Biofuel Research Journal 27 (2020) 1178-1194

Biofuel Research Journal

Journal homepage: www.biofueljournal.com

Original Research Paper

Production of sorghum pellets for electricity generation in Indonesia: A life cycle assessment

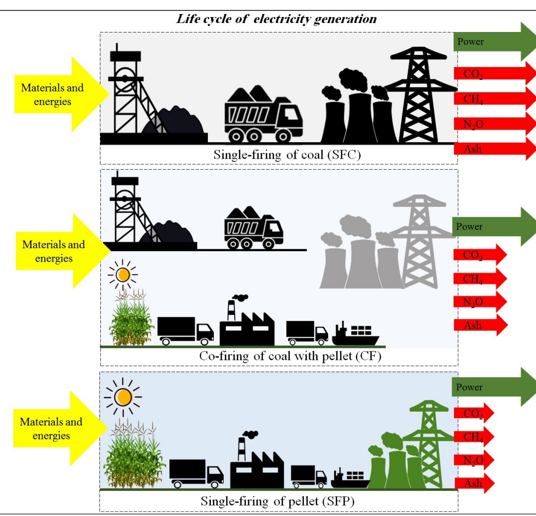
Edi Iswanto Wiloso [1,2,*], Arief Ameir Rahman Setiawan[1], Hafiizh Prasetia[3], Muryanto[3], Adisa Ramadhan Wiloso[2], Subyakto[4], I. Made Sudiana[5], Reni Lestari[6], Satya Nugroho[7], Dede Hermawan[8], Kai Fang[9,10], Reinout Heijungs[11,12]

[1]Research Center for Science, Technology and Innovation Policy and Management, Indonesian Institute of Sciences, Jakarta 12710, Indonesia.
[2]Pamulang University, South Tangerang 15435, Indonesia.
[3]Research Center for Chemistry, Indonesian Institute of Sciences, South Tangerang 15343, Indonesia.
[4]Research Center for Biomaterials, [5]Research Center for Biology, [6]Research Center for Plant Conservation and Botanic Gardens, [7]Research Center for Biotechnology, Indonesian Institute of Sciences, Bogor 16911, Indonesia.
[8]Bogor Agricultural University, Bogor 16680, Indonesia.
[9]School of Public Affairs, Zhejiang University, Hangzhou 310058, China.
[10]Center of Social Welfare and Governance, Zhejiang University, Hangzhou 310058, China.
[11]School of Business and Economics, Vrije Universiteit Amsterdam, 1081 HV Amsterdam, The Netherlands.
[12]Institute of Environmental Sciences, Leiden University, 2300 RA Leiden, The Netherlands.

HIGHLIGHTS

- Utilization of marginal land to produce sorghum pellet electricity is modeled.
- Energy content of 1.12 tons of sorghum pellets is equivalent to 1 ton of coal.
- Burden shifting is avoided by considering a comprehensive system boundary.
- The pellet processing stage contributes the most to global warming impacts.
- A sensitivity analysis shows greenhouse gas savings ranging between 70% and 85%.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 6 June 2020
Received in revised form 4 August 2020
Accepted 13 August 2020
Available online 1 September 2020

Keywords:
Bioenergy
Flores Island
Grass pellet
Greenhouse gas
Marginal land
Climate change mitigation

ABSTRACT

The current study makes use of life cycle assessment to evaluate the potential greenhouse gas (GHG) savings in coal electricity generation by 5% co-firing with sorghum pellets. The research models the utilization of 100 thousand hectares of under-utilized marginal land in Flores (Indonesia) for biomass sorghum cultivation. Based on equivalent energy content, 1.12 tons of pellets can substitute one ton of coal. The calculated fossil energy ratio of the pellets was 5.8, indicating that the production of pellets for fuel is energetically feasible. Based on a biomass yield of 48 ton/ha·yr, 4.8 million tons of pellets can be produced annually. In comparison with a coal system, the combustion of only pellets to generate 8,300 GWh of electricity can reduce global warming impacts by 7.9 million tons of CO_2-eq, which is equivalent to an 85% reduction in GHG emissions. However, these results changed when reduced biomass yield of 24 ton/ha·yr, biomass loss, field emissions, and incomplete combustion were considered in the model. A sensitivity analysis of the above factors showed that the potential GHG savings could decrease from the initially projected 85% to as low as 70%. Overall, the production of sorghum pellets in Flores and their utilization for electricity generation can significantly reduce the reliance on fossil fuels and contribute to climate change mitigation. Some limitations to these conclusions were also discussed herein. The results of this scenario study can assist the Indonesian government in exploring the potential utilization of marginal land for bioenergy development, both in Indonesia and beyond.

* Corresponding authors at:
E-mail address: ediiswanto@yahoo.com ; edi.iswanto.wiloso@lipi.go.id

Please cite this article as: Wiloso E.I., Setiawan A.A.R., Prasetia H., Muryanto, Wiloso A.R., Subyakto, Sudiana I.M., Lestari R., Nugroho S., Hermawan D., Fang K., Heijungs R. Production of sorghum pellets for electricity generation in Indonesia: A life cycle assessment. Biofuel Research Journal 27 (2020) 1178-1194. DOI: 10.18331/BRJ2020.7.3.2

Contents

Abbreviations	
CF	Co-firing of coal with pellets
CH_4	Methane
CFB	Continuous fluidized bed
FER	Fossil energy ratio
FU	Functional unit
GCV	Gross calorific value
GHG	Greenhouse gas
GLO	Global
GWP	Global warming potential
ID	Indonesia
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LCA	Life cycle assessment
LCDI	Low carbon development initiative
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LHV	Lower heating value
LUC	Land-use change
mwd	man work-day
NCV	Net calorific value
NDC	Nationally determined contributions
N_2O	Dinitrogen monoxide
NTT	East Nusa Tenggara
PC	Pulverized coal
RoW	Rest-of-world
SFC	Single-firing of coal
SFP	Single-firing of pellets

1. Introduction

1.1. The potential and importance of developing bioenergy in Indonesia

After being stable for three years, global carbon dioxide (CO_2) emissions from fossil fuel combustion started to rise again, reaching 32.8 billion tons in 2017 (IEA, 2019a). These emissions were largely contributed by the electricity and heat generation sectors (41%), followed by transportation (24%), industry (24%), and building (8%) (IEA, 2019a). Coal provided 66.5% of global electricity and heat production in 2017 (IEA, 2019b). At the global level, China remains the largest coal-consuming country, followed by India and the USA. Indonesia is the 6th-largest coal consumer, but exhibits a faster-increasing trend in consumption (+18.76%) than any of the aforementioned countries (USA, -2.9%; China, +2.9%; and India, +13.79%). Moreover, Indonesia has been the largest coal-exporting country since 2017 (IEA, 2019b).

According to Indonesia's state-owned electricity company, the energy mix in Indonesia is still dominated by fossil fuels, including coal (59.9%), natural gas (22.3%), and crude oil (6%) (PLN, 2019). However, the Indonesian government has set an optimistic target of adopting 23% renewable energy by 2025 (MEMR, 2019). This will partly be achieved by replacing old coal power plants with renewable energy plants, with a total capacity of over 11,000 MW (Reuters, 2020). At present, however, energy from biomass remains marginal, as hydropower (53%) and geothermal (44%) are the dominating sources of renewable energy in Indonesia (PLN, 2019). This is largely due to the higher monetary costs of bioenergy compared to those of other renewables and coal as well (Bappenas, 2019).

Global consumption of wood pellets by the energy and heating sectors increased by around 60% between 2010 and 2016, reaching approximately 30 million tons in 2016 (IEA, 2017). The major markets were the European Union, North America, Japan, and Korea (IEA, 2017). Considering its extensive land resources and high primary productivity, Indonesia has the potential to become a major pellet producer to meet domestic and global demands (Hidayat, 2009).

Please cite this article as: Wiloso E.I., Setiawan A.A.R., Prasetia H., Muryanto, Wiloso A.R., Subyakto, Sudiana I.M., Lestari R., Nugroho S., Hermawan D., Fang K., Heijungs R. Production of sorghum pellets for electricity generation in Indonesia: A life cycle assessment. Biofuel Research Journal 27 (2020) 1178-1194. DOI: 10.18331/BRJ2020.7.3.2

1.2. The Indonesian government's climate commitments

In 2017, Indonesia launched the Low Carbon Development Initiative (LCDI) to fulfill commitments to addressing the global issue of climate change (Bappenas, 2019). The most conservative scenario is to meet its unconditional Nationally Determined Contributions (NDC) target of 29%-lower emissions in 2030 compared to the baseline scenario (no intervention), based on the reference year of 2017. To implement the policy, the government issued the Ministry of Energy and Mineral Resources Regulation No. 50 of 2017 concerning the utilization of renewable energy sources for electricity supply. In the context of this development, collaboration with local governments is needed to provide sufficient land for biomass production and to create supporting regulations regarding biofuel prices (MEMR, 2018a). One way of facilitating the rapid development of Indonesia's biomass energy industry is to utilize marginal land resources for planting energy crops.

1.3. Marginal land and the potential of biomass production in Flores

Marginal land is defined as any land characterized by lower productivity mainly due to poor soil quality, undesirable climatic conditions, high erodibility, or other environmental risks, thus being less suitable for cultivating field crops (Gelfand et al., 2013). According to the Ministry of Environment and Forestry, Indonesia has approximately 14 million ha of marginal land in total (MoEF, 2018).

East Nusa Tenggara (NTT) is the southernmost province, located in the eastern part of Indonesia. Forest cover in NTT was estimated at only 9.6% of the land area (Russel-Smith et al., 2007). As one of the major islands comprising NTT, Flores hosts approximately 400,000 ha of marginal land (BPDASHL Benain Noelmina, 2018), mostly has not been utilized and predominantly covered by grassland savannas (Russell-Smith et al., 2007). It exhibits diverse physiographic conditions, ranging from wavy to hilly to sloped lands (Matheus et al., 2017). Cultivating sorghum, as an energy crop, in these areas is very potential, considering its adaptability to marginal conditions (Gelfand et al., 2013; Mulyani et al., 2013; Qu et al., 2014; Sainju et al., 2015). **Figure 1** provides an illustration of the marginal land distribution in Flores. Further details on marginal land distribution in Indonesia and Flores can be found in **Table S1** and **Table S2**, respectively (*Supplementary Information*).

NTT, including Flores, receives less rainfall than other areas in Indonesia (Mulyani et al., 2013; Kurniawan and Yuniati, 2015; BPS NTT, 2020). The soil of Flores is derived from volcanic material such as Haplustepts and Haplustolls (Mulyani et al., 2013). For areas in Flores with a specific climate (<1,000 mm annual rainfall) and soil conditions (<50 cm soil depth), Mulyani et al. (2013) recommended the cultivation of adaptable crops, including sorghum.

Types of fuel used in a power plant should match with combustion technologies. Pulverized coal (PC) combustion and continuous fluidized bed (CFB) combustion are conventional technologies employed in coal-fired power plants in Indonesia (Khaerunisa et al., 2009). Detailed descriptions of the types of coal power plant technologies commonly used in Indonesia can be found in **Table S3** (*Supplementary Information*).

Criteria for the solid fuel (coal or biomass pellets) for different types of power plant technologies are summarized in **Table S4** (*Supplementary Information*) (Stromberg, 2006). According to these criteria, sorghum pellets are technically feasible for combustion in both PC or CFB power plants. The use of pellets as a substitute for coal in a power plant can be enabled either by retrofitting existing power plants to a co-firing system (combustion of coal together with biomass) or by refurbishing the plant such that it can be entirely operated on pellets (Morrison and Golden, 2017). A brief overview of the studies on the application of biomass co-firing in various power plant technologies can be found in **Table S5** (*Supplementary Information*).

1.4. Issues of coal and pellet combustion in power plants

PC is the standard technology for coal-fired electricity generation,

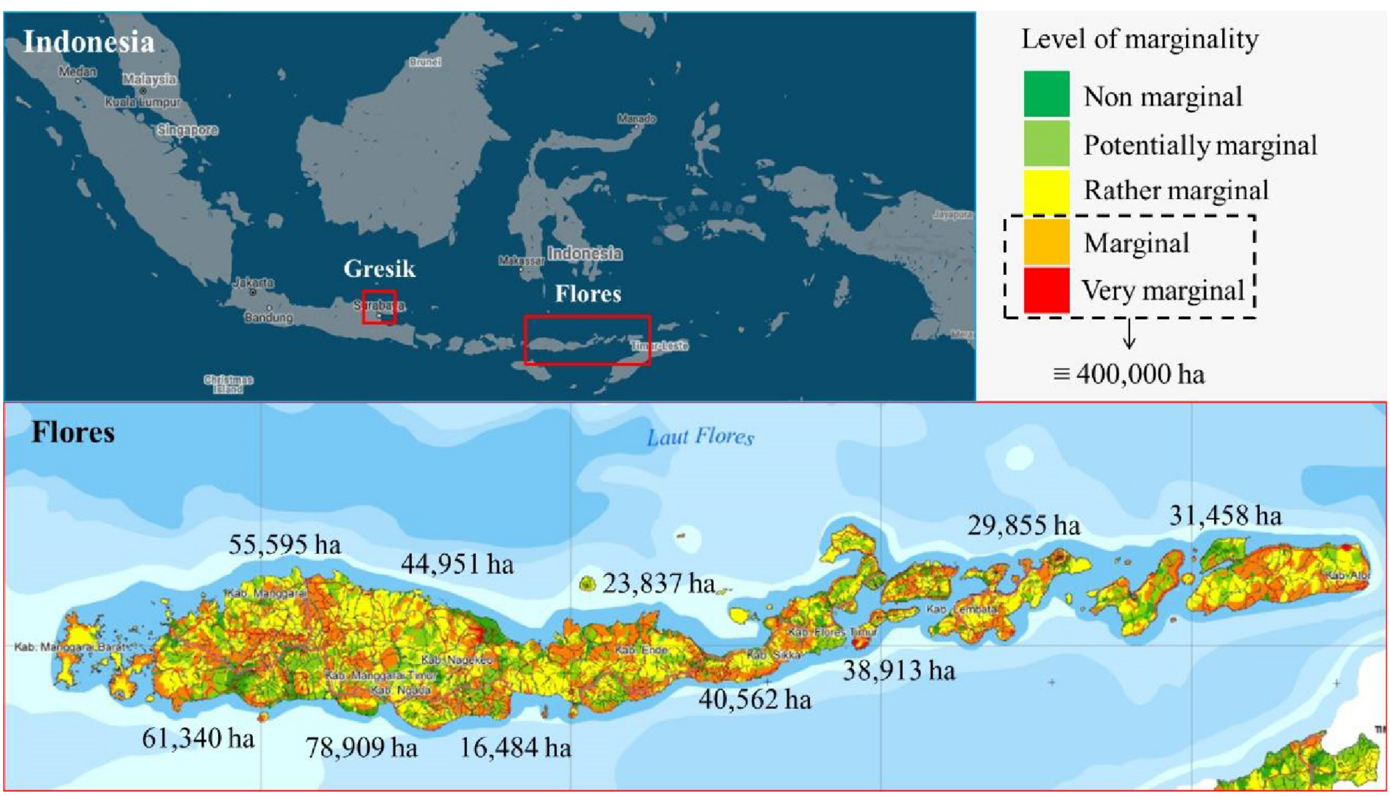


Fig. 1. Marginal land distribution in Flores island (BPDASHL Benain Noelmina, 2018) (Gresik, East Java, is the location of the field trial; Flores, NTT, is the location of the scenario study; Numbers indicate area of marginal and very-marginal lands in Flores).

Please cite this article as: Wiloso E.I., Setiawan A.A.R., Prasetia H., Muryanto, Wiloso A.R., Subyakto, Sudiana I.M., Lestari R., Nugroho S., Hermawan D., Fang K., Heijungs R. Production of sorghum pellets for electricity generation in Indonesia: A life cycle assessment. Biofuel Research Journal 27 (2020) 1178-1194. DOI: 10.18331/BRJ2020.7.3.2

accounting for over 95% of the total global capacity (Lockwood, 2013). In comparison with pulverized fuel, circulating fluidized bed combustion, which is a configuration of fluidized bed combustion technology, enables better control of emissions and higher fuel flexibility (Aho et al., 2013). Power plants operating on PC (Dunaievska et al., 2016) and CFB (Aho et al., 2013) technologies could, however, be applied to a co-firing system, thus making it possible to reduce greenhouse gas (GHG) emissions.

Trial co-firing under both combustion types has taken place at several coal power plants in Indonesia (MEMR, 2020). For example, the Jeranjang power plant (25 MW), with CFB combustion technology, has realized the co-firing of coal with domestic waste pellets (Fadli et al., 2019). The Indramayu coal-fired power plant (330 MW), with PC technology, has realized co-firing with 5% wood pellets (Husaini, 2020).

The formation of slagging (on furnace walls) or fouling (on convective surfaces, such as the superheater) deposits is a fundamental issue related to the ash content in coal power plant technologies (Demirbas, 2004; Miller, 2004). Coals used in thermal power plants generally contain ash levels ranging from 8% to as high as 55% (on an as-received basis) (Bhatt, 2006). For herbaceous biomass, such as grass (including sorghum), the high contents of alkali metals (such as Na and K) and chlorine results in ash with a low melting point which promotes the formation of corrosive deposits (Lockwood, 2013). Furthermore, the alkali-chloride deposits act as a glue, making it hard to clean (Aho et al., 2013). When the biomass is pulverized in a PC power plant, the fibrous parts of the biomass can also accumulate over time (Lockwood, 2013). Moreover, pellet dust creates a fire hazard that is potentially disruptive to the automated feeding system (Mostafa et al., 2019). In a CFB power plant, however, solid fuel is only crushed just before being fed into the boiler, and no grinding mills are required.

1.5. Life cycle assessment for scenario modeling

According to the ISO standard (ISO 14040, 2006), life cycle assessment (LCA) is a tool for evaluating potential environmental impacts throughout a product's life cycle, from raw material acquisition through production, use, end-of-life treatment, recycling, and final disposal (i.e., cradle-to-grave). By covering the entire life cycle of a product system, LCA can avoid potential burden-shifting. Also, it can cover several impact categories which promotes holistic solutions.

A recent literature review conducted by Barros et al. (2019), indicated that the number of studies on LCA of electricity has been increasing considerably, focusing mostly on reducing GHG emissions to mitigate climate change through the replacement of fossil fuels by renewable ones.

The current study is in line with the global trend as it considers the potential reductions in the impacts of global warming through the use of renewable energy. In addition, the current study provides key information needed by the Indonesian Government to support public policy toward developing bioenergy to substitute fossil fuels.

There have been several prior LCA studies on the benefits of substituting fossil energy sources with pellets made from grasses. None of these involved sorghum, but rather used miscanthus (Lewandowski et al., 1995; Murphy et al., 2013) and switchgrass (Bergman et al., 2015). In addition to not including power plant infrastructures, Lewandowski et al. (1995) and Bergman et al. (2015) did not model the incomplete combustion of biomass either. Bergman et al. (2015) also did not consider field emissions stemming from fertilizer application. These inventories (infrastructure, incomplete combustion, and field emission) could potentially contribute to the emission of important GHGs such as N_2O and CH_4. Hence, excluding these parameters in the models is likely to increase deviation from reality. In this context, the current study contributes to this research topic in the following way. It is the first LCA study on electricity generation by sorghum pellets that managed to overcome previous modeling gaps by carrying out a sensitivity analysis in consideration of the aforementioned parameters.

1.6. Formulation of the research questions

This study presents an effort to reduce GHG emissions from the energy sector in Indonesia. We carried out a scenario study by developing an LCA model of the utilization of marginal land in Flores for sorghum cultivation, and the utilization of its biomass for electricity generation. Implementation of 100% biomass firing (single-firing of biomass) for electricity generation is technically possible (Morrison and Golden, 2017). However, since infrastructure and policies for 100% biomass firing applications have not been established on a commercial scale in Indonesia (MEMR, 2019), co-firing applications in existing coal power plants were considered to be more practical. Further, this scheme could reduce the capital and operational costs of generating renewable electricity (Boylan, 1996). However, the risk of increased ash deposition on boilers and other surfaces due to the biomass needs to be sufficiently addressed (Livingston, 2016).

To this end, the general objective of this study was to evaluate the potential GHG savings in coal electricity generation by co-firing with sorghum pellets using LCA. The co-firing biomass electricity ratio was set at 5%, considering that a co-firing ratio of up to 10% would not cause serious technical problems (Sondreal et al., 2001). This study also quantified the complete replacement of coal with biomass to illustrate the maximum potential GHG savings. The above objective was broken down into the following specific research questions:

Q1. What quantity of sorghum pellets corresponds to the energy content of 1 ton of coal?
Q2. What is the fossil energy ratio (FER) of sorghum pellets?
Q3. How much pellets are required to generate 5,300 GWh electricity *via* 5% co-firing in all coal-fired power plants in Indonesia?
Q4. What extent of GHG-emission reductions could be expected if the pellets were used for 5% co-firing in all coal-fired power plants in Indonesia?
Q5. What are the effects of considering incomplete biomass combustion and field emissions from fertilizer application on the final results?

The paper is presented by first evaluating sorghum cultivation in fields, biomass processing in pellet factories, and electricity generation in power plants. Further, energy analysis and global warming impacts are evaluated for the pellet product and the generated electricity. The global warming impacts of electricity generation are then calculated by assuming complete combustion of biomass and no field emissions from fertilizer application, herein representing the reference scenario. Finally, a sensitivity analysis is carried out by considering the two important aforementioned parameters, herein referred to as the alternative scenarios.

2. Methodology

Available marginal land in Flores is approximately 400,000 ha. However, some areas are very unlikely to be utilized, for example, because the area is too steep. Thus, a conservative approach was taken in this study, assuming that only 25% of the marginal lands (100,000 ha) is a flat area where sorghum cultivation is possible. Further detail is available in **Table 1** and **Table S2** (*Supplementary Information*). Sorghum for energy production is classified as either sweet or biomass-type (Ameen et al., 2017). Our study used the latter, while producing only small amounts of grain and sweet juice. In LCA, this is considered as a mono-functional system, producing only biomass. For this reason, allocation (Suh et al., 2010) or substitution (Weidema, 2000) procedures were not explored further.

Two transportation modes were included in this study, i.e., land transport (sorghum field to pellet factory to port), and sea transport (port to power plants). In the modeling, the loss of sorghum biomass or pellet product due to production or transport was assumed to be negligible. The pellets were used to substitute coal for the generation of electricity in all coal-fired power plants in Indonesia in a co-firing system.

Indonesian annual coal electricity production in 2017 was 105,651 GWh (MEMR, 2018b). This amount was used for the baseline case. The scenario model did not consider the trajectory for future models, as discussed by Döll et al. (2008), but rather used a specific point in time, namely 2017. To determine the GHG savings of various scenarios, we developed an LCA model using SimaPro 9.0 for electricity generation in different combustion systems: single-firing of coal (SFC), co-firing of coal with pellets (CF), and single-firing of pellets (SFP).

It should be noted that the co-firing ratio was based on energy values, i.e., 5% from sorghum pellets and 95% from coal. GHG savings represent the difference in global warming impacts between scenario models (CF and SFP) and the baseline model (SFC). As indicated previously, the CF model

Please cite this article as: Wiloso E.I., Setiawan A.A.R., Prasetia H., Muryanto, Wiloso A.R., Subyakto, Sudiana I.M., Lestari R., Nugroho S., Hermawan D., Fang K., Heijungs R. Production of sorghum pellets for electricity generation in Indonesia: A life cycle assessment. Biofuel Research Journal 27 (2020) 1178-1194. DOI: 10.18331/BRJ2020.7.3.2

Table 1.
Descriptions of assumptions used in this study.

Assumption	Description
Agricultural conditions*	Sorghum cultivation scenarios in Flores use agricultural data from Gresik, East Java (Indonesia), assuming similarities in soil fertility and regional climate.
Area of sorghum cultivation	The marginal land area available in Flores is approximately 400,000 ha. We use a conservative approach, assuming that only 25% of the marginal lands (100,000 ha) is a flat area where sorghum cultivation is possible.
Carbon-neutral	"The carbon sequestered by biomass through photosynthesis is considered equal to the carbon feedstock in wood that is eventually released throughout its life cycle" (Head et al., 2019).
Combustion conditions*	Burning of sorghum pellets in a power plant assumes complete combustion (i.e., no CH_4 and N_2O emissions).
Field emission*	This study did not consider field emissions.
Human labor	Some agricultural activities in this study still rely on "human power." However, it was not counted in the inventory model.
Infrastructure parameters	Infrastructure data in this study was obtained from ecoinvent datasets. The assumed parameters are life span, capacity, and capacity factor. The approach taken was conservative.
Mass loss*	There is no biomass loss within the sorghum harvesting, pellet processing, and transportation stages.
Transport	Most of the power plants are typically located near their respective ports. Therefore, land transports from the ports to power plants were considered negligible, such that they were not modeled. Impact calculations of transport activities in the foreground system were based on a one-way trip assumption.

*The context of assumptions was varied in the sensitivity analysis (see *Section 3.4*).

has been tested at several power plants and will be expanded to others in Indonesia, while the SFP model was included only to illustrate the maximum potential of GHG savings. To summarize, the overall LCA models in this study were developed by first creating a baseline model, followed by the reference scenarios and the alternative scenarios, as shown in **Figure 2**.

2.1. Goal and scope definition

An attributional LCA was carried out to compare three electricity product systems. Their system boundaries were cradle-to-gate covering fuel production, transport, and electricity generation. **Figure 3** shows the system boundaries of the three product systems using the same functional unit (FU), 1 kWh of electricity produced. The foreground and background systems in each product system were identified.

2.2. Data source and assumption

2.2.1. Data source

Primary data used in this study included sorghum cultivation and pellet processing data collected from a field trial at PT Kaliandra Merah, a wood-based pellet processing facility located in Gresik, East Java (Indonesia). Inventory for electricity production was based on Widiyanto et al. (2003), and flow quantities were adjusted to obtain more representative conditions. For coal data, we used secondary data from the ecoinvent database. Data of sorghum and pellets transports were obtained from assumed locations of sorghum fields and pellet factories, while coal transport used the default ecoinvent dataset. The coal transport is treated as a background system, meaning it does not represent a specific condition, but generic. Emissions from fuel combustion in the foreground system were calculated based on emission factors from the IPCC (2006a). Detail emission factors can be found in **Table S6** (*Supplementary Information*).

We used the ecoinvent database version 3.5 (Wernet et al., 2016) to develop input and output flows in the background system. The "market" category was selected for datasets in the background system, such as fertilizer, electricity, and diesel. This does not represent specific conditions, but rather reflects a generic model (Wernet et al., 2016). However, it is quite relevant considering that this study aims to find a general picture of potential GHG savings by the LCA method in Indonesia. The geographical priority for the ecoinvent dataset selection, consecutively, was Indonesia (ID), rest-of-world (RoW), and global (GLO). The ecoinvent datasets used to represent the inventory in this study are compiled in **Table S7** (*Supplementary Information*).

2.2.2. Assumptions

ISO 14044 regulates assumptions used in LCA studies. Assumptions will produce uncertainties, so the results of the study analysis should be accompanied by a sensitivity analysis to reach robust conclusions. This is particularly important if the conclusions are to be used for providing recommendations (ISO 14044, 2006). In this study, sensitivity analyses were carried out in certain situations, i.e., if emissions due to nitrogenous fertilizer application (N_2O) and incomplete combustion of biomass in a power plant (CH_4 and N_2O) were considered in the model. Sorghum pellets are considered carbon-neutral, so the CO_2 released through combustion at the power plant was assumed zero net CO_2 emissions. The concept of carbon-neutral is an issue that is still being debated (Wiloso et al., 2016; Head et al., 2019). Considering a broad system boundary covering sorghum cultivation, pellet processing, transport, and electricity generation, we simplified the model using the carbon-neutral assumption. This same approach was used by a number of prior LCA studies on biopellet, including García et al. (2019), Lewandowski et al. (1995), Murphy et al. (2013), Nian (2016), Schakel et al. (2014), Yang et al. (2019). **Table 1** summarizes the assumptions used in this study.

2.3. Impact assessment method

The impact category considered in this study was global warming (midpoint impact). To calculate the global warming impact of each product, we used the CML-IA baseline 3.5 method. There are 183 types of emissions identified as impact indicators for the global warming category according to this method. The characterization factor followed the principles developed by the Intergovernmental Panel on Climate Change (IPCC) 2013 with a 100-year time horizon (GWP 100a). This assessment method, by default, excludes biogenic carbon emissions as an impact indicator. This study also did not consider the global warming impacts associated with land-use change (LUC). Even if LUC was considered, it would have minimal impact in the case of the conversion of marginal land into cropland or grassland (Bergman et al., 2015; Daystar et al., 2015), such as sorghum field.

2.4. Energy analysis

In this study, an energy analysis was carried out on sorghum pellets using FER index, following the same approach used by Pradhan et al. (2010) and Rajaeifar et al. (2013). FER is defined as the ratio of the energy content of the product over the primary fossil fuel inputs (Zaimes et al., 2013). FER is calculated through **Equation 1**, and values greater than 1 indicate net energy positive, reflecting more energy in the pellet products than the fossil energy consumed during production (Zaimes et al., 2013). The heating value that is pertinent to the power plant, according to this study, was based on the lower heating value (LHV) or net calorific value (NCV). The reason for this is that we assumed that the power plant under study does not use a heat recovery system, such that the latent heat of vaporization of water in the reaction products is not recovered (Lee, 2015). Thus, to calculate the total primary energy used for pellet processing, we used the "Cumulative Energy Demand (LHV) V1.00" method (Weidema et al., 2013). The method distinguishes primary energy types into eight categories, including non-renewable resources (fossil, nuclear, and primary forest) and renewable resources (biomass, wind, solar, geothermal, and water) (Frischknecht et al., 2007).

$$FER = \frac{Energy\ content\ in\ sorghum\ pellet}{Primary\ fossil\ energy\ input} \quad \text{(Eq. 1)}$$

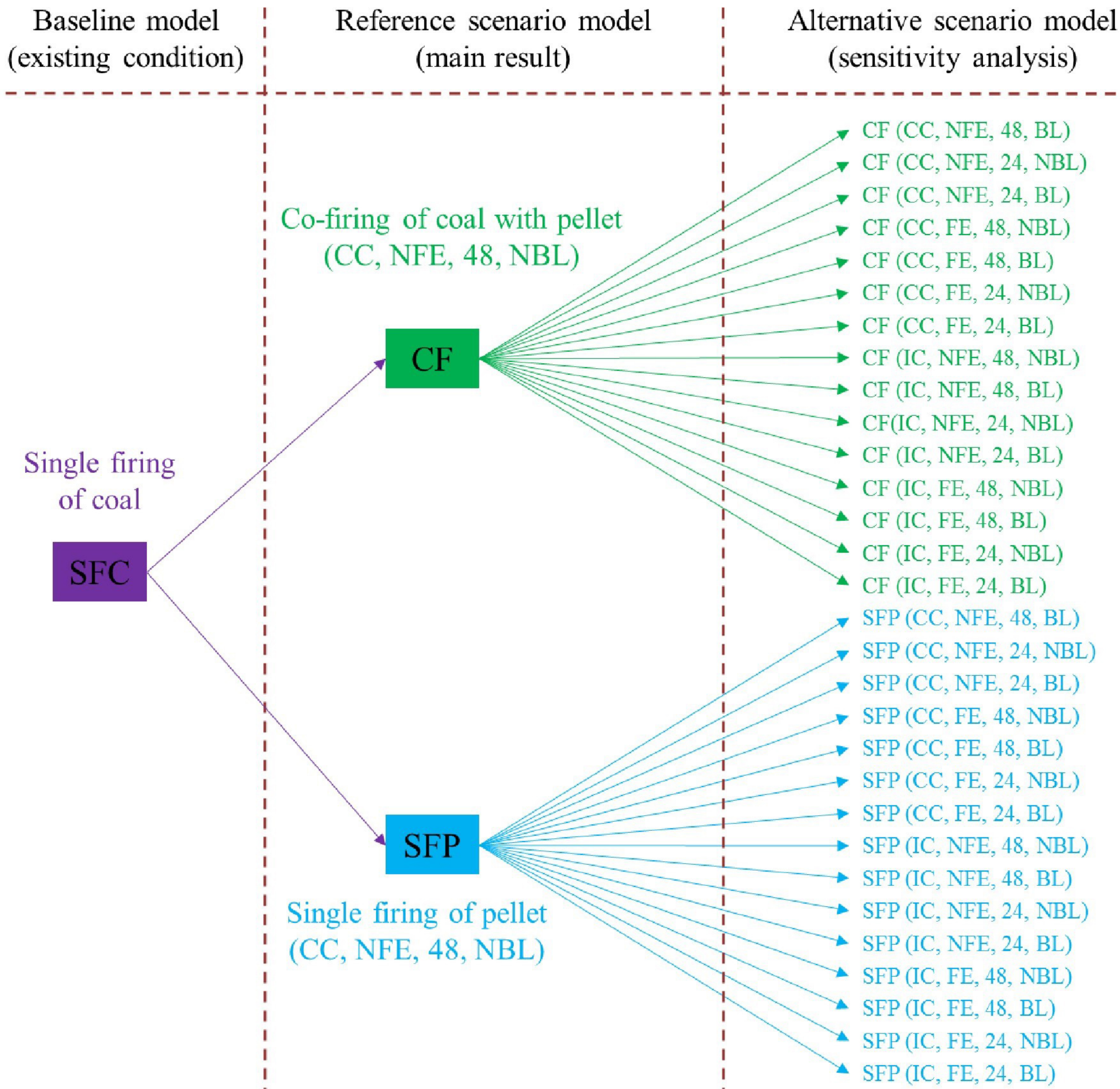


Fig. 2. The overall LCA models developed in this study.
(SFC = single-firing of coal; CF = co-firing of coal with pellet; SFP = single-firing of pellet; CC = complete biomass combustion; IC = incomplete biomass combustion; FE = field emissions due to fertilizer application; NFE = no field emissions; 48 = sorghum yield is equal to 48 ton/ha·year; 24 = sorghum yield is equal to 24 ton/ha·year; BL = biomass loss; NBL = no biomass loss. The baseline model is the existing condition, the combustion of 100% coal; The reference scenario models represent the generation of 5% (CF) or 100% (SFP) of electricity from biomass; The alternative scenario models are for the sensitivity analysis, considering variations in combustion conditions and field emissions).

The heating value of pellets was obtained from primary data through chemical analysis, while the heating value of coal was obtained based on the average value in Indonesia, both on an as-received basis (Miller, 2004; Lee, 2015). **Table 2** shows the chemical analysis of the pellets produced in pellet-processing facilities in Gresik; more detailed results are given in **Table S8** (*Supplementary Information*).

According to the Ministry of National Development Planning of Indonesia (Bappenas, 2016), coal reserves in Indonesia are dominated (approximately 60%) by coal with a medium calorific value of 5,100-6,100 kcal/kg. However, 80% of the coal produced is exported to other countries, while the remaining coal of lower quality (<5,100 kcal/kg) is destined for domestic consumption. Details on domestic coal consumption between

Please cite this article as: Wiloso E.I., Setiawan A.A.R., Prasetia H., Muryanto, Wiloso A.R., Subyakto, Sudiana I.M., Lestari R., Nugroho S., Hermawan D., Fang K., Heijungs R. Production of sorghum pellets for electricity generation in Indonesia: A life cycle assessment. Biofuel Research Journal 27 (2020) 1178-1194. DOI: 10.18331/BRJ2020.7.3.2

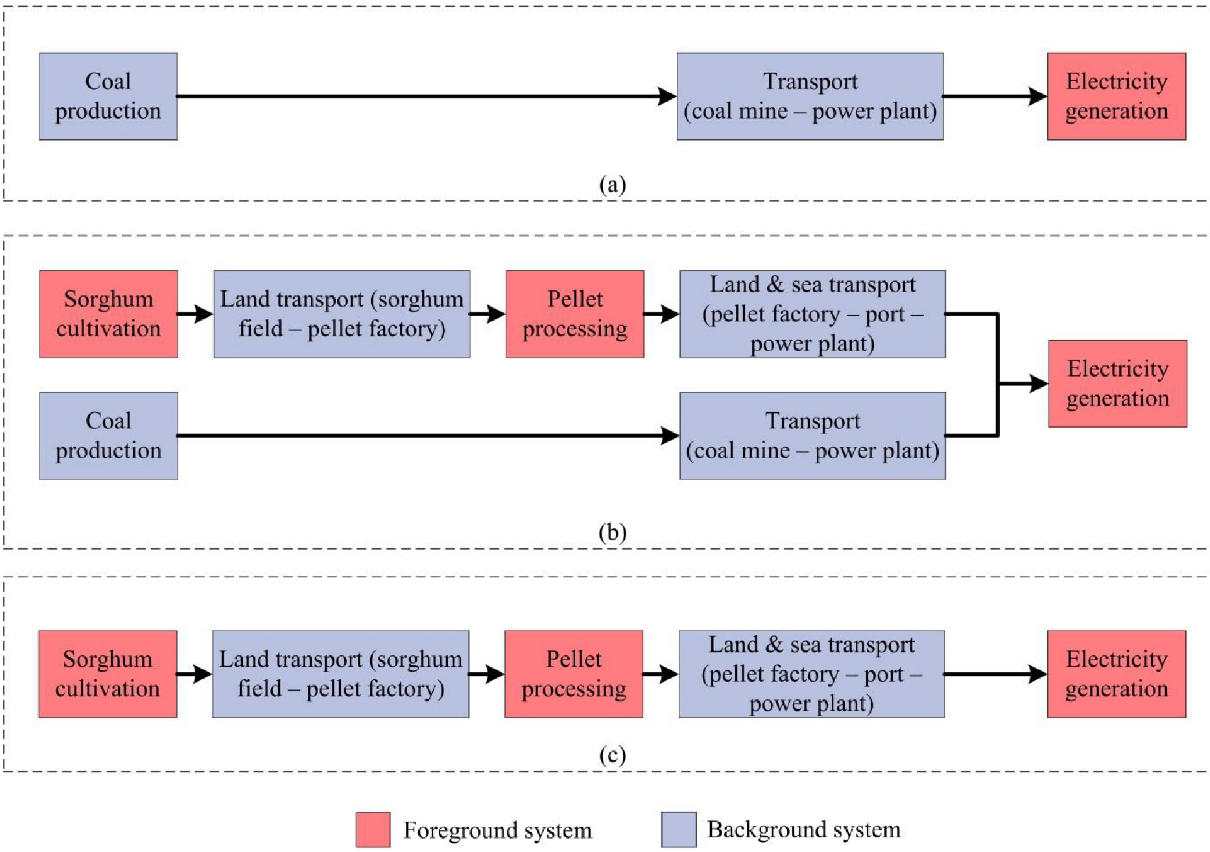


Fig. 3. System boundaries of the compared product systems
(a) single-firing of coal (SFC); (b) co-firing of coal with pellet (CF); and (c) single-firing of pellet (SFP).

Table 2.
Chemical analysis of the sorghum pellets produced in Gresik, East Java.

Parameter	Value (as-received)
Ash (wt.%)	7.28
Carbon (wt.%)	45.61
Hydrogen (wt.%)	5.18
Nitrogen (wt.%)	0.36
Oxygen (wt.%)	37.84
Sulfur (wt.%)	0.09
Total moisture (wt.%)	3.64
Gross calorific value (kcal/kg)	4,156*

*4,156 kcal/kg = 17.4 MJ/kg (Ansermet and Brechet, 2018).

2013 and 2018 are given in **Table S9** (*Supplementary Information*). This study used the average gross calorific value (GCV) of coal used in Indonesian power plants, i.e., 4,600 kcal/kg or 19.3 MJ/kg (Bappenas, 2016). Based on the calorific value, it is classified as lignite (hereafter referred to as brown coal) according to the IEA classification system (IEA, 2019c). Brown coal is the typical coal used in power plants in Indonesia. **Table 3** summarizes the pellet and brown coal requirements in the power plant.

There was a slight decrease in the gross efficiency value due to differences in the NCV between pellets and brown coal (Beér, 2007; Schakel et al., 2014). Based on the amount of each fuel required to generate electricity in a power plant, 1 kg of brown coal can be replaced by 1.12 kg of sorghum pellets.

2.5. Life cycle inventory

2.5.1. Sorghum cultivation

The product system of sorghum was divided into five stages: land processing, planting, fertilizing, maintenance, and harvesting. Primary data for sorghum cultivation was taken from a field trial in Gresik, East Java (Indonesia). **Table 4** shows the inventory of sorghum cultivation with a reference flow of 1 ha·yr, yielding 48 tons of dry sorghum biomass/ha·yr based on data from the field trial in Gresik. Thus, the total annual production of sorghum for an area of 100,000 ha is 4.8 million tons, assuming there is no mass loss during sorghum harvesting. However, to be more realistic, a 7% mass loss was also considered in the sensitivity analysis.

The sorghum yield considered in this study (48 ton/ha·yr) is rather high compared to those reported in literature, i.e., 43 ton/ha·yr (Qu et al., 2014)

Please cite this article as: Wiloso E.I., Setiawan A.A.R., Prasetia H., Muryanto, Wiloso A.R., Subyakto, Sudiana I.M., Lestari R., Nugroho S., Hermawan D., Fang K., Heijungs R. Production of sorghum pellets for electricity generation in Indonesia: A life cycle assessment. Biofuel Research Journal 27 (2020) 1178-1194. DOI: 10.18331/BRJ2020.7.3.2

Table 3.
Fuel requirements for a power plant.

Type of fuel	Energy content (MJ/kg)		Power plant efficiency (%)		Fuel requirements (kg/kWh)
	GCV[a]	NCV[b]	Gross	Net	
Brown coal	19.26	18.30	36.1	38.0	0.518
Pellet	17.40	16.40	35.8	38.0	0.578

[a] Brown coal GCV (Bappenas, 2016). GCV of pellets was obtained from the chemical analysis in Table 2.
[b] Net calorific value (NCV) of brown coal is 5% lower than its GCV (IEA, 2004). NCV of pellets = GCV - [(212 x X_H)+(0.8 x (X_O + X_N)] × (1-0.01 M) × 24.5 M, where X_H, X_O, X_N, and *M* are percentages of hydrogen, oxygen, nitrogen, and moisture, respectively (Lee, 2015).

Table 4.
Life cycle inventory of 1 ha·yr sorghum at various cultivation stages.

Cultivation stage	Flow	Direction	Amount	Unit
Land processing	Compost	Input	5	ton
	Manpower	Input	80	mwd[b]
	Diesel[a]	Input	134	L
	CO_2	Output	358	kg
	CH_4	Output	4.78E-2	kg
	N_2O	Output	9.56E-3	kg
Planting	Sorghum seed	Input	30	kg
	Nitrogen fertilizer	Input	200	kg
	Phosphate fertilizer	Input	150	kg
	Potassium fertilizer	Input	15	kg
	Furadan (pesticide)	Input	5	kg
	Decis (pesticide)	Input	2	L
	Water, from well	Input	20,000	L
	Manpower	Input	60	mwd[b]
Fertilizing	Nitrogen fertilizer[c]	Input	150	kg
	Phosphate fertilizer[c]	Input	150	kg
	Potassium fertilizer[c]	Input	150	kg
Maintenance	Manpower	Input	190	mwd[b]
	Diesel[a]	Input	100	liter
	CO_2	Output	267	kg
	CH_4	Output	3.57E-2	kg
	N_2O	Output	7.14E-3	kg
Harvesting	Manpower	Input	140	mwd[b]

The unit 'ton' refers to a metric ton (1 metric ton = 1,000 kg).
[a] Emission factors = 7.48E-2 kg CO_2/MJ; 10E-6 kg CH_4/MJ; 2E-6 kg NO_2/MJ (IPCC, 2006a). The density and energy content (NCV) of the diesel used in this study were 0.83 kg/L and 43 MJ/kg, respectively (Jungbluth et al., 2018).
[b] mwd = man work-day is defined as work done by one person in one day (eight hours) (Wahyuni, 2014).
[c] Nitrogen fertilizer = urea; Phosphate fertilizer = TSP (Triple super phosphate); Potassium fertilizer = KCl (Potassium chloride).

and 17.4–42.1 ton/ha·yr (Tang et al., 2018). This value was in fact obtained from fertile soil in Gresik. In contrast, the sites in Flores is marginal and its annual precipitation is much lower (Mulyani et al., 2013) than Gresik. These drawbacks are very likely to affect the sorghum yield. Thus, a sensitivity analysis was carried out considering a sorghum yield of 24 ton/ha·yr.

According to Khoshnevisan (2013), a one-hour human labor energy input is equivalent to 1.96 MJ. Therefore, a one mwd (man work-day, 8 h/d) is equal to 15.68 MJ. In total, energy derived from human labor for 1 ha·yr of sorghum cultivation is equivalent to 7,369.6 MJ (15.68 MJ/mwd × 470 mwd). Some flow quantities expressed in units of volume were converted to units of mass using a conversion factor from the literature (NCBI, 2004 and 2014; Jungbluth et al., 2018), as SimaPro tends to use units of mass as reference quantities. There was no dataset for sorghum seed in the ecoinvent database. Instead, we used "market for wheat seed, for sowing GLO" to represent sorghum seed, as both belong to a grass family.

2.5.2. Pellet processing

This study assumed no sorghum loss due to the transport and pellet processing, such that all sorghum crops were converted 100% into pellets. To be more practical, this study also considered 10% of mass loss during pellet processing in the sensitivity analysis. Primary data for pellet processing factors such as electricity, diesel, lubricating oil, and grease were taken from a field trial in Gresik. **Table 5** shows the life cycle inventory (LCI) for processing 1 ton of pellets. The current study used the same datasets for grease and lubricating oil, adopting the same approach conducted by Elduque et al. (2015).

The infrastructure models for a pellet factory referenced the ecoinvent dataset "market for wood pellet factory GLO," assuming a lifespan of 40 years. This was a conservative estimate, as the ecoinvent dataset "wood pellet production RoW" uses a life span of 50 years (Wernet et al., 2016). Based on a production trial of 85 tons of pellet/d and 24 working d/month, the annual production capacity of sorghum pellets was 24,000 ton/yr. Electricity input used the dataset "market for electricity, medium voltage ID" to represent the average electricity mix in Indonesia. The pelleting step consumed the highest portion of electricity (37%), followed by pre-grinding (22%), fine-grinding (16%), and drying (13%). Details of the electricity inputs for pellet processing can be found in **Table S10** (*Supplementary Information*).

Table 5.
Life cycle inventory of 1 ton of pellets in the production stage.

Flow	Direction	Amount	Unit
Sorghum	Input	1	ton
Pellet factory[a]	Input	1.04E-6	piece[b]
Electricity	Input	148.67	kWh
Lubricating oil	Input	0.012	L
Grease	Input	0.050	L
Diesel[c]	Input	0.774	L
CO_2	Output	2.07	kg
CH_4	Output	2.76E-4	kg
N_2O	Output	5.52E-5	kg
Waste mineral oil	Output	0.062	L

The unit 'ton' refers to a metric ton (1 metric ton = 1,000 kg).
[a] Refer to the ecoinvent dataset.
[b] Unit for the infrastructure for a pellet factory. One piece = total pellet processing during the life span of the infrastructure (24,000 ton/year × 40 years = 960,000 ton). One-ton pellet processing requires only 1/960,000 piece of infrastructure, which is 1.04E-6 piece.
[c] Emission factors = 7.48E-2 kg CO_2/MJ; 10E-6 kg CH_4/MJ; 2E-6 kg NO_2/MJ (IPCC, 2006a). The density and energy content (NCV) of the diesel used in this study were 0.83 kg/liter and 43 MJ/kg, respectively (Jungbluth et al., 2018).

2.5.3. Electricity generation

Table 6 shows the inventories for 1 kWh electricity generated from different combustion systems. The inventory is based on inventory data of the Suralaya power plant in Banten (Widiyanto et al., 2003) which uses PC combustion technology; details can be found in **Table S11** (*Supplementary Information*). The infrastructure model for a power plant referenced the "market for hard coal GLO power plant" dataset from the ecoinvent. It consisted of a mix of 500 MW- (72%) and 100 MW- (28%) capacity power plants. This did not represent the specific distribution of coal-fired power plants in Indonesia (see **Table S12**; *Supplementary Information*). Since the infrastructure of the coal power plant contributes lesser impacts than those of the operational stage (Atilgan and Azapagic, 2015), we considered that the choice of the dataset was not problematic. The characteristics of power plant infrastructure shown in **Table 6** are based on the following parameter values: (i) lifespan of 37.5 years; (ii) 4,000 operating hours/yr; (iii) 500 MW power plant capacity; and (iv) capacity factor of 0.7. The values of parameters (i), (ii), and (iii) were taken from the ecoinvent dataset "electricity production, hard coal RoW" (Wernet et al., 2016), while the capacity factor of 0.7 was added by the authors as a conservative assumption.

Please cite this article as: Wiloso E.I., Setiawan A.A.R., Prasetia H., Muryanto, Wiloso A.R., Subyakto, Sudiana I.M., Lestari R., Nugroho S., Hermawan D., Fang K., Heijungs R. Production of sorghum pellets for electricity generation in Indonesia: A life cycle assessment. Biofuel Research Journal 27 (2020) 1178-1194. DOI: 10.18331/BRJ2020.7.3.2

Table 6.
Life cycle inventory of 1 kWh electricity for different product systems.

Flow	Direction	Amount[a]	Unit
SFC (single-firing of coal)[b]			
Lime	Input	0.007	kg
Limestone	Input	0.093	kg
Power plant	Input	1.90E-11	piece
Coal[c]	Input	0.518	kg
CO_2	Output	1.09	kg
CH_4	Output	2.84E-5	kg
N_2O	Output	4.74E-5	kg
Ash (coal)	Output	0.138	kg
CF (co-firing of coal with pellet)			
Lime	Input	0.007	kg
Limestone	Input	0.093	kg
Power plant	Input	1.90E-11	piece
Pellet	Input	0.029	kg
Coal	Input	0.492	kg
CO_2	Output	1.04	kg
CH_4	Output	2.70E-5	kg
N_2O	Output	4.50E-5	kg
Ash (coal)	Output	0.131	kg
Ash (pellet)	Output	2.17E-3	kg
SFP (single-firing of pellet)			
Lime	Input	0.008	kg
Limestone	Input	0.103	kg
Power plant	Input	1.90E-11	piece
Pellet	Input	0.578	kg
Ash (pellet)	Output	0.043	kg

The unit 'ton' refers to a metric ton (1 metric ton = 1,000 kg).
[a] Amount of coal (kg/kWh) in this study was obtained through calculations based on PLN Indonesia statistical data for 2017 (MEMR, 2018b), while the amounts of other materials in the SFP model were adjusted proportionally to changes in the amount of coal.
[b] Source: Widiyanto et al. (2003)
[c] Emission factors = 1.15E-1 kg CO_2/MJ; 3E-6 kg CH_4/MJ; 5E-6 kg N_2O/MJ (IPCC, 2006a). The energy content (NCV) of the coal used in this study was 18.3 MJ/kg (see **Table 3**).

2.6. Land and sea transports

Only domestic land and sea transport were considered in this study, with ton-kilometer (t·km) as the functional unit. These were differentiated into three transportation models: (I) land transport of sorghum biomass from fields to pellet factories; (II) land transport of sorghum pellets from factories to the Marapokot port; and (III) sea transport of sorghum pellets from the Marapokot port to coal-fired power plants. The datasets used for land and sea transport in this study were "market for transport, freight, lorry 16-32 metric ton, EURO3 RoW" and "market for transport, freight, sea, transoceanic ship GLO," respectively. The selection of datasets for land transport represented a conservative approach, considering that the "EURO3" category has a higher emission level than the other EURO categories (Simons, 2016).

Figure 4 shows the assumed locations of sorghum cultivation and pellet factories. Sorghum fields totaling 100,000 ha were modeled, along with their distribution over Flores Island. Each green marker represents 5,000 ha for each of the 20 sorghum fields, while the locations of the 4 pellet factories are represented by the black markers. This results in a ratio of 1:5 for the number of pellet factories to sorghum fields. Therefore, to process all harvested sorghum biomass from five sorghum fields into pellets (at a ratio of 1:1 for sorghum input and pellet output), each pellet factory must have a capacity of 1.2 million tons of sorghum annually (50 × 24,000 ton/yr, see *Section 2.5.2*). Infrastructure calculations were carried out linearly (Weidema et al., 2013) to simplify the model, i.e., each pellet factory in **Figure 4** represents 50 factories under real conditions.

The average distance of land transport section (I) was 20 km, and the yields from each sorghum field were assumed to be similar, i.e., 240,000 tons (48 ton/ha·yr × 5,000 ha). By multiplying the two parameters (load and distance), a transport value of 4.8 million t·km was obtained. Thus, the total for transport from the 20 sorghum fields to pellet mills is 96 million t·km.

The land transport section (II) utilized stockpiles at the Marapokot port. A stockpile was modeled as a dummy inventory to store the pellets for further shipping to all coal-fired power plants in Indonesia. Various distance and transport values of the pellets from the pellet factories to the port (in t·km) are given in **Table S13** (*Supplementary Information*)

This study assumed that the pellets transported by ships reach the power plant without any additional transport, considering that almost all power plants are either located near seaports or supported with port facilities (IEA Clean Coal Centre, 2016).

Details regarding the number of pellets distributed *via* sea routes (from the port to coal power plants) can be found in **Table S14** (*Supplementary Information*). The distribution of pellets to the power plant was modeled using "transoceanic ship" datasets. This is typically used for transporting bulk materials such as coal through sea routes. The quantity of pellets needed for each power plant varied, and was calculated based on the actual annual production of coal electricity in 2017, rather than on the production capacity (see **Table S15**; *Supplementary Information*). The transportation value of pellets from the port to power plants were expressed in two values: 0.04 t·km/kWh for CF and 0.8 t·km/kWh for SFP. It should be noted that the t·km value for SFP was derived from the t·km value for CF divided by 0.05, the co-firing ratio applied. An illustration of pellet

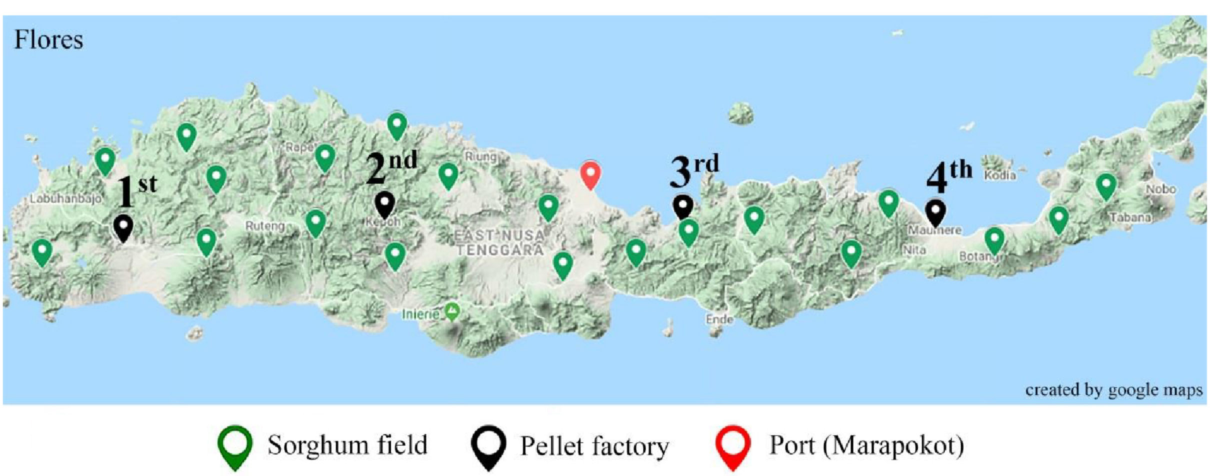


Fig. 4. Assumed locations of sorghum fields and pellet factories.

Please cite this article as: Wiloso E.I., Setiawan A.A.R., Prasetia H., Muryanto, Wiloso A.R., Subyakto, Sudiana I.M., Lestari R., Nugroho S., Hermawan D., Fang K., Heijungs R. Production of sorghum pellets for electricity generation in Indonesia: A life cycle assessment. Biofuel Research Journal 27 (2020) 1178-1194. DOI: 10.18331/BRJ2020.7.3.2

distribution *via* sea routes can be seen in **Figure S1** (*Supplementary Information*).

2.7. Field emissions

Field emissions are considered an important issue in agricultural activities, and mainly consist of CH_4 and N_2O emissions primarily due to anaerobic processes and the application of nitrogenous fertilizers (van Amstel and Swart, 1994). In that regard, we also considered these emissions in the sensitivity analysis. Methane emissions are likely to occur under strictly anaerobic conditions (Oertel et al., 2016), such as a wet system in a rice field (Chen et al., 2011). As sorghum cultivation typically does not involve a submerged system, anaerobic conditions are unlikely to be present. Consequently, CH_4 emissions should be very low, such that it can be ignored. In this context, Murphy et al. (2013), who studied the LCA of miscanthus, a grass plant similar to sorghum, did not consider CH_4 emissions either.

Besides originating from artificial or compost fertilizers, N_2O emissions in managed soil are also derived from urine, crop residues, and soil organic matter (Brentrup et al., 2000). In the current study, we used the IPCC guidelines to calculate N_2O field emissions (IPCC, 2006b). Due to lack of data on other parameters, only direct N_2O emissions and those from N inputs to managed soil were considered. The nitrogen contents of the synthetic fertilizer and compost were around 50% (field-trial in Gresik, East Java) and 2% (Kim et al., 2014), respectively. Based on the calculations (see detail in **Table S16**; *Supplementary Information*), the field emission value was 4.09 kg N_2O/ha·yr. This would certainly give a lower amount of N_2O field emissions than the ideal method, i.e., including both direct and indirect N_2O emissions from all sources. However, the total N_2O emissions from an agricultural field are generally dominated by direct N_2O emissions, which contributes approximately 75% of total N_2O emissions (Cavigelli et al., 2012). Thus, the sensitivity analysis related to field emissions from agricultural activities captures the major aspects of concern. In addition to N_2O emissions, CO_2 emissions from the application of N fertilizer (urea) were also considered in the sensitivity analysis using the method recommended by the IPCC (2006b), which value was 257 kg CO_2/ha·yr.

Besides N fertilizer application, land modification can also be a significant contributor to the global warming impact, as soil carbon is released into the atmosphere (Baker et al., 2007). In this regard, Robertson et al. (2017) indicated that proper cultivation management techniques is a key factor to improve soil carbon accumulation. For example, in sorghum cultivation, the cover cropping techniques with hairy vetch/rye wheat could increase soil carbon (Sainju et al., 2015). However, GHG emissions associated with soil carbon is outside the scope of the current study, and not discussed any further herein.

3. Results and Discussion

3.1. Global warming impacts

The global warming impacts of electricity generation were evaluated for the SFC, CF, and SFP product systems. GHG savings were determined by subtracting the values of the scenario models (CF or SFP) from the baseline model (SFC). **Table 7** summarizes the results of the global warming impacts of electricity generated by the three product systems, and the GHG savings associated with the CF and SFP scenarios.

Table 7 shows that pellet production based on 100,000 ha·yr is 4.8 million tons. Meanwhile, the total amount of pellets needed for 5% co-firing in all coal power plants in Indonesia is only 3.05 million tons. Under these conditions, there will thus be an excess of 1.75 million tons of pellets annually. We further elaborated the results presented in **Table 7** to determine which life cycle stages contributed the most to the global warming impacts by conducting a hotspot analysis. The results for each product system are shown in **Table 8**.

Assuming 100% conversion of harvested sorghum biomass into pellets, the total annual production volume of pellets was 4.8 million tons, which represents 83.5 million GJ of potential energy (based on GCV). Furthermore, if the pellets are sent to power plants, they could generate 29.9 million GJ or 8,309.34 GWh electricity (based on a gross efficiency of 35.8%).

For the purpose of calculating FER index, the energy of the pellets and the primary fossil energy required for their production were expressed on an NCV basis. The energy required to produce the pellets was calculated *via* the “cumulative energy demand (LHV) V1.00/cumulative energy demand” method (Weidema et al., 2013), which was conducted with SimaPro. The results showed that the production of 1 ton of sorghum pellets (16.4 GJ) required 2.85 GJ of fossil energy. Hence, the FER of sorghum pellets was 5.75.

Table 7.
The global warming impacts of electricity for different product systems and functional units.

Product system[a]	Fuel requirement (kg)		Global warming[b] (kg CO_2-eq)	GHG savings[c]	
	Coal	Pellet		kg CO_2-eq	%
Functional unit (FU) = 1 kWh electricity[d]					
SFC	0.518	-	1.12	-	-
CF	0.492	0.029	1.07	0.05	4
SFP	-	0.578	0.17	0.95	85
FU = 8,309.34 GWh electricity (utilizing 100,000 ha·yr field)					
SFC	4.30E9	-	9.31E9	-	-
CF	4.09E9	2.40E8	8.89E9	4.15E8	4
SFP	-	4.80E9	1.39E9	7.92E9	85
FU = 105,651.39 GWh electricity (1-year coal-based electricity production in Indonesia)					
SFC	5.47E10	-	1.18E11	-	-
CF[e]	5.20E10	3.05E09	1.13E11	5.28E09	4
SFP	-	6.10E10	1.76E10	1.01E11	85

[a] SFC = single-firing of coal; CF = co-firing of coal with pellet; SFP = single-firing of pellets (see *Section 2.1*).
[b] Considering complete combustion of pellets in power plants, and not considering field emissions from sorghum cultivation activities.
[c] The reference scenario for reducing global warming is SFC.
[d] The result of this functional unit is illustrated in **Figure 5**.
[e] Implementing 5% co-firing in all existing coal power plants in Indonesia requires 3.05 million tons of pellets and reduces the global warming impacts by 5.28 million ton CO_2-eq from the baseline of 118 million ton CO_2-eq over a year (4% GHG savings).

Table 8.
Contribution of life cycle stages to global warming impacts for different product systems.

Life cycle stage of product system	Global warming (kg CO_2eq/kWh)	Contribution (%)
SFC (single-firing of coal)		
Coal production[a]	0.014	1.26
Electricity generation	1.106	98.74
CF (co-firing of coal with pellet)		
Coal production	0.013	1.25
Pellet production[b]	0.008	0.76
Electricity production	1.050	97.99
SFP (single-firing of sorghum pellet)		
Sorghum production	0.036	21.62
Land transport (I)[c]	0.002	1.15
Pellet processing	0.100	59.89
Land transport (II)[d]	0.016	9.40
Sea transport[e]	0.009	5.58
Electricity generation	0.004	2.36

[a] Includes coal transport from mining areas
[b] Includes sorghum cultivation and biomass transport
[c] Sorghum biomass from fields to pellet factory
[d] Pellet product from factories to ports
[e] Pellet product from ports to power plants

3.2. Hotspot analysis

Figure 5a illustrates a comparison of the global warming impacts between the three electricity product systems, the values for which were derived from **Table 8**. It shows that the life cycle stage of electricity generation (orange bar) for the SFP scenario had the lowest global warming impacts (0.167 kg CO_2-eq/kWh) in comparison with those of the SFC and CF scenarios (1.12 kg CO_2-eq/kWh and 1.07 kg CO_2-eq/kWh, respectively). The pellet production under CF (blue bar in **Figure 5a**)

Please cite this article as: Wiloso E.I., Setiawan A.A.R., Prasetia H., Muryanto, Wiloso A.R., Subyakto, Sudiana I.M., Lestari R., Nugroho S., Hermawan D., Fang K., Heijungs R. Production of sorghum pellets for electricity generation in Indonesia: A life cycle assessment. Biofuel Research Journal 27 (2020) 1178-1194. DOI: 10.18331/BRJ2020.7.3.2

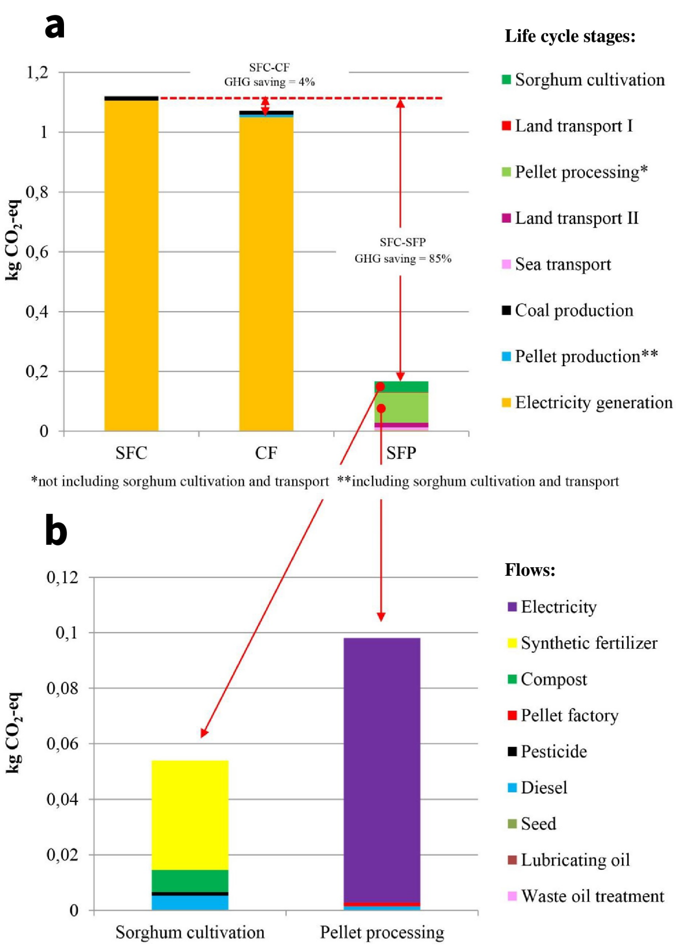


Fig. 5. Hotspot analysis for 1 kWh of electricity generated in different product systems.
(a) SFC (single-firing of coal), CF (co-firing of coal with pellet), and SFP (single-firing of pellet);
(b) Sorghum-cultivation and pellet-processing fractions for SFP.

included upstream processes such as transport and sorghum production, while the pellet processing under SFP (light green bar) did not.

The hotspots for the SFC and CF scenarios were electricity generation, while that for the SFP scenario was pellet processing. The lowest impact of SFP is due to the fact that GHG emissions from pellet combustion were not calculated, following the carbon-neutral principle. The same approach was adopted in other studies on pellets made from grasses such as switchgrass (Bergman et al., 2015) and miscanthus (Lewandowski et al., 1995). Similarly, the GHG emissions from 5% biomass electricity in the CF scenario were not counted as an impact on global warming. Therefore, in comparison with the SFC scenario, the potential reduction in global warming impacts under the SFP scenario in the current study (SFC-SFP) was 85%. Meanwhile, Lewandowski et al. (1995) and Bergman et al. (2015) reported more or less similar results, of 90% and 80%, respectively. Since the CF scenario considers only 5% electricity production from biomass, the impact reduction under the CF scenario (SFC-CF) was proportionally lower (4%).

Pellet processing shared the largest impact toward global warming, followed by decreasing contributions by sorghum cultivation and electricity generation. The dominant impact of pellet processing over sorghum cultivation is in line with the results obtained in the previous studies (Murphy et al., 2013; Bergman et al., 2015). **Figure 5b** shows the relative contributions of sorghum cultivation and pellet processing in SFP systems. It illustrates the contribution of each flow (electricity, fertilizer, pesticide, diesel, and others) to the overall global warming impact.

3.3. Sensitivity analysis

As a number of assumptions were made in the modeling, we considered four important issues as the basis for the sensitivity analysis. These were assumptions related to the conditions of the combustion systems (complete or incomplete), field emissions due to fertilizer application, reduced sorghum yield, and biomass loss.

In practice, complete combustion is very rare (van Amstel and Swart, 1994). In spite of that, several studies on grass pellets have also taken this approach to simplify calculations (Lewandowski et al., 1995; Bergman et al., 2015). Concerning field emissions due to fertilizer application, it should be noted that there is an ongoing debate regarding whether or not agricultural land is part of the product system, as it sits at the interface between anthropogenic and environmental systems (Guinée et al., 2002; Goglio et al., 2015). This will lead to differences in LCA modeling directly related to field emissions. For example, Lewandowski et al. (1995) and Murphy et al. (2013) studied miscanthus pellets considering field emissions, while Bergman et al. (2015) did not consider field emissions in their study on switchgrass pellets. Considering marginal land condition and less water input (10,000 liter/ha·yr) in large scale operation (100,000 ha), the sorghum yield of 24 ton/ha·yr was applied in the sensitivity analysis. A biomass loss of 10% in sorghum harvesting and 7% in pellet processing (Jannasch et al., 2001; Murphy et al., 2013; Serra et al., 2017) also underwent the same analysis. **Table 9** summarizes the results of the sensitivity analysis.

Based on the results of the sensitivity analysis, the various choices regarding the modeling resulted in GHG savings ranging from 85% (reference scenario) to 70% (alternative scenarios) under the SFC-SFP model. However, the GHG savings under the SFC-CF model did not change between the reference and alternative scenarios, after rounding to the nearest whole number. Thus, the CF model was less sensitive than the SFP model to the four modeling choices or assumptions. This is mainly because the co-firing percentage was only 5%. For CF models with higher co-firing ratios (e.g., 10%), the differences in the estimated GHG savings between the reference and alternative models should be more significant. For illustration, we performed a simulation under the CF model with a co-firing ratio of 10%, which resulted in GHG savings of 9% for the reference models and 8% for all of the alternative models.

3.4. Comparisons of inventory and impacts

The current study finds that the global warming impacts of pellet production are higher than those of coal production. However, if the boundary is expanded to include fuel combustion at power plants as well, electricity generated from the pellets becomes “greener” than coal (see **Fig. 5**). This is mainly due to the carbon-neutral assumption, as biomass has the advantage of zero net CO_2 emissions in a combustion process (Sajdak et al., 2019). **Figure 5b** further indicates that fertilizer and electricity are the hotspots in the sorghum cultivation and pellet processing stages, respectively.

Comparisons with similar LCA studies on pellets produced from grasses, in particular from miscanthus (Lewandowski et al., 1995; Murphy et al., 2013) and switchgrass (Bergman et al., 2015), were conducted to enhance the interpretation of the results. **Table 10** summarizes the characteristics of various grass pellets. It shows that sorghum is superior in terms of yield, but has a lower energy content than those produced from miscanthus or switchgrass. Reductions in GHG emissions due to substitution of fossil fuels with pellets were also analyzed by Lewandowski et al. (1995) and Bergman et al. (2015).

We compared the results of this study with those of previous studies on two levels, i.e., life cycle inventory (LCI) and life cycle impact assessment (LCIA). At the LCI level, the comparison was made for those identified as the hotspots in biomass production and pellet processing, i.e., fertilizer and electricity, respectively. To obtain comparable data in the same units, we modified the literature values by considering their specific yield (ton/ha) and energy content (MJ/kg) as conversion factors. **Table 11** shows a comparison of the fertilizer and electricity inputs between the current study and previous studies. As presented, there are considerable differences in the amount of fertilizer applied among the studies considered, but the values of the current study (16.98 kg/ton biomass) and those from Lewandowski et

Table 9.
Sensitivity analysis on several modeling choices.

Choice in modeling				Global warming ($kg\ CO_2$-eq/kWh)			GHG saving (%)	
Combustion conditions	**Field emissions**[a]	**Sorghum yield (ton/ha·yr)**	**Mass loss**	**SFC**	**CF**	**SFP**	**SFC-CF**	**SFC-SFP**
Complete[b]	No	48	No	1.12	1.07	0.171	4	85
			Yes	1.12	1.07	0.186	4	83
		24	No	1.12	1.07	0.207	4	82
			Yes	1.12	1.08	0.229	4	80
	Yes	48	No	1.12	1.07	0.187	4	83
			Yes	1.12	1.07	0.206	4	82
		24	No	1.12	1.08	0.239	4	79
			Yes	1.12	1.08	0.268	4	76
Incomplete[c]	No	48	No	1.12	1.08	0.235	4	79
			Yes	1.12	1.08	0.250	4	78
		24	No	1.12	1.08	0.271	4	76
			Yes	1.12	1.08	0.294	4	74
	Yes	48	No	1.12	1.08	0.251	4	78
			Yes	1.12	1.08	0.270	4	76
		24	No	1.12	1.08	0.303	4	73
			Yes	1.12	1.08	0.332	4	70

SFC= single-firing of coal; CF= co-firing of coal with pellet; SFP= single-firing of sorghum pellet (see *Section 2.1*).
[a] Considered CO_2 and N_2O emissions. The reason for not including CH_4 field emission has been explained in *Section 2.7*.
[b] There are no CH_4 and N_2O emissions from sorghum pellet combustion at the power plant.
[c] There are CH_4 and N_2O emission from sorghum pellet combustion at the power plant.

Table 10.
Comparison of the characteristics of various grass pellets.

Parameter	*This study*	Lewandowski et al. (1998)	Murphy et al. (2013)	Bergman et al. (2015)
Type of grass biomass	Sorghum	Miscanthus	Miscanthus	Switchgrass
Yield (ton/ha)	48	20	11.5	13.9
Harvest efficiency[a]	1	1	0.9	1
Net yield (ton/ha)	48	20	10.35	13.9
Production site	Indonesia	Germany	Ireland	Southeast USA
Energy content (MJ/kg)[b]	16.4	18.6	18	18
Energy equivalency (kg pellet/kg coal)[c]	1.12	0.98	1.02	1.02

[a] Ratio between actual and potential biomass harvest.
[b] All based on the net caloric value (NCV).
[c] Refers to the brown coal used in this study, with an energy content of 18.3 MJ/kg (see **Table 3**).

al. (1995) (17.5 kg/ton biomass) are quite similar. Meanwhile, Bergman et al. (2015) considered the application of only 5.26 kg of fertilizer. In summary, the ratio of fertilizer used in the studies listed in **Table 11**, from left to right, is approximately 3:3:2:1. Sorghum has a high absorption efficiency for nitrogenous fertilizers (Ameen et al., 2017). Further, as indicated in *Section 1.3*, marginal land is characterized by low fertility, leading to higher fertilizer requirements in order to produce the same amount of biomass. Since sorghum is cultivated on marginal land in this study, soil fertility is likely to be the dominant controlling factor.

Like in the current study, Murphy et al. (2013) and Bergman et al. (2015) also found that electricity is the input flow that contributes the most to the global warming impacts of pellet processing. Referring to **Table 11**, the ratio of electricity used among the studies considered, from left to right, is approximately 3:2:1:3. The amount of electricity required for the production of 1 ton of pellets in this study was 148.67 kWh, which is nearly the same as the 145.67 kWh reported in the study by Bergman et al. (2015).

In 2017, the proportion contributed by coal to the electricity mix in Indonesia was 58% (PLN, 2018), while those in the United States and Europe were 14% (Eurostat, 2019; U.S. Energy Information Administration, 2019). Rather than referring to PLN (2018), our model considered an energy mix that differed from the actual conditions. We used the ecoinvent dataset "market for electricity, medium voltage ID" to represent the average electricity mix in Indonesia, which consists of approximately 46% lignite (brown coal), followed by natural gas and oil. Meanwhile, Bergman et al. (2015) used an electricity input of the eastern US grid mix between 2008 and 2010, consisting of approximately 58% coal, followed by decreasing contributions by nuclear energy and natural gas. Since Bergman et al. (2015) considered electrical energy with a similar energy mix, their results should be comparable with those of the current study. **Table 12** compares the global warming impacts among the

Table 11.
Comparison of fertilizer and electricity inputs of various grass pellets.

Flow*	*This study*	Lewandowski et al. (1995)	Murphy et al. (2013)	Bergman et al. (2015)
	Sorghum	**Miscanthus**	**Miscanthus**	**Switchgrass**
N-Fertilizer (kg/ton biomass)	7.29	5	5.22	4.77
P-Fertilizer (kg/ton biomass)	6.25	2.5	0.78	0.49
K-Fertilizer (kg/ton biomass)	3.44	10	5.11	-
Total fertilizer (kg/ton biomass)	16.98	17.5	11.11	5.26
Electricity (kWh/ton pellet)	148.67	90.08	58.11	145.67

N-fertilizer = urea; P-fertilizer = TSP (Triple Super Phosphate); K-fertilizer = KCl (Potassium Chloride).
* **Table S17** (*Supplementary Information*) provides a more detailed LCI comparison.

Please cite this article as: Wiloso E.I., Setiawan A.A.R., Prasetia H., Muryanto, Wiloso A.R., Subyakto, Sudiana I.M., Lestari R., Nugroho S., Hermawan D., Fang K., Heijungs R. Production of sorghum pellets for electricity generation in Indonesia: A life cycle assessment. Biofuel Research Journal 27 (2020) 1178-1194. DOI: 10.18331/BRJ2020.7.3.2

Table 12.
Comparison of the global warming impact of 1 kg pellet.

Life cycle stages	Global warming impact (kg CO_2-eq)			
	This study (Sorghum)	Lewandowski et al. (1995) (Miscanthus)	Murphy et al. (2013) (Miscanthus)	Bergman et al. (2015) (Switchgrass)
Biomass production	0.062	0.077	0.101	0.006
Pellet processing	0.177	0.034	0.263	0.197
Electricity generation*	0.050	0	-	-
Total	0.289	0.111	0.364	0.203

*Of the four studies, only this study and Lewandowski et al. (1995) modeled the electricity generation. Both used a carbon-neutral assumption for pellet combustion. Furthermore, only this study considered emissions from the power plant infrastructure and ash treatment.

considered studies at the level of life cycle stage (biomass production, pellet processing, and electricity generation).

Considering the different modeling choices and assumptions, the results of the various studies listed in **Table 12** should be interpreted carefully. In general, it is shown that pellet processing has a higher global warming impact than biomass production, with the exception of the results of Lewandowski et al. (1995) which indicated the opposite. The current study indicated that pellet processing has an impact almost three times higher than that of biomass production, whereas Murphy et al. (2013) reported a slightly smaller difference (almost 2.5 times higher). Surprisingly, Bergman et al. (2015) reported an exceptionally low impact from the stage of biomass production.

As indicated in *Section 2.2.1*, the sorghum pellet dataset was based on primary data from a field trial, while the data for coal was derived from the ecoinvent dataset "market for lignite RoW". The LCA results showed that for the FU of 1 kg fuel, the global warming impacts of pellets and coal were 0.239 kg CO_2-eq and 0.0273 kg CO_2-eq, respectively. The global warming impacts of 1 MJ pellets and coal were 0.0146 kg CO_2-eq and 0.0015 kg CO_2-eq, respectively. The impact ratio between pellets and coal was approximately 9:1 for both FU (based on kg of fuel or MJ of energy produced). Furthermore, the global warming impacts of sorghum pellets in the current study are within the range of values reported in other studies on grass pellets. For example, the impact reported for switchgrass was 0.203 kg CO_2-eq/kg (Bergman et al., 2015), and those for miscanthus were 0.111 kg CO_2-eq/kg (Lewandowski et al., 1995) and 0.364 kg CO_2-eq/kg (Murphy et al., 2013). The above analysis confirms that the global impact of pellets is in general higher than that of coal.

The current study indicates that to generate the same amount of electricity, 1.12 kg of sorghum pellets is required to substitute 1 kg of coal. Lewandowski et al. (1995) reported higher values, i.e., 1.67 kg of miscanthus pellets for 1 kg of coal. This difference might correlate to the type of coals used in their study. For example, Lewandowski et al. (1995) used hard coal with a higher energy content (29.3 MJ/kg, NCV), whereas the current study used brown coal of lower energy content (18.3 MJ/kg, NCV). Furthermore, setting brown coal as a reference, the quantity of pellets needed to replace 1 kg of coal varied among studies. Based on **Table 10**, the current study indicates that more pellets are needed to replace coal than the amounts reported in the other studies. This is because the energy content of the pellets considered in this study is lower (16.4 GJ/ton) than those of the pellets considered in the other studies (18-18.6 GJ/ton).

This study explored the impact of the transport of pellets, whereas the transport of coal was not explicitly expressed as it is already aggregated in the coal datasets. Of the three transport systems modeled, land transport (II) (pellet product from factory to ports) contributed the most to the global warming impacts (0.016 kg CO_2-eq/kWh), followed by sea transport and land transport (I) (sorghum biomass from fields to pellet factory). Sea transport, involving distances of up to 1,000 km, had a lower impact than land transport (II), involving maximum distances of only 299 km. This demonstrates that the sea transport system is far more efficient than land transport in transporting bulky material over long distances. A similar observation was reported by Wiloso et al. (2019).

3.5. Study limitations

The limitations of this study are primarily related to the choices and assumptions made within the LCA modeling. The LCA results are underpinned by at least two main factors, namely the choices of power plant inventories and the assumption of similarity in agricultural conditions (soil properties and climate) between the locations of the field trial (Gresik) and the current scenario study (Flores). Inventory data for the power plant was developed based on the operation of the Suralaya power plant in Banten (Widiyanto et al., 2003). Thus, the material inputs considered were not necessarily exactly representative of the Suralaya power plant in 2017 (Zwebek and Pilidis, 2003). Moreover, this scenario study would have benefitted from the use of a national average of mixed technologies. However, this might not be too problematic as we used the same Suralaya power plant model to compare the three product systems (SFC, CF, and SFP). Thus, the results would be comparable in relative terms.

The inventory for sorghum cultivation in this study came from the agricultural data in Gresik, while the sorghum cultivation scenario was modeled in Flores. In this study, differences in soil fertility and regional climate between the two sites were not considered, which could have resulted in different inventories. Such differences would consequently introduce errors. In practice, this should be adjusted to better reflect fertilizer requirement in Flores, thus improving the quality of the estimate of global warming impacts.

4. Conclusions and future prospects

There have been ongoing debates concerning the environmental status of bioenergy systems. Bioenergy is believed to possess significant GHG mitigation potentials, but is simultaneously suspected to increase GHG emissions due to the loss of carbon stocks as a consequence of LUC. Such risk was minimized in this study since the sorghum was grown on parts of under-utilized marginal land, a flat area where sorghum cultivation is possible. Moreover, the revegetation of grassland in Flores with sorghum would likely improve biodiversity and soil properties. This study also considered a comprehensive system boundary encompassing sorghum cultivation, pellet processing, and electricity generation. With this approach, burden-shifting along the life cycle of the product system is minimized. Finally, the sensitivity analysis was carried out to also consider reduced biomass yield, incomplete combustion of biomass, and field emissions from fertilizer application. These three factors (revegetation of marginal land, the comprehensive system boundary, and sensitivity analysis) are believed to have substantially improved the scientific robustness of the following conclusions:

This scenario study modeled the utilization of 100 thousand ha of marginal land in Flores for sorghum biomass cultivation. The following statements answer the five research questions posed in *Section 1.6* (Q1-Q5). Based on a biomass yield of 48 ton/ha·yr, 4.8 million tons of pellets can be produced annually. This amount can in turn generate 8,300 GWh of biomass electricity. For that purpose, 1 ton of coal can be replaced by 1.12

tons of pellets (Q1). This equivalency is based on maximum potential substitution (100% displacement), a typical approach in attributional LCA. The calculated FER of the pellets was 5.8, indicating that the production of pellets for fuel is energetically feasible (Q2). As compared to a coal system, the sole combustion of pellets to generate 8,300 GWh of electricity can reduce global warming impacts by 7.9 million tons CO_2-eq, which is equivalent to an 85% reduction in GHG emissions. In co-firing operations, 5% of the annual electricity produced by all coal-fired power plants in Indonesia, equivalent to 5,300 GWh, can be generated *via* the combustion of 3 million tons of pellets at the plants (Q3). The substitution of coal in this operation reduces global warming impacts by 5.3 million tons CO_2-eq (Q4). However, these results would change if emissions from incomplete biomass-combustion (N_2O and CH_4) and field application of nitrogenous fertilizers (N_2O) were included in the model (Q5). A sensitivity analysis of the above factors, including reduced biomass yield and biomass loss, showed that the projected GHG savings could be reduced from the initial value of 85% to as low as 70%.

This study found that sorghum cultivation and pellet processing were the hotspots of the electricity generated from sorghum pellets. This is in line with the results of similar studies based on different grass pellets, namely switchgrass and miscanthus. Further investigations showed that fertilizer application in sorghum cultivation and electricity requirements in pellet processing were the most responsible factors.

Sorghum pellets have a relatively high ash content, which may make combustion chambers prone to technical problems such as slagging or fouling. In comparison with coal, the ash content of pellets (7%) is actually acceptable for application in both PC and CFB technologies. However, the presence of inorganic elements such as N, K, and Cl may pose problems, especially if applied in a PC power plant converted from an oil-fired boiler system. Such power plants require pellets with ash content of less than 1% (Stromberg, 2006). In this regard, further research toward reducing the ash content of pellets is recommended, for example *via* washing the biomass with water prior to pellet processing, or mixing of the sorghum pellets with other pellets of lower ash content.

It is concluded that the production of sorghum pellets in Flores and its utilization for electricity generation can significantly reduce the reliance on fossil fuels and contribute to climate change mitigation. Sensitivity analysis shows that 2.4 million tons of pellets, based on 24 ton sorghum/ha·yr, can generate 4,150 GWh electricity. In contrast to the reference scenario, the reduced biomass amount can supply only 78% of existing coal-fired power plants capacity in Indonesia for 5% co-firing operation.

In addition to the above findings; however, other impact categories and factors outside the system boundary might contribute to these aspects as well. Hence, a more complete impact category coverage and a consequential approach considering market mechanism may be needed for more comprehensive examination. Further studies considering actual carbon balance (uptake and release) instead of a carbon-neutral assumption is also recommended. The results of this scenario study can also assist the government in exploring the potential utilization of marginal land for bioenergy development, both in Indonesia and beyond.

Acknowledgments

We would like to thank Patrik J.G. Henriksson of the Stockholm Resilience Centre, Stockholm University and WorldFish for his valuable input and suggestions on an earlier version of the manuscript. This work was supported by SATREPS-JICA, the project for producing biomass energy and material through the revegetation of Alang-alang (Imperata cylindrica) fields, a collaborative project between the Indonesian Institute of Sciences (LIPI), Indonesia, and Kyoto University, Japan.

References

[1] Aho, M., Envall, T., Kauppinen, J., 2013. Corrosivity of flue gases during co-firing Chinese biomass with coal at fluidised bed conditions. Fuel Process. Technol. 105, 82-88.

[2] Ameen, A., Yang, X., Chen, F., Tang, C., Du, F., Fahad, S., Xie, G.H., 2017. Biomass yield and nutrient uptake of energy sorghum in response to nitrogen fertilizer rate on marginal land in a semi-arid region. Bioenergy Res. 10(2), 363-376.

[3] Ansermet, J.P., Brechet, S.D., 2019. Principles of Thermodynamics. Cambridge University Press.

[4] Atilgan, B., Azapagic, A., 2015. Life cycle environmental impacts of electricity from fossil fuels in Turkey. J. Clean. Prod. 106, 555-564.

[5] Baker, J.M., Ochsner, T.E., Venterea, R.T., Griffis, T.J., 2007. Tillage and soil carbon sequestration-what do we really know?. Agric. Ecosyst. Environ. 118(1-4), 1-5.

[6] Bappenas, 2016. Laporan Akhir: Kajian Ketercapaian Target DMO Batubara Sebesar 60% Produksi Nasional pada Tahun 2019.

[7] Bappenas, 2019. Low Carbon Development: A Paradigm Shift Towards a Green Economy in Indonesia.

[8] Barros, M.V., Salvador, R., Piekarski, C.M., de Francisco, A.C., Freire, F.M.C.S., 2019. Life cycle assessment of electricity generation: a review of the characteristics of existing literature. Int. J. Life Cycle Assess. 25(1), 36-54.

[9] Beér, J.M., 2007. High efficiency electric power generation: the environmental role. Prog. Energy Combust. Sci. 33(2), 107-134.

[10] Bergman, R.D., Reed, D.L., Taylor, A.M., Harper, D.P., Hodges, D.G., 2015. Cradle-to-gate life cycle assessment of switchgrass fuel pellets manufactured in the Southeastern United States1. Wood Fiber Sci. 47(2), 147-159.

[11] Bhatt, M.S., 2006. Effect of ash in coal on the performance of coal fired thermal power plants. Part II: capacity and secondary energy effects. Energy Sources Part A. 28(1), 43-58.

[12] Boylan, D.M., 1996. Southern company tests of wood/coal cofiring in pulverized coal units. Biomass Bioenergy. 10(2-3), 139-147.

[13] BPDASHL Benain Noelmina, 2018. Peta Lahan Kritis Wilayah Kerja BPDAS Benain Noelmina. East Nusa Tenggara.

[14] BPS NTT, 2020. Nusa Tenggara Timur Province in Figures 2019. BPS NTT Province. Kupang.

[15] Brentrup, F., Küsters, J., Lammel, J., Kuhlmann, H., 2000. Methods to estimate on-field nitrogen emissions from crop production as an input to LCA studies in the agricultural sector. Int. J. Life Cycle Assess. 5(6), 349.

[16] Cavigelli, M.A., Grosso, S.J., Liebig, M.A., Snyder, C.S., Fixen, P.E., Venterea, R.T., Leytem, A.B., McLain, J.E., Watts, D.B., 2012. US agricultural nitrous oxide emissions: context, status, and trends. Front. Ecol. Environ. 10(10), 537-546.

[17] Chen, R., Lin, X., Wang, Y., Hu, J., 2011. Mitigating methane emissions from irrigated paddy fields by application of aerobically composted livestock manures in eastern China. Soil Use Manage. 27(1), 103-109.

[18] Daystar, J., Reeb, C., Gonzalez, R., Venditti, R., Kelley, S.S., 2015. Environmental life cycle impacts of cellulosic ethanol in the Southern U.S. produced from loblolly pine, eucalyptus, unmanaged hardwoods, forest residues, and switchgrass using a thermochemical conversion pathway. Fuel Process. Technol. 138, 164-174.

[19] Demirbas, A., 2004. Combustion characteristics of different biomass fuels. Prog. Energy Combust. Sci. 30(2), 219-230.

[20] Döll, P., Petschel-Held, G., Leemans, R., 2008. Scale issues in scenario development. Environ. Futur. Pract. Environ. Scenar. Anal. 1-16.

[21] Dunaievska, N., Chernyavskiy, M., Shchudlo, T., 2016. Co-combustion of solid biomass in pulverized anthracite-coal firing boilers. Ukr. Food J. 5(4), 748-764.

[22] Elduque, A., Javierre, C., Elduque, D., Fernández, Á., 2015. LCI databases sensitivity analysis of the environmental impact of the injection molding process. Sustainability. 7(4), 3792-3800.

[23] Eurostat, 2019. Energy statistics-an overview. Eurostat Official Website.

[24] Fadli, M., Kamal, D.M., Adhi, P.M., 2019. SWOT analysis for direct coal co-firing with waste pellets on CFBC type boilers. J. Poli-Teknologi. 18, 271-280.

[25] Frischknecht, R., Jungbluth, N., Althaus, H.J., Bauer, C., Doka, G., Dones, R., Hischier, R., Hellweg, S., Humbert, S., Köllner, T., Loerincik, Y., 2007. Implementation of Life Cycle Impact Assessment Methods.

[26] García, R., Gil, M.V., Rubiera, F., Pevida, C., 2019. Pelletization of wood and alternative residual biomass blends for producing industrial quality pellets. Fuel. 251, 739-753.

Please cite this article as: Wiloso E.I., Setiawan A.A.R., Prasetia H., Muryanto, Wiloso A.R., Subyakto, Sudiana I.M., Lestari R., Nugroho S., Hermawan D., Fang K., Heijungs R. Production of sorghum pellets for electricity generation in Indonesia: A life cycle assessment. Biofuel Research Journal 27 (2020) 1178-1194. DOI: 10.18331/BRJ2020.7.3.2

[27] Gelfand, I., Sahajpal, R., Zhang, X., Izaurralde, R.C., Gross, K.L., Robertson, G.P., 2013. Sustainable bioenergy production from marginal lands in the US Midwest. Nature. 493(7433), 514-517.
[28] Goglio, P., Smith, W.N., Grant, B.B., Desjardins, R.L., McConkey, B.G., Campbell, C.A., Nemecek, T., 2015. Accounting for soil carbon changes in agricultural life cycle assessment (LCA): a review. J. Clean. Prod. 104, 23-39.
[29] Guinée, J.B., Gorrée, M., Heijungs, R., Huppes, G., Kleijn, R., Koning, A., de, Oers, L. van, Sleeswijk, A.W., Suh, S., Udo de Haes, H.A., Bruijn, H., de Duin, R., van Huijbregts, M.A.J., 2002. Handbook on life cycle assessment: Operational guide to the ISO standards. Springer Science and Business Media. 7.
[30] Head, M., Bernier, P., Levasseur, A., Beauregard, R., Margni, M., 2019. Forestry carbon budget models to improve biogenic carbon accounting in life cycle assessment. J. Cleaner Prod. 213, 289-299.
[31] Hidayat, A., 2009. Sumberdaya lahan Indonesia: potensi, permasalahan, dan strategi pemanfaatan. J. Sumberdaya Lahan. 3(2), 107-117.
[32] Husaini, A., 2020. PLTU Indramayu ujicoba gunakan wood pellet untuk bahan bakar pembangkit.
[33] IEA, 2019a. CO2 emissions from fuel combustion: overview.
[34] IEA, 2019b. Coal Information: overview.
[35] IEA, 2019c. Coal Information 2019 Edition.
[36] IEA, 2017. Technology Roadmap-Delivering Sustainable Bioenergy. International Energy Agency.
[37] IEA, 2004. Energy Statistics Manual, Energy Statistics Manual.
[38] IEA Clean Coal Centre, 2016. Potential water sources for coal-fired power plants.
[39] IPCC, 2006a. IPCC Guidelines for National Greenhouse Gas Inventories.
[40] IPCC, 2006b. IPCC-N_2O Emissions from managed Soils and CO_2 Emissions From, Agriculture.
[41] ISO 14040, 2006. Environmental management-Life cycle assessment-Principles and framework.
[42] ISO 14044, 2006. Environmental management-Life cycle assessment-Requirements and guidelines.
[43] Jannasch, R., Quan, Y., Samson, R., 2001. A process and energy analysis of pelletizing switchgrass. Prepared REAP Can.Natural Resour. Can.
[44] Jungbluth, N., Meili, C., Wenzel, P., 2018. Life cycle inventories of oil refinery processing and products. ESU-services Ltd. BFE, BAFU, Erdöl-Vereinigung.
[45] Khaerunisa, H., Huda, M., Damayanti, R., Antono, H.T., Komarudin Yaskuri, D., Lutfi, M., Suryati, E., Alimano, M., Nurhadi, H., Sibarani, L., Hayati, I., Mujahidin, S., 2009. Study of CO_2 emissions from coal combustion in Indonesia. Bandung.
[46] Khoshnevisan, B., Rafiee, S., Omid, M., Yousefi, M., Movahedi, M., 2013. Modeling of energy consumption and GHG (greenhouse gas) emissions in wheat production in Esfahan province of Iran using artificial neural networks. Energy. 52, 333-338.
[47] Kim, S.Y., Pramanik, P., Gutierrez, J., Hwang, H.Y., Kim, P.J., 2014. Comparison of methane emission characteristics in air-dried and composted cattle manure amended paddy soil during rice cultivation. Agric. Ecosyst. Environ. 197, 60-67.
[48] Kurniawan, H., Yuniati, D., 2015. Carbon sink potency in three types of savannah in Nusa Tenggara Timur (in Indonesian). J. Penelitian Kehutanan Wallacea. 4(1), 51-62.
[49] Lee, J.S., 2015. Calorific value of wood pellets. The University of British Columbia.
[50] Lewandowski, I., Kicherer, A., Vonier, P., 1995. CO_2-balance for the cultivation combustion of *Miscanthus*. Biomass Bioenergy. 8(2), 81-90.
[51] Livingston, W.R., 2016. The status of large scale biomass firing. The milling and combustion of biomass materials in large pulverised coal boilers. IEA Bioenergy: Task 32: Biomass Combustion and co-firing.
[52] Lockwood, T., 2013. Techno-economic analysis of PC versus CFB combustion technology. IEA Clean Coal Centre, Report CCC/226, London, UK.
[53] Matheus, R., Basri, M., Rompon, M.S., Neonufa, N., 2017. Strategi pengelolaan pertanian lahan kering dalam meningkatkan ketahanan pangan di Nusa Tenggara Timur. Partner. 22(2), 529-541.
[54] MEMR, 2018a. Pengesahan rencana usaha penyediaan tenaga listrik PT PLN 2018-2027. Ministry of Energy and Mineral Resources. Indonesia.
[55] MEMR, 2018b. Statistik Ketenagalistrikan T.A. 2018. Ministry of Energy and Mineral Resources. Indonesia.
[56] MEMR, 2019. Outlook Energy Indonesia 2019. Ministry of Energy and Mineral Resources. Indonesia.
[57] MEMR, 2020. Dukung target bauran EBT, PLN lakukan uji coba metode co-firing PLTU. Ministry of Energy and Mineral Resources of the Republic of Indonesia.
[58] Miller, B.G., 2004. Coal Energy Systems. Elsevier Academic Press, Cambridge.
[59] MoEF, 2018. Keputusan Menteri Lingkungan Hidup dan Kehutanan nomor: SK. 306/MENLHK/PDASHL/DAS.0/7/2018. Tentang Penetapan Lahan Kritis Nasional. Ministry of Environment and Forestry. Indonesia.
[60] Morrison, B., Golden, J.S., 2017. Life cycle assessment of co-firing coal and wood pellets in the Southeastern United States. J. Clean. Prod. 150, 188-196.
[61] Mostafa, M.E., Hu, S., Wang, Y., Su, S., Hu, X., Elsayed, S.A., Xiang, J., 2019. The significance of pelletization operating conditions: an analysis of physical and mechanical characteristics as well as energy consumption of biomass pellets. Renew. Sust. Energy Rev. 105, 332-348.
[62] Mulyani, A., Priyono, A. Agus, F., 2013. Semiarid soils of eastern Indonesia: soil classification and Land Uses, in: Shahid, S.A., et al. (Eds.), Developments in Soil Classification, Land Use Planning and Policy Implications: Innovative Thinking of Soil Inventory for Land Use Planning and Management of Land Resources. Springer Science and Business Media Dordrecht. pp. 449-466.
[63] Murphy, F., Devlin, G., McDonnell, K., 2013. Miscanthus production and processing in Ireland: an analysis of energy requirements and environmental impacts. Renew. Sust. Energy Rev. 23, 412-420.
[64] NCBI, 2014. PubChem Database. Deltamethrin, CID=40585.
[65] NCBI, 2004. PubChem Database. Carbofuran, CID=2566.
[66] Nian, V., 2016. The carbon neutrality of electricity generation from woody biomass and coal, a critical comparative evaluation. Appl. Energy. 179, 1069-1080.
[67] Oertel, C., Matschullat, J., Zurba, K., Zimmermann, F., Erasmi, S., 2016. Greenhouse gas emissions from soils-a review. Geochemistry. 76(3), 327-352.
[68] PLN, 2018. Statistik PLN 2017. Sekretariat Perusahaan PT PLN (Persero), Jakarta.
[69] PLN, 2019. Buku Statistik PLN 2018. Sekretariat Perusahaan PT PLN (Persero), Jakarta.
[70] Pradhan, A., Shrestha, D.S., McAloon, A., Yee, W., Haas, M., Duffield, J.A., Shapouri, H., 2010. Energy life-cycle assessment of soybean biodiesel. Biofuel Lifecycle Issues Res. 121.
[71] Qu, H., Liu, X.B., Dong, C.F., Lu, X.Y., Shen, Y.X., 2014. Field performance and nutritive value of sweet sorghum in eastern China. Field Crops Res. 157, 84-88.
[72] Rajaeifar, M.A., Ghobadian, B., Heidari, M.D., Fayyazi, E., 2013. Energy consumption and greenhouse gas emissions of biodiesel production from rapeseed in Iran. J. Renew. Sust. Energy. 5(6), 1-14.
[73] Reuters, 2020. Indonesia plans to replace old coal power plants with renewable plants: minister.
[74] Robertson, G.P., Hamilton, S.K., Barham, B.L., Dale, B.E., Izaurralde, R.C., Jackson, R.D., Landis, D.A., Swinton, S.M., Thelen, K.D., Tiedje, J.M., 2017. Cellulosic biofuel contributions to a sustainable energy future: choices and outcomes. Science. 356(6345).
[75] Russell-Smith, J., Djoeroemana, S., Maan, J., Pandanga, P., 2007. Rural livelihoods and burning practices in Savanna landscapes of Nusa Tenggara Timur, Eastern Indonesia. Hum. Ecol. 35(3), 345-359.
[76] Sainju, U.M., Singh, H.P., Singh, B.P., 2015. Cover crop effects on soil carbon and nitrogen under bioenergy sorghum crops. J. Soil Water Conserv. 70(6), 410-417.
[77] Sajdak, M., Kmieć, M., Micek, B., Hrabak, J., 2019. Determination of the optimal ratio of coal to biomass in the co-firing process: feed mixture properties. Int. J. Environ. Sci. Technol. 16(7), 2989-3000.
[78] Schakel, W., Meerman, H., Talaei, A., Ramírez, A., Faaij, A., 2014. Comparative life cycle assessment of biomass co-firing plants with carbon capture and storage. Appl. Energy. 131, 441-467.

Please cite this article as: Wiloso E.I., Setiawan A.A.R., Prasetia H., Muryanto, Wiloso A.R., Subyakto, Sudiana I.M., Lestari R., Nugroho S., Hermawan D., Fang K., Heijungs R. Production of sorghum pellets for electricity generation in Indonesia: A life cycle assessment. Biofuel Research Journal 27 (2020) 1178-1194. DOI: 10.18331/BRJ2020.7.3.2

[79] Serra, P., Colauzzi, M., Amaducci, S., 2017. Biomass sorghum production risk assessment analysis: a case study on electricity production in the Po Valley. Biomass Bioenergy. 96, 75-86.

[80] Simons, A., 2016. Road transport: new life cycle inventories for fossil-fuelled passenger cars and non-exhaust emissions in ecoinvent v3. Int. J. Life Cycle Assess. 21(9), 1299-1313.

[81] Sondreal, E.A., Benson, S.A., Hurley, J.P., Mann, M.D., Pavlish, J.H., Swanson, M.L., Weber, G.F., Zygarlicke, C.J., 2001. Review of advances in combustion technology and biomass cofiring. Fuel Process. Technol. 71(1-3), 7-38.

[82] Stromberg, B., 2006. Fuel Handbook. Stockholm (Sweden).

[83] Suh, S., Weidema, B., Schmidt, J.H., Heijungs, R., 2010. Generalized make and use framework for allocation in life cycle assessment. J. Ind. Ecol. 14(2), 335-353.

[84] Tang, C., Li, S., Li, M., Xie, G.H., 2018. Bioethanol potential of energy sorghum grown on marginal and arable lands. Front. Plant Sci. 9, 440.

[85] U.S. Energy Information Administration, 2019. September 2019 Monthly Energy Review, U.S. Energy Information Administration.

[86] van Amstel, A.R., Swart, R.J., 1994. Methane and nitrous oxide emissions: an introduction. Fert. Res. 37(3), 213-225.

[87] Wahyuni, N., 2014. Working time allocation and income of cattle farmers at Megang Sakti Subdistrict Musi Rawas Regency. Societa: Jurnal Ilmu-Ilmu Agribisnis.

[88] Weidema, B., 2000. Avoiding co-product allocation in life-cycle assessment. J. Ind. Ecol. 4(3), 11-33.

[89] Weidema, B.P., Bauer, C., Hischier, R., Mutel, C., Nemecek, T., Reinhard, J., Vadenbo, C.O., Wenet, G., 2013. Data quality guideline for the ecoinvent database version 3. Ecoinvent Report 1 (v3). Swiss Cent. Life Cycle Invent. 3.

[90] Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. Int. J. Life Cycle Assess. 21(9), 1218-1230.

[91] Widiyanto, A., Kato, S., Maruyama, N., 2003. Environmental impact analysis of indonesian electric generation system (development of a life cycle inventory of indonesian electricity). JSME Int. J., Ser. B. 46(4), 650-659.

[92] Wiloso, E.I., Heijungs, R., Huppes, G., Fang, K., 2016. Effect of biogenic carbon inventory on the LCA of bioenergy: challenges to the neutrality assumption. J. Clean. Prod. 125, 78-85.

[93] Wiloso, E.I., Sinke, P., Muryanto, Setiawan, A.A.R., Sari, A.A., Waluyo, J., Putri, A.M.H., Guinée, J., 2019. Hotspot identification in the Indonesian tempeh supply chain using life cycle assessment. Int. J. Life Cycle Assess. 24(11), 1948-1961.

[94] Yang, B., Wei, Y.M., Hou, Y., Li, H., Wang, P., 2019. Life cycle environmental impact assessment of fuel mix-based biomass co-firing plants with CO_2 capture and storage. Appl. Energy. 252, 113483.

[95] Zaimes G., Borkowski, M., Khanna, V., 2013. Life-Cycle Environmental Impacts of Biofuels and Co-products, in: Gupta, V.K., Tuohy, M.G. (Eds.), Biofuel Technologies: Recent Developments. Springer Heidelberg New York Dordrecht London. pp.471-499.

[96] Zwebek, A., Pilidis, P., 2003. Degradation effects on combined cycle power plant performance-Part II: steam turbine cycle component degradation effects. J. Eng. Gas Turbines Power. 125(3), 658-663.

Dr. Edi Iswanto Wiloso is the head of LCA research group at the Research Center for Science, Technology and Innovation Policy and Management, Indonesian Institute of Sciences. Edi received his PhD from the Institute of Environmental Sciences, Leiden University, The Netherlands. Currently, he serves as the chief editor at the Indonesian Journal of Life Cycle Assessment and Sustainability. Edi is also a co-founder of the Indonesian LCA Network, for which he served as the 1st chairman between 2015 and 2018. His research interest is on environmental sustainability of products and life cycle assessment.

Dr. Reinout Heijungs is an Associate Professor at the School of Business and Economics of Vrije Universiteit Amsterdam, The Netherlands. He has been active in quantitative sustainability analysis since 1991, and takes a special interest in mathematical and statistical aspects.

Arief Ameir Rahman Setiawan is a researcher at the Research Center for Science, Technology and Innovation Policy and Management, Indonesian Institute of Sciences. He received a master degree from the Graduate School of Industrial and Management System Engineering, Waseda University. He serves as the managing editor of the Indonesian Journal of Life Cycle Assessment and Sustainability. His research interest includes life cycle assessment in particular related to green supply chain and sustainable technology development.

Dr. I Made Sudiana is a Professor in microbial ecology at the Research Center for Biology, Indonesian Institute of Sciences. He has been working on the revegetation of deteriorated ecosystems and marginal lands, introduction of microbial ecology tools to assess the microbial diversity status of soil ecosystem, and development of microbial technologies to increase soil productivity and sustainability. Sudiana is the secretary of the Research Professor Association in Indonesia.

Please cite this article as: Wiloso E.I., Setiawan A.A.R., Prasetia H., Muryanto, Wiloso A.R., Subyakto, Sudiana I.M., Lestari R., Nugroho S., Hermawan D., Fang K., Heijungs R. Production of sorghum pellets for electricity generation in Indonesia: A life cycle assessment. Biofuel Research Journal 27 (2020) 1178-1194. DOI: 10.18331/BRJ2020.7.3.2

Dr. Satya Nugroho is a plant molecular biologist and breeder at the Research Center for Biotechnology, Indonesian Institute of Sciences. He is involved in research and development in crop biotechtechnology and especially rice in Indonesia. He received his PhD in Biochemistry and Molecular Biology from the Research School for Biological Sciences at the Australian National University. Currently, he also serves as the head of the Plant Group of the Technical Team for Environmental Biosafety of GM Crops, and has been involved in the development of the current regulations and guidance on the release of GM Crops in Indonesia.

Adisa Ramadhan Wiloso holds a bachelor in mechanical and biosystem engineering from the Bogor Agricultural University, Indonesia. He is currently pursuing his master degree at the Pamulang University. His research interests include life cycle assessment and bioenergy.

Muryanto is a researcher at the Research Centre for Chemistry, Indonesia Institute of Sciences. He received his master degree in chemical engineering from the University of Indonesia. His research fields are bioenergy and the environment. Currently, he is active in research on bioethanol and biorefinery from lignocellulosic biomass, wastewater treatment, and life cycle assessment on several chemical products.

Dr. Subyakto is a Research Professor at the Research Center for Biomaterials, Indonesian Institute of Sciences. He received his doctoral degree in Agriculture Science from the Kyoto University, Japan. His research interests include development of bio-composites from wood and natural fibers and their properties enhancement.

Dr. Reni Lestari is a senior researcher at the Research Center for Plant Conservation and Botanic Gardens, Indonesian Institute of Sciences. She obtained her bachelor degree in agriculture at the IPB University, Indonesia and master degree in botany at the James Cook University of Northern Queensland, Australia. She received her PhD from the Faculty of Agriculture and Horticulture of Humboldt University of Berlin, Germany. She has been collaborating with the Botanic Garden Conservation International Congress (Oxford, UK) and the University of Hohenheim (Stuttgart, Germany). Her research interests include botany, plant conservation, horticulture and agriculture

Dr. Dede Hermawan is an Associate Professor at the Forest Product Technology Department, Faculty of Forestry and Environment, IPB University (Bogor, Indonesia). His research interests include the utilization of biomass as raw materials for biocomposites and bioenergy.

Dr. Kai Fang is a tenured Associate Professor in environmental management at the Zhejiang University. He received his PhD from the Institute of Environmental Sciences (CML), Leiden University. His research interests include environmental footprints, integrated sustainability assessment and climate change economics. He is now a member of the editorial board of Journal of Cleaner Production and Regional Sustainability.

Dr. Hafiizh Prasetia is a research associate at the Research Centre for Chemistry, Indonesia Institute of Sciences. He received his PhD from the Brawijaya University, Malang, Indonesia. He serves as the Section Editor at the Indonesian Journal of Life Cycle Assessment and Sustainability. His research interests include Analytical and Environment Chemistry.

Please cite this article as: Wiloso E.I., Setiawan A.A.R., Prasetia H., Muryanto, Wiloso A.R., Subyakto, Sudiana I.M., Lestari R., Nugroho S., Hermawan D., Fang K., Heijungs R. Production of sorghum pellets for electricity generation in Indonesia: A life cycle assessment. Biofuel Research Journal 27 (2020) 1178-1194. DOI: 10.18331/BRJ2020.7.3.2

Supplementary Information

Table S1.
Marginal land distribution in Indonesia*.

No.	Province	Critical land area (ha)
1	Nanggroe Aceh Darusalam	316,637
2	Sumatera Utara	1,338,810
3	Sumatera Barat	651,970
4	Riau	710,873
5	Kepulauan Riau	8,230
6	Jambi	213,985
7	Bengkulu	148,887
8	Sumatera Selatan	733,756
9	Bangka Belitung	20,687
10	Lampung	403,910
11	Banten	330,408
12	DKI Jakarta	-
13	Jawa Barat	911,192
14	Jawa Tengah	375,733
15	DI. Yongyakarta	79,123
16	Jawa Timur	432,225
17	Bali	46,895
18	Nusa Tenggara Barat	65,799
19	Nusa Tenggara Timur	840,914
20	Kalimantan Barat	1,015,631
21	Kalimantan Tengah	861,240
22	Kalimantan Selatan	511,594
23	Kalimantan Timur	275,272
24	Kalimantan Utara	199,734
25	Sulawesi Utara	289,782
26	Gorontalo	332,298
27	Sulawesi Tengah	264,874
28	Sulawesi Barat	88,421
29	Sulawesi Selatan	449,606
30	Sulawesi Tenggara	424,655
31	Maluku	299,607
32	Maluku Utara	387,889
33	Papua Barat	437,288
34	Papua	538,523
Total		**14.006.450**

* Source: Ministry of Environment and Forestry of Indonesia
(Report on national critical land area per province in 2018)

Table S2.
Marginal land distribution in Flores Island*.

Region	Level of marginality					
	Non marginal (a)	Potentially marginal (b)	Rather marginal (c)	Marginal [a] (d)	Very marginal (e)	Marginal+ very marginal (d+e)
Alor	8,329	22,534	236,731	28,800	2,657	31,458
Ende	6,129	26,045	157,299	23,837	-	23,837
Flores Timur	4,105	20,644	114,966	37,677	1,236	38,913
Lembata	7,316	20,288	72,082	28,929	926	29,855
Manggarai	-	3,372	77,998	55,561	34	55,595
Manggarai Barat	5,513	23,668	230,415	59,555	1,784	61,340
Manggarai Timur	6,499	13,534	146,759	78,413	497	78,909
Nagekeo	21,155	66,853	42,581	16,484	-	16,484
Ngada	6,208	32,169	89,481	43,675	1,276	44,951
Sikka	6,382	36,853	87,554	40,376	186	40,562
Total	**71,635**	**265,960**	**1,255,866**	**413,307**	**8,596**	**421,904**

* Source: BPDASHL Benain Noelmina (2018)
[a] The term critical land is equivalent to marginal land (as used throughout this section of the paper).

Please cite this article as: Wiloso E.I., Setiawan A.A.R., Prasetia H., Muryanto, Wiloso A.R., Subyakto, Sudiana I.M., Lestari R., Nugroho S., Hermawan D., Fang K., Heijungs R. Production of sorghum pellets for electricity generation in Indonesia: A life cycle assessment. Biofuel Research Journal 27 (2020) 1178-1194. DOI: 10.18331/BRJ2020.7.3.2

Table S3.
Power plant technology commonly used in Indonesia*.

Power plant	Location	Year of operation	Installed capacity	Type [b]
Ombilin	West Sumatera	1996	2x100 MW	PC
Bukit Asam	South Sumatera	1987 (unit 1 & 2) 1994 (unit 3) 1995 (unit 4)	4x65 MW	PC
Paiton PLN	East Java	1993 (unit 2) 1994 (unit 1)	2x400 MW	PC
Asam-Asam	South Kalimantan	2000	2x65 MW	PC
Tarahan 3 & 4	Lampung	2007	2x100 MW	CFB
Tanjung Jati B	Central Java	2006	2x660 MW	PC
Labuhan Angin	North Sumatera	2008 (unit 2) 2009 (unit 1)	2x115 MW	CFB
Suralaya[a] 1-8	Banten	1984 (unit 1 & 2) 1989 (unit 3 & 4) 1997 (unit 5, 6, & 7) 2011 (unit 8)	400 MW (unit 1 – 4) 600 MW (unit 5 – 7) 625 MW (unit 8)	PC

* Source: Khaerunisa et al. (2009)
[a] Source: PTIP (2018)
[b]PC=pulverized coal; CFB=circulating fluidized bed

Table S4.
Suitability of fuel characteristics and power plant technologies*.

Fuel parameter	Standard characteristic	
	PC	CFB
Calorific value	Medium to high > 15 MJ/kg	Wide range from about 5 MJ/kg to dry fuels
Moisture content	< 15 % moisture content. Dry fuel necessary for quick ignition.	High moisture contents may be acceptable. Range of 5–60 %, depending on design
Ash content	< 1 % for converted oil-fired boilers. Other pulverized fuel boilers more insensitive.	Insensitive to ash with high melting point. Low content if ash is difficult.
Alkali content	High content generally causes deposits. High combustion temperature causes alkali in the gas phase/fly ash.	High content may lead to the risk of bed sintering and risk of deposits
Chlorine and sulphur content	Of general importance to high and low temperature corrosion and to the formation of deposits	Of general importance to high and low temperature corrosion and to the formation of deposits. Scope for effective sulphur capture in the bed.

* Source: Stromberg (2006)
PC= pulverized coal; CFB= circulating fluidized bed.

Table S5.
The application of biomass co-firing in various power plant technologies*.

Study	Type of biomass	Form of biomass	Power plant type
Tabata et al. (2011)	Wood	Briquettes	PC
Schakel et al. (2014)	Wood & straw	Pellets	PC & IGCC
Morrison and Golden (2017)	Wood	Pellets	PC
Shafie et al. (2013)	Straw	Straw (without forming/shaping treatment)	PC
Woytiuk et al. (2017)	Willow	Torrefied pellets	PC & CFBG
Wu et al. (2016)	Corn stalk	Stalk (without forming/shaping treatment)	PC
Sathitruangsak and Madhiyanon (2017)	Rice husk	Rice husk (without forming/shaping treatment)	CFB
Gungor (2013)	Rice husk and wood chips	Rice husk (without forming/shaping treatment) and chips	CFB
Aho et al. (2013)	Wheat straw, corn straw and saw dust	Without forming/shaping treatment	CFB

* Source: primary data
PC=pulverized coal; IGCC=integrated gasification combined cycle; CFB=circulating fluidized bed; CFBG=circulating fluidized bed gasifier.

Please cite this article as: Wiloso E.I., Setiawan A.A.R., Prasetia H., Muryanto, Wiloso A.R., Subyakto, Sudiana I.M., Lestari R., Nugroho S., Hermawan D., Fang K., Heijungs R. Production of sorghum pellets for electricity generation in Indonesia: A life cycle assessment. Biofuel Research Journal 27 (2020) 1178-1194. DOI: 10.18331/BRJ2020.7.3.2

Table S6.
Emission factors used in this study.

Fuel	Emission factor (kg/MJ) [a]			Activity
	CO_2	CH_4	N_2O	
Diesel	7.48E-2	10E-6	2E-6	Sorghum cultivation and pellet processing
Brown coal	1.15E-1	3E-6	5E-6	Electricity generation (SFC and CF)
Pellet [b]	0	1E-4	1.5E-5	Electricity generation (CF and SFP)

[a] IPCC (2006a)
[b] Pellets are considered equivalent to the "other primary solid biomass" fuel category at the IPCC, 2006a. The emission factor of pellet combustion is modified to zero, as this study assumes "net zero CO_2 emission". Moreover, CH_4 and N_2O emissions from pellet combustion are only considered in the scenario model for sensitivity analysis (see **Table 9**).

Table S7.
The ecoinvent dataset used in this study.

No.	Flow	Dataset name	Life cycle stage
1	Diesel	Diesel {RoW}| market for | APOS, S	Sorghum cultivation, pellet processing
2	Compost	Compost {RoW}| treatment of biowaste, industrial composting | APOS, S	Sorghum cultivation
3	Sorghum seed	Wheat seed, for sowing {GLO}| market for | APOS, S	Sorghum cultivation
4	N fertiliser	Urea, as N {GLO}| market for | APOS, S	Sorghum cultivation
5	P fertiliser	Phosphate fertiliser, as P2O5 {GLO}| market for | APOS, S	Sorghum cultivation
6	K fertiliser	Potassium fertiliser, as K2O {GLO}| market for | APOS, S	Sorghum cultivation
7	Furadan[a]	[thio]carbamate-compound {GLO}| market for | APOS, S	Sorghum cultivation
8	Decis[b]	Pyrethroid-compound {GLO}| market for | APOS, S	Sorghum cultivation
9	Lubricating oil and grease[c]	Lubricating oil {RoW}| market for lubricating oil | APOS, S	Pellet processing
10	Pellet factory	Wood pellet factory {GLO}| market for | APOS, S	Pellet processing
11	Electricity mix Indonesia	Electricity, medium voltage {ID}| market for | APOS, S	Pellet processing
12	Oil waste treatment	Waste mineral oil {RoW}| market for waste mineral oil | APOS, S	Pellet processing
13	Land transport	Transport, freight, lorry 16-32 metric ton, euro3 {RoW}| market for transport, freight, lorry 16-32 metric ton, EURO3 | APOS, S	Transport I & II
14	Sea transport	Transport, freight, sea, transoceanic ship {GLO}| market for | APOS, S	Transport III
15	Brown coal	Lignite {RoW}| market for | APOS, S[d]	Electricity generation
16	Lime	Lime {RoW}| market for lime | APOS, S	Electricity generation
17	Limestone	Limestone, crushed, washed {RoW}| market for limestone, crushed, washed | APOS, S	Electricity generation
18	Power plant	Hard coal power plant {GLO}| market for | APOS, S	Electricity generation
19	Waste treatment for coal ash	Lignite ash {RoW}| market for lignite ash | APOS, S	Electricity generation
20	Waste treatment for wood ash	Wood ash mixture, pure {RoW}| market for wood ash mixture, pure | APOS, S	Electricity generation

[a] Furadan is considered equivalent to carbamate (NCBI, 2004)
[b] Decis is considered equivalent to pyrethroid (NCBI, 2014)
[c] Lubricating oil and grease are considered equivalent (Elduque et al., 2015)
[d] This dataset does not seem to consider coal-mine fire.

Please cite this article as: Wiloso E.I., Setiawan A.A.R., Prasetia H., Muryanto, Wiloso A.R., Subyakto, Sudiana I.M., Lestari R., Nugroho S., Hermawan D., Fang K., Heijungs R. Production of sorghum pellets for electricity generation in Indonesia: A life cycle assessment. Biofuel Research Journal 27 (2020) 1178-1194. DOI: 10.18331/BRJ2020.7.3.2

Table S8.
Chemical analysis of pellets.

Parameter	**Unit**	**Aa received**	**Dry basis**	**Test Method**
Total moisture	wt.%	3.64	-	ASTM D 2961 - 17
Ash content	wt.%	7.28	7.56	ASTM D 3174 - 12
Volatile matter	wt.%	70.90	73.58	ASTM D 3175 - 18
Fixed carbon	wt.%	18.18	18.86	ASTM D 3172 - 13
Total sulfur	wt.%	0.09	0.09	ASTM D 4239 - 18
Gross caloric value	Kcal/Kg	4156	4313	ASTM D 5865 - 13
Ultimate analysis				
Carbon	wt.%	45.61	47.33	ASTM D 5373 – 16
Hydrogen	wt.%	5.18	5.37	ASTM D 5373 – 16
Nitrogen	wt.%	0.36	0.38	ASTM D 5373 – 16
Oxygen	wt.%	37.84	39.27	ASTM D 3176 – 15
Parameter		**Test results**		
Aluminum (Al)	mg/kg	1.02		ISO 16967 : 2015
Calcium (Ca)	mg/kg	8.59		ISO 16967 : 2015
Silicon (Si)	mg/kg	24.42		ISO 16967 : 2015
Zinc (Zn)	ppm	609.56		ICP
Lead (Pb)	ppm	63.25		ICP
Cadmium (Cd)	ppm	2.99		ICP
Nickel (Ni)	ppm	54.03		ICP
Chromium (Cr)	ppm	84.41		ICP
Copper (Cu)	ppm	242.78		ICP
Mercury (Hg)	ppm	13.65		AAS
Arsenic (As)	ppm	0.60		AAS
Chlorine (Cl_2)	wt.%	0.04		ASTM D 7359 - 18
Bulk Density	Kg/m^3	626		ASTM D 1895

Table S9.
Domestic coal consumption 2013-2018*.

Year	**Steam coal (ton)**
2013	39,601,034.00
2014	44,604,980.72
2015	48,995,169.00
2016	50,556,446.00
2017	54,711,846.87
2018	60,481,244.55

* Source: PLN (2019)

Please cite this article as: Wiloso E.I., Setiawan A.A.R., Prasetia H., Muryanto, Wiloso A.R., Subyakto, Sudiana I.M., Lestari R., Nugroho S., Hermawan D., Fang K., Heijungs R. Production of sorghum pellets for electricity generation in Indonesia: A life cycle assessment. Biofuel Research Journal 27 (2020) 1178-1194. DOI: 10.18331/BRJ2020.7.3.2

Table S10.
Energy and material requirements for pellet processing.

No.	Name	Power required /equipment (kW/unit) (1)	Number of equipment (unit) (2)	Total power required (kW) (1)*(2)
		Crushing Section		
1	Chain feeding conveyor	3	1	3
2	Chipper	150	1	150
3	Belt conveyor	7.5	1	7.5
		Pre-grinding section		
1	Belt conveyor	4	3	12
2	Hammer factory	132	3	396
3	Fan blower	37	3	111
4	Airlock	4	3	12
5	Belt conveyor	7.5	1	7.5
6	Bucket elevator	7.5	1	7.5
7	Screw conveyor	7.5	1	7.5
8	Hydraulic bin	11	1	11
9	Screw conveyor	7.5	1	7.5
		Drying section		
1	Belt conveyor	4	1	4
2	Bucket elevator	11	1	11
3	Buffer silo	11	1	11
4	Belt conveyor	2.2	2	4.4
5	Airlock	5.5	2	11
6	Rum rotary dryer	37	2	74
7	Screw conveyor	7.5	4	30
8	Fan blower	55	2	110
9	Airlock	4	4	16
10	Belt conveyor	3	2	6
11	Bucket elevator	7.5	2	15
12	Screw conveyor	7.5	1	7.5
13	Hydraulic bin	22	1	22
14	Screw conveyor	5.5	2	11
		Fine-grinding section		
1	Belt conveyor	3	2	6
2	Hummer factory	132	2	264
3	Fan blower	37	2	74
4	Airlock	4	2	8
5	Belt conveyor	5.5	2	11
6	Bucket elevator	7.5	1	7.5
7	Screw conveyor	7.5	1	7.5
8	Hydraulic bin	22	1	22
9	Screw conveyor	5.5	2	11
		Pellet processing section		
1	Belt conveyor	3	2	6
2	Bucket elevator	7.5	2	15
3	Buffer silo	5.5	1	5.5
4	Screw feeder	4	4	16
5	Pellet machine	227	4	908
6	Belt conveyor	3	1	3
		Cooling section		
1	Bucket elevator	7.5	1	7.5
2	Airlock	4	1	4
3	Fan blower	55	1	55
4	Simple screener	0.5	1	0.5
5	Bucket elevator	2.2	1	2.2
		Packing section		
1	Bucket elevator	7.5	1	7.5
2	Jumbo bag packing	0.55	1	0.55
		Workshop dust removing section		
1	Bug dust removing system	37	1	37
		Total power: 2,544.15 kW		
		Energy consumption: 1,784 kWh[a]		
		Required transformer: 3,185 kVA		

Material (reference flow = daily pellet processing[b])

Flow	Amount	Unit
Lubricating oil	1	L
Diesel	65	L
Grease	100	L

[a] Electricity consumption per hour. Pellet processing capacity per hour is 10-14 tons. by using the median value of pellet processing per hour, which is 12 tons of pellets, electricity consumption per ton is 148.67 kWh.

[b] Additional data/information on pellet processing: 1. Oil = 1 L/d ; 2. Diesel = 65 L/d ; 3. Lubrication (stempet/grease): 100 L/d Wood pellet processing: 85 tons/d (2000 tons/month).

Please cite this article as: Wiloso E.I., Setiawan A.A.R., Prasetia H., Muryanto, Wiloso A.R., Subyakto, Sudiana I.M., Lestari R., Nugroho S., Hermawan D., Fang K., Heijungs R. Production of sorghum pellets for electricity generation in Indonesia: A life cycle assessment. Biofuel Research Journal 27 (2020) 1178-1194. DOI: 10.18331/BRJ2020.7.3.2

Table S11.
Inventory of 1 kWh electricity generation*.

Material	Amount (kg/kWh net)
Coal –input (as-received)	0.436
Lime for FGC waste treatment (input)	0.006
Limestone (input)	0.078
FGC waste[1] –dry total	0.085
Ash –moisture free total	0.031

* Source: Widiyanto et al. (2003)
[1] In this study, FGC waste is considered equivalent to coal-ash waste (Spath et al., 1999).

Table S12.
Coal power plant distribution in Indonesia*.

No	Power plant name	Owner	Location	Commercial Operating Date	Capacity (MW)	Status
1	Nagan Raya	PLN	Aceh	Existing	220	In operation
2	Pangkalan Susu	PLN	North Sumatera	Existing	440	In operation
3	Labuhan Angin	PLN	North Sumatera	Existing	230	In operation
4	Bukit Carok	PLN	Riau	Existing	14	In operation
5	Air Raja	PLN	Riau	Existing	30	In operation
6	Suge	PLN	Bangka Belitung	Existing	16.5	In operation
7	Babel 3	PLN	Bangka Belitung	Existing	60	In operation
8	Ombilin	PLN	West Sumatera	Existing	190	In operation
9	Teluk Sirih	PLN	West Sumatera	Existing	224	In operation
10	Bukit Asam	PLN	South Sumatera	Existing	260	In operation
11	Tarahan	PLN	Lampung	Existing	300	In operation
12	Suralaya 1- 7	IPP	Banten	Existing	3,400	In operation
13	Suralaya 8	PLN	Banten	Existing	625	In operation
14	Labuan 1 – 3	PLN	Banten	Existing	600	In operation
15	Lontar 1 – 3	PLN	Banten	Existing	945	In operation
16	Indramayu 1 – 3	PLN	West Java	Existing	990	In operation
17	Cirebon	IPP	West Java	Existing	660	In operation
18	Pelabuhan Ratu 1 – 3	PLN	West Java	Existing	1,050	In operation
19	Cilacap 1 – 2	IPP	Central Java	Existing	600	In operation
20	Tanjung Jati B 1 – 2	PLN	Central Java	Existing	1,320	In operation
21	Tanjung Jati B 3 – 4	PLN	Central Java	Existing	1,320	In operation
22	Rembang	PLN	Central Java	Existing	630	In operation
23	Paiton	PJB	East Java	Existing	800	In operation
24	Paiton PEC	IPP	East Java	Existing	1,230	In operation
25	Paiton JP	IPP	East Java	Existing	1,220	In operation
26	Paiton 3	PLN	East Java	Existing	815	In operation
27	Paiton 9	PLN	East Java	Existing	660	In operation
28	Pacitan 1 – 2	PLN	East Java	Existing	630	In operation
29	Tanjung Awar – awar 1	PLN	East Java	Existing	350	In operation
30	Celukan Bawang	IPP	Bali	Existing	380	In operation
31	Sistem Barito	PLN	South Kalimantan	Existing	260	In operation
32	Sistem Barito	IPP	South Kalimantan	Existing	86	In operation
33	Amurang	PLN	North Sulawesi	Existing	50	In operation
34	Sistem Palu-Parigi	IPP	Central Sulawesi	Existing	27	In operation
35	Molotabu	IPP	Gorontalo	Existing	20	In operation
36	Barru 1 – 2	PLN	South Sulawesi	Existing	100	In operation
37	Jeneponto 1 – 2	IPP	South Sulawesi	Existing	200	In operation
38	Kendari	PLN	Southeast Sulawesi	Existing	20	In operation
39	Bau-bau	PLN	Southeast Sulawesi	Existing	14	In operation
40	TB Karimun 2 (FTP1)	PLN	Riau	2016	7	Under construction
41	Belitung Baru 2 (FTP1)	PLN	Bangka Belitung	2016	16.5	Under construction
42	Keban Agung	IPP	South Sumatera	2016	225	Under construction
43	Sumsel 5	IPP	South Sumatera	2016	300	Under construction
44	Tarahan 4 (FTP1)	PLN	Lampung	2016	100	Under construction
45	Adipala	PLN	Central Java	2016	660	Under construction
46	Cilacap exp	IPP	Central Java	2016	614	Under construction

Please cite this article as: Wiloso E.I., Setiawan A.A.R., Prasetia H., Muryanto, Wiloso A.R., Subyakto, Sudiana I.M., Lestari R., Nugroho S., Hermawan D., Fang K., Heijungs R. Production of sorghum pellets for electricity generation in Indonesia: A life cycle assessment. Biofuel Research Journal 27 (2020) 1178-1194. DOI: 10.18331/BRJ2020.7.3.2

Table S12.

No	Power plant name	Owner	Location	Commercial Operating Date	Capacity (MW)	Status
47	Tanjung Awar-awar	PLN	East Java	2016	350	Under construction
48	Sintang	PLN	West Kalimantan	2016/17	21	Under construction
49	Ketapang	IPP	West Kalimantan	2016/17	12	Under construction
50	Ketapang	PLN	West Kalimantan	2016	10	Under construction
51	Pulau Pisau	PLN	Central Kalimantan	2016	120	Under construction
52	Teluk Balikpapan (FTP1)	PLN	East Kalimantan	2016	220	Under construction
53	Tawaeli (exp)	IPP	Central Sulawesi	2016	30	Under construction
54	Maluku Utara / Tidore (FTP1)	PLN	North Maluku	2016	14	Under construction
55	Jayapura (FTP1)	PLN	Papua	2016	20	Under construction
56	Lombok (FTP1)	PLN	NTB	2016	50	Under construction
57	Bima (FTP1)	PLN	NTB	2016	20	Under construction
58	Ende	PLN	NTT	2016	7	Under construction
59	Kupang	IPP	NTT	2016	30	Under construction
60	Kotabaru	PLN	South Kalimantan	2017	14	Under construction
61	Kuala Pambuang	PLN	South Kalimantan	2017	6	Under construction
62	Tanjung Redep	PLN	East Kalimantan	2017	14	Under construction
63	Tanah Grogot	IPP	East Kalimantan	2017	14	Under construction
64	Malinau	PLN	North Kalimantan	2017	6	Under construction
65	Parit Bary (FTP1)	PLN	West Kalimantan	2017/18	100	Under construction
66	Kaltim (MT)	IPP	East Kalimantan	2017/18	52	Under construction
67	Amurang	IPP	North Sulawesi	2017/18	50	Under construction
68	Tanjung Selow	PLN	North Kalimantan	2017	14	Under construction
69	Talaud	PLN	North Sulawesi	2017	6	Under construction
70	Ampana	PLN	Central Sulawesi	2017	6	Under construction
71	Gorontalo (FTP1)	PLN	Gorontalo	2017	50	Under construction
72	Mamuju	IPP	West Sulawesi	2017	50	Under construction
73	Sumbawa Barat	PLN	NTB	2017	14	Under construction
74	Lombok Timur	IPP	NTB	2017	50	Under construction
75	Rote Ndao	PLN	NTT	2017	6	Under construction
76	Alor	PLN	NTT	2017	6	Under construction

* Source: Bappenas (2016). It is assumed that all power plants whose status is under construction (with completion targets in 2017) have all been completed in 2017.

Table S13.
Transportation values (from pellet factories to Marapokot port).

Distance and load of land transport from pellet factories to Marapokot port

Pellet factory	Distance (km)	Load (ton pellet)	Transport value (tkm)*
1st	299	1,200,000	358,800,000
2nd	126	1,200,000	151,200,000
3rd	49	1,200,000	58,800,000
4th	178	1,200,000	213,600,000
Total	**652**	**4,800,000**	**782.400.000**

* tkm=ton × km

Please cite this article as: Wiloso E.I., Setiawan A.A.R., Prasetia H., Muryanto, Wiloso A.R., Subyakto, Sudiana I.M., Lestari R., Nugroho S., Hermawan D., Fang K., Heijungs R. Production of sorghum pellets for electricity generation in Indonesia: A life cycle assessment. Biofuel Research Journal 27 (2020) 1178-1194. DOI: 10.18331/BRJ2020.7.3.2

Table S14.
Transportation values (from pellet factories to Marapokot port).

Distance and load of sea transport from Marapokot port to power plants

Port destination		Coverage area[a]	Electricity[b] (GWh)	Distance (km)	Load (ton pellet)	Transport (tkm)
A	Riau Islands	North Sumatera, Riau	4.87E3	2.44E3	1.41E5	3.44E8
B	Bangka Belitung	South Sumatera	3.77E3	1.87E3	1.09E5	2.03E8
C	Banten	West Java	3.56E4	1.68E3	1.03E6	1.72E9
D	Central Java	-	4.29E4	1.32E3	1.24E6	1.64E9
E	East Java	Bali	1.40E4	7.91E2	4.03E5	3.19E8
F	West Kalimantan	-	2.80E2	1.66E3	8.08E3	1.34E7
G	South Kalimantan	-	2.12E3	1.00E3	6.11E4	6.12E7
H	North Kalimantan	East Kalimantan	3.91E2	1.71E3	1.13E4	1.93E7
I	South Sulawesi	-	6.98E2	3.81E2	2.02E4	7.68E6
J	East Nusa Tenggara	West Nusa Tenggara	4.48E2	0[c]	1.29E4	0
K	Southeast Sulawesi	-	1.51E2	5.04E2	4.37E3	2.20E6
L	North Sulawesi	-	2.30E2	1.25E3	6.64E3	8.28E6
M	Maluku		7.48E1	1.05E3	2.16E3	2.28E6
N	Papua	West Papua	1.48E2	2.86E3	4.26E3	1.22E7
Total			**1.06E5**	**1.85E4**	**3.05E6**	**4.35E9**

[a] Including the port area that receives pellet.
[b] Based on the 2017 national electricity report data (MEMR, 2018b), some values per region are the result of calculations by the author because some data cannot be directly divided into regions in this study, but the total value is the same (105,651.39 GWh).
[c] Port of pellet provider. The distance value is zero, as the port is a supplier of the pellet.

Table S15.
Indonesian coal electricity production in 2017*.

No	Region	Coal electricity production (GWh)
1	Riau Islands	50.26
2	Bangka Belitung	287.11
3	West Kalimantan	158.96
4	South Kalimantan	2,115.55
5	East Kalimantan	391.40
6	North Sulawesi	229.91
7	South Sulawesi	423.51
8	South East Sulawesi	151.43
9	Maluku	74.82
10	Papua	17.29
11	West Papua	9.49
12	West Nusa Tenggara	159.86
13	East Nusa Tenggara	123.31
14	Kit Sumbagut	3,612.36
15	Kit Sumbagsel	3,483.99
Outside Java		**11,289.25**
16	PT. Indonesia Power	23,894.44
17	PT. PJB	9,809.39
18	Pembangkitan Tanjung Jati B	19,352.86
19	Kit Jawa Bagian Barat	12,466.92
20	Kit Jawa Bagian Tengah	17,563.24
21	Kit Jawa Bagian Timur dan Bali	11,275.29
Java		**94,362.14**
Outside Java + Java (Indonesia)		**105,651.39**

* Source: PLN (2018)

Table S16.
Field emission.

Nitrous oxide emissions from sorghum cultivation stages

Life cycle stages	Input flow (kg/ha.year)		N_2O (kg/ha.year)[c]
	Synthetic Fertilizer[a]	Compost[b]	
Land processing	-	5,000	1.34
Planting	200	-	1.57
Fertilizing	150	-	1.18
Maintenance	-	-	-
Harvesting	-	-	-
Total emission			**4.09**

[a] Synthetic fertilizer: 50% N-content (data from field-trial in Gresik, East Java)
[b] Compost: 1.71% N-content (based on a study conducted by Kim et al., 2014)
[c] IPCC (2006b). The current study only calculates direct N_2O emissions and only those that come from fertilizer applications.

Parameter values for calculation of N_2O field (direct) emission (area of 1 ha)

Parameter	Value	Unit
F_{SN}[a]	175	kg N yr^{-1}
F_{ON}[b]	85.5	kg N yr^{-1}
F_{CR}[c]	0	kg N yr^{-1}
F_{SOM}[c]	0	kg N yr^{-1}
N_2O-$N_{N\ inputs}$	260.5	kg N yr^{-1}
EF_1	0.01	kg N_2O-N (kg N)$^{-1}$
N_2O_{Direct}-N[d]	2.61	kg N_2O-N yr^{-1}
N_2O_{Direct}	4.09	kg N_2O yr^{-1}

[a] F_{SN} = annual amount of synthetic fertiliser N applied to soils; F_{SN} = (200 kg + 150 kg synthetic fertiliser N) × 50% = 175. The N content of applied synthetic fertiliser N is 50% (from field-trial in Gresik, East Java).
[b] F_{ON} = annual amount of animal manure, compost, sewage sludge and other organic N additions applied to soils; F_{ON} = (5,000 kg compost) × 1.71% = 85.5. The N content of applied compost fertiliser N is 1.71% (based on Kim et al., 2014).
[c] Not considered in this study due to lack of the data. F_{CR} = annual amount of N in crop residues (above-ground and below-ground), including N-fixing crops, and from forage/pasture renewal, returned to soils, kg N yr^{-1}. F_{SOM} = annual amount of N in mineral soils that is mineralised, in association with loss of soil C from soil organic matter as a result of changes to land use or management, kg N yr^{-1}.
[d] The conversion factor from N_2O_{Direct}-N to N_2O_{Direct} is 44/28 (IPCC, 2006b).

Please cite this article as: Wiloso E.I., Setiawan A.A.R., Prasetia H., Muryanto, Wiloso A.R., Subyakto, Sudiana I.M., Lestari R., Nugroho S., Hermawan D., Fang K., Heijungs R. Production of sorghum pellets for electricity generation in Indonesia: A life cycle assessment. Biofuel Research Journal 27 (2020) 1178-1194. DOI: 10.18331/BRJ2020.7.3.2

Table S17.
LCI comparison between this study and literature.

Life cycle stage	Input flow	Unit	Crop (amount)			
			Sorghum (48 t/ha) [a]	Miscanthus (20 t/ha)[b]	Misacanthis (11.5 t/ha)[c]	Switchgrass (13.9 t/ha)[d]
Land processing	Diesel	L	134	-	-	-
	Compost	ton	5	-	-	-
	Manpower	mwd*	80	-	-	-
Planting	Sorghum seed	kg	30	-	-	-
	Nitrogen fertilizer	kg	200	100	60	66.30
	Phosphate fertilizer	kg	150	50	9	6.81
	Potassium fertilizer	kg	15	200	58.75	-
	Furadan (pesticide)	kg	5	-	-	1.39
	Decis (pesticide)	L	2	-	-	-
	Water, from well	L	20,000	-	-	-
	Man power	mwd*	60	-	-	-
Fertilizing	Nitrogen fertilizer	kg	150	-	-	-
	Phosphate fertilizer	kg	150	-	-	-
	Potassium fertilizer	kg	150	-	-	-
Maintenance	Manpower	mwd*	190	-	-	-
	Diesel	L	100	-	-	-
Harvesting	Manpower	mwd*	140	-	-	-
Pelleting	Biomass	ton	48	20	11.5	13.21
	Pellet factory[1)]	Piece[2)]	5.0E-5	-	-	-
	Electricity	kWh	7,136	1,802	668	2,025
	Diesel	L	37.152	-	-	-
	Lubricating oil	L	0.576	-	-	-
	Grease	L	2.4	-	-	-

*mwd = man work-day is defined as work done by one person in one day for eight hours (Wahyuni, 2014).
[1)] added by referring to the ecoinvent dataset because of limited primary data.
[2)] unit for infrastructure (pellet factory). One-piece = total pellet processing during the life span of infrastructure (24,000 ton/year * 40 years = 960,000 ton). 48-ton pellet processing requires only 48 / 960,000 piece of infrastructure, which is 5.05E-5 piece.
[a] *This study*
[b] Lewandowski (1995)
[c] Murphy et al. (2013)
[d] Bergman et al. (2015)

Please cite this article as: Wiloso E.I., Setiawan A.A.R., Prasetia H., Muryanto, Wiloso A.R., Subyakto, Sudiana I.M., Lestari R., Nugroho S., Hermawan D., Fang K., Heijungs R. Production of sorghum pellets for electricity generation in Indonesia: A life cycle assessment. Biofuel Research Journal 27 (2020) 1178-1194. DOI: 10.18331/BRJ2020.7.3.2

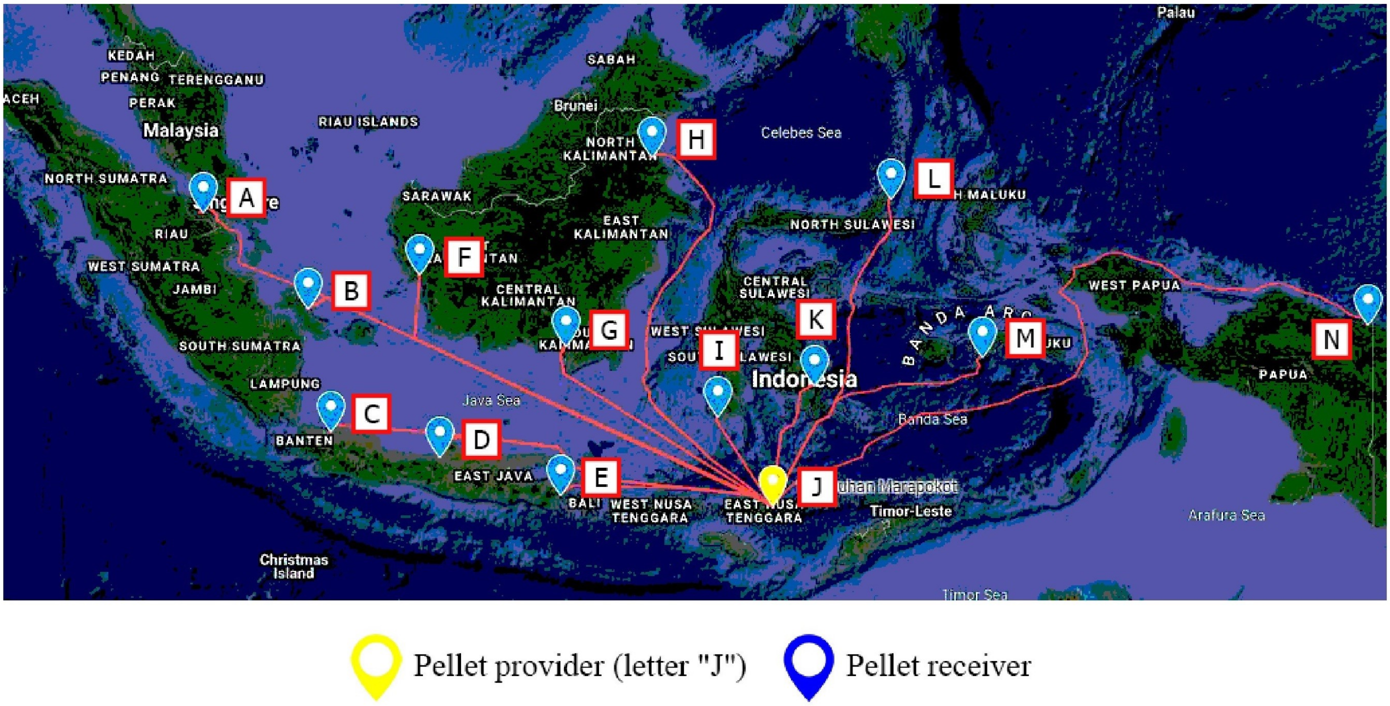


Fig. S1. Sea transport map.

References

[1] Aho, M., Envall, T., Kauppinen, J., 2013. Corrosivity of flue gases during co-firing Chinese biomass with coal at fluidised bed conditions. Fuel Process. Technol. 105, 82-88.

[2] Bappenas, 2016. Laporan Akhir: Kajian Ketercapaian Target DMO Batubara Sebesar 60% Produksi Nasional pada Tahun 2019.

[3] Bergman, R.D., Reed, D.L., Taylor, A.M., Harper, D.P., Hodges, D.G., 2015. Cradle-to-gate life cycle assessment of switchgrass fuel pellets manufactured in the Southeastern United States1. Wood Fiber Sci. 47(2), 147-159.

[4] BPDASHL Benain Noelmina, 2018. Peta Lahan Kritis Wilayah Kerja BPDAS Benain Noelmina. East Nusa Tenggara.

[5] Elduque, A., Javierre, C., Elduque, D., Fernández, Á., 2015. LCI databases sensitivity analysis of the environmental impact of the injection molding process. Sustainability. 7(4), 3792-3800.

[6] Gungor, A., 2013. Simulation of co-firing coal and biomass in circulating fluidized beds. Energy Convers. Manag. 65, 574–579.

[7] IPCC, 2006a. IPCC Guidelines for National Greenhouse Gas Inventories.

[8] IPCC, 2006b. IPCC-N_2O Emissions from managed Soils and CO_2 Emissions From, Agriculture.

[9] Khaerunisa, H., Huda, M., Damayanti, R., Antono, H.T., Komarudin Yaskuri, D., Lutfi, M., Suryati, E., Alimano, M., Nurhadi, H., Sibarani, L., Hayati, I., Mujahidin, S., 2009. Study of CO_2 emissions from coal combustion in Indonesia. Bandung.

[10] Kim, S.Y., Pramanik, P., Gutierrez, J., Hwang, H.Y., Kim, P.J., 2014. Comparison of methane emission characteristics in air-dried and composted cattle manure amended paddy soil during rice cultivation. Agric. Ecosyst. Environ. 197, 60-67.

[11] Lewandowski, I., Kicherer, A., Vonier, P., 1995. CO_2-balance for the cultivation combustion of *Miscanthus*. Biomass Bioenergy. 8(2), 81-90.

[12] MEMR, 2018b. Statistik Ketenagalistrikan T.A. 2018. Ministry of Energy and Mineral Resources. Indonesia.

[13] Morrison, B., Golden, J.S., 2017. Life cycle assessment of co-firing coal and wood pellets in the Southeastern United States. J. Clean. Prod. 150, 188-196.

[14] Murphy, F., Devlin, G., McDonnell, K., 2013. Miscanthus production and processing in Ireland: an analysis of energy requirements and environmental impacts. Renew. Sust. Energy Rev. 23, 412-420.

[15] NCBI, 2014. PubChem Database. Deltamethrin, CID=40585.

[16] NCBI, 2004. PubChem Database. Carbofuran, CID=2566.

[17] PLN, 2018. Statistik PLN 2017. Sekretariat Perusahaan PT PLN (Persero), Jakarta.

[18] PLN, 2019. Buku Statistik PLN 2018. Sekretariat Perusahaan PT PLN (Persero), Jakarta.

[19] PTIP, 2018. Laporan Statistik PT Indonesia Power 2018.

[20] Sathitruangsak, P., Madhiyanon, T., 2017. Effect of Operating Conditions on the Combustion Characteristics of Coal, Rice Husk, and Co-firing of Coal and Rice Husk in a Circulating Fluidized Bed Combustor. Energy Fuels 31, 12741–12755.

[21] Schakel, W., Meerman, H., Talaei, A., Ramírez, A., Faaij, A., 2014. Comparative life cycle assessment of biomass co-firing plants with carbon capture and storage. Appl. Energy. 131, 441-467.

[22] Shafie, S.M., Mahlia, T.M.I., Masjuki, H.H., 2013. Life cycle assessment of rice straw co-firing with coal power generation in Malaysia. Energy 57, 284–294.

[23] Spath, P.L., Mann, M.K., Kerr, D.R., 1999. Life cycle assessment of coal-fired power production. Technical Report: NREL/TP-570-25119; TRN: US200307%%179.

[24] Stromberg, B., 2006. Fuel Handbook. Stockholm (Sweden).

[25] Tabata, T., Torikai, H., Tsurumaki, M., Genchi, Y., Ukegawa, K., 2011. Life cycle assessment for co-firing semi-carbonized fuel manufactured using woody biomass with coal: A case study in the central area of Wakayama, Japan. Renew. Sust. Energy Rev. 15(6), 2772-2778.

[26] Wahyuni, N., 2014. Working time allocation and income of cattle farmers at Megang Sakti Subdistrict Musi Rawas Regency. Societa: Jurnal Ilmu-Ilmu Agribisnis.

[27] Widiyanto, A., Kato, S., Maruyama, N., 2003. Environmental impact analysis of indonesian electric generation system (development of a life cycle inventory of indonesian electricity). JSME Int. J. Ser. B. 46(4), 650-659.

Please cite this article as: Wiloso E.I., Setiawan A.A.R., Prasetia H., Muryanto, Wiloso A.R., Subyakto, Sudiana I.M., Lestari R., Nugroho S., Hermawan D., Fang K., Heijungs R. Production of sorghum pellets for electricity generation in Indonesia: A life cycle assessment. Biofuel Research Journal 27 (2020) 1178-1194. DOI: 10.18331/BRJ2020.7.3.2

[28] Woytiuk, K., Sanscartier, D., Amichev, B.Y., Campbell, W., Van Rees, K., 2017. Life-cycle assessment of torrefi ed coppice willow co-fi ring with lignite coal in an existing pulverized coal boiler. Biofuel. Bioprod. Bior. 11, 830–846.

[29] Wu, J., Kong, L., Wang, L., Sun, Y., 2016. Life cycle assessment of a co-firing power generation system in China. J. Biobased Mater. Bioenergy 10, 129–136.

Please cite this article as: Wiloso E.I., Setiawan A.A.R., Prasetia H., Muryanto, Wiloso A.R., Subyakto, Sudiana I.M., Lestari R., Nugroho S., Hermawan D., Fang K., Heijungs R. Production of sorghum pellets for electricity generation in Indonesia: A life cycle assessment. Biofuel Research Journal 27 (2020) 1178-1194. DOI: 10.18331/BRJ2020.7.3.2