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Published by the Faculty of Engineering, Khon Kaen University, Thailand

# Net energy analysis of small-scale producer gas production from Jatropha seed

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Received 15 May 2020
Revised 22 July 2020
Accepted 11 August 2020

**Abstract**

Net energy analysis (NEA) of biodiesel production from Jatropha energy crop has been extensively studied. The commercialization of the Jatropha biodiesel, however, is not available yet due to high energy input for seed pressing and oil processing, which lowers the net energy balance (NEB) and the net energy ratio (NER) of the biodiesel production. Gasification technology is an alternative, which can bypass seed pressing and oil processing. This study aims to investigate the NEA of producer gas production from Jatropha seed per hectare of plantation for a 20-year lifetime, but the Jatropha shell and tree are not included in the studied system boundary. The energy output is the amount of diesel fuel replaced by producer gas for 1 kWeh electricity generation. 10 kg of gas replaced diesel fuel by 0.22 kg, or 46.9 MJ of gas replaced diesel fuel by 9.68 MJ. The results highlighted that the NEB and NER were 490.14 GJ and 5.45, respectively. The total $CO_2$ emission was 296 tonnes (t). If the gasifier and gas cleaning system perform more efficiently, the NEB and NER become higher, and the $CO_2$ emission decreases. If the energy input for introducing gasifying agent and cleaning producer gas is saved, the NEB and NER will increase up to 543.41 GJ and 9.57, respectively. Furthermore, the optimization of engine operation parameters can minimize $CO_2$ emissions and improve the NEB and NER. Overall, the production of producer gas from Jatropha seed can be considered as a renewable system based on the findings of the renewability indicators of NEB and NER.

**Keywords:** Renewability indicators, Energy crop, $CO_2$ emission, Syngas, Diesel fuel, Dual fuel mode

## 1. Introduction

An exploration of alternative fuels converted from biomass feedstock has received much attention in recent years due to the concerns of fossil fuel reservoir depletion and greenhouse gas (GHG) emissions. Jatropha is a potential energy crop for biodiesel production because of its merits such as high oil content with physicochemical properties similar to fossil diesel, sustainable fatty acid composition, non-edibility and renewability, and resistance to various agro-climatic conditions, among others [1, 2]. Jatropha oil can be converted to biodiesel that is used to substitute the fossil diesel fully or partially to power compression ignition (CI) engines [3]. Many studies have already investigated the net energy analysis (NEA) of biodiesel produced from the Jatropha energy crop using different Jatropha plantation systems, oil transesterifying catalysts, and end uses [4-10]. There are 27 energy indicators of renewability and sustainability of biodiesel production [11]. Most of the studies, however, used Net Energy Balance (NEB) and Net Energy Ratio (NER) as the renewability indicators of the Jatropha biodiesel production. According to the previous studies, the NERs of the Jatropha biodiesel were 1.77 [4], 1.85 [5], 1.42 [6], 2.42 [12], and 1.4 [8]. The NER can increase up to 8.6 [8] or higher depending upon methodology, oil processing technique, and energy allocation model [4]. For instance, the NER decreases when the energy input for transporting seedlings, fertilizers, biomass, and biodiesel is included [5]. The study of the NEA of palm oil production in Indonesia also corroborated this statement [13]. Energy input used for building and powering production facilities, operating biofuel production, manufacturing farm machinery, and powering dwellings for workers and their households also affects the renewability indicators [14]. However, these energy allocation criteria have been less considered probably due to limited data availability, specifically for case studies of developing countries. The NER increases if the by-products of biodiesel production and biomass residues are considered as the energy output [4-6]. A considerable variation in energy values mainly depends on allocating energy criteria [11, 15, 16]. The NER is widely varied upon site requirements and treatment, a technique of propagation and plantation, tending practice of the plantation and annual rainfall, and energy input for oil expelling and biodiesel processing [4, 13, 16]. Seed pressing and oil processing are the most consumed energy processes, thereby lowering the NER [4]. Seed pressing and oil processing accounted for 34.85% and 24% of the total energy input of Jatropha biodiesel production, respectively [4]. These high energy input requirements lower the NER.

Consequently, we need to check whether there is another more efficient energy production pathway for the Jatropha bioenergy crop and compare it with the NEA of the Jatropha biodiesel production as the baseline. Gasification technology can bypass seed pressing and oil processing to save considerable energy input. Gasification is a renewable technology that is applied to convert dried biomass to combustible gas, widely called syngas or producer gas, through the thermochemical process. This technology is not new, and it has been applied for

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doi: 10.14456/easr.2021.22

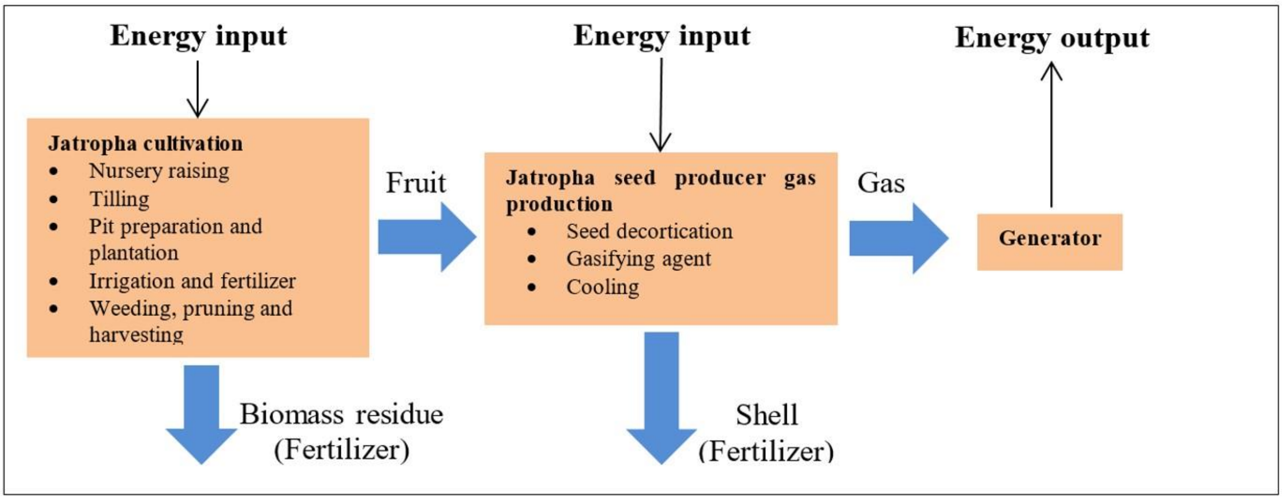


**Figure 1** A system boundary of Jatropha seed producer gas production

over 180 years [17]. A combustible gas converted from agricultural residue through gasification technology is a waste-to-wealth paradigm. A gasifier can be coupled with a diesel engine, and dried biomass is used as the feedstock for a gasifier-engine system to replace diesel fuel partially. The technical feasibility of a gasifier-engine system using various biomass types (e.g., charcoal, wood chip, coir-pith, sawdust, ground nutshell, and bagasse) has been extensively studied [18-27]. The producer gas could replace diesel fuel by 49 - 86% [28, 29]. The varied diesel replacement rate is attributed to biomass type and properties, specific gasifier design, oxidation agent type, and oxidation agent flow rate, among other variables [17, 30]. There are a few studies of technical feasibility (i.e., engine performance, emissions, and combustion characteristics) of the gasifier-engine system using the Jatropha shell [31], Jatropha seed cake [3, 32, 33], Jatropha seed [28, 34], and a mixture of Jatropha seed and seed cake [35]. The optimization studies of Jatropha seed and Jatropha seed cake producer gas flow rates have been carried out to minimize electricity generation cost, specific diesel consumption, specific $CO_2$ emissions [36, 37], and the optimum gas flow rate should be about 10 kg/h. The combustion characteristics (i.e., combustion pressure, net heat release rate, and cumulative heat release) perform poorly with an increase in a gas flow rate of more than 10 kg/h [34]. The Jatropha biomasses (i.e., shell, seed, and seedcake) can be the potential feedstocks for the gasifier-diesel engine system, based on the technical feasibility of the previous studies.

Based on the above-mentioned literature, the primary motivation of our research is that the NEA of Jatropha seed-derived producer gas production has remained unknown mainly. Consequently, the thrust of this study intends to investigate the NEA of Jatropha seed producer gas production and compare it to biodiesel production to provide a more efficient pathway of Jatropha bioenergy production and exploitation. The findings would be informative to support bioenergy policymaking in developing countries and further research. The originality of our study is the investigation of the energy and environmental benefits of producer gas production from the Jatropha seed, widely known as an energy crop.

## 2. Methodology

*2.1 Goal, scope, and system boundary*

*2.1.1 Study goal*

This study attempts to investigate the NEA of Jatropha seed producer gas production. As already mentioned, two renewability indicators of the NEA are considered in our study, i.e., NEB and NER. The latter is accepted as an indicator of the energy production system efficiency. The NEB and NER are calculated using the equations below:

$$\text{NEB} = \text{energy output} - \text{energy input} \tag{1}$$

$$\text{NER} = \text{energy output}/\text{energy input} \tag{2}$$

where the unit of energy output and energy input is GJ, and the allocation factor is not considered in our study. The present study was based on one hectare (ha) of Jatropha plantation for a period of 20 years of the life cycle. The fully ripen Jatropha seed was used as the biomass feedstock for a gasifier, while the shell was deliberately removed.

*2.1.2 Scope of the study*

The designed system includes Jatropha cultivation, producer gas production, and producer gas combustion in a pilot-scale diesel generator to run on dual fuel mode. The main reason for producer gas exploitation for a diesel generator to run on dual fuel mode is that the producer gas is convenient and accessible for decentralized power generation, especially for a remote district that is difficult to access to fossil fuels.

*2.1.3 System boundary*

The system boundary consists of Jatropha farming, seed decortication, Jatropha seed gasification, and producer gas combustion in an electrical generator (see Figure 1). A Gasifier-generator unit was assumed to be installed close to a Jatropha plantation. Therefore, the energy utilization for transporting the fruit from the Jatropha plantation to the power plant was zero. All agricultural activities and energy consumption for gasification technology were included in the system boundary.

All the energy consumption for manufacturing the machinery was deliberately exclusive, i.e., power tiller or tractor, gasifier system, generator set, Jatropha seed shelling machine, and power shed. The impact of the disposal of this machinery to the environment was not considered in the designed system of our study.

*2.2 Data source*

*2.2.1 Jatropha seed production*

**Table 1** Distribution of energy input per hectare for the first five years [4]

| Jatropha cultivation | Energy input (GJ) |
|---|---|
| Nursery raising | 0.52 |
| Tilling | 0.45 |
| Fertilizer during plantation | 30 |
| Irrigation | 4.11 |
| **Total** | **35.08** |

**Table 2** Jatropha yield per hectare for the initial five years [4]

| Plantation year | Fruit yield (t/ha.year) | Seed yield (t/ha.year) |
|---|---|---|
| First | Nil | Nil |
| Second | 0.75 | 0.45 |
| Third | 3.125 | 1.875 |
| Forth | 7.5 | 4.5 |
| Fifth | 11.25 | 6.75 |

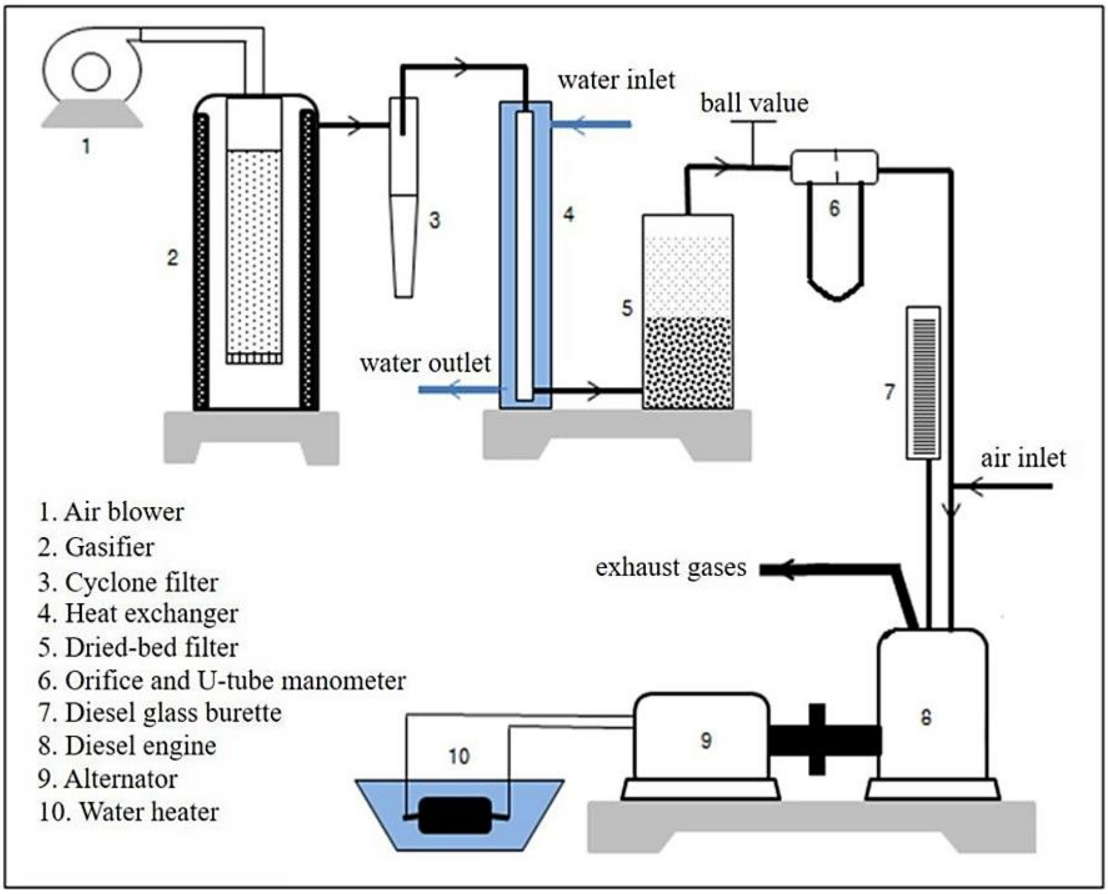


**Figure 2** Schematic representation of the gasifier-generator system [28]

The density of a Jatropha plantation was assumed to be 2,500 plants/ha (with a spacing of $2 \times 2$ m) [4]. The distribution of energy consumption for agricultural activities is listed in Table 1. Fertilizer accounts for the largest share of 30 GJ, followed by irrigation (4.11 GJ), nursery raising (0.52 GJ), and tilling (0.45 GJ). This translates that the fertilizer is responsible for 85.52% of the total energy consumption for the Jatropha cultivation.

Table 2 lists the Jatropha seed yields for the first five years. The seed yield of the 6$^{th}$ year onwards was assumed to be the same as that of the 5$^{th}$ year [4]. The seed harvesting, pruning, and weeding were assumed to be done manually. Energy consumption for these cultivation activities, therefore, was zero. Jatropha fruit is composed of 60% seed and 40% shell, on a weight basis [4]. It was assumed that a 1.5 kW mechanical decorticator with a capacity of 150 kg/h of fruit was used to remove the Jatropha shells from the seeds [4].

*2.2.2 Jatropha seed producer gas production*

The gasifier-generator system was adopted from [28], see Figure 2. Air was used as a gasifying agent for the thermochemical process of the Jatropha seed. A 250 W air blower is used to introduce air into a gasifier to supply the thermochemical process of the Jatropha seed. The gasified Jatropha seed exiting the gasifier is hot and dirty. A cyclone filter is used as a preliminary gas cleaner, followed by a shell-tube heat exchanger and dried-bed filter. An 18 W water pump is used to circulate the water for the heat exchanger, respectively. The average efficiency of fossil fuel-fired power plants for electricity generation in developing Asian countries was 38.8% [38], or the production of 1 kWeh electricity consumed 9.28 MJ of fossil diesel. The Jatropha seed consumption rate and gas production

**Table 3** Basic technical specifications of the gasifier [28]

| Item | Description |
|---|---|
| Type | Close top, throatless, downdraft |
| Gasifying agent | Air |
| Gasifier's weight (kg) | 30 |
| Critical dimensions (mm) | D = 350/ h=1800 |
| Capacity ($kW_{th}$) | 130 |
| Biomass consumption rate (kg/h) | 5 |
| Biomass feedstock | Jatropha seed |
| Efficiency (%) | ~77 |

**Table 4** Parameters and machines

| Parameters | Value | References |
|---|---|---|
| Jatropha seed yield for a 20-year lifetime (t) | 114.825 | Adopted from [4] |
| Calorific value of Jatropha seed (MJ/kg) | 26 | Adopted from [39] |
| Calorific value of producer gas (MJ/kg) | 4.69 | [37] |
| Calorific value of diesel (MJ/kg) | 44 | [40] |
| Density of diesel fuel (kg/L) | 0.85 | |
| Jatropha seed consumption rate (kg/h) | 5 | [28] |
| Producer gas production rate (kg/h) | 27 | [28] |
| Fossil fuel consumed for 1 kWeh electricity generation (MJ) | 9.28 | Adopted from [38] |
| Fossil diesel replaced by 10 kg of producer gas (kg) | 0.22 | Adopted from [36] |
| **Machines** | **Capacity** | **References** |
| Mechanical decorticator | | |
| Power (kWe) | 1.5 | [4] |
| Capacity (kg/h) | 50 | [4] |
| Air blower (kWe) | 0.018 | [28] |
| Water pump (kWe) | 0.25 | [28] |

rate were 5 kg/h and 27 kg/h, respectively [28]. This indicated that 1 kg of Jatropha seed produced 5.4 kg of producer gas. The technical specifications of the gasifier are tabulated in Table 3.

*2.2.3 Jatropha seed producer gas exploitation*

The cleaned producer gas was fumigated in a 2.5 kWe generator, and fossil diesel was injected to ignite the gas because the producer gas cannot be auto-ignited under the default compression ratio of a diesel engine, unlike diesel. The generator was operated at 70% of the rated power on producer gas-diesel dual fuel mode with a constant rotational speed of 3,000 rpm and a diesel injection timing of 9 degrees before the top dead center. The specific diesel consumption rate was 0.395 kg/kWeh for the neat diesel operation and 0.175 kg/kWeh for the dual fuel mode operation of a 10 kg/h producer gas flow rate [36]. Therefore, the combustion of 10 kg of producer gas in the dual fuel mode could save 0.22 kg of diesel fuel. In other words, 1 kg of Jatropha seed was equivalent to 0.119 kg of fossil diesel because 1 kg seed could produce 5.4 kg of gas, as mentioned earlier. The amount of fossil diesel replaced by producer gas was chosen as the energy output. Table 4 lists various main parameters and machines for each stage of Jatropha producer gas production and exploitation.

## 3. Results and discussion

*3.1 Energy input and output of producer gas production*

The total Jatropha seed was estimated at 114.83 t/ha, which was equal to 620.05 t/ha of producer gas for 20 years of the life cycle. The total producer gas replaced diesel fuel by 13.64 t or 600.21 GJ. The distribution of energy consumption and $CO_2$ emission of each stage for the perennial plantation of a 20-year lifetime is summarized in Table 5. The total energy consumption for the producer gas production accounted for 110.07 GJ, and the total energy output was 600.21 GJ. The most consumed energy activity was the gasification process, which was responsible for 51.88% of the total energy use. However, this energy consumption was 57.11 GJ, which was relatively much less than that of the seed pressing stage for Jatropha biodiesel production. The application of chemical fertilizer was the second most consumed energy consumption, which was responsible for 25.26%, followed by the trend of decortication, irrigation, gas cooling, nursery raising, and tilling at rates of 11.15%, 8.83%, 3.48%, 0.47%, and 0.41% respectively. The last column of Table 5 lists the $CO_2$ emission of each stage. It highlighted that the total $CO_2$ emission for gas production was 8.16 t. The $CO_2$ emission of the gas combustion in a diesel engine was 287.83 t. Therefore, the total $CO_2$ emission of Jatropha producer gas from production until exploitation was 295.99 t for a 20-year lifetime per hectare of plantation.

*3.2 Net energy balance (NEB) and net energy ratio (NER)*

The analysis of energy efficiency defines the terms of renewability, and if the NER is greater than one, the system is renewable [11]. Furthermore, to be a viable alternative to fossil fuel, the production of an alternative fuel should provide a net energy gain over the energy sources [14]. As apparent from the last two rows of Table 5, the NEB and the NER of the gasified Jatropha seed production per hectare of plantation for a 20-year lifetime are 490.14 GJ and 5.45, respectively. Therefore, it corroborated that the system of producer gas production from Jatropha is renewable. As mentioned earlier, 10 kg of gas replaced fossil diesel by 0.22 kg, or 46.9 MJ thermal energy of the gas replaced 9.68 MJ of diesel. In other words, one tonne of the gasified Jatropha seed replaced the diesel fuel by 5.37 GJ. This result was much lower than Jatropha biodiesel, roughly 50%. For the Jatropha biodiesel, an energy output of 11.907 GJ was generated from one tonne of Jatropha seed (adopted from [4]). However, the energy input for seed pressing is also high. The NEB and NER are the significant criteria for comparisons.

The NEB and NER will increase if an Imbert gasifier is used in place of a throatless gasifier and a gas cleaning unit is more efficient. The Imbert gasifier can produce the gas with better quality than the throatless gasifier because the former is designed with a throat that plays an important role to increase the gasification temperature, thereby reducing the tar content in the

**Table 5** Energy input and output per hectare for 20 years of the Jatropha life cycle

| Energy input | Unit (GJ) | Percentage share (%) | $CO_2$ emissions (t) |
|---|---|---|---|
| **Jatropha cultivation** | | | |
| Nursery raising | 0.52[a] | 0.47 | 0.02[a] |
| Tilling | 0.45[a] | 0.41 | 0.03[a] |
| Fertilizer during plantation | 30[a] | 27.25 | 1.18[a] |
| Irrigation | 9.72[b] | 8.83 | 0.71b[b] |
| **Decortication** | 12.27[b] | 11.15 | 1.12b[b] |
| **Gasification operation** | | | |
| Gasifying agent | 53.27 | 48.40 | 3.95[c] |
| Gas cooling | 3.84 | 3.48 | 0.28[c] |
| **Net energy analysis** | | | |
| **Total energy input** | **110.07** | | **8.16[c]** |
| **Energy output** | **600.02** | | 287.83[d] |
| **Net energy balance** | **490.14** | | |
| **Net energy ratio** | | **5.45** | |

[a] [4]
[b] Adopted from [4].
[c] $CO_2$ emission factor of diesel combustion is 74.10 t/ TJ [41]. This factor was used to calculate $CO_2$ emissions of Jatropha decortication because the Jatropha decorticator is fueled with diesel, as assumed above.
[d] Based on the Intergovernmental Panel on Climate Change (IPCC) [42], $CO_2$ emissions = Fuel × C content × Oxidation Fraction × 44/12, and C content of producer gas is 0.1266 kg per one kg of gas [37]. As mentioned already, the gas production for a 20-year lifetime was 620.05 t/ha.

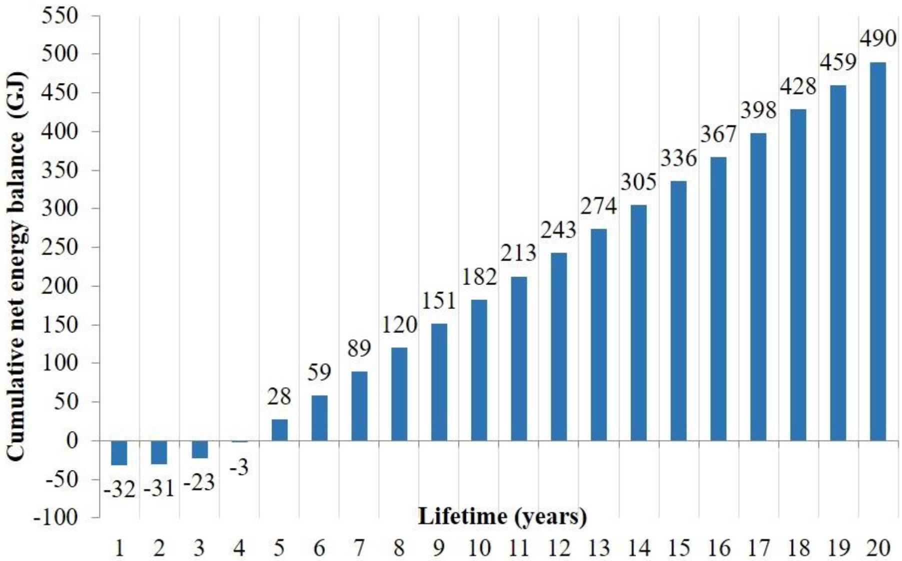


**Figure 3** Cumulative net energy balance of producer gas production from Jatropha seed

producer gas [17, 30]. Furthermore, it requires less operating cost and energy input for gas cleaning [30]. Especially, the Imbert gasifier connected with a diesel engine requires neither an air blower nor an air inducer [3, 21-23, 28], and therefore, the energy consumption for the introduction of a gasifying agent can be saved. The gasifying agent accounted for the largest share (48.40% or 53.27 GJ) for a 20-year lifecycle. For the gas cleaning unit, if the air is used instead of water to cool the hot gas, the energy requirement for gas cooling can be saved by 3.48%. Correspondingly, the NEB and NER would increase up to 543.41 GJ and 9.57, respectively. These values would have increased further had the dual-fuel engine been operated at medium speed (e.g., 1,500 rpm) in place of high speed (i.e., 3,000 rpm). The NER of the producer gas was found considerably higher than that of the biodiesel, regarding previous studies. The NER of the biodiesel production from Jatropha in rural India was only 1.85, and this value increased up to 3.40 with an addition of the Jatropha byproduct biogas as the energy output [5]. The NER of Jatropha biodiesel in Thailand was 7.5 when the Jatropha tree was included as the energy output [6]. The NERs of Jatropha biodiesel of other previous studies were 1.92 in Malaysia [43], 2.0 in China [44], 1.77 in India [4], and 2.42 in Thailand [12]. The NER of Jatropha-based biodiesel production varies from 1.4 to 8.0, subject to the methodologies and system boundaries [45].

The NER of Jatropha producer gas was significantly higher than that of Jatropha biodiesel because of low energy input for the gasification process (i.e., 57.11 GJ for 114.83 t of the seed), as can be seen from Table 5. In other words, gasifying one tonne of Jatropha seed consumed 0.497 GJ of diesel fuel, and this value was even lower than the energy input required for Jatropha biodiesel production (i.e., 3.978 GJ [1]). In other words, the Jatropha biodiesel production consumed energy eight times as much as the Jatropha producer gas production[2].

*3.3 Net energy analysis and $CO_2$ emissions*

*3.3.1 Net energy analysis*

Figure 3 shows the cumulative NEB in terms of year. It was found that the cumulative NEB was negative before the fifth year

[1] Adopted from [4].
[2] The energy input for cultivation was not included.

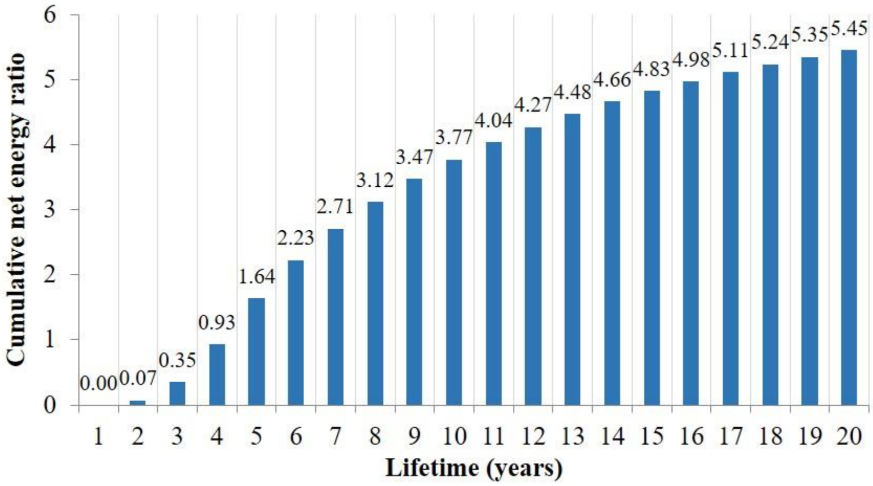


**Figure 4** Cumulative net energy ratio of producer gas production from Jatropha seed

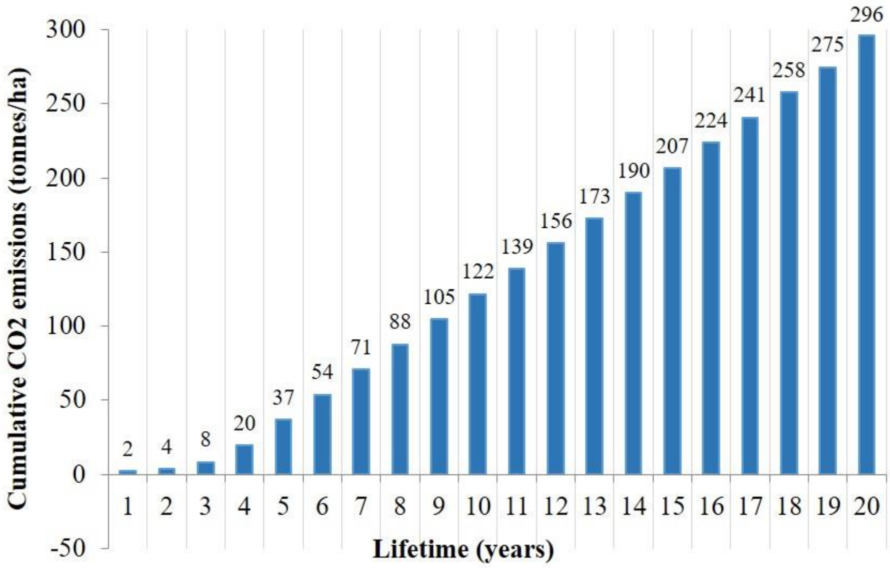


**Figure 5** Cumulative $CO_2$ emissions of producer gas production and exploitation

because of the high energy input used for the agricultural activities and low seed yield that could not offset. The cumulative NEB became positive from the fifth year and linearly increased due to high seed yield and fixed energy input for nursery raising, tilling, and chemical fertilizer during the plantation. The cumulative NER is highly correlated with the cumulative NEB, and the NER is lower than one only if the cumulative NEB is negative. The cumulative NER of gasified Jatropha seed was higher than one from the fifth year onwards, as can be seen from Figure 4. The cumulative NER dramatically increased when the life cycle year increased on account of no chemical fertilizer and lesser irrigation requirements. The cumulative NER sharply increased from year 5 to 13 on account of a considerable drop in energy input and an increase in seed yield. Afterward, the ensuing NER linearly increased because of seed yield at a constant rate, along with an irrigation requirement.

### *3.3.2 $CO_2$ emissions*

Figure 5 shows the cumulative total $CO_2$ emissions, i.e., production and exploitation. The amount of $CO_2$ emissions exponentially increased from 2 t in the first year to 37 t in the $5^{th}$ year, and it further increased linearly up to 296 t in year 20. The $CO_2$ emission of Jatropha producer gas was found higher than that of the Jatropha biodiesel (i.e, 20 t for the first five years [4]) because the combustion of producer gas is less efficient than combustion of biodiesel [17, 18, 20, 23], and there is a high presence of $CO_2$ constituent in producer gas [17, 33, 34].

This issue can be mitigated by improving the gas quality and combustion characteristics of a dual-fuel engine. The gas quality can be improved through 1) utilization of $CO_2$, steam, oxygen, or any mixture of them as a gasifying agent in place of air [46], 2) operation of an Imbert gasifier or a gasifier with advanced technology [17, 30, 47], 3) optimization of gasification temperature [48], and 4) proper design of gas cleaning system [28]. The combustion characteristics of dual producer gas-diesel fuel can be improved by 1) a proper design of a gas-air mixer [23, 33], 2) improvement of combustion cylinder [49] and diesel injection system [25], 3) operation at medium engine speed [33, 34], and 4) optimization of diesel injection timing [36, 37] and combustion pressure ratio [50].

### *3.4 Energy consumption for one kWeh electricity generation*

Figure 6 illustrates the comparison of the dual producer gas-diesel mode with the neat diesel mode for the generation of 1 kWeh electricity. The neat diesel operation consumes 17.38 MJ of diesel fuel. For the dual-fuel mode, 7.7 MJ of fossil energy combined with 10 kg of producer gas was combusted to generate 1 kWeh electricity. Production of 10 kg Jatropha producer gas

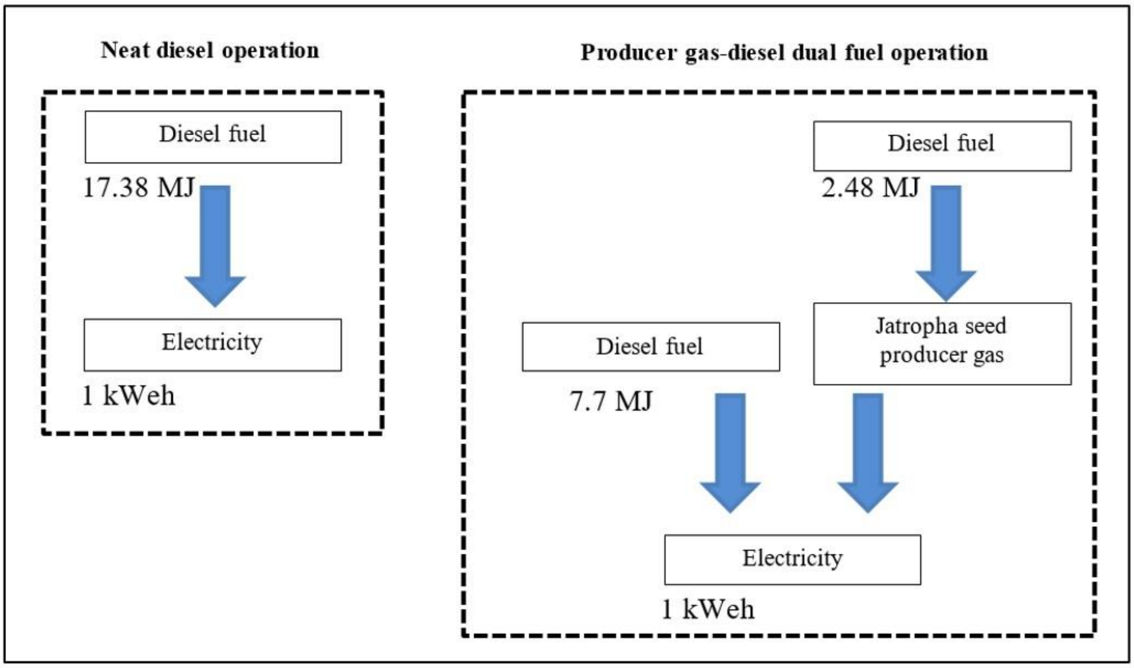


**Figure 6** Comparative neat diesel fuel operation with dual producer gas-diesel fuel operation

required 2.48 MJ of fossil energy input. Therefore, the total fossil energy requirement for dual fuel mode was 10.18 MJ. As compared with the neat diesel operation, the dual-fuel operation saved fossil energy by 7.23 MJ or 41.60% for 1 kWeh electricity generation. Upon the mathematical model developed in [37], the specific $CO_2$ emission for the neat diesel mode was 0.153 kg/kWeh, while that of the dual producer gas-diesel mode with a 10 kg/h gas flow rate was 0.599 kg/kWeh. The dual-fuel mode produced the $CO_2$ emission about four times as high as the neat diesel mode did because the engine was operated at high engine speed (i.e, 3,000 rpm), and the engine was designed for the neat diesel fuel mode, not for producer gas [37]. The specific $CO_2$ emissions would have been decreased had the engine been designed for the producer gas, which is more efficient for the combustion of producer gas. This implies the consumption of less producer gas, thereby lowering the concentration of $CO_2$ and CO content in the flue gas emissions. An increase in producer gas consumption is significantly associated with higher CO and $CO_2$ emissions due to an increased ignition delay period and the presence of CO and $CO_2$ constituents in producer gas [17, 28, 51, 52]. The CO gas emitted from the fossil fuel-powered engine is slowly oxidized by molecular oxygen in the lower atmosphere to formulate $CO_2$ gas [53]. However, the technical feasibility of the gasified Jatropha seed for the internal combustion engine has been less studied. As discussed above, the $CO_2$ emission of producer gas production and exploitation can be mitigated via various ways, and the Jatropha trees also play an important role to absorb $CO_2$ gas.

## 4. Conclusions and recommendations

The present study investigated the net energy analysis (NEA) of Jatropha seed-based producer gas production per hectare plantation for a 20-year lifetime. Net energy balance (NEB) and net energy ratio (NER) were used as the renewability indicators. The Jatropha shell and tree were deliberately excluded in the system boundary of energy production. The findings are concluded as follows:

- The NEB and NER were 490 GJ and 5.45, respectively. If the energy input for introducing gasifying agent and cleaning producer gas was saved through improving the gasifier and gas cleaning system, the NEB and NER would increase up to 543.41 GJ and 9.57, respectively.
- The gasification process accounted for the largest share of 57.11 GJ energy consumption (or 51.88% of the total energy input). This energy consumption could be saved by using an Imbert gasifier or other gasifiers with advanced technology.
- Jatropha biodiesel production consumed energy input eight times as much as the Jatropha producer gas production. This implies that gasification technology might be an alternative pathway of Jatropha exploitation for bioenergy production.
- The total $CO_2$ emission was 296 t, and this value can be reduced by improving the gas quality and combustion characteristics of the engine.
- 10 kg (or 46.9 MJ) of producer gas saved the diesel fuel by 7.23 MJ (or 41.60%) for one kWeh electricity generation. However, the specific $CO_2$ emission considerably increased from 0.153 kg/kWeh for the neat diesel mode to 0.599 kg/kWeh for the dual fuel mode at a 10 kg/h gas flow rate.

Further efforts are required to enable the gasification technology with more efficiency for the application and commercialization of Jatropha bioenergy. The gas quality can be improved through the selection of a more efficient gasifying agent (i.e., $CO_2$, steam, oxygen, or any mixture of them) and a more efficient gasifier, optimization of gasification temperature and gasifying agent flow rate, and an appropriate design of gas cleaning system. The combustion characteristics of producer gas-diesel dual fuel can be improved by a proper design of a gas-air mixer, improvement of combustion cylinder and diesel injection system, operation at medium engine speed, and optimization of diesel injection timing and combustion pressure ratio. These recommendations should be considered for future studies. Additionally, a cost-benefit analysis of producer gas production based on Jatropha seed is yet to be studied. Finally, the current challenge of producer gas exploitation is that producer gas cannot be used to replace fossil fuel for motor-driven vehicles. Therefore, future research should pay much attention to how to store the producer gas safely and efficiently for automobiles.

## 5. Acknowledgments

The authors are very thankful to two anonymous peer reviewers for their voluntary efforts and objective comments on the initial draft of the manuscript. This research was funded by the Japan International Cooperation Agency (JICA) under the AUN/SEED-Net Project for a Master's Degree program at De La Salle University, Philippines.

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