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

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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\textsubscript{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.

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

Life cycle of electricity generation

MATERIALS AND ENERGY

Single firing of coal (SFC)

Co-firing of coal with pellets (CF)

Single firing of pellet (SFP)

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ABSTRACT

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1. Introduction

1.1. The potential and importance of developing bioenergy in Indonesia

After being stable for three years, global carbon dioxide (CO₂) 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).

Abbreviations

CF - Co-firing of coal with pellets
CH₄ - 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
LCIDI - 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
N₂O - Dinitrogen monoxide
NTT - East Nusa Tenggara
PC - Pulverized coal
RoW - Rest-of-world
SFC - Single-firing of coal
SFP - Single-firing of pellets
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 National 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 Noelmima, 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,
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 alkalai 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 NO and CH₄. 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.

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
Table 1. Descriptions of assumptions used in this study.

| Assumption                      | Description                                                                 |
|---------------------------------|-----------------------------------------------------------------------------|
| Agricultural conditions¹        | 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 conditions²          | Burning of sorghum pellets in a power plant assumes complete combustion (i.e., no CH₄ and N₂O 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 loss¹                      | 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. |

¹The context of assumptions varied in the sensitivity analysis (see Section 3.4).

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 Kalianda 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 based pellet processing facility located in Gresik, East Java (Indonesia).

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 (N₂O) and incomplete combustion of biomass in a power plant (CH₄ and N₂O) were considered in the model. Sorghum pellets are considered carbon-neutral, so the CO₂ released through combustion at the power plant was assumed zero net CO₂ emissions. The concept of carbon-neutral is an issue that is still being debated (Wilošo 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 Garcia et al. (2019), Lewandowski et al. (1995), Murphy et al. (2013), Nian (2016), Schakel et al. (2014), and 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 Rajaiefar 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) V’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).

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

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**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).
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).
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 lifespan of 50 years (Wernet et al., 2016). Based on a production trial of 85 tons of pellets/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 preprocessing (22%), fine-grinding (16%), and drying (13%). Details of the electricity inputs for pellet processing can be found in Table S10 (Supplementary Information).

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 (Widyantoro et al., 2003) which uses PC combustion technology; details can be found in Table S12 (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; Jungbluth et al., 2018). Since the infrastructure of the coal power plant contributes lesser impacts than those of the operational stage (Atigilan 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.

Table 3. Fuel requirements for a power plant.

| Type of fuel | Energy content (MJ/kg) | Power plant efficiency (%) | Fuel requirements (kg/kWh) |
|--------------|------------------------|-----------------------------|---------------------------|
| Brown coal   | 19.26                  | 18.30                       | 36.1                      | 38.0                     | 0.518                      | 0.578                      |
| Pellet       | 17.40                  | 16.40                       | 35.8                      | 38.0                     | 0.558                      |                          |

*Brown coal GCV (Happas, 2016). GCV of pellets was obtained from the chemical analysis in Table 2.

*Net calorific value (NCV) of brown coal is 5% lower than its GCV (IEA, 2004). NCV of pellets = GCV * (0.8 x (X_H + X_O + X_N)) / (1+0.01 M) x 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 |
|------------------|-----------------------|-----------|--------|------|
| Compost          | Input                 |           | 5      | ton  |
| Manpower         | Input                 |           | 80     | mwd  |
| Land processing  |                       |           |        |      |
| Diesel           | Input                 |           | 134    | L    |
| CO_2             | Output                |           | 358    | kg   |
| CH_4             | Output                |           | 4.78E-2 kg |
| N,O              | Output                |           | 9.56E-3 kg |
| 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  |
| Fertilizing      |                       |           |        |      |
| Nitrogen fertilizer | Input           |           | 150    | kg   |
| Phosphate fertilizer | Input            |           | 150    | kg   |
| Potassium fertilizer | Input          |           | 150    | kg   |
| Maintenance      |                       |           |        |      |
| Manpower         | Input                 |           | 190    | mwd  |
| Diesel           | Input                 |           | 100    | liter |
| CO_2             | Output                |           | 267    | kg   |
| CH_4             | Output                |           | 3.57E-2 kg |
| N,O              | Output                |           | 7.14E-3 kg |
| Harvesting       |                       |           |        |      |
| Manpower         | Input                 |           | 140    | mwd  |

The unit 'ton' refers to a metric ton (1 metric ton = 1,000 kg).

* Refer to the ecoinvent dataset.

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

| Flow                  | Direction | Amount | Unit |
|-----------------------|-----------|--------|------|
| Sorghum               | Input     | 1      | ton  |
| Pellet factory        | Input     | 1.04E-6 | piece |
| Electricity           | Input     | 148.67 | kWh  |
| Lubricating oil       | Input     | 0.012  | L    |
| Grease                | Input     | 0.050  | L    |
| Diesel                | Input     | 0.774  | L    |
| CO_2                  | Output    | 2.07   | kg   |
| CH_4                  | Output    | 2.76E-4 | kg |
| N,O                   | Output    | 5.52E-5 | kg |
| Waste mineral oil     | Output    | 0.086  | L    |

The unit 'ton' refers to a metric ton (1 metric ton = 1,000 kg).

* 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.

* Emission factors = 7.48E-2 kg CO_2/MJ; 1.0E-6 kg CH_4/MJ; 2.6E-6 kg NO_x/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 (Widyantoro et al., 2003) which uses PC combustion technology; details can be found in Table S12 (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; Jungbluth et al., 2018). Since the infrastructure of the coal power plant contributes lesser impacts than those of the operational stage (Atigilan 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.

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 x 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.
The unit ‘ton’ refers to a metric ton (1 metric ton = 1,000 kg).

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

| Flow                  | Direction | Amount† | Unit     |
|-----------------------|-----------|---------|----------|
| SFP (single-firing of coal)³ |           |         |          |
| Lime                  | Input     | 0.007   | kg       |
| Limestone             | Input     | 0.093   | kg       |
| Power plant           | Input     | 1.90E-11| piece    |
| Coal²                 | Output    | 0.518   | kg       |
| CO₂                   | Output    | 1.09    | kg       |
| CH₄                   | Output    | 2.84E-5| kg       |
| N₂O                   | 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       |
| CO₂                   | Output    | 1.04    | kg       |
| CH₄                   | Output    | 2.70E-5| kg       |
| N₂O                   | 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).

† 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.

² Source: Widiyanto et al. (2003)

³ Emission factors = 1.15E-1 kg CO₂/MJ; 3E-6 kg CH₄/MJ; 5E-6 kg N₂O/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 (Widemba 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 distances 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 transport from the port to power plants is shown in Figure 4.
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 CH₄ and N₂O 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, CH₄ emissions should be very low, such that it can be ignored. In this context, Murphy et al. (2013), who studied the LCA of mulchgrass, a grass plant similar to sorghum, did not consider CH₄ emissions either.

Besides originating from artificial or compost fertilizers, N₂O 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 N₂O field emissions (IPCC, 2006b). Due to lack of data on other parameters, only direct N₂O 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 N₂O/ha·yr. This would certainly give a lower amount of N₂O field emissions than the ideal method, i.e., including both direct and indirect N₂O emissions from all sources. However, the total N₂O emissions from an agricultural field are generally dominated by direct N₂O emissions, which contributes approximately 75% of total N₂O 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 N₂O emissions, CO₂ 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 CO₂/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 of electricity generation (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 estimated 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 PER 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

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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 CO₂ 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 al.
Comparison of the characteristics of various grass pellets.

Table 9.
Sensitivity analysis on several modeling choices.

| Combustion conditions | Field emissions | Sorghum yield (ton/ha·yr) | Mass loss | Global warming (kg CO₂-eq/kWh) | GHG saving (%) |
|-----------------------|-----------------|---------------------------|-----------|-------------------------------|----------------|
|                       |                 |                           | SFC       | CF                            | SFP            |
|                       |                 |                           | SFC-CF    | SFC-SFP                       |                |
| Complete              | No              | 48                        | 1.12      | 1.07                          | 0.171          | 4              | 85           |
|                       | Yes             | 24                        | 1.12      | 1.07                          | 0.186          | 4              | 83           |
|                       |                 |                           | No        | 1.12                          | 1.07           | 0.207          | 4              | 82           |
|                       |                 |                           | Yes       | 1.12                          | 1.08           | 0.229          | 4              | 80           |
| Incomplete            | No              | 48                        | 1.12      | 1.07                          | 0.213          | 4              | 79           |
|                       | Yes             | 24                        | 1.12      | 1.08                          | 0.239          | 4              | 79           |

SFC= single-firing of coal; CF= co-firing of coal with pellet; SFP= single-firing of sorghum pellet (see Section 2.1).

a Considered CO₂ and N₂O emissions. The reason for not including CH₄ field emission has been explained in Section 2.7.

b There are no CH₄ and N₂O emissions from sorghum pellet combustion at the power plant.

c There are CH₄ and N₂O 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 efficiencya    | 1          | 1                         | 0.9                  | 1                    |
| Net yield (ton/ha)     | 48         | 20                        | 10.35                | 13.9                 |
| Production site        | Indonesia  | Germany                   | Ireland              | Southeast             |
| 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.

| Flowa | This study | Lewandowski et al. (1998) | Murphy et al. (2013) | Bergman et al. (2015) |
|--------|------------|---------------------------|----------------------|----------------------|
|        | Sorghum    | Miscanthus                | Miscanthus           | Switchgrass          |
| N-Fertilizer (kg/ton biomass) | 7.29 | 5 | 5.22 | 4.71 |
| 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 |

a N-fertilizer = urea; P-fertilizer = TSP (Triple Super Phosphate); K-fertilizer = KCI (Potassium Chloride).

b Table S17 (Supplementary Information) provides a more detailed LCI comparison.
Table 12. Comparison of the global warming impact of 1 kg pellet.

| Life cycle stages     | 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                             |

*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.

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 study scenario 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 statement answers 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 consider 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\textsubscript{2}-eq and 0.0273 kg CO\textsubscript{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\textsubscript{2}-eq/kg (Bergman et al., 2015), and those for miscanthus were 0.111 kg CO\textsubscript{2}-eq/kg (Lewandowski et al., 1995) and 0.364 kg CO\textsubscript{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\textsubscript{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).
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 CO₂-equ, 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 CO₂-equ (Q4). However, these results would change if emissions from incomplete biomass-combustion (N₂O and CH₄) and field application of nitrogenous fertilizers (N₂O) 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 to 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.

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### 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                 | 20,667                  |
| 10  | Lampung                         | 403,910                 |
| 11  | Banten                          | 330,408                 |
| 12  | DKI Jakarta                     | -                       |
| 13  | Jawa Barat                      | 911,192                 |
| 14  | Jawa Tengah                     | 375,733                 |
| 15  | DI. Yogyakarta                  | 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          | Non marginal (a) | Potentially marginal (b) | Rather marginal (c) | Marginal (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            | 23,688                   | 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            | 38,853                   | 87,354              | 40,376      | 186              | 40,562                        |
| **Total**       | **71,635**       | **265,960**              | **1,255,866**       | **413,307** | **8,596**        | **421,904**                   |

* Source: BPDASHL Benin Noelmina (2018)

* The term critical land is equivalent to marginal land (as used throughout this section of the paper).
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) | 4x65 MW            | PC      |
|                 |                | 1994 (unit 3)     |                    |         |
|                 |                | 1995 (unit 4)     |                    |         |
| Patim PLN       | East Java      | 1993 (unit 2)     | 2x400 MW           | PC      |
|                 |                | 1994 (unit 1)     |                    |         |
| 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)     | 2x115 MW           | CFB     |
|                 |                | 2009 (unit 1)     |                    |         |
| Suralaya* 1-8   | Banten         | 1984 (unit 1 & 2) | 400 MW (unit 1 – 4)| PC      |
|                 |                | 1989 (unit 3 & 4) | 600 MW (unit 5 – 7)|         |
|                 |                | 1997 (unit 5, 6, & 7) |                |         |
|                 |                | 2011 (unit 8)     | 625 MW (unit 8)    |         |

* 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                                                                 |
|---------------------------------|------------------------------------------------------------------------------------------|
| 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              |
| Sathiruang sak and Madhyanon (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.
Table S6.
Emission factors used in this study.

| Fuel          | Emission factor (kg/MJ) | Activity                                      |
|---------------|-------------------------|-----------------------------------------------|
|               | CO₂        | CH₄       | N₂O       |                                   |
| 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 CO₂ emission”. Moreover, CH₄ and N₂O 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   | Furadan⁵             | [thio]carbamate-compound [GLO]| market for | APOS, S                                       | Sorghum cultivation |
| 8   | Decis⁶               | Pyrethroid-compound [GLO]| market for | APOS, S                                       | Sorghum cultivation |
| 9   | Lubricating oil and grease⁶ | 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, S⁷                                    | 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 |

⁵ Furadan is considered equivalent to carbamate (NCBI, 2004)
⁶ Decis is considered equivalent to pyrethroid (NCBI, 2014)
⁷ Lubricating oil and grease are considered equivalent (Elduque et al., 2015)
⁸ This dataset does not seem to consider coal-mine fire.
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

| Parameter   | wt.%     | Test results |
|-------------|----------|--------------|
| Carbon      |          |              | ASTM D 5373 – 16 |
| Hydrogen    |          |              | ASTM D 5373 – 16 |
| Nitrogen    |          |              | ASTM D 5373 – 16 |
| Oxygen      |          |              | ASTM D 3176 – 15 |

| Parameter        | Test results |
|------------------|--------------|
| Aluminum (Al)    | 1.02         |
| Calcium (Ca)     | 8.59         |
| Silicon (Si)     | 24.42        |
| Zinc (Zn)        | 609.56       |
| Lead (Pb)        | 63.25        |
| Cadmium (Cd)     | 2.99         |
| Nickel (Ni)      | 54.03        |
| Chromium (Cr)    | 84.41        |
| Copper (Cu)      | 242.78       |
| Mercury (Hg)     | 13.65        |
| Arsenic (As)     | 0.60         |
| Chlorine (Cl₂)   | 0.04         |
| Bulk Density     | 626          |

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)
Table S10.
Energy and material requirements for pellet processing.

| No. | Name                      | Power required /equipment (kW/unit) | Number of equipment (unit) | Total power required (kW) |
|-----|---------------------------|-------------------------------------|---------------------------|--------------------------|
|     |                           | (1)                                 | (2)                       | (1)*(2)                  |

**Crushing Section**

1. Chain feeding conveyor 150 1 150
2. Chipper 7.5 1 7.5

**Pre-grinding section**

1. Belt conveyor 3 3 9
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. Hammer 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 screen 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 0.35 1 0.35

**Workshop dust removing section**

1. Bag dust removing system 37 1 37

**Total power:** 2,544.15 kW

**Energy consumption:** 1,784 kWh

**Required transformer:** 3,185 kVA

**Material (reference flow = daily pellet processing)**

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

---

*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.

 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).
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 – dry total                            | 0.085               |
| Ash – moisture free total                        | 0.031               |

* Source: Widyanto 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 Belfinung    | Existing                  | 16.5          | In operation |
| 7  | Babel 3              | PLN   | Bangka Belfinung    | Existing                  | 60            | In operation |
| 8  | Umbulan              | PLN   | West Sumatera       | Existing                  | 190           | In operation |
| 9  | Teluk Sireh          | 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 | Baru 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 Belfinung    | 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 |

* Under construction means the power plant is under construction and not yet operational.
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 | Mahuku 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 | Talaid                 | 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).

| 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

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

| Port destination | Coverage areaa | Electricityb (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            | 1.60E3       | 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       | 6.1E4            | 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             | 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 Sumbagun            | 3,612.36                         |
| 15 | Kit Sumbagusan          | 3,483.99                         |
|    | Outside Java            | 11,289.25                        |
| 16 | PT. Indonesia Power     | 23,894.44                        |
| 17 | PT. PJB                 | 9,809.39                         |
| 18 | Pembukitan 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   |
|    | Total Outside Java = Java (Indonesia) | 105,651.39            |

a Source: PLN (2018)

Table S16.
Nitrous oxide emissions from sorghum cultivation stages.

| Life cycle stages | Input flow (kg/ha.year) | NOx emissions (kg N/ha.year) |
|-------------------|-------------------------|-----------------------------|
| Synthetic Fertilizer |                        |                             |
| Compost           |                        |                             |
| Land processing   | -                       | 5.000                       |
| Planting          | 200                     | -                           |
| Fertilizing       | 150                     | -                           |
| 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 NOx emissions and only those that come from fertilizer applications.

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

| Parameter | Value | Unit |
|-----------|-------|------|
| FON       | 0     | kg N yr⁻¹ |
| FNO₂      | 0     | kg N yr⁻¹ |
| FON-total | 0     | kg N yr⁻¹ |
| N₂O-N-synth | 260.5 | kg N yr⁻¹ |
| EF⁻¹      | 0.01  | kg N²O-N (kg N)⁻¹ |
| N₂O-N⁻¹    | 2.61  | kg N²O-N yr⁻² |
| N₂O-N⁻²    | 4.09  | kg N²O-N yr⁻³ |

a FON = annual amount of synthetic fertiliser N applied to soils; FON = (200 kg + 150 kg synthetic fertiliser N) = 0.5 = 175. The N content of applied synthetic fertiliser N is 50% (from field-trial in Gresik, East Java).
b FNO₂ = annual amount of animal manure, compost, sewage sludge and other organic N additions applied to soils; FNO₂ = (5,000 kg compost) × 1.71% = 85.5. The N content of applied compost N is 1.71% (based on Kim et al., 2014).
c Not considered in this study due to lack of the data. FON = 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. FON-total = 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 Conversion factor from NOx field to NOx-plant is 44/28 (IPCC, 2006b).

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Table S17.
LCI comparison between this study and literature.

| Life cycle stage | Input flow | Unit | Sorghum (48 t/ha) a | Miscanthus (20 t/ha) b | Miscanacnthis (11.5 t/ha) c | Switchgrass (13.9 t/ha) d |
|------------------|------------|------|---------------------|------------------------|---------------------------|--------------------------|
| Land processing  | Diesel     | L    | 134                 | 5                      | 2                          | 80                       |
|                  | Compost    | ton  | 5                   | -                      | -                         | -                        |
|                  | Manpower   | mwd* | 80                  | -                      | -                         | -                        |
| Planting         | Sorghum seed | kg   | 30                   | -                      | -                         | -                        |
|                  | Nitrogen fertilizer | kg | 200 | - | 6.60 | 66.30 |
|                  | Phosphate fertilizer | kg | 150 | 50 | - | 6.81 |
|                  | Potassium fertilizer | kg | 15 | 200 | 58.75 | - |
|                  | Furadan (pesticide) | kg | 5 | 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 | Piece | 7,136 | 1,802 | 668 | 2,025 |
|                  | Electricity | kWh | 137.152 | - | - | - |
|                  | Lubricating oil | L | 0.576 | - | - | - |
|                  | Grease | L | 2.4 | - | - | - |

*a mwd = man work-day is defined as work done by one person in one day for eight hours (Wahyuni, 2014).
b)added by referring to the ecoinvent dataset because of limited primary data.
c)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.

d) This study

* Lewandowski (1995)
* Murphy et al. (2013)
* Bergman et al. (2015)
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