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LCA FOR ENERGY SYSTEMS AND FOOD PRODUCTS

Life cycle inventories and life cycle assessment for an electricity grid network: case study of the Jamali grid, Indonesia

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Abstract

Purpose The electricity and heat sectors are reported to contribute approximately 40% of total CO_2 emissions from the energy sector in Indonesia. Nonetheless, Indonesia is composed of several interconnected electricity-grid networks with different characteristics. This study was conducted to identify the life cycle inventories (LCIs) and perform a life cycle assessment (LCA) to determine the potential environmental impacts of electricity distributed in the Jamali grid network, contributing to 72% of the total electricity produced in Indonesia.

Methods An LCA was conducted with a functional unit of 1 kWh of electricity generated and transmitted in the distribution line in the Jamali grid network in 2018. The system boundary used in this study was cradle-to-gate, covering fuel production and transportation, electricity generation, and electricity distribution. The LCIs were gathered for each power plant's technology connected to the grid, which includes fuel consumption, fuel-related wastes, infrastructure, land use, water use, and air emissions. The following impact categories were assessed: global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), photochemical oxidation potential (POX), abiotic depletion potential (ADP), abiotic depletion potential–fossil fuels (ADF), and water scarcity footprint (WSF). Methods used to calculate those categories include IPCC GWP 100a, CML-IA (Baseline and Non-baseline), ReCiPe, and AWARE.

Results and discussion LCI analysis showed that the subcritical coal-fired power plants contributed to the highest electricity generation (58.80%), energy consumption (89.39%), and CO_2 production (70.52%) among other technologies connected to the grid. Subsequently, for every 1 kWh of electricity distributed in the grid, the power plants' operation produced the largest GWP, AP, and POX. Each category produced a total of 1.06 kg CO_2 eq., 5.89×10^{-03} kg SO_2 eq, and 4.08×10^{-03} kg NMVOC, respectively. The EP and ADF produced were 2.62×10^{-03} kg PO_4 eq. and 1.58×10^{1} MJ, respectively, mainly resulting from coal mining. ADP produced was 2.30×10^{-05} kg Sb eq. and WSF produced was 3.8×10^{-02} m^3, both majorly contributed by the production of transmission and distribution grid materials.

Conclusions LCA performed to determine the potential environmental impacts from the electricity distributed in the Jamali grid showed that the electricity produced from subcritical coal-fired power plants dominated the electricity mix in 2018. Subsequently, it contributed significantly to multiple impact categories, namely GWP, AP, and POX. Reducing the use of subcritical coal-fired power plants is thus essential to reduce the environmental impacts, which is aligned with the Indonesian government's plan to reach net-zero emissions by 2060.

Keywords Electricity · Electricity mix · Life cycle inventory · Life cycle assessment · Jamali grid · Indonesia

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1 Introduction

Indonesia produced approximately 538 million tons of CO_2 in 2018 from the energy sector, of which electricity and heat contributed to approximately 40% of its total emissions (IEA 2018). Performing a life cycle assessment (LCA) could play a role in identifying potential hotspots and developing mitigation measures to lower emissions. However, as the largest archipelagic country in Southeast Asia, Indonesia has several interconnected electricity grid networks located within or between islands. One of Indonesia's major electricity grid networks is the Java-Madura-Bali (Jamali) grid, which provides electricity to the Java, Madura, and Bali areas. The Jamali grid produced approximately 72% of the total Indonesian electricity demand in 2018 (Directorate General of Electricity 2018b).

A product category rule (PCR) can serve as a guideline for building a study with consistent and comparable results to similar studies when performing an LCA study. A PCR is a type III environmental declaration program commonly developed based on ISO 14025:2006 (ISO 2009) and regulates aspects that should be incorporated within a specific LCA study, including scope and life cycle inventories (LCIs). A PCR can thus facilitate researchers and LCA practitioners to develop consistent and comparable results within similar studies. In the context of electricity generation, a PCR for electricity, steam, and hot water generation and distribution (EPD International AB 2020) was established, with the first version being put in place in 2007.

However, following the whole PCR regulations often faces data availability problems, especially when it comes to a larger geographical area, such as assessing the impacts of the electricity mix in a regional/national context. Further complexity also arises in complying with PCR regulations, as there is a need to use specific data in some aspects. Existing studies, such as one performed by Lelek et al. (2016) and Hondo (2005), to name a few, commonly cover and use specific data on aspects that correlate directly with the electricity generation process, such as fuel and energy consumption, the amount of electricity generated, and the electricity generation mix. Some studies used secondary data in some aspects, despite the PCR requirement to use specific data, such as air emissions and fuel-related waste (Barros et al. 2018; Burchart-Korol et al. 2018; Gaete-Morales et al. 2018; Turconi et al. 2014; Widiyanto et al. 2003). Other aspects related to the operation of energy conversion plants are only addressed in a few studies, such as water consumption (Kabayo et al. 2019) and land use (Burchart-Korol et al. 2018; Gaete-Morales et al. 2018; Kabayo et al. 2019; Turconi et al. 2014).

Furthermore, although LCA studies on electricity generation have been widely performed, most of these studies have mainly investigated the LCA of the average electricity generation mix at the country level, for example, Brazil (Barros et al. 2018), Portugal (Garcia et al. 2014; Kabayo et al. 2019), and Japan (Hondo 2005). Only a few studies discussed the topic within a grid network in a country, such as Mallia dan Lewis (2013), who conducted an LCA study of electricity generated in Ontario's grid network in Canada. In the context of Indonesia, Widiyanto et al. (2003) performed LCA study of the average electricity generation mix from electricity systems in Indonesia using data from the year of 1998. An Ecoinvent 3 dataset has also been built based on data from a 2016 report (Wernet et al. 2016). The geographical scope of both studies is Indonesia at the country level.

Therefore, an LCA study of the electricity generation mix that complies, or at least has proximity, with the PCR regulations should be carried out to develop more comprehensive and comparable results. Given that the electricity grid networks in Indonesia are located on different islands, identifying the life cycle inventories (LCIs) as well as performing LCA for a grid network is also necessary to define specific hotspots and environmental problems in a particular grid. Thus, this study fills these gaps by determining the potential environmental impacts from 1 kWh of electricity generated and distributed in the Jamali grid through LCA, which approximately complies with PCR. The output of this study can be beneficial as a policy input to develop better strategies to mitigate the negative environmental impacts that result explicitly from the Jamali grid.

2 Method

The LCA study followed the ISO 14044 standard (ISO 2006). The scope of this study was the Jamali grid network of 2018. The functional unit was 1 kWh of electricity generated and distributed to customers through the Jamali grid. The Jamali electricity grid network is illustrated in Fig. 1.

The cradle-to-gate system boundary was used in this study. Three different process categories construct the system boundary: upstream, core, and downstream. Each process is defined as follows.

1. Upstream processes include coal mining, oil and gas production, diesel fuel production, liquefied natural gas (LNG) production, and transportation of fuels to power plants.
2. Core processes include electricity generation from power plants connected to the Jamali electricity grid network in 2018 (Directorate General of Electricity 2018b). These include subcritical coal-fired power plants (CF-SUB), supercritical coal-fired power plants (CF-SUPER), gas-fired steam power plants (GF), diesel-fired power plants

Fig. 1 Jamali Electricity Grid Network (Indonesian Ministry of Energy and Mineral Resources 2021)

(DF), open-cycle gas turbine power plants (OCGT), combined-cycle gas turbine power plants (CCGT), reservoir-type hydropower plants (hydro), and dry-steam geothermal power plants (Geo). The characteristics of each power plant are described in the Electronic Supplementary Material (ESM), Annex B.

3. Downstream processes include the delivery of electricity in the transmission and distribution grid.

The complete system boundary is shown in Fig. 2. Further descriptions of each process category are provided in Sects. 2.3, 2.4, and 2.5.

2.1 Life cycle inventories description

The gathered LCI data can be classified into specific and secondary data. Subsequently, both data were evaluated using the International Life Cycle Data System (ILCD) approach (European Commission 2010). The specific data used in this study are based on sustainability reports by energy producers and official reports from companies submitted to the government. Thus, the data belong to verified data and are based on measurements, indicating that the data have very good quality in terms of time, geographical, and technology coverage and precision.

Meanwhile, the secondary data used in this study consist of estimated and calculated data derived from peer-reviewed journals, official documents, personal communication with experts, and datasets from databases such as Ecoinvent 3. Most of the secondary data used in this study were valid when the study was finished. However, there are variations in geographical scope, ranging from Jamali area–specific data to national/global data (two-level larger zone at the most). Furthermore, LCA modeling applies a cutoff approach. The

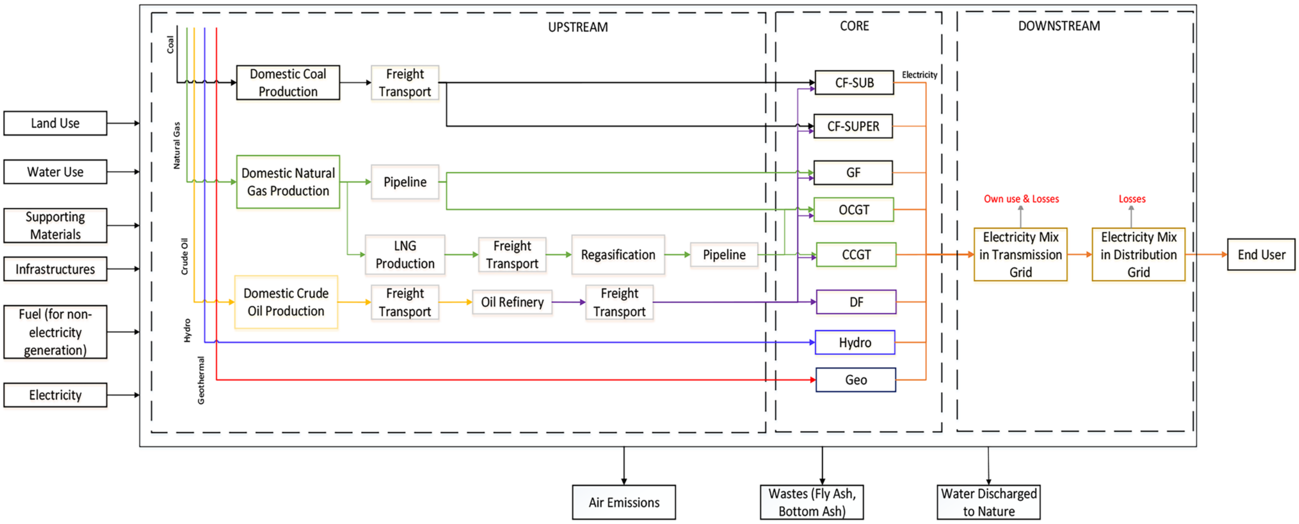

Fig. 2 System boundary of the study

following sections provide further details of the LCI used in this study. The study's detailed assumptions and limitations are described in ESM Annex C.

2.2 Compliance of the LCI with PCR

This study was performed to comply with the regulations stated in the PCR. However, some LCIs still needed to be excluded from this study because of the lack of data. Notably, no data were excluded in the upstream processes, as secondary data were mainly used and gathered from the Ecoinvent 3 database. Within the core processes, the LCIs excluded were maintenance activities, reserve power and heat operations, transportation of fuel-related wastes and other wastes generated, and infrastructure reinvestment. Furthermore, the infrastructures in this study, namely, the power plants, pipelines, freight vehicles, and transmission and distribution lines, are not specific data. Finally, the dismantling and decommissioning of power plants and other infrastructure are not considered in the downstream processes.

2.3 Upstream process description

2.3.1 Coal mining and transportation process

The coal mining process was represented using secondary data based on the Ecoinvent 3 database. Most of the coal used to fuel the power plants in the Jamali grid was low-to-mid-rank coal, which lies within the sub-bituminous and lignite type (Directorate General of Mineral and Coal 2018). Transportation of coal to the power plants was derived from the Ecoinvent 3 dataset (Hard coal {ID}| market for | Cutoff, U), with some adjustments made. First, parts of the dataset were omitted, such as coal mining (modeled separately) and coal import data (only domestic coal produced was used for power plants in Indonesia). Subsequently, adjustments were made to the average coal transport distance. Coal transportation using a conveyor belt was set to 2 km, whereas coal barge transportation was adjusted depending on the coal type. Sub-bituminous coal was assumed to be produced and transported from the three highest coal-producing regions, derived from the Directorate General of Mineral and Coal's report (Directorate General of Mineral and Coal 2018). It was identified that 44.25%, 34.67%, and 12.78% were produced in East Borneo, South Borneo, and South Sumatra.

In contrast, the source of lignite for CF-SUPER was primarily from Borneo (PT. Cirebon Power 2018; PT. PJB 2018b). It is then assumed that 76.74% of the lignite came from South Borneo and 23.26% came from East Borneo, based on the sustainability report of a national electricity company subsidiary (PT. PJB 2018b). From each site, the transportation distance from a coal terminal or port located in each of those regions to a port in every Jamali region (west, central, and east) was measured using Google Maps. Accordingly, the average distance was calculated based on the production volume of coal in each corresponding region.

2.3.2 Natural gas production and transportation processes

Similar to the coal mining process, the natural gas production process used secondary data from the Ecoinvent 3 database. However, natural gas production also envisages the type of production site (offshore or onshore). The production sites were determined based on the Ministry of Energy and Mineral Resources' decree that regulates the use and allocation of natural gas for power plants (Indonesian Ministry of Energy and Mineral Resources 2018), and the location of the sites can be identified from the map of oil and gas production sites in Indonesia (Indonesian Ministry of Energy and Mineral Resources 2021). Overall, it was indicated that 77.84% of the natural gas supplied to fuel the Jamali power plants was produced from offshore production sites, and the rest was made from the onshore.

Depending on the identified production sites and company, natural gas can be directly delivered to the power plants using the existing natural gas pipeline network or transported using LNG barges through LNG form. Existing natural gas pipeline information (e.g., availability, length, size, and capacities) was derived from the Ministry of Energy and Mineral Resources' Decree no. 2700/K/11/MEM/2012 about the National Planning of Natural Gas Transmission and Distribution Pipeline 2012–2025 (Indonesian Ministry of Energy and Mineral Resources 2012). Offshore pipelines include Trans-Island pipelines and pipelines used for transport from offshore production fields, while the rest are onshore pipelines. In contrast, transporting natural gas using LNG barges requires liquefaction, transportation, and regasification. The liquefaction process was assumed to follow the conventional APCI C3-MR process. The LCIs of the liquefaction process include propane as the refrigerant and electricity. An LNG barge is considered to travel from each production site's nearest port to a regasification point. The distances were measured using Google Maps. Boil-off gas built up along the LNG supply chain, calculated based on Mokhatab et al. (2013), was also included, and additional gas was added during the natural gas production process.

2.3.3 Oil extraction, diesel production, and transportation processes

Similar to natural gas production, the oil extraction process also considers the type of oil production site. A secondary dataset from the Ecoinvent 3 database was used to represent the extraction process at each site. In this case, production sites were defined based on the origin of the refineries' primary crude oil feedstock that provides diesel for power plants in the Jamali area. Overall, it was identified that 46.53% of the primary crude oil feedstock was produced in the Sumatra region, 42.78% in the West Java region, and 10.69% in the East Borneo region.

The transportation of crude oil to refineries requires oil barges. The LCIs of the oil refinery process were collected from a national refinery's sustainability report (PT. Pertamina RU VI 2017). It is assumed that similar technology and input–output are applied to both refineries. As refineries produce multiple products, the allocation procedure is performed based on the energy of each product (net calorific value). Oil trucks are used to transport diesel products to the power plants. For simplification, the transportation distance was only measured from a refinery to the power plants with the highest diesel demand in every Jamali region (west, central, and east). Further details regarding the transportation modes can be found in the ESM and Appendix D.

2.4 Core process description

Subcritical coal-fired power plant technology (CF-SUB) is a power plant primarily fueled with sub-bituminous coal. In contrast, supercritical coal-fired power plants (CF-SUPERs) are mainly driven by brown coal or lignite. Both fuels are burned in a boiler to generate steam. Gas-fired steam power plants (GF) use natural gas to power steam turbines. Steam is used to power steam turbines and to generate electricity. A diesel-fired power plant (DF) uses an internal combustion engine (ICE) to burn fuel and generate electricity. Gas turbines are used in open-cycle gas turbines (OCGT) and combined-cycle gas turbine power plants (CCGT). The difference between the OCGT and CCGT is that the CCGT has a heat recovery system that transforms the excess heat from gas turbines to electricity, thereby increasing the overall efficiency. Most hydropower plants (hydro) and geothermal power plants (Geo) connected to the Jamali electricity grid are reservoir-type hydropower plants and dry-steam geothermal power plants. The electricity production mix in the Jamali grid is shown in Table 1 (Directorate General of Electricity 2018b). Based on the table, CF-SUB was mainly contributed to the total electricity generated (excluding the own use and losses) with around 59% share, followed by the CCGT with a share of 23%. The total of own use electricity and electricity losses is about 13.22% of the total gross electricity generation. The net electricity distributed in the distribution grid is thus 126,550.72 GWh.

For the core processes, the LCIs gathered were fuel consumption, electricity generated, waste (fly ash and bottom ash), infrastructure, land use of the power plants, and air emissions. The fuel consumption data were derived from the National Electricity Statistics published by the Directorate General of Electricity in 2018 (Directorate General of Electricity 2018b). No data were available for CF-SUPER in the statistics, as all coal-fired power plant technologies were generalized. Hence, the collected total coal data were subtracted from the amount of coal explicitly used for the CF-SUPER power plants, which were gathered from two official Indonesian electricity companies' reports (PT. Cirebon Power 2018; PT. PJB 2018a). The average fly ash and bottom ash data were estimated based on the data from the PT. Indonesia's power sustainability report (PT. Indonesia Power 2018) for the CF-SUB and PT. Pembangkitan Jawa-Bali's sustainability report (PT. PJB 2018b) for the CF-SUPER. Water withdrawal, consumption, and discharge data were obtained from the Asian Development Bank report (Asian Development Bank 2016) and are further described in the ESM, Annex E, Section e. The power plant infrastructure is represented with secondary data from the Ecoinvent 3 database, and the number of power plants connected to the Jamali grid for each of the technologies was obtained from the Directorate General of Electricity's statistic (Directorate General of Electricity 2018b). Meanwhile, the average land use data were defined based on several power plants in the Jamali grid gathered from personal communication with experts (Personal Communication 2020). The data are further described in the ESM, Annex E, and Section f.

The GHG emissions data (CO_2, CH_4, and N_2O) were calculated for the thermal power plants based on the Directorate General of Electricity's guidance (Directorate General of

Table 1 Electricity mix profile in Jamali grid 2018 (Directorate General of Electricity 2018b)

Electricity generation	Unit	Amount of electricity generated
CF-SUB	TWh	85.76
CF-SUPER	TWh	10.47
GF	TWh	4.19
OCGT	TWh	2.12
CCGT	TWh	33.93
DF	TWh	0.86
Hydro	TWh	5.64
Geo	TWh	2.87
Total electricity generated from all power plants	TWh	145.84
Electricity Losses	**Unit**	**Amount of Electricity Loss**
Own use electricity	TWh	7.34
Transmission grid loss	TWh	3.27
Distribution grid loss	TWh	8.68
Net electricity distributed in the distribution grid	**TWh**	**126.55**

Electricity 2018a). Other air emissions, namely SO_2, NOx, particulate matter (PM), and CO, were derived based on the emission factor from the US-EPA (US-EPA 1995). The emissions from hydropower and geothermal power plants were derived from Kadiyala et al. (2016) and personal communication with experts from geothermal power plant companies (2020). Defining emissions from thermal power plants requires information on fuel characteristics, such as carbon content, calorific values, sulfur content, and ash content. These fuel characteristics and methodologies to estimate and calculate each characteristic are further explained in the ESM, Annex E, and Annex F, respectively. Accordingly, the methods for calculating the air emissions produced are also described in the ESM, Annex E, Section d.

2.5 Downstream process description

The data for the electricity transmission process through the transmission and distribution line consider the aggregated own-use electricity before entering the transmission line, electricity losses in the transmission and distribution lines, and the infrastructure of both lines. Except for the infrastructure data, all data were derived from the Directorate General of Electricity's statistics (Directorate General of Electricity 2018b). Line infrastructure data were obtained from the Ecoinvent 3 database. The overall LCIs are listed in Table 2.

2.6 Life cycle impact assessment

Life cycle impact assessment (LCIA) was performed using SimaPro software version 9.1.0.8. It considers the default impact categories and calculation methods defined in the international EPD system (Environdec 2021). The impact categories were global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), photochemical oxidant formation potential (POX), abiotic depletion potential (ADP), abiotic depletion potential (fossil fuels (ADF), and water scarcity footprint (WSF). The IPCC GWP 100a method was used to calculate GWP. The EP, ADP, and ADF impact categories were measured using the CML-IA Baseline (World 2000) method, while AP was measured using CML-IA Non-Baseline (World 2000). The POX was calculated using the ReCiPe Midpoint (H) (2008) method, and the WSF was determined using the AWARE method.

2.7 Uncertainty analysis

In this study, an uncertainty analysis of the impact assessment results for the electricity mix in the Jamali grid was performed to identify the uncertainty issues caused by the variability of the inventory data quality. Remarkably, the data varied in reliability, completeness, geographical correlation, temporal correlation, and technological correlation. Each of those aspects is scored with a certain value to depict the quality of certain inventory data and, consequently, represent the data's uncertainty. This scoring system and the score for some inventory data are further explained in ESM Annex G. The uncertainty analysis was conducted by applying the Monte Carlo simulation built within the SimaPro software, which is based on Frischknecht et al. (2005), with 1000 iterations and a significance level of $\alpha = 0.05$.

Table 2 Life cycle inventories for 1 kWh electricity distributed in the Jamali grid

Input	Unit	Amount/kWh electricity distributed
Power plants' fuel materials		
Sub-bituminous coal	Ton	3.51×10^{-04}
Lignite coal	Ton	4.53×10^{-05}
Natural gas	MMSCF	2.66×10^{-06}
Crude oil	Liter	1.35×10^{-02}
Total energy from fuels	GJ	44.38
Water consumption		
Ocean water	m^3	2.12×10^{-03}
River water	m^3	2.85×10^{-03}
Total water consumption	m^3	4.96×10^{-03}
Wastes		
Fly ashes	Ton	1.74×10^{-05}
Bottom ashes	Ton	1.46×10^{-06}
Air emissions		
CO_2	Ton	9.45×10^{-04}
CH_4	Ton	1.53×10^{-08}
N_2O	Ton	1.32×10^{-08}
SO_2	Ton	1.67×10^{-06}
NOx	Ton	2.90×10^{-06}
Particulates	Ton	1.72×10^{-07}
CO	Ton	1.77×10^{-07}
Others		
Total transportation	km	4.62×10^{-08}
Land occupation	ha	9.58×10^{-08}
Land transformation	ha/year	1.90×10^{-09}
Propane for LNG	Ton	3.45×10^{-08}
Energy for LNG production and refinery process	GJ	5.11×10^{-05}
LNG produced	MMSCF	1.41×10^{-07}
Diesel produced	kiloliter	4.71×10^{-06}

3 Results

The results of the LCIA performed for this study are listed in Table 3. The table showed that for 1 kWh of electricity generated and distributed in the Jamali grid, 1.06 kg CO_2 eq. of GWP, 5.89×10^{-03} kg SO_2 eq. of AP, 2.62×10^{-03} kg PO_4^{3-} eq. of EP,4.08×10^{-03} kg NMVOC of

Table 3 Results of the LCIA of this study and its comparison with the EcoInvent Indonesian electricity dataset

Categories	This study	Ecoinvent 3 (Electricity, high voltage {ID}c| market for | Cut-off, U)	Value gaps
Scope and boundary	Cradle-to-Gate, average electricity mix in Jamali grid, including losses and infrastructures of transmission and distribution grid	Cradle-to-Gate, average electricity mix in Indonesia, excluding distribution grid infrastructures and losses	
Functional unit	1 kWh electricity distributed in the distribution grid	1 kWh electricity distributed in the transmission grid	
GWP (kg CO_2 eq.)	1.06	1.06	↑ 0.51%
AP (kg SO_2 eq.)	5.89×10^{-03}	4.66×10^{-03}	↑ 20.76%
EP (kg PO_4^{3-} eq.)	2.62×10^{-03}	5.56×10^{-03}	↓ 112.34%
POX (kg NMVOC)	4.08×10^{-03}	3.08×10^{-03}	↑ 24.60%
ADP (kg Sb eq.)	2.30×10^{-03}	1.32×10^{-03}	↑ 94.28%
ADF (MJ)	1.16×10^{1}	1.10×10^{1}	↑ 4.82%
WSF (m^3)	3.76×10^{-02}	1.5×10^{-1}	↓ 311.43%

POX, 2.30×10^{-05} kg Sb eq of ADP, 11.58 MJ of ADF, and 3.76×10^{-02} m^3 of WSF were produced. For further analysis, a comparison between the LCIA results of this study and the Ecoinvent 3.0 dataset was conducted, and the results are also presented in Table 3. The analysis of the comparison will be further discussed in Sect. 4.3. Meanwhile, Fig. 3 shows the major process contributors for each impact category. The major process contributors are processes that produce the highest impact, with up to 80% of the total impact. Overall, nine processes were identified: electricity generation from CF-SUB, CF-SUPER, and CCGT; production of transmission and distribution grid materials (e.g., copper, zinc, and lead); production of natural gas; production of sub-bituminous coal; production of lignite; and production of natural gas pipeline materials (e.g., steel).

4 Discussion

4.1 LCI analysis for each of the power plants

The LCI analysis in this study focuses on the water consumption, energy consumption, and air emissions produced by each power plant, as these aspects might contribute significantly to environmental impacts. Figure 4 shows the proportion of these aspects contributed by each power plant. Apart from water consumption, coal-fired power plants dominate the energy use and emissions produced. CF-SUB accounted for the highest energy consumption with about 89.39% share, corresponding well with CF-SUB being the most significant contributor to the electricity mix. Subsequently, with sub-bituminous coal as its primary fuel,

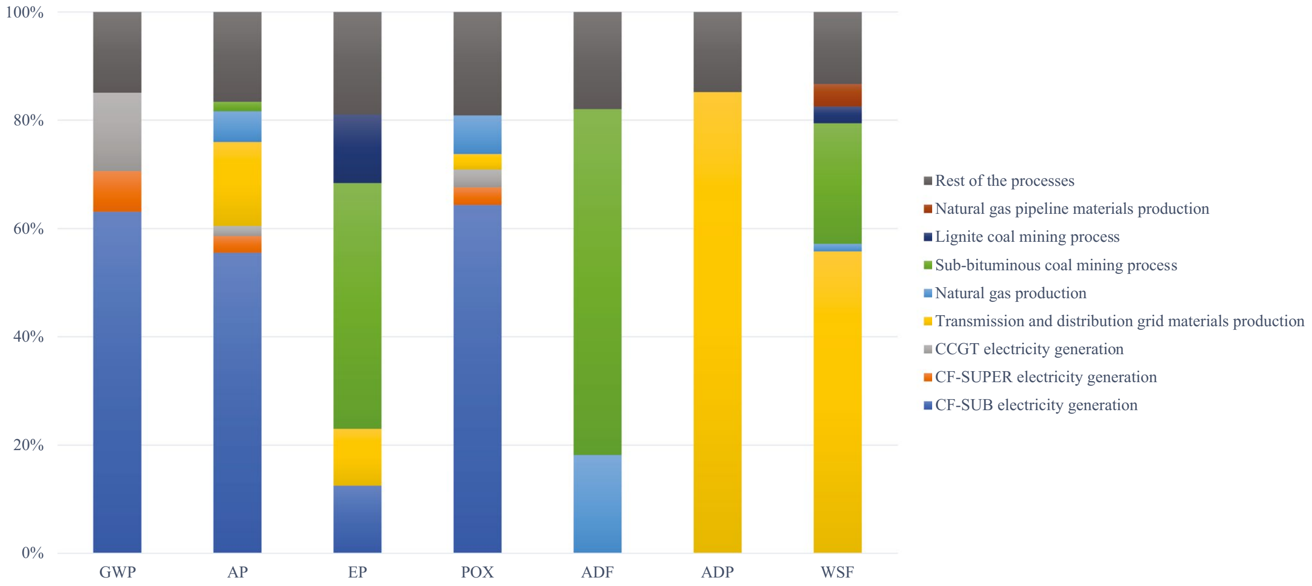

Fig. 3 Major process contributors of the potential environmental impacts

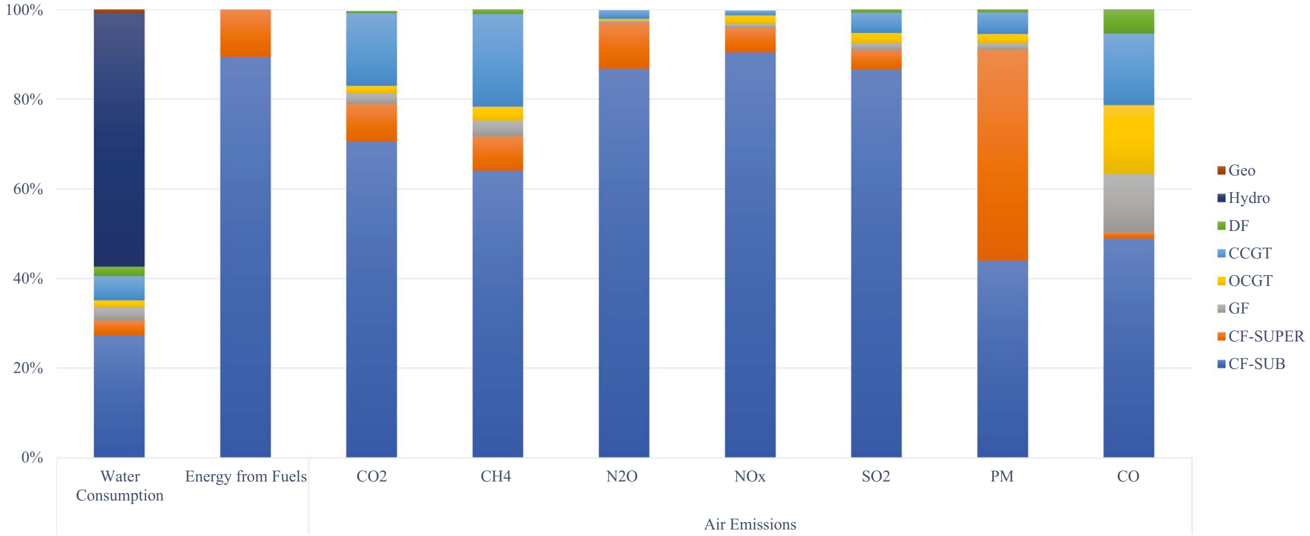

Fig. 4 Share of water consumption, energy consumption, and air emissions produced per power plant

CF-SUB produced the highest amount of most of the air emission substances investigated. Only PM emissions were primarily produced by the CF-SUPER because of the lower quality of coal (lignite), resulting in a higher emission factor. Hydropower plants had the largest share at approximately 56.58% in the water consumption aspect.

4.2 Potential environmental impact analysis

Based on the results of the LCIA, the potential environmental impacts can be further analyzed. Electricity generation from CF-SUB is the most significant process contributing to three impact categories: GWP, AP, and POX. The result shows that CF-SUB accounts for approximately 63.11% of the total GWP produced, 55.55% of the total AP produced, and 64.40% of the total POX produced. Furthermore, the sub-bituminous coal mining process, part of the CF-SUB supply chain, also had the highest EP and ADF impact, with 45.38% of the total EP produced and 63.87% of the total ADF produced, respectively. The indirect emissions caused by the production of materials to build the transmission and distribution grids mainly causes the ADP and WSF, accounting for 85.20% of the total ADP produced and 55.80% of the total WSF produced. Specifically, concerning the secondary data from Ecoinvent 3 used to represent the transmission and distribution grid (explained in the ESM, Annex C), the production of lead concentrate and zinc concentrate produced a significant amount of ADP, with a share of 48.9% and 29.4%, respectively. Meanwhile, 30.61% of WSF produced was contributed by the production of copper concentrate. Based on the dataset, the distribution grid is made from a large amount of copper (about 7.3 tons of copper concentrate/km of distribution grid constructed), in which 1 ton of copper concentrate production requires around 32.59 m^3 of water (Wernet et al. 2016). Apart from the production of transmission and distribution grid materials, the sub-bituminous coal mining process also contributed to the WSF with a share of 22.25%. It was also identified that there is an insignificant impact of WSF resulting from the water consumption of the power plants, as most of the power plants withdraw and discharge the water from and to the ocean. This resulted in a zero-emission factor in the AWARE method.

4.3 Comparison of the results with existing data

As explained in Sect. 3, further analysis was performed by comparing the potential impact categories produced in this study and the Ecoinvent 3 dataset (Electricity, high-voltage {ID}| market for | Cutoff, U). The Ecoinvent 3 dataset is currently a commonly used dataset for representing the Indonesian electricity mix in LCA. The results, shown in Table 3, indicate that similar values are found in the GWP and ADF categories, with the GWP produced only 0.51% higher and the ADF produced about 4.82% higher. A below 1% gap in the GWP produced was found as the (calculated) emissions from the major process contributors, such as the operation of coal-fired power plants (or CF-SUB and CF-SUPER in this study) and the gas-fired power plants (OCGT and CCGT), are similar. However, a different dataset was used to represent the coal-fired power plants. In the Ecoinvent 3 dataset, the CF-SUB and CF-SUPER data were aggregated into single coal-fired power plant data with lignite coal as its primary fuel (Lignite {RoW}| mine operation | Cutoff, U). Meanwhile, this study separates sub-bituminous coal (represented by the hard coal Ecoinvent 3 data) and lignite coal. Further analysis showed that this caused the higher production of ADF and the significantly lower EP and WSF (more than 100% differences).

The AP, POX, and ADP were higher (more than 20% differences) in this study, mainly due to the presence of the transmission and distribution grid infrastructure utilization, which significantly impacted these impact categories.

4.4 Uncertainty of the LCIA

Figure 5 shows the result of the uncertainty analysis for the electricity generation mix in the Jamali grid, where WSF is seen to have the most significant uncertainty among the others, followed by EP. This high degree of uncertainty can be caused by the low data quality of the largest process contributors in each category: transmission and distribution grid material production, sub-bituminous coal mining processes, and lignite mining processes. As seen in ESM Annex G, these processes possess relatively low data quality in terms of completeness, geographical correlation, and technological correlation, due to the global/national dataset used as the underlying secondary data. For example, performing WSF uncertainty analysis on the underlying secondary data of the distribution grid network using the same method resulted in large uncertainty values with almost 3000% on the upper bound and almost − 3000% on the lower bound. Specific to the WSF, another factor that may affect the high uncertainty result is the difference between the AWARE's characterization factor distribution and the distribution used in the Monte Carlo method. The Monte Carlo method applies parametric probability distribution, while the AWARE's characterization factor, as the input variables, can be nonparametric due to AWARE's functions that comprehend discrete steps (Lee et al. 2018). This may give a complex estimation of the distribution and produce a high uncertainty result of the WSF. The use of secondary datasets also can cause the negative uncertainty value in the WSF, as some datasets cover inventories/processes that discharge water to the environment (other than the ocean) and give an increase to the water availability in the corresponding area (e.g., processes that produce water as a byproduct and discharge it to a river/well/ground). These processes are considered to bring positive environmental impacts and subsequently possess negative characterization factors in AWARE and give negative WSF values. Overall, there is a need to gather more specific data, e.g., region-specific transmission and distribution grid data production along with its material production, to reduce the uncertainty of the WSF and, consequently, increase the precision and reliability of the LCIA.

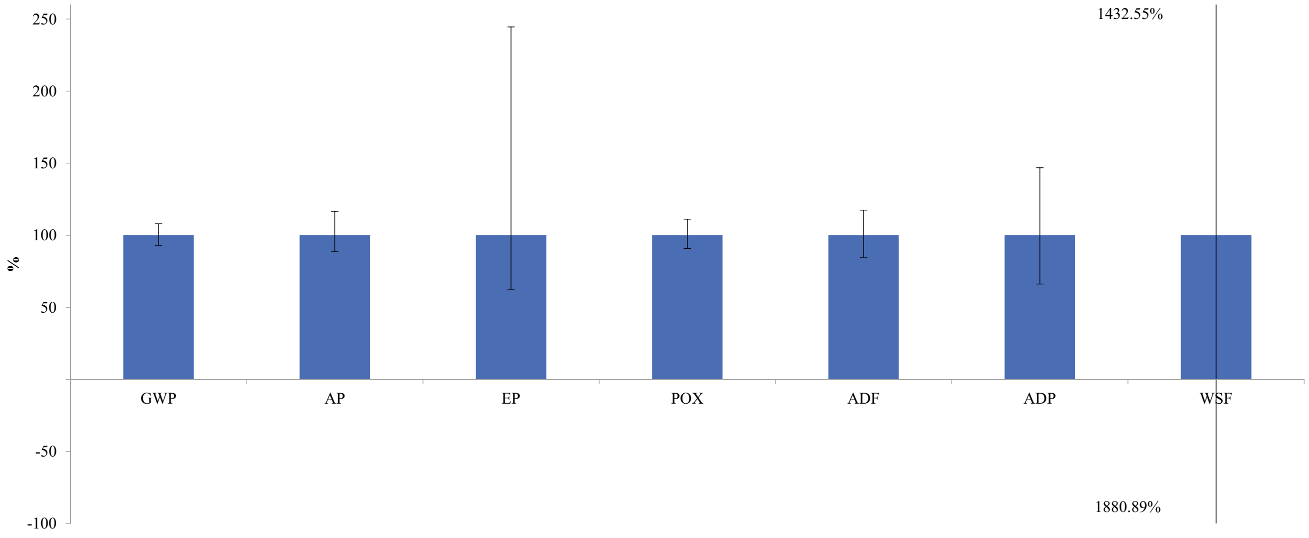

Fig. 5 Uncertainty analysis showing the impact assessment results for 1 kWh electricity distributed in the Jamali grid (blue bars), with a confidence interval of 95% is shown by the error bars. The error bars depict that the result would be within the range in 95% of the cases

5 Conclusion

An LCA for a specific grid network closely aligned with the PCR was performed in this study, with a functional unit of 1 kWh electricity distributed in the Jamali grid in 2018. The system boundary is cradle-to-gate and includes fuel material extraction, production, transportation, electricity generation, and electricity transmission in the transmission and distribution grids. The gathered LCIs showed that eight power plant technologies were connected to the Jamali grid in 2018, with the highest electricity produced from CF-SUB accounting for 58.80% of the total electricity generated. Accordingly, CF-SUB also contributed to almost 90% of the energy consumption and accounted for the highest emitter for most air emissions.

The potential impact assessment results show that for 1 kWh of electricity distributed in the grid produced 1.06 kg CO_2 eq. of GWP, 5.89×10^{-03} kg SO_2 eq. of AP, 4.08×10^{-03} kg NMVOC of POX, 2.62×10^{-03} kg PO_4^{3-} eq. of EP, 11.58 MJ of ADF, 2.30×10^{-05} kg Sb eq of ADP, and 3.76×10^{-02} m^3 of WSF. The electricity generated from CF-SUB has contributed to various impacts, including GWP, AP, and POX. In addition, the sub-bituminous coal mining process is considered the most significant process contributor to EP and ADF. ADP and WSF are mainly produced from transmission and distribution grid materials, such as copper and zinc. It can be concluded from the results that there is an urgent need to reduce or replace the use of coal-fired power plants in Indonesia, specifically with subcritical technology, with more sustainable and environmentally friendly power plant technology. This is in line with the Indonesian government's plan to start retiring subcritical coal-fired power plants in 2030 and move to environmentally friendly coal-fired power plants such as supercritical and ultra-supercritical power plants (IRU 2021).

Comparing the potential impact assessment results from this study and the Indonesian electricity mix dataset from Ecoinvent 3 (Electricity, high voltage {ID}| market for | Cut-off, U) showed that both datasets produced similar results in GWP and ADF, with only approximately 0.51% and 4.82% differences, respectively. On the other hand, this study's EP and WSF produced were more than 100% lower. The segregation of coal-fired power plants into subcritical and supercritical technologies, in which each technology uses different types of coal, was found to be the main cause of the higher ADF as well as lower EP and WSF production. The inclusion of transmission and distribution grid infrastructure in this study resulted in higher AP, POX, and ADP, with more than 20% differences. Overall, this study shows that performing LCA for a more specific region and adhering to PCR can provide distinctive results that enhance the reliability and robustness of LCA studies.

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Data availability The authors declare that some data supporting the findings of this study are available as stated within this published article (and its Supplementary information file). Complete datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests The authors declare no interests.

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