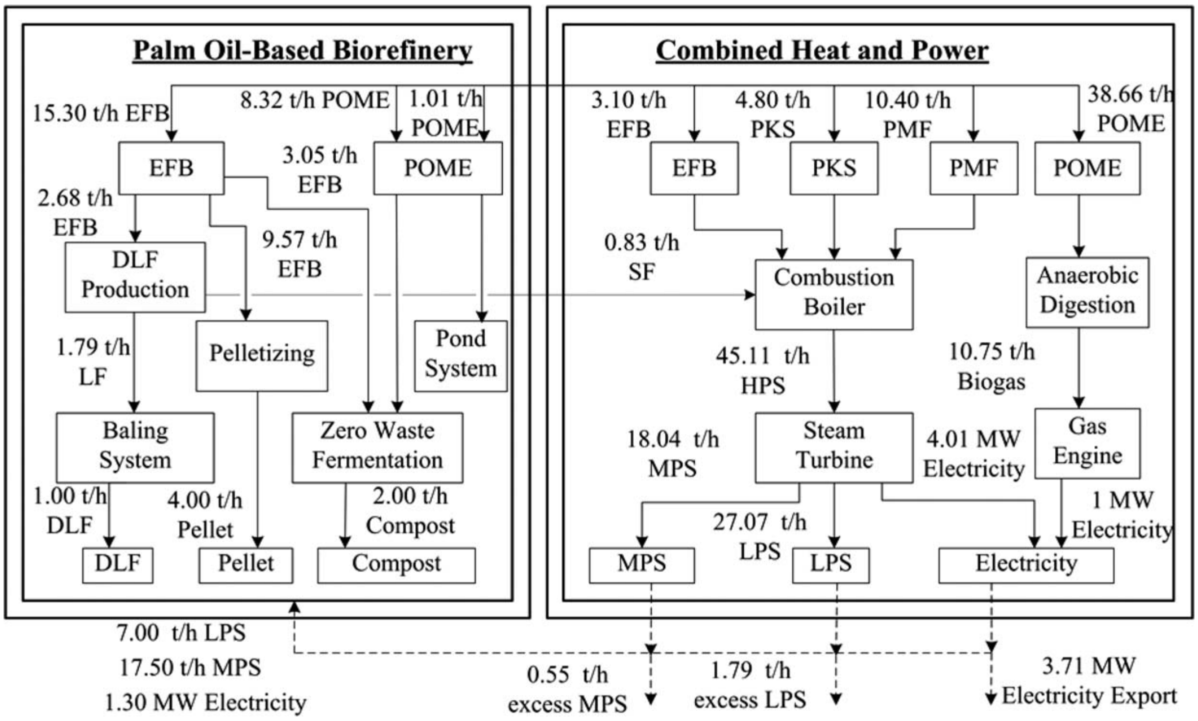

Figure 5. Optimized allocation for Scenario 2.

constraints in Eqs. 1–15, 17–20, 24, 32–34 and data tabulated in Tables 1–5.

Minimize TSI

Based on the optimized result in Table 6, the minimum TSI is determined as 58, with EP of USD 7.81 million, TEI of −28.80 and THI of 53. In order to achieve minimum TSI in the integrated palm oil-based biorefinery, production pathways with lower inherent safety impact are chosen. Based on the optimized result, pellet and compost productions are selected, whereas boiler and steam turbine is selected in CHP as shown in Figure 6. A total of 4.00 t/h pellet is produced with 10.40 t/h EFB input. Meanwhile, 8.32 t/h POME is fermented with 3.05 t/h EFB to produce 2.00 t/h compost. The remaining EFB is mixed with 4.00 t/h PKS and 10.40 t/h PMF before sending into boiler for steam generation. 44.59 t/h HPS, 3.97 MW electricity, 17.84 t/h MPS, and 26.76 t/h LPS are generated through boiler and steam turbine. Since the palm oil-based biorefinery requires 1.00 MW, the extra electricity generated (2.97 MW) can be fed into national grid system. Besides, the remaining PKS (0.80 t/h) can be sold directly and excess POME (36.67 t/h) is treated in existing pond system before discharge into river.

Scenario 4: Design for Minimum THI

In this scenario, design of integrated palm oil-based biorefinery with CHP with minimum THI is presented. The objective function of minimize THI is solved, subjecting to the Eqs. 1–15, 17–20, 24, 32–34 and data tabulated in Tables 1–5.

Minimize THI

Based on the optimized result in Table 6, the optimized result of this scenario is identical to Scenario 3. The minimum THI is targeted at 53, with EP of USD 7.81 million, TEI of −28.80, and TSI of 58. According to Tables 4 and 5, ISI score is directly proportional to IOHI score. This is due to the similar development principle of both indices. As mentioned earlier, the penalty system in both index is designed in a way that greater penalty indicates greater hazard. Besides, both index adapted additive-based calculation approach. Therefore, the technologies with more subprocesses and operate at higher operating pressure and temperature have higher ISI and IOHI scores. In this scenario, it is noted that the utilization of biomass is identical with Scenario 3.

Scenario 5: Design for Multiobjectives Optimization

In order to consider all objectives simultaneously, fuzzy optimization is adapted in this study. As shown in Eqs. 28–31, upper and lower limits of the predefined EP, TEI, TSI, and THI are needed. The maximum and minimum values obtained from the previous scenarios for all four objective functions (EP, TEI, TSI, and THI) are taken as the limits. Based on Table 6, EP^U, EP^L, TEI^U, TEI^L, TSI^U, and TSI^L are USD 29.52 million, USD 7.81 million, −25.43, −34.90, 123, 58, 114, and 53, respectively. Thus, Eqs. 28–31 are revised and given as

$$\frac{\text{EP-}7.81\times10^6}{29.52\times10^6-7.81\times10^6} \geq \lambda \tag{35}$$

$$\frac{\text{-25.43-TEI}}{\text{-25.43-(-34.90)}} \geq \lambda \tag{36}$$

$$\frac{\text{123-TSI}}{\text{123-58}} \geq \lambda \tag{37}$$

$$\frac{\text{114-THI}}{\text{114-53}} \geq \lambda \tag{38}$$

The model is solved by maximizing the degree of level satisfaction λ with constraints of Eqs. 1–15, 17–20, 24, 32–38 and data tabulated in Tables 1–5. The optimum pathway of this scenario is showed in Figure 7. The targeted λ is determined as 0.49 and EP is targeted at USD 18.47 million with

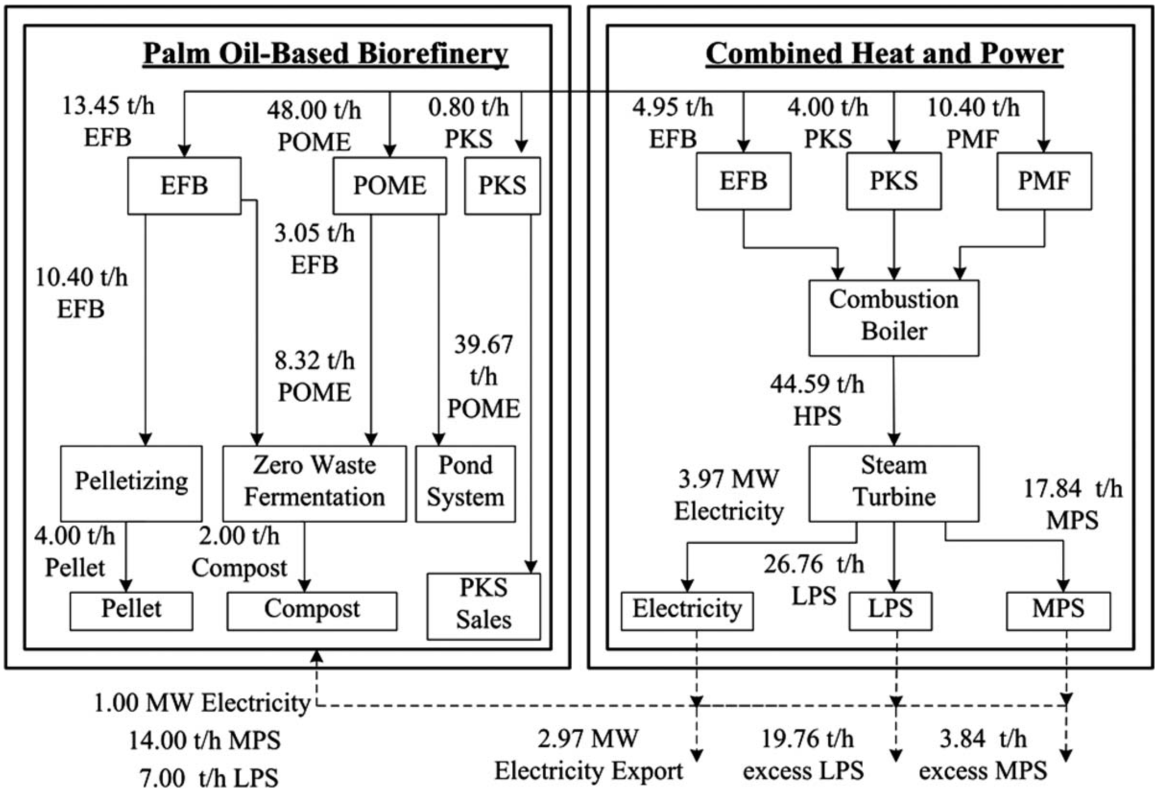

Figure 6. Optimized allocation for Scenarios 3 and 4.

the associated environmental, safety, and health performance at −30.08, 65, and 72. Note that lowest value of λ is targeted to optimize all objectives. By inserting EP, TEI, TSI, and THI targeted into Eqs. 35–38, individual λ of each equation is target 0.49, 0.89, 0.69, and 0.49 for EP, TEI, TSI, and THI, respectively. Thus, lowest λ is targeted to trade-off four objective functions simultaneously. Besides, the payback period of the optimized configuration is located at 3.58 years. According to Figure 7, DLF and compost production are chosen as optimum pathways in the integrated palm oil-based biorefinery. 8.03 t/h of EFB is utilized to produce 3.00 t/h DLF, whereas 6.00 t/h compost is produced by mixing 9.16 t/h EFB

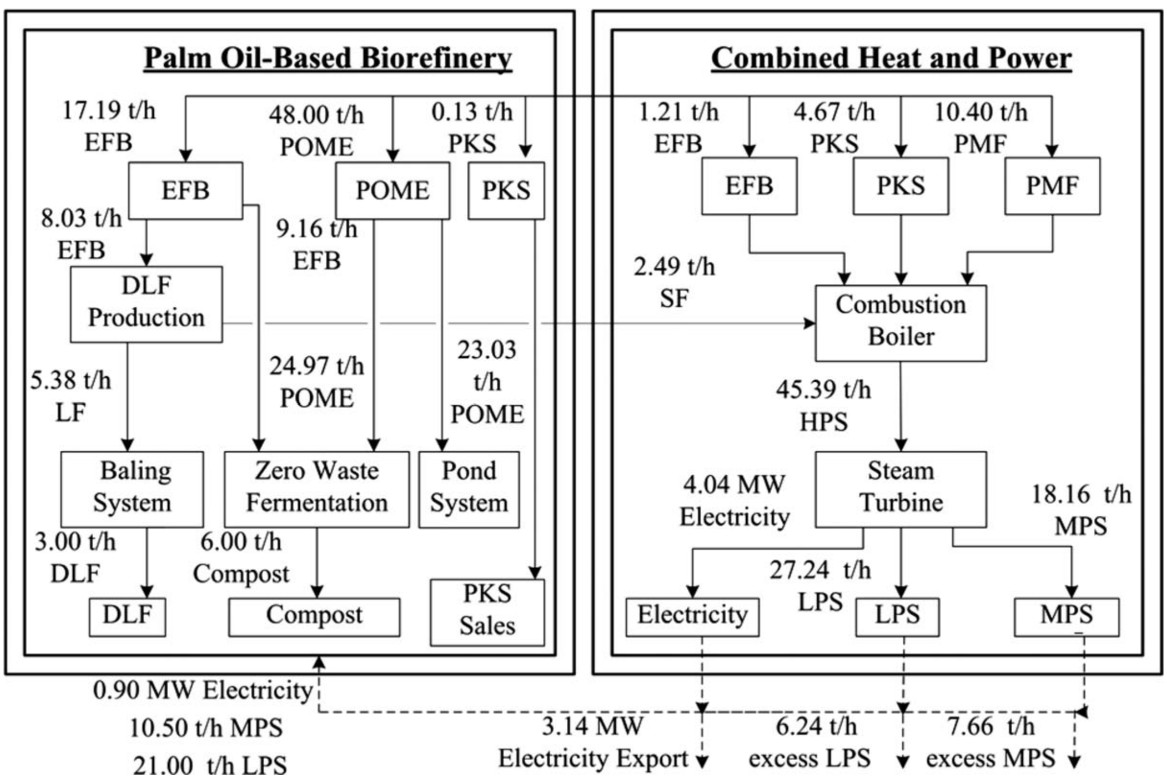

Figure 7. Optimized allocation for Scenario 5.

and 24.97 t/h POME. By-product from DLF production (2.49 t/h SF) is fed into boiler with 1.21 t/h EFB, 4.67 t/h PKS and 10.40 t/h PMF. It is noted that 45.39 t/h HPS is produced and 18.16 t/h MPS, 27.24 t/h LPS and 4.04 MW electricity are produced via steam turbine. Excess 6.24 t/h LPS and 7.66 t/h MPS can be supplied to palm oil mill or other nearest plant.

Conclusion

In this work, a systematic multiobjective optimization approach for the synthesis of a sustainable integrated biorefinery is presented. Health impact is included together with economic, environmental and safety impacts evaluation in synthesizing task. Fuzzy optimization model is adapted to determine the detailed allocation of biomasses to achieve the maximum EP, and minimum TEI, TSI and THI simultaneously. The proposed approach can be easily revised and reformulated to synthesize processes in different industries. LCA, quantitative inherent safety and inherent occupational health assessments will be included in the future work to synthesize integrated biorefinery.

Acknowledgment

The financial support from Global Green Synergy Sdn. Bhd., Malaysia and University of Nottingham Research Committee through New Researcher Fund (NRF 5021/A2RL32) are gratefully acknowledged. In addition, authors would also like to acknowledge financial support from Ministry of Higher Education, Malaysia through LRGS Grant (project code: 5526100) and UTM Research University Grant Scheme (RUGS) Tier 1 (Q.J130000.7125.00H45).

Notation

Abbreviation

C-H-O = Carbon-Hydrogen-Oxygen
CHP = Combined Heat and Power
CPKO = crude palm kernel oil
CPO = crude palm oil
DLF = dried long fiber
EFBs = empty fruit bunches
FFBs = fresh fruit bunches
HPS = high-pressure steam
LPS = low-pressure steam
MPS = medium pressure steam
PKS = palm kernel shell
PMF = palm mesocarp fiber
POB = palm oil-based biorefinery
POM = palm oil mill
POME = palm oil mill effluent

Sets

e = index for primary energy
e' = index for secondary energy
g = index for technology to produce primary energy
g' = index for technology to produce secondary energy
i = index for biomass
j = index for technology to produce intermediate
j' = index for technology to produce green product
k = index for intermediate
q = index for green product
s = index for substance
r = index for all technologies j, j', g and g'

Parameters

AOT = annual operating time, h/y
C_{jk}^{Cap} = fixed capital cost via technology j per unit intermediate k, USD/t
$C_{j'q}^{\mathrm{Cap}}$ = fixed capital cost via technology j' per unit product q, USD/t
C_{ge}^{Cap} = fixed capital cost via technology g per unit energy, USD/unit energy
$C_{g'e'}^{\mathrm{Cap}}$ = fixed capital cost via technology g' per unit energy, USD/unit energy
$C^{\mathrm{Cap\text{-}Fixed}}$ = miscellaneous fixed capital cost, USD
$C_{e'}^{\mathrm{Imp}}$ = cost of imported energy, USD/unit energy
C_{jk}^{Proc} = general expenses via technology j per unit intermediate k, USD/t
$C_{j'q}^{\mathrm{Proc}}$ = general expenses via technology j' per unit product q, USD/t
C_{ge}^{Proc} = general expenses via technology g per unit energy, USD/unit energy
$C_{g'e'}^{\mathrm{Proc}}$ = general expenses via technology g' per unit energy, USD/unit energy
C_{q}^{PR} = revenue from green product q, USD/t
C_{i}^{BIO} = cost of biomass i, USD/t
DEP = depreciation
GOV = government incentives or penalties
H = enthalpy
HEDGE = expenses associated with hedging against catastrophic market actions
EP^{U} = upper limit of economic performance
EP^{L} = lower limit of economic performance
$\mathrm{HI}_{r}^{\mathrm{HH}}$ = health hazards index
$\mathrm{HI}_{r}^{\mathrm{PM}}$ = subindex of mode of process in physical and process hazards index
$\mathrm{HI}_{s}^{\mathrm{MS}}$ = subindex of material phase in physical and process hazards index
$\mathrm{HI}_{s}^{\mathrm{V}}$ = subindex of volatility in physical and process hazards index
$\mathrm{HI}_{s}^{\mathrm{C}}$ = subindex of corrosiveness of construction material in physical and process hazards index
$\mathrm{HI}_{r}^{\mathrm{P}}$ = subindex of process pressure in physical and process hazards index
$\mathrm{HI}_{r}^{\mathrm{T}}$ = subindex of process temperature in physical and process hazards index
$\mathrm{HI}_{s}^{\mathrm{EL}}$ = subindex of exposure limit in health hazards index
$\mathrm{HI}_{s}^{\mathrm{R}}$ = subindex of R-phrase in health hazards index
ISI = inherent safety index
IOHI = inherent occupational health index
L = lower bounds
NPF = normalized potency factor
$\mathrm{NPF}_{jk}^{\mathrm{I}}$ = normalized potency factor of technology pathway jk
$\mathrm{NPF}_{j'q}^{\mathrm{II}}$ = normalized potency factor of technology pathway $j'q$
$\mathrm{NPF}_{i}^{\mathrm{BIO}}$ = normalized potency factor of biomass i
$\mathrm{NPF}_{e'}^{\mathrm{Energy}}$ = normalized potency factor of energy e'
PF = potency factor
ROR = expected rate of return
$\mathrm{SI}_{r}^{\mathrm{CI}}$ = chemical inherent safety index
$\mathrm{SI}_{r}^{\mathrm{PI}}$ = process inherent safety index
$\mathrm{SI}_{s}^{\mathrm{RM}}$ = subindex of heat of main reaction in chemical inherent safety index
$\mathrm{SI}_{s}^{\mathrm{RS}}$ = subindex of heat of side reaction in chemical inherent safety index
$\mathrm{SI}_{s}^{\mathrm{INT}}$ = subindex of the chemical interaction in chemical inherent safety index
$\mathrm{SI}_{s}^{\mathrm{FL}}$ = subindex of flammability in chemical inherent safety index
$\mathrm{SI}_{s}^{\mathrm{EX}}$ = subindex of explosiveness in chemical inherent safety index
$\mathrm{SI}_{s}^{\mathrm{TOX}}$ = subindex of toxicity in chemical inherent safety index
$\mathrm{SI}_{s}^{\mathrm{COR}}$ = subindex of corrosiveness in chemical inherent safety index
$\mathrm{SI}_{r}^{\mathrm{I}}$ = subindex of inventory in process inherent safety index
$\mathrm{SI}_{s}^{\mathrm{T}}$ = subindex of process temperature in process inherent safety index
$\mathrm{SI}_{s}^{\mathrm{P}}$ = subindex of process pressure in process inherent safety index
$\mathrm{SI}_{s}^{\mathrm{EQ}}$ = subindex of equipment safety in process inherent safety index
$\mathrm{SI}_{s}^{\mathrm{ST}}$ = subindex of process structure in process inherent safety index
$t_{\max}$ = designed lifespan of biorefinery, year
TAX = marginal tax rate
TEB = total environmental burden
$\mathrm{TEI}^{\mathrm{U}}$ = upper limit of total environmental impact

TEI^{L} = lower limit of total environmental impact
THI^{U} = upper limit of total health impact
THI^{L} = lower limit of total health impact
TSI^{U} = upper limit of total safety impact
TSI^{L} = lower limit of total safety impact
U = upper bound
$X^{II}_{kj'q}$ = conversion of intermediate k to green product q via technology j'
X^{I}_{ijk} = conversion of biomass i to intermediate k via technology j
Y^{I}_{ige} = conversion of primary energy per unit of biomass i via technology g
$Y^{II}_{eg'e'}$ = conversion of secondary energy per unit of primary energy e via technology g'
Y^{I}_{ige} = conversion of primary energy per unit of biomass i via technology g
$Y^{II}_{eg'e'}$ = conversion of secondary energy per unit of primary energy e via technology g'
$Y^{I}_{e'jk}$ = conversions of consumption of energy via technology j
$Y^{II}_{e'j'q}$ = conversions of consumption of energy via technology j'

Variables

$E^{Imp}_{e'}$ = total energy that are bought from external, MW for electricity and t/h for steam
$E^{Exp}_{e'}$ = total excess energy that are sold to any third party plants, MW for electricity and t/h for steam
$E^{Gen}_{e'}$ = total energy generated from technology g', MW for electricity and t/h for steam
E^{Gen}_{e} = total energy generated from technology g, MW for electricity and t/h for steam
$E^{Con}_{e'}$ = total energy requirement of the integrated palm oil-based biorefinery, MW for electricity and t/h for steam
E^{I}_{ge} = energy generated from technology g, MW for electricity and t/h for steam
$E^{II}_{g'e'}$ = energy generated from technology g', MW for electricity and t/h for steam
EP = economic performance, USD
F = material flow rate of intermediate W^{INT}_{k}, product W^{PR}_{q} or energy flow rate of primary energy $E^{Gen\text{-}CHP}_{e}$ and secondary energy $E^{Gen}_{e'}$
GP = gross profit per unit time, USD/year
I_r = binary variable
NPV = net present value, USD
TEI = total environmental impact
THI = total health impact
TSI = total safety impact
W^{PR}_{q} = total flow rate of green product q, t/h
W^{INT}_{k} = total flow rate of intermediate k, t/h
$W^{II}_{kj'}$ = flow rate of intermediate k to technology j', t/h
W^{I}_{ig} = flow rate of biomass i to technology g, t/h
W^{I}_{ij} = flow rate of biomass i to technology j, t/h
$W^{II}_{j'q}$ = flow rate of green product q produced from technology j', t/h
W^{I}_{jk} = flow rate of green intermediate k produced from technology j, t/h
W^{BIO}_{i} = flow rate of biomass i, t/h
λ = degree of satisfaction

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Appendix

In this section, PKS charcoal production (r = PKS charcoal production) is used to demonstrate the index calculations of IOHI as summarized in Table A1. Based on below sample calculation, ISI and IOHI calculation can be repeated based on operating conditions of every process shown in Table 2.

Table A1. IOHI Calculation of PKS Carbonization

		Penalty		
		PKS	PKS Charcoal	Penalty Shown
Factor	Symbol	$s=1$	$s=2$	in Table 5
Mode of process	HI_r^{PM}		3	3
Pressure	HI_r^{P}		0	0
Temperature	HI_r^{T}		3	3
Material phase	HI_s^{MS}	3	3	3
Corrosiveness	HI_s^{C}	0	0	0
Volatility	HI_s^{V}	0	3	3
Process hazards index	HI_r^{PPH}			12
Exposure limit	HI_s^{EL}	0	0	0
R-phase	HI_s^{R}	0	0	0
Health hazard index	HI_r^{HH}			0
IOHI of PKS Carbonization				12

In PKS charcoal production, both substances (s = 1–PKS inlet and s = 2–PKS charcoal outlet) are analyzed. Carbonization is a batch process, thus HI_r^{PM} is equal to 3. Based on Table 2, the operating conditions of carbonization process are 700°C and 1 bar), HI_r^{T} and HI_r^{P} are 3 and 0, respectively. Both inlet and outlet substances are in solid form, $HI_{s=1}^{MS}$ and $HI_{s=2}^{MS}$ are equal to 3. Both PKS and PKS charcoal are noncorrosive materials, $HI_{s=1}^{C}$ and $HI_{s=2}^{C}$ are equal to 0. Nondusty solid (PKS) is fed into carbonization kiln and produces PKS charcoal with fine ash, thus $HI_{s=1}^{V}$ and $HI_{s=2}^{V}$ are 0 and 3, respectively. As mentioned in problem formulation, maximum penalty of HI_s^{MS}, HI_s^{C}, and HI_s^{V} are considered in determining HI_r^{PPH}. In this technology, PKS charcoal′s volatility ($HI_{s=2}^{V}=3$) as highlighted in Table 6 is considered. Therefore, HI_r^{PPH} is calculated as 12. HI_r^{HH} is equal to zero as both PKS and PKS charcoal do not have exposure limit and R-phase data.

Manuscript received Jan. 9, 2013, and revision received Apr. 24, 2013.