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A novel perspective for techno-economic assessments and effects of parameters on techno-economic assessments for biodiesel production under economic and technical uncertainties

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Various parameters, such as biodiesel price, capital cost, interest rate, operating cost, feedstock price, maintenance rate, biodiesel conversion efficiency and glycerol price, may exhibit variation in the techno-economic assessments of biodiesel production within the project's lifetime due to economic and technical uncertainties. This paper first defines a new indicator for techno-economic assessments of biodiesel production when all uncertain parameters are regarded as being uniformly distributed within their variation ranges. This new indicator is named economical infeasibility probability (EIP), which defines the probability that total profit, payback period and net present value (NPV) of biodiesel production or one of them or two of them do not satisfy the prescribed requirements, and the Monte Carlo Simulation (MCS) method is employed to evaluate EIP. Based on economical infeasibility analysis, the sensitivity analysis of EIP with respect to an individual uncertain parameter is defined, and MCS is utilized to evaluate the effect. It is found that EIP for the studied biodiesel production is 0.3676 under the selected distributions of uncertain parameters, and biodiesel price, feedstock price, biodiesel conversion efficiency and operating cost have significant effects on EIP, while capital cost, maintenance rate, interest rate and glycerol price have negligible effects.

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1. Introduction

Many deleterious emissions, such as NO_x, greenhouse gases, hydrocarbons and particulate matter, are yielded by the burning of fossil fuels in engines. These harmful substances have caused various adverse impacts on the global climate, environment and local air quality.^{1–3} In order to reduce such negative effects, many researchers are seeking alternative clean, economic and easy-to-use energy sources. Biodiesel is such an important renewable fuel, which has better environmental friendliness than the conventional fossil fuels.^{4–7} Many studies have reported biodiesel production using various feedstocks: palm oil,⁸ vegetable oils,⁹ waste cooking oil,¹⁰ *Jatropha curcas* L,¹¹ soybean oil,¹² *etc.*

Biodiesel industry is growing rapidly, but various uncertain factors such as variability in feedstock and biodiesel price, can bring about the instability of biodiesel production,¹³ and can further affect the economical feasibility of biodiesel production. In order to decrease the effects of these factors and obtain a comprehensive understanding on the

economical feasibility of biodiesel production, many studies have reported the techno-economic assessments (TEAs) of biodiesel production.^{14–20} These works have promoted the advancement of the TEAs of biodiesel production with the precondition that all of the parameters were assumed as constants within the project's lifetime. In practical, considering these parameters as constants may not be rational due to the fact that there are numerous inevitable economic and technical uncertainties involved in the TEAs of biodiesel production within the project's lifetime,¹³ such as the variability in the feedstock and biodiesel prices²¹ and the variation of the interest rate.²² Some researchers have investigated the TEAs of biodiesel production subjected to uncertain parameters.^{23–25} They have found that the uncertainties in the parameters can considerably affect the TEAs. The authors also analysed the effects of uncertainties on the TEAs of biodiesel production and identified the key parameters.²⁶

Based on the previous study of the authors,²⁶ this paper will further perform the TEAs of biodiesel production from another perspective. The investment for biodiesel production desires larger net present value (NPV), more total profit and shorter payback period. Thus, both the NPV and total profit should be larger than zero, while the payback period needs to be less than the permitted limit in terms of the economical

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feasibility. However, diverse economic and technical uncertainties involved in biodiesel production within the project's lifetime can give rise to the variation in the NPV, the total profit and the payback period. Thus, there is a chance that the NPV is less than zero or the total profit is less than zero or the payback period is larger than the prescribed limit, which will lead to the economical infeasibility. Then, the economical infeasibility probability (EIP) is further derived, and the effect of the uncertain parameter on the EIP is also defined and quantified. Finally, the EIP of a crude-palm-oil-derived biodiesel production are obtained, and the influential parameters are identified.

The paper is organized as follows. Section 2 introduces the TEAs of a crude-palm-oil-derived biodiesel production under eight uncertain parameters, the definition of EIP and the effects of uncertain parameters on EIP. Section 3 evaluates EIP and the effects of uncertain parameters for a crude-palm-oil-derived biodiesel production. Conclusions are drawn in Section 4.

2. Materials and methods

In this section, some important concepts in the TEAs of biodiesel production, including life cycle cost, net present value, payback period and total profit, are first introduced, and some uncertain parameters involved in the TEAs are also given. Secondly, EIP is defined when three of them (*i.e.*, net present value, payback period and total profit) or two of them or one of them do not fulfill the permitted requirement. Then, the Monte Carlo Simulation method is introduced to carry out economical infeasibility analysis. Finally, effect of an individual uncertain parameter on EIP is defined.

2.1 Techno-economic assessments of a crude-palm-oil-derived biodiesel production

The TEAs of a crude-palm-oil-derived biodiesel production without considering the economic and technical uncertainties involved in the parameters within the project's lifetime was studied by researchers.¹⁹ Here, some basic terminologies related to the TEAs of the research are briefly introduced, and the variation ranges of parameters with uncertainties are also given.

The LCC of a crude-palm-oil-derived biodiesel production within the prescribed project's lifetime can be expressed by

$$LCC = CC + FC + OC + MC - SV - BPC, \quad (1)$$

where LCC represents the life cycle cost; CC is the capital cost; FC represents the feedstock cost; OC is the operating cost; MC denotes the maintenance cost; SV indicates the salvage value and BPC denotes byproduct credit.

In order to avoid the effect of the cash flows at different times within the project's lifetime, LCC needs to be formulated in the form of the present value, which is written by

$$LCC = CC + \sum_{i=1}^n \frac{FC_i + OC_i + MC_i}{(1+r)^i} - \frac{SV}{(1+r)^n} - \sum_{i=1}^n \frac{BPC_i}{(1+r)^i}, \quad (2)$$

where n represents the project's lifetime, *i.e.*, $n = 20$ years; FC_i , OC_i , MC_i and BPC_i denote the feedstock cost, the operating cost, the maintenance cost and the byproduct credit of the i th year, respectively; r is the interest rate, *i.e.*, $r \in [4.44\%, 13.53\%]$.²⁷

The following will provide the definitions of CC, FC, OC, MC, SV and BPC. The plant has the annual biodiesel production capacity of 50k tons, *i.e.*, $PC = 50$ k tons, and the corresponding capital cost varies from \$9 million to \$15 million, *i.e.*, $CC \in [\$9 \text{ million}, \$15 \text{ million}]$.¹⁹

FC is the major cost of biodiesel production and it generally accounts for 80–90% of LCC.²⁸ The FC of a crude-palm-oil-derived biodiesel production is defined by

$$FC = \sum_{i=1}^n FC_i = \sum_{i=1}^n \frac{FP \times FU}{(1+r)^i} = \sum_{i=1}^n \frac{FP \times \frac{PC \times 1000}{CE}}{(1+r)^i}, \quad (3)$$

where FP represents the feedstock price or the crude palm oil price, which varied from \$200 per ton to \$1200 per ton in the past twelve years, *i.e.*, $FP \in [\$200 \text{ per ton}, \$1200 \text{ per ton}]$;¹⁹ FU denotes the annual total feedstock consumption; CE indicates the conversion efficiency from feedstock to biodiesel, which usually takes values from 96% to 99%, *i.e.*, $CE \in [96\%, 99\%]$.²⁹

OC is an important ingredient of LCC and it generally comprises less than 15% of LCC within the project's lifetime.³⁰ The OC of a crude-palm-oil-derived biodiesel production is formulated by

$$OC = \sum_{i=1}^n OC_i = \sum_{i=1}^n \frac{OR \times PC \times 1000}{(1+r)^i}, \quad (4)$$

where OR represents the operating rate or the operating cost of per-ton crude-palm-oil-derived biodiesel production. Here, the percentage that FC accounts for in LCC is 80%,²⁸ and the percentage that OC comprises in LCC takes the value of 15%.³⁰ Therefore, the operating rate or the operating cost of per-ton crude-palm-oil-derived biodiesel production can be assessed as $OR \in [\$37.5 \text{ per ton}, \$225 \text{ per ton}]$ by the feedstock price $FP \in [\$200 \text{ per ton}, \$1200 \text{ per ton}]$.¹⁹

The total MC of a crude-palm-oil-derived biodiesel production within the project's lifetime is given by

$$MC = \sum_{i=1}^n MC_i = \sum_{i=1}^n \frac{MR \times CC}{(1+r)^i}, \quad (5)$$

where MR is the maintenance rate. MR takes a value of 2% in some works, and it is 1% in other study.^{15,19} Here, MR takes values from 1% to 2%, *i.e.*, $MR \in [1\%, 2\%]$.

Salvage value (SV) is the remaining value of the components and the assets of the plant at the end of the project's lifetime. The SV of a crude-palm-oil-derived biodiesel production is expressed by

$$SV = RC \times (1-d)^{n-1} \times PWF_n = \frac{RC \times (1-d)^{n-1}}{(1+r)^n}, \quad (6)$$

where d represents the depreciation rate, *i.e.*, $d = 5\%$; $n = 20$ years denotes the project's lifetime of the plant; RC indicates



the replacement cost, *i.e.*, RC = \$10 million;¹⁹ PWF_{*n*} represents the present worth factor in the year *n*.

Glycerol is an important byproduct of a crude-palm-oil-derived biodiesel production, and the sale of glycerol can bring byproduct credit. The total byproduct credit within the project's lifetime is given by

$$\text{BPC} = \sum_{i=1}^n \text{BPC}_i = \sum_{i=1}^n \frac{\text{GP} \times \text{GCF} \times \text{PC} \times 10^6}{(1+r)^i}, \quad (7)$$

where GP represents the glycerol price, *i.e.*, GP ∈ [\$0.08 per kg, \$0.2 per kg];³¹ GCF is the glycerol conversion factor, *i.e.*, GCF = 0.0985.¹⁹

The previous sections have defined LCC and all of the items in LCC. The following will define the total profit, the payback period and the net present value of biodiesel production. The total profit of a crude-palm-oil-derived biodiesel production within the project's time can be defined by

$$\text{TotalProfit} = (\text{TBS} - \text{TAX}) \times n - \text{LCC} = (\text{TBS} - \text{TAX}) \times 20 - \text{LCC}, \quad (8)$$

where TotalProfit is the total profit; TBS is the annual total biodiesel sales when all of the produced biodiesel is sold out; TAX represents the annual total taxation; *n* = 20 years is the project's lifetime. TBS and TAX can be defined by

$$\text{TBS} = \text{PC} \times 10^6 / \rho \times \text{BP}, \quad (9)$$

$$\text{TAX} = \text{TBS} \times \text{TR}, \quad (10)$$

where BP is the biodiesel price, *i.e.*, BP ∈ [\$0.66 per liter, \$1.58 per liter];³² ρ is the density of the biodiesel, *i.e.*, ρ = 0.95 kg per liter; TR = 15% represents the tax rate, *i.e.*, 15% of the biodiesel sales.

The payback period of a given investment is defined as the length of time required to recover the initial cost of the investment (*i.e.*, the capital cost). The payback period of a crude-palm-oil-derived biodiesel production is defined by¹⁹

$$\text{PP} = \frac{\text{CC}}{(\text{TotalProfit}/n)} = \frac{n \times \text{CC}}{\text{TotalProfit}}, \quad (11)$$

where PP represents the payback period of the biodiesel production; CC denotes the capital cost; *n* is the project's lifetime, *i.e.*, *n* = 20 years.

The mathematical formula for net present value (NPV) of a crude-palm-oil-derived biodiesel production is as follows:

$$\text{NPV} = -\text{CC} + \sum_{i=1}^n \frac{(\text{TBS}_i - \text{TAX}_i) + \text{BPC}_i - \text{FC}_i - \text{OC}_i - \text{MC}_i}{(1+r)^i} + \frac{\text{SV}}{(1+r)^n}, \quad (12)$$

with TBS_{*i*} = TBS and TAX_{*i*} = TAX, where TBS_{*i*} and TAX_{*i*} are the total biodiesel sales and total taxation of the *i*th year. Using eqn (8)–(10), one can obtain NPV as:

$$\begin{aligned} \text{NPV} &= \text{NPV} = -\text{CC} \\ &+ \sum_{i=1}^n \frac{(\text{TBS} - \text{TAX}) + \text{BPC}_i - \text{FC}_i - \text{OC}_i - \text{MC}_i}{(1+r)^i} \\ &+ \frac{\text{SV}}{(1+r)^n} = \sum_{i=1}^n \frac{(\text{TBS} - \text{TAX})}{(1+r)^i} - \text{LCC} \\ &= \sum_{i=1}^n \frac{\text{TotalProfit} + \text{LCC}}{n(1+r)^i} - \text{LCC} \\ &= \frac{\text{TotalProfit} + \text{LCC}}{n} \sum_{i=1}^n \frac{1}{(1+r)^i} - \text{LCC}. \end{aligned} \quad (13)$$

This section involves some uncertain parameters, as summarized in Table 1. Table 1 includes the lower and upper bounds of all of the parameters. The bounds of the capital cost (*x*₁),¹⁹ the interest rate (*x*₂),²⁷ the operating rate (*x*₃),^{19,28,30} the feedstock price (*x*₄),¹⁹ the glycerol price (*x*₅),³¹ the maintenance rate (*x*₆),^{15,19} the biodiesel conversion efficiency (*x*₇)²⁹ and the biodiesel price (*x*₈)³² are obtained by the available data. All of the uncertain parameters follow the uniform distributions within their bounds. The principle of the selected uniform distribution is given in the following paragraph.

The maximum entropy principle (MEP)³³ was originally proposed to assign numerical values to probabilities in circumstances where certain particle information is available. The main idea associated with MEP is that the probability density function (PDF) of the output response can be estimated by maximizing the entropy subjected to the known partial information like the minimum, the maximum, the statistical moments and so on. In the case where only a minimum and a maximum are known for a variable, the corresponding maximum entropy distribution is a uniform distribution between the specified minimum and maximum for the variable. In this study, we only have the maximum values and minimum values for these uncertain parameters, thus the selection of uniform distribution within the specified minimum and maximum for an uncertain parameter is justified. When more statistical data are gathered, the different maximum entropy distribution may be obtained.

Table 1 Bounds of uncertain parameters for a crude-palm-oil-derived biodiesel production

Parameters	Lower bound (<i>x</i> _l ⁱ)	Upper bound (<i>x</i> _u ⁱ)
Capital cost (CC: <i>x</i> ₁) ¹⁹	\$9 million	\$15 million
Interest rate (<i>r</i> : <i>x</i> ₂) ²⁷	4.44%	13.53%
Operating rate (OR: <i>x</i> ₃) ^{19,28,30}	\$37.5 per ton	\$225 per ton
Feedstock price (FP: <i>x</i> ₄) ¹⁹	\$200 per ton	\$1200 per ton
Glycerol price (GP: <i>x</i> ₅) ³¹	\$0.08 kg ⁻¹	\$0.2 kg ⁻¹
Maintenance rate (MR: <i>x</i> ₆) ^{15,19}	1%	2%
Biodiesel conversion efficiency (CE: <i>x</i> ₇) ²⁹	96%	99%
Biodiesel price (BP: <i>x</i> ₈) ³²	\$0.66 per liter	\$1.58 per liter



2.2 The definition of the economical infeasibility probability

The total profit of the investment for a crude-palm-oil-derived biodiesel production is desired to be larger than zero, *i.e.*,

$$\text{TotalProfit} \geq 0 \quad (14)$$

In addition, the payback period is expected to not exceed a prescribed upper limit, *i.e.*,

$$\text{PP} = \frac{\text{CC}}{(\text{TotalProfit}/n)} = \frac{n \times \text{CC}}{\text{TotalProfit}} \leq \text{PP}^u. \quad (15)$$

where PP^u is the allowable upper limit. In this paper, PP^u takes value of one third of the project's lifetime, *i.e.*, $\text{PP}^u = n/3 = 20/3$ years.

Further, eqn (15) can lead to eqn (16)

$$\frac{n \times \text{CC}}{\text{TotalProfit}} \leq \text{PP}^u \Rightarrow \text{TotalProfit} \geq \frac{n \times \text{CC}}{\text{PP}^u}. \quad (16)$$

Finally, NPV should be larger than zero in order to ensure the feasibility of crude-palm-oil-derived biodiesel production plant, specifically,

$$\text{NPV} = \frac{\text{TotalProfit} + \text{LCC}}{n} \sum_{i=1}^n \frac{1}{(1+r)^i} - \text{LCC} \geq 0. \quad (17)$$

Further, eqn (17) can lead to eqn (18)

$$\text{TotalProfit} \geq \left(\frac{n}{\sum_{i=1}^n \frac{1}{(1+r)^i}} - 1 \right) \times \text{LCC}. \quad (18)$$

Therefore, the biodiesel production should simultaneously satisfy eqn (14), (16) and (18) in order to ensure economical feasibility. For the sake of convenience, eqn (14), (16) and (18) are rewritten as

$$g_1(x_1, \dots, x_8) = g_1(\mathbf{x}) = \text{TotalProfit} \geq 0, \quad (19)$$

$$g_2(x_1, \dots, x_8) = g_2(\mathbf{x}) = \text{TotalProfit} - \frac{n \times \text{CC}}{\text{PP}^u} \geq 0, \quad (20)$$

$$g_3(x_1, \dots, x_8) = g_3(\mathbf{x}) = \text{TotalProfit} - \left(\frac{n}{\sum_{i=1}^n \frac{1}{(1+r)^i}} - 1 \right) \times \text{LCC} \geq 0 \quad (21)$$

where $g_j(\mathbf{x})$ ($j = 1, 2, 3$) represents the limit state function; $\mathbf{x} = (x_1, \dots, x_8)$ denotes the vector of the uncertain parameters summarized in Table 1.

The crude-palm-oil-derived biodiesel production will not be feasible if any one of the three equations does not hold. The uncertainties in the parameters given in Table 1 will result in the variation in the NPV, TotalProfit and payback period, and

then one of the three equations (*i.e.*, eqn (19)–(21)) or two of the three equations or all of the three equations may not hold, indicating that biodiesel production is not feasible in terms of economical efficiency. Thus, in order to ensure the economical feasibility, eqn (19)–(21) should simultaneously hold, and then the economical infeasibility probability can further be defined by

$$\begin{aligned} \text{EIP} &= 1 - P\{g_1(\mathbf{x}) \geq 0 \cap g_2(\mathbf{x}) \geq 0 \cap g_3(\mathbf{x}) \geq 0\} \\ &= 1 - P\{\min(g_1(\mathbf{x}), g_2(\mathbf{x}), g_3(\mathbf{x})) \geq 0\} \\ &= 1 - \{g(\mathbf{x}) \geq 0\} \end{aligned} \quad (22)$$

with

$$g(\mathbf{x}) = \min(g_1(\mathbf{x}), g_2(\mathbf{x}), g_3(\mathbf{x}))$$

where the notation “ \cap ” means the intersection of sets; EIP represents the economical infeasibility probability of biodiesel production; $P\{\cdot\}$ indicates the probability that the event occurs; $\min(g_1(\mathbf{x}), g_2(\mathbf{x}), g_3(\mathbf{x}))$ is the minimum value of the set consisting of $g_1(\mathbf{x})$, $g_2(\mathbf{x})$ and $g_3(\mathbf{x})$. The following will discuss the significance associated with EIP in detail.

Probability is a measure of likelihood that an event will occur, which is quantified as a number between 0 and 1, in which 0 implies impossibility and 1 implies certainty.³⁴ The higher the probability of an event, the more certain that the event will occur, and *vice versa*.³⁴ Accordingly, EIP is a measure of likelihood that the crude-palm-oil-derived biodiesel production is economically infeasible. A lower value for EIP corresponds to the more certain that the project will be profitable under the known statistical information in Table 1, and *vice versa*. A value of one for EIP indicates that the project will certainly not be profitable, while a value of zero for EIP indicates that the project will certainly be profitable under the known partial statistical information in Table 1. More additional statistical data may be needed to help engineers further assess the economical feasibility of the crude-palm-oil-derived biodiesel production.

2.3 Evaluation of the economical infeasibility probability

EIP defined in eqn (22) can further be written by³⁵

$$\text{EIP} = 1 - P\{g(\mathbf{x}) \geq 0\} = 1 - \int_{\Omega} \delta_1[g(\mathbf{x})] \prod_{i=1}^8 p_i(x_i) \prod_{i=1}^8 dx_i \quad (23)$$

with $\Omega = \Omega_1 \times \Omega_2 \times \dots \times \Omega_8$ and

$$\delta_1[g(\mathbf{x})] = \begin{cases} 1, & \text{for } g(\mathbf{x}) \in [0, +\infty) \\ 0, & \text{otherwise} \end{cases} \quad (24)$$

where EIP represents the economical infeasibility probability of biodiesel production; $\delta_1[g(\mathbf{x})]$ is an indicator function with $\delta_1[g(\mathbf{x})] = 1$ if $g(\mathbf{x}) \in [0, +\infty)$ and $\delta_1[g(\mathbf{x})] = 0$ otherwise; and Ω_i and $p_i(x_i)$ are the sample space and the probability density function (PDF) of the i th parameter x_i , respectively.

Using Monte Carlo simulation method, eqn (23) can be expressed by³⁵



$$\begin{aligned} \text{EIP} &= 1 - \int_{\Omega} \delta_1[g(\mathbf{x})] \prod_{i=1}^8 p_i(x_i) \prod_{i=1}^8 dx_i \\ &= 1 - E\{\delta_1[g(\mathbf{x})]\} \approx 1 - \frac{1}{N} \sum_{j=1}^N \delta_1[g(x_j)] \end{aligned} \quad (25)$$

where $\mathbf{x} = [x_1, \dots, x_8]$ are the uncertain parameters; $\delta_1[g(\mathbf{x})]$ denotes the indicator function as defined in eqn (24); $E[\cdot]$ represents the expected value of a random variable; and x_j ($j = 1, \dots, N$) denotes the j th sample generated by the pseudo-random generator according to the PDFs of the uncertain parameters \mathbf{x} .

2.4 Effect of an individual parameter on the economical infeasibility probability

The expected shift in the EIP due to the elimination of uncertainty in x_i can be employed to measure the effect of x_i on the output, which is defined by

$$\text{IM}_i = E_{x_i}[\Delta\text{EIP}(x_i)] \quad (26)$$

with

$$\Delta\text{EIP}(x_i) = |\text{EIP} - \text{EIP}_{x_i}|, \quad (27)$$

where EIP is the original economical infeasibility probability considering the uncertainties in all of the parameters; EIP_{x_i} represents the conditional economical infeasibility probability given x_i ; $E_{x_i}[\cdot]$ represents the mathematical expectation with respect to x_i . $\Delta\text{EIP}(x_i)$ measures the absolute difference between EIP and EIP_{x_i} , as sketched in Fig. 1. In Fig. 1, $p_G(g)$ is the original PDF of the limit state function g , and $p_{G|x_i=x_i^*}(g)$ represents the condition PDF of the limit state function g when fixing x_i to x_i^* , i.e., $x_i = x_i^*$. Meanwhile, EIP denotes the original EIP that is the

area surrounded by OC, CD and DO, while $\text{EIP}_{x_i=x_i^*}$ indicates the conditional EIP that is the area surrounded by OA, AB and BO.

Similar to IM_i , the expected shift rate in the EIP due to the elimination of uncertainty in x_i can be defined by

$$\text{IMR}_i = E_{x_i}[\Delta\text{EIPR}(x_i)] \quad (28)$$

with

$$\Delta\text{EIPR}(x_i) = \frac{|\text{EIP} - \text{EIP}_{x_i}|}{\text{EIP}}, \quad (29)$$

where $\Delta\text{EIPR}(x_i)$ measures the absolute difference rate between EIP and EIP_{x_i} with respect to EIP, in which x_i is fixed to one of its realizations.

In this paper, IM_i and IMR_i will be utilized to identify the influential parameters and the uninfluential parameters. If IM_i and IMR_i for x_i are very small, x_i can be considered as an uninfluential parameter and can be fixed to any value within its variation range.

3. Results and discussion

In this section, EIP is first evaluated. Then, IM_i and IMR_i for x_i are further assessed. Finally, the influential parameters and the uninfluential parameters are identified.

For EIP given in eqn (25), 100 independent repeated evaluations are carried out to obtain 100 replicates, and their average $\overline{\text{EIP}}(N)$ is considered as the final result of EIP. The root mean square error (RMSE) of the 100 replicates is regarded as an indicator of convergence at sample size N , as defined by:

$$\text{RMSE}(N) = \sqrt{\frac{\sum_{l=1}^{100} [\overline{\text{EIP}}_l(N) - \overline{\text{EIP}}(N)]^2}{100}} \quad (30)$$

$$\overline{\text{EIP}}(N) = \frac{1}{100} \sum_{l=1}^{100} \overline{\text{EIP}}_l(N) \quad (31)$$

where $\text{RMSE}(N)$ represents the root mean square error of the 100 replicates at sample size N ; $\overline{\text{EIP}}_l(N)$ denotes the l th replicate, and $\overline{\text{EIP}}(N)$ is the average of the 100 replicates.

Similar to EIP, 100 independent repeated calculations are also performed for IM_i defined in eqn (26) and IMR_i defined in eqn (28), and the averages and the root mean square errors of the 100 replicates are regarded as the final results and the indicators of convergence for them, respectively.

3.1 Evaluation of the economical infeasibility probability

Eight uncertain parameters have been considered for a crude-palm-oil-derived biodiesel production, as shown in Table 1. Fig. 2 shows the PDFs for the net present value defined in eqn (13), the total profit defined in eqn (8) and the limit state functions $g_i(\mathbf{x})$ ($i = 1, 2, 3$) defined in eqn (19)–(21) under these uncertain parameters, in which these PDFs are estimated by the efficient kernel density estimation method.³⁶ Fig. 2 reflects two significant observations. The first is that these uncertain parameters have given rise to the variation in the net present

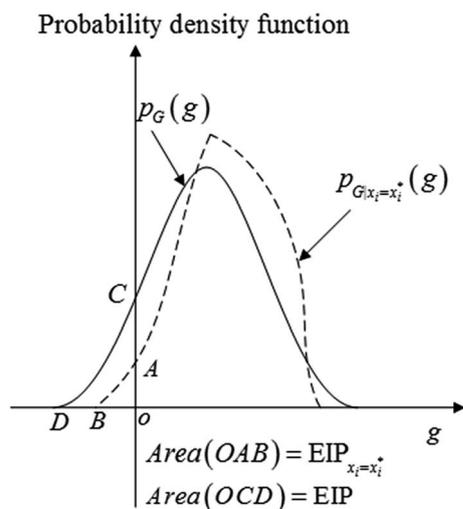


Fig. 1 Original probability density function $p_G(g)$ (solid), conditional probability density function $p_{G|x_i=x_i^*}(g)$ (dashed), original economical infeasibility probability EIP and conditional economical infeasibility probability $\text{EIP}_{x_i=x_i^*}$.



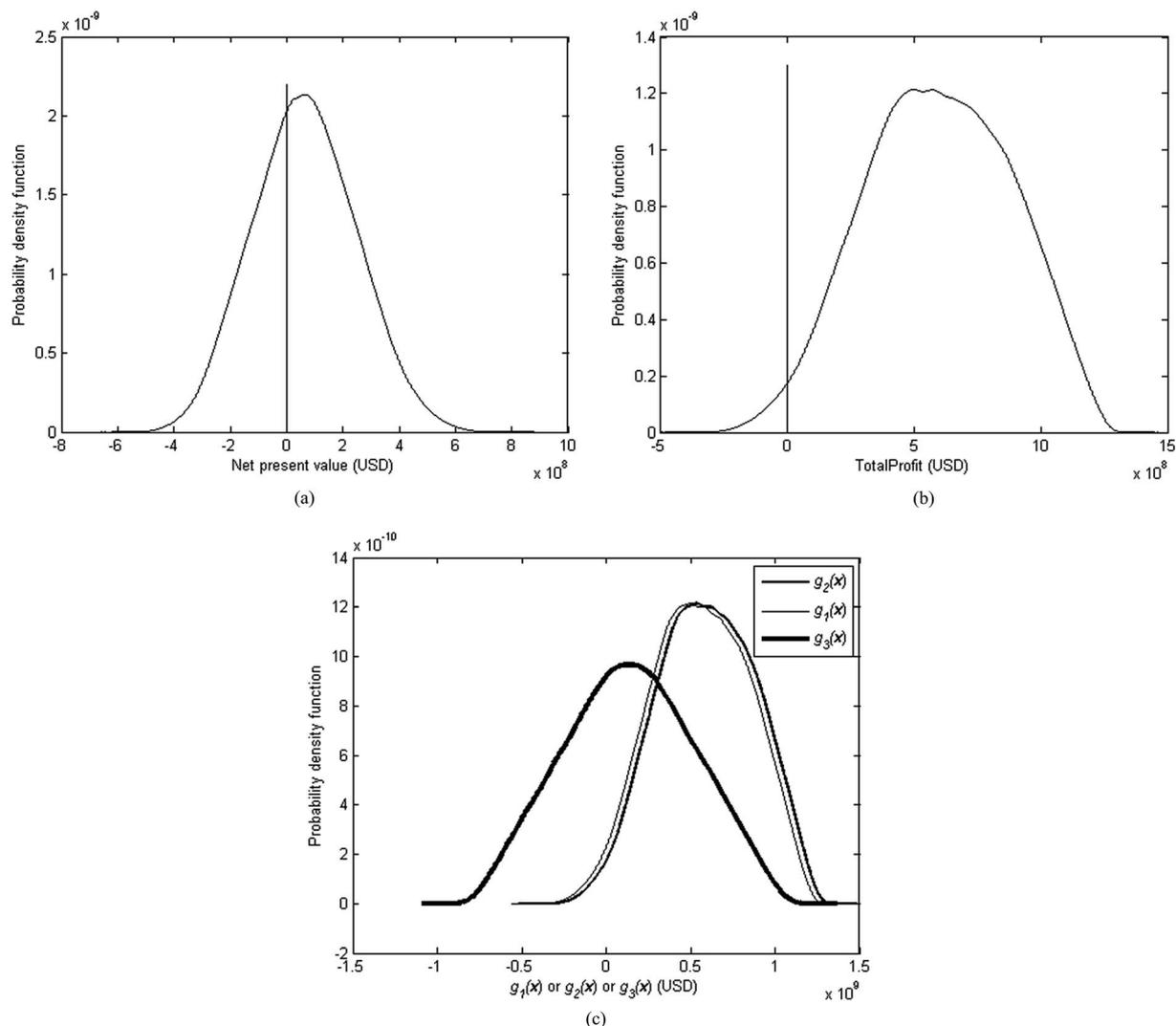


Fig. 2 Probability density functions (PDFs) for the net present value, the total profit and the limit state functions, (a) PDF for NPV, (b) PDF for TotalProfit and (c) PDFs for $g_i(x)$ ($i = 1, 2, 3$).

value, the total profit and the limit state functions $g_i(x)$ ($i = 1, 2, 3$). The second observation is that a fraction of the net present value, the total profit and the limit state functions $g_i(x)$ ($i = 1, 2, 3$) have been less than zero due to the effects of these uncertain parameters, indicating the possibility of the economical infeasibility.

Fig. 3 depicts the estimated EIP and the RMSE of the estimated EIP with the increasing samples, in which the number of samples is plotted by a log transformation. As revealed by Fig. 3, the sequence of the estimated EIP values converges to the accurate EIP with the increasing samples, and the RMSE of the estimated EIP decreases. Meanwhile, Fig. 3 illuminates that 5×10^4 samples have led to the convergence of the results and the estimated EIP value is 0.3676. A value of 0.3676 for EIP indicates that the project will not be profitable with the probability of 0.3676 (or 36.76%), in other words, 36.76 out of 100 outcomes will not be economically feasible under the known partial statistical information given in Table 1.

In summary, these uncertain parameters can lead to remarkable impacts on the techno-economic assessments. The uncertainties in these parameters have produced the economical infeasibility of a crude-palm-oil-derived biodiesel production. The following will assess the effect of an individual uncertain parameter on EIP.

3.2 Assessment of the effect of an individual parameter

Fig. 4 shows the estimated sensitivity values and the RMSE of the estimated sensitivities for IM and IMR with the increasing samples. Fig. 4a and c show that 10^3 samples have yielded good results for IM_i ($i = 1, \dots, 8$) and IMR_i ($i = 1, \dots, 8$), while Fig. 4b and d illustrate that 10^5 samples are required to obtain the reasonable results of these two indicators with low values of RMSE. In addition, Fig. 4a and c indicate that x_7 (the biodiesel conversion efficiency), x_3 (the operating rate), x_4 (the feedstock price) and x_8 (the biodiesel price) generate considerable effects



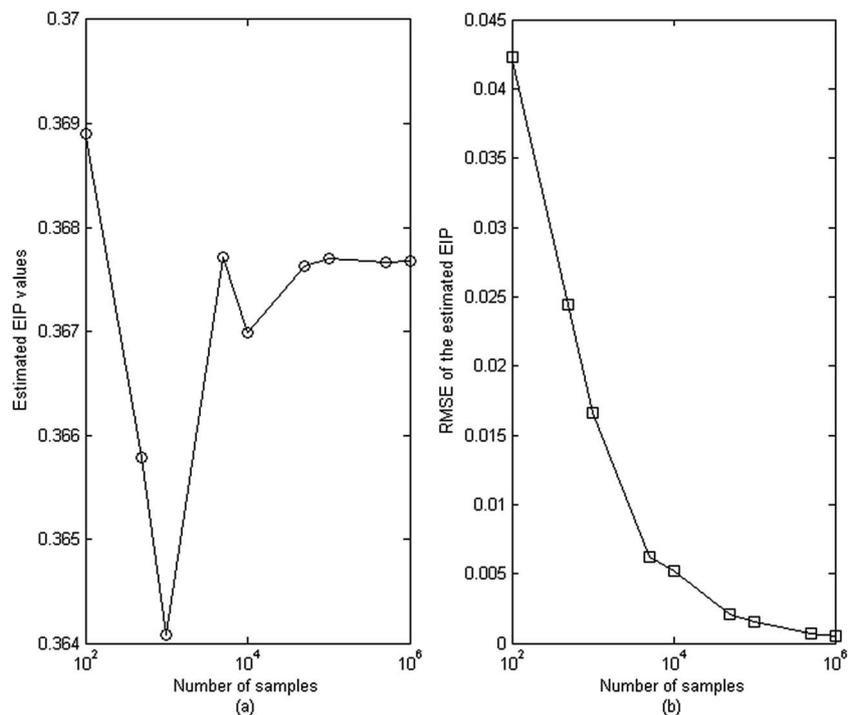


Fig. 3 Estimated EIP values and RMSE of the estimated EIP with the increasing samples, (a) estimated EIP values and (b) RMSE of the estimated EIP.

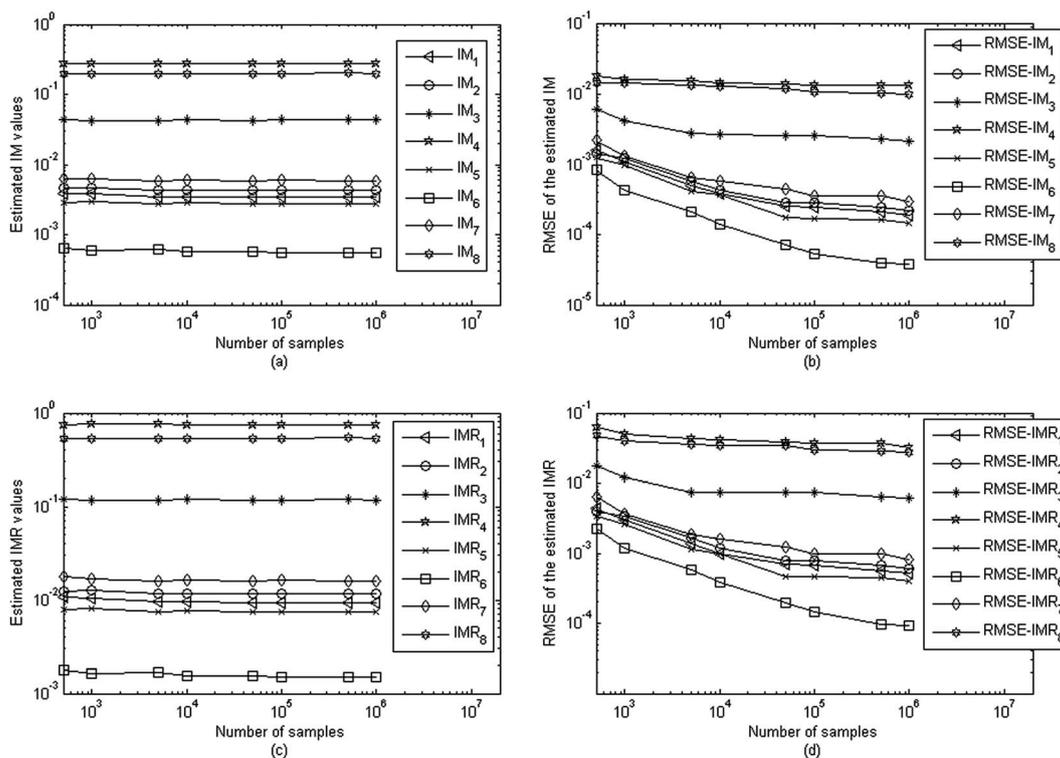


Fig. 4 Estimated sensitivity values and RMSE of the estimated sensitivities with the increasing samples, (a) estimated IM values, (b) RMSE of the estimated IM, (c) estimated IMR values and (d) RMSE of the estimated IMR.



Table 2 The estimated values of the NPV-based sensitivity

Parameters	IM _{<i>i</i>} (<i>i</i> = 1, 2, ..., 8)	IMR _{<i>i</i>} (<i>i</i> = 1, 2, ..., 8)
Capital cost (CC: x_1)	3.5010×10^{-3}	9.5217×10^{-3}
Interest rate (r : x_2)	4.2695×10^{-3}	1.1606×10^{-2}
Operating rate (OR: x_3)	4.3712×10^{-2}	1.1882×10^{-1}
Feedstock price (FP: x_4)	2.7550×10^{-1}	7.4952×10^{-1}
Glycerol price (GP: x_5)	2.7324×10^{-3}	7.4317×10^{-3}
Maintenance rate (MR: x_6)	5.5935×10^{-4}	1.5207×10^{-3}
Biodiesel conversion efficiency (CE: x_7)	5.9706×10^{-3}	1.6246×10^{-2}
Biodiesel price (BP: x_8)	1.9841×10^{-1}	5.3959×10^{-1}

on EIP, while the other parameters exert lower influences on EIP. This leads to the importance ranking of the uncertain parameters: $x_4 > x_8 > x_3 > x_7 > x_2 > x_1 > x_5 > x_6$. If we take $g(\mathbf{x}) = g_3(\mathbf{x})$ defined in eqn (21) and (22), we can similarly define the NPV-based sensitivity to uncertainty parameters by eqn (26) and (28). Then, we can similarly evaluate the estimated values for the corresponding NPV-based IM_{*i*} (*i* = 1, 2, ..., 8) and IMR_{*i*} (*i* = 1, 2, ..., 8), as summarized in Table 2. According to the results given in Table 2, we can obtain the ranking of the uncertain parameters as $x_4 > x_8 > x_3 > x_7 > x_2 > x_1 > x_5 > x_6$. Thus, we have obtained the same ranking of sensitivity parameters for the proposed novel EIP and NPV.

The results of IM and IMR shown in Fig. 4a and c and Table 2 can classify the parameters into two categories: the influential

parameters and the uninfluential parameters. The influential parameters include x_3 , x_4 , x_7 and x_8 , whereas the uninfluential parameters comprise x_1 , x_2 , x_5 and x_6 . For these uninfluential parameters, eliminating the uncertainties in them and fixing them to any values within their variation ranges will not bring about distinct effects on EIP and $g(\mathbf{x})$. Fig. 5 shows the original and conditional PDFs of $g(\mathbf{x})$, in which the original PDF is the probability density function of $g(\mathbf{x})$ subjected to all of the eight uncertain parameters, while the condition PDF of $g(\mathbf{x})$ is determined when the uninfluential parameter x_i (*i* = 1, 2, 5, 6) is fixed to a value within its variation range, *i.e.*, $x_i = x_{ij}$ (*i* = 1, 2, 5, 6; *j* = 1, 2, 3). The shifts between the original PDF and the conditional PDF are negligible, which indicates that removing the uncertainties in the uninfluential parameters will not remarkably impact EIP and $g(\mathbf{x})$.

Fig. 6 depicts the original and conditional PDFs of $g(\mathbf{x})$ when the influential parameters x_3 , x_4 , x_7 and x_8 are fixed to the values within their variation ranges, *i.e.*, $x_i = x_{ij}$ (*i* = 3, 4, 7, 8; *j* = 1, 2, 3). It can be seen that eliminating the uncertainties in the influential parameters can cause distinct variation of $g(\mathbf{x})$ and EIP.

As revealed by the previous results, more concern should be focused on these influential parameters during the project's lifetime including x_7 (the biodiesel conversion efficiency), x_3 (the operating rate), x_4 (the feedstock price) and x_8 (the biodiesel price) in order to ensure economical feasibility. Meanwhile, these uninfluential parameters can be fixed to any values within their variation ranges without causing distinct influence on EIP.

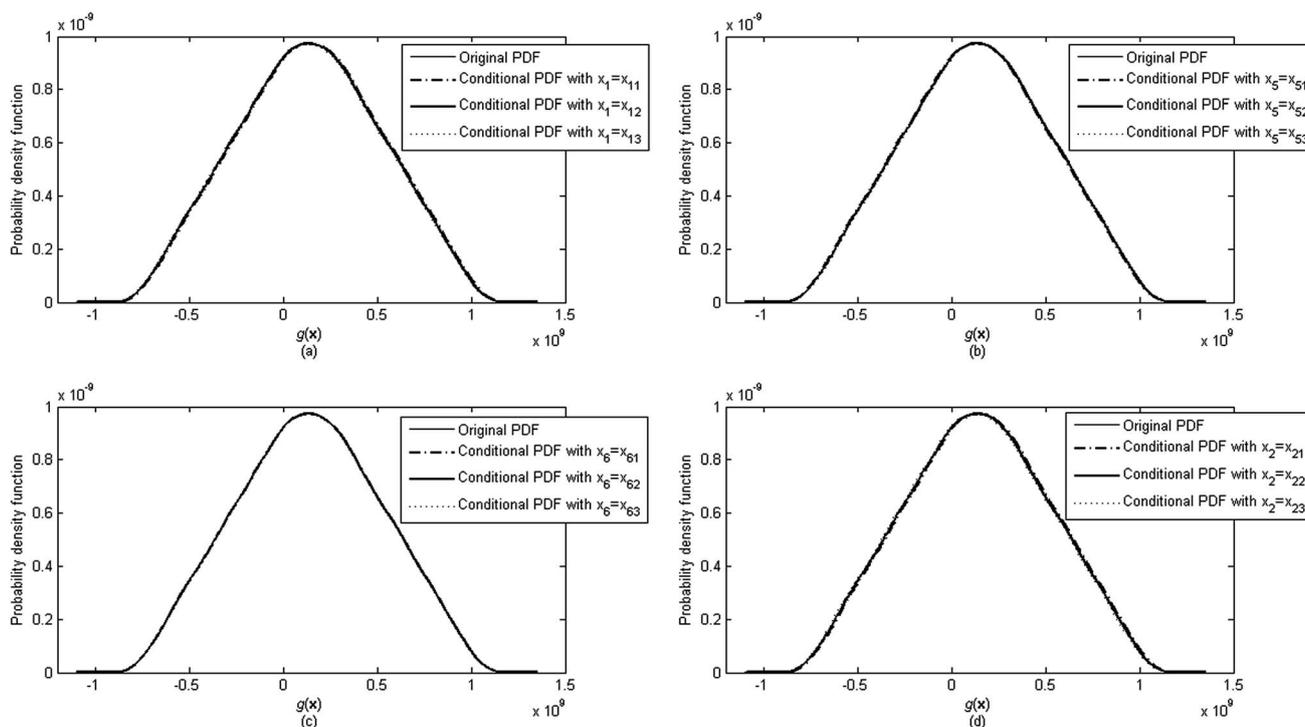


Fig. 5 Original probability density function and conditional probability density function fixing unimportant parameters for $g(\mathbf{x})$, (a) fixing the capital cost, (b) fixing the glycerol price, (c) fixing the maintenance rate and (d) fixing the interest rate.



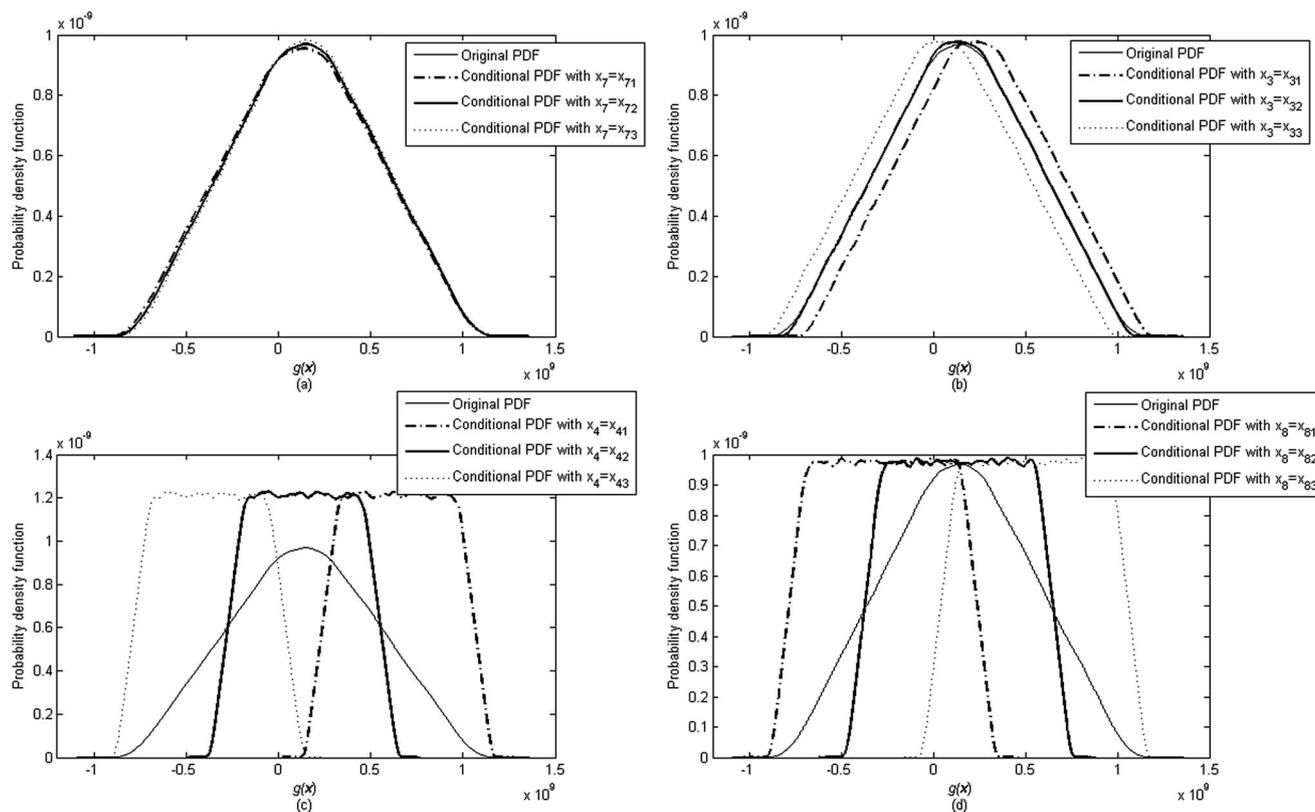


Fig. 6 Original and conditional probability density functions for $g(x)$, (a) fixing the biodiesel conversion efficiency, (b) fixing the operating rate, (c) fixing the feedstock price and (d) fixing the biodiesel price.

4. Conclusions

The economical infeasibility probability and the influence of an individual parameter on the economical infeasibility probability have been considered for the techno-economic assessments of a crude-palm-oil-derived biodiesel production with eight random parameters. The final results reveal two important conclusions. The first is that the economical infeasibility probability is 0.3676, and the second is that the biodiesel conversion efficiency, the operating rate, the feedstock price and the biodiesel price can generate major effects on the economical infeasibility probability.

Nomenclature

BP	Biodiesel price
BPC	Byproduct credit
BPC_i	Byproduct credit of the i th year
CC	Capital cost
CE	Conversion efficiency from feedstock to biodiesel
d	Depreciation rate
EIP	Economical infeasibility probability
FC	Feedstock cost
FC_i	Feedstock cost of the i th year
FP	Feedstock price

FU	Annual total feedstock consumption
GCF	Glycerol conversion factor
GP	Glycerol price
LCC	Life cycle cost
MC	Maintenance cost
MC_i	Maintenance cost of the i th year
MCS	Monte Carlo simulation
MEP	Maximum entropy principle
MR	Maintenance rate
NPV	Net present value
OC	Operating cost
OC_i	Operating cost of the i th year
OR	Operating rate or operating cost of per-ton crude-palm-oil-derived biodiesel production
PC	Production capacity
PP	Payback period of the biodiesel production
PP^u	Allowable upper limit of payback period
PWF_n	Worth factor in the year n
RC	Replacement cost
r	Interest rate
SV	Salvage value
TAX	Annual total taxation
TBS	Annual total biodiesel sales
TEA	Techno-economic assessments
TotalProfit	Total profit
TR	Tax rate
ρ	Density of the biodiesel



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