Economic analysis and environmental assessment of aluminum debris power generator for deployment to communal-scale disaster areas

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ABSTRACT

The potential use of aluminum debris as an energy source and carrier has been recently highlighted in the research. An aluminum debris power generator is a promising system that can be deployed in the aftermath of various types of disasters and provide portable electricity. Such a power generator produces electricity while simultaneously handling aluminum debris in disaster areas. We assess the economic and environmental performance of the aluminum debris power generator deployed to communal-scale disaster areas to determine its feasibility. The economic analysis indicates that aluminum debris power generators have a higher net present cost and levelized cost of energy than diesel generators, which are currently used for emergency power generation. However, aluminum debris power generators can improve their economic feasibility when the valuable boehmite by-product is considered. The aluminum debris power generator outperforms the diesel generator for the environmental impact on climate change. The life cycle assessment indicates that the primary source of the environmental impact comes from generator manufacturing. Our results suggest that recycling valuable materials and redesigning manufacture to reduce the use of critical materials can improve the profile of environmental impacts and provide economic benefits for aluminum debris power generators. Future research should be conducted to devise an ecosystem facilitating the sustainability of this type of generator.

1. Introduction

Indonesia is frequently hit by natural disasters such as tsunamis, earthquakes, volcano eruptions, and floods. In 2019, 1,322 natural disasters of varying intensity occurred in Indonesia (The Indonesian National Disaster Management Agency – BNPB, 2020b). The most recent massive disaster occurred on September 28, 2018. An earthquake with a magnitude ranging from 5 – 7 of the Richter Scale followed by liquefaction and a tsunami in Donggala and Palu, Central Sulawesi, caused extensive damage to more than 66,000 buildings and major infrastructures and 2,045 causalities (BNPB, 2018). Moreover, power and communications were interrupted due to heavy damage to the supporting infrastructure. Usually, it takes several days to fix infrastructure and restore services in the aftermath of a disaster. Without an electricity supply, the relief efforts are hampered. Hence, solutions that leverage local resources for immediate relief must be devised.

Aluminum debris from a disaster area, usually from roof trusses, door frames, window frames, and cooking utensils, may be used for power generation. Due to its zero self-discharge and high energy density (29 MJ/kg), aluminum is a promising energy source and carrier. Shkolnikov et al. (2011) performed a feasibility analysis of aluminum and highlighted its capabilities for long-time storage and easy transport, which are suitable characteristics for deployment to disaster areas. Wang et al. (2009) suggested that aluminum scrap, which is not suitable for recycling, can be consumed for hydrogen generation for reducing or eliminating the costs associated with other energy sources. Due to the high potential of aluminum to serve as an alternative energy source, several aluminum-based energy generation technologies for different applications have been developed, including portable systems for deployment to disaster areas.

During an emergency, diesel generators are commonly used to provide electricity. Alternatively, using aluminum debris allows power generation at low or no cost of energy resources while providing clean and safe energy, as no hazardous emissions are produced. Furthermore, this type of power generation allows processing debris from disaster areas. Thus, aluminum debris power generators offer various advantages over their diesel counterparts. However, replacing diesel with aluminum...
debris power generators involves various challenges. Energy transition toward sustainability is not only dealing with technological shift, but various dimensions, i.e., financial, ecological, social, and institutional, should also be analyzed (Markard et al., 2012). An aluminum debris power generator deployed to disaster areas was recently developed by Godart et al. (2020). A similar generator could then be used for deployment to communal-scale disaster areas to provide electricity in Indonesia. Therefore, to evaluate its feasibility prior to the deployment, we conducted the economic analysis and environmental assessment of aluminum debris power generators for potential deployment in Indonesia. For the economic analysis, we considered the net present cost (NPC), levelized cost of energy (LCoE), and net present value (NPV), whereas the environmental assessment was based on the life cycle assessment (LCA) according to the ISO 14040 and 14044 standards.

Although extracting energy from waste has been widely investigated, research on converting energy from debris in the aftermath of disasters is scarce. Portugal-Pereira and Lee (2016) conducted a study on the use of disaster aftermath debris for power generation. Specifically, they investigated the technical and environmental feasibility of converting biomass debris into electrical energy after Japan’s most powerful earthquake in 2011. The study consisted of handling disaster debris and enhancing the power generation mix of renewables. Regarding aluminum debris, few studies are available. Siregar (2012) demonstrated the technical feasibility of using aluminum waste (i.e., aluminum foil of food wraps and aluminum beverage cans) in laboratory settings to produce hydrogen and eventually generate electricity using a fuel cell. It was found that 0.1 g of aluminum foil yielded 12.13 Watt of electrical energy. Ho and Huang (2016), Setiani et al. (2018), and Xu et al. (2019) further investigated the mechanism of hydrogen production using aluminum waste. Godart et al. (2020) have recently developed an aluminum debris power generator for deployment to disaster areas. The generator was designed to produce electricity in 3 kW and used as a portable energy source during an emergency. Using aluminum debris from disaster aftermaths as fuel seems promising in Indonesia due to the high frequency of disasters. From January to October 2020, the 2,256 reported disasters affected 34,100 residential houses, from which 7,045 were severely damaged (BNPB, 2020a). To improve support during disaster response, we analyzed the applicability of the aluminum debris power generator regarding the economic and environmental feasibility for deployment to communal-scale disaster areas in Indonesia.

Existing studies of aluminum waste-based electricity generation (e.g., Wang et al., 2009; Siregar, 2012; Ho and Huang, 2016; Setiani et al., 2018; Xu et al., 2019; Godart et al., 2020) have focused on the technical aspect and operations of the generator. The good technical feasibility of aluminum waste-based electricity generation requires further studies examining economic and environmental viability, which is still rare in the existing literature. Barros et al. (2020) has drawn attention to address economic and environmental aspects to complement the significant technological advances. Closing the gap, the present paper has the novelty in the comprehensive economic and environmental analysis of the aluminum debris power generation, particularly for disasters that have not been addressed in the literature. Furthermore, a sustainable transition is shaped by spatial context and functional domains (Markard et al., 2012). As sustainable transitions in developed countries have dominated existing literature, in which 62.5% of the life cycle assessment of electricity generation was based on Europe (Barros et al., 2020), the present study contributes to the body of knowledge by extending the geographical reach of transition studies to a developing region. Moreover, the study provides insights on an environmental alternative of emergency power generation to promote sustainable communities, particularly in a developing country.

2. Background

In this section, we present state-of-art developments in aluminum fuel toward aluminum-based power generation. In addition, we briefly describe aluminum debris power generation, which will be analyzed in this study.

2.1. Aluminum fuel

Besides conventional methods, electricity can be generated from renewable sources such as wind, water, or solar irradiance. Power generation from renewable sources is both environmentally friendly and economically beneficial. Thus, renewables have shifted the paradigm from fuel consumption to power generation that can be used as a fuel replacement. Many components and materials, such as batteries, hydrogen, ammonia, aluminum, and iron, have been investigated as potential energy carriers. Aluminum, characterized by its high specific energy, energy density, recyclability, and long-term storage, is a suitable energy carrier (Shkolnikov et al., 2011). Moreover, aluminum can realize a zero-carbon-emission reduction of aluminum. As electricity cannot be stored, shipped, and traded as hydrocarbon fuels, aluminum is a promising energy carrier compared to hydrogen, which has a low energy density and safety problems.

Aluminum fuel can be developed by removing the oxide layer that inhibits oxidation reactions such as corrosion. As the oxide layer provides resistance against corrosion, aluminum has been widely used for construction. However, that resistance hinders the development of aluminum fuel. Wang et al. (2009) reviewed several methods to activate aluminum by facilitating aluminum–water reactions through chemical activation using alkaline solutions such as NaOH, KOH, and Ca(OH)₂, mechanical activation such as grinding, and metal dissolution and deposition with elements such as gallium. For instance, Slocum (2017) demonstrated that aluminum fuel can be developed using only 2–5% of alloying metals such as gallium and indium. Xu et al. (2019) conducted experiments using liquid metals including gallium, indium, and selenium to activate aluminum for generating aluminum–water reactions.

In the aftermath of a disaster, suitable fuels to provide energy should be selected according to aspects such as availability, energy density, storage period, and transportability. Aluminum debris is abundant and cheap in disaster areas because roof trusses, door frames, and window frames of modern houses are generally made of aluminum. Moreover, aluminum has a higher energy density than diesel. Jung et al. (2008) found that aluminum is the best fuel to produce hydrogen for power generation in fuel cells due to its considerable amount of hydrogen per gram. In addition, aluminum is easy to transport under space limitations and long-term storage, thus outperforming alternatives like diesel for deployment during emergencies such as natural disasters.

Furthermore, aluminum is a clean energy carrier for applications requiring sustained high-power supply and short refueling, such as long-distance transportation. Overall, aluminum is a promising energy source and carrier in disaster areas. Trowell et al. (2020) identified the potential of aluminum as fuel by using accumulated aluminum debris in remote regions and disaster areas, where collecting and transporting the aluminum for recycling is cost-inefficient. Moreover, using aluminum debris to generate power would resolve the waste problem while providing electricity, whose supply is usually interrupted during the aftermath of disasters.

2.2. Aluminum-based power generation

Several technological solutions to generate power using aluminum are available. Aluminum combustion and aluminum–water reactions satisfy scalable power needs for various applications. Aluminum combustion has been used for process heating and external combustion engines, whereas aluminum–water reactions have been used for underwater propulsion. Such reactions can be carried out using alkaline solutions as a catalyst, by reaction with alcohol, under neutral conditions, or at elevated temperatures (Wang et al., 2009).

In disaster areas, power generation must meet several specifications. The power generator must provide high transportability and safety (easy
to operate at moderate temperatures and without emitting hazardous substances), and it must be easily maintained and have a long shelf life of fuel. Therefore, aluminum–water reactions are suitable for power generation in disaster areas. This generation approach can be operated at ambient temperature and atmospheric pressure, and it is relatively easy to control compared with aluminum combustion. Moreover, aluminum–water reactions allow closed-loop operation (Franzoni et al., 2010). However, aluminum–water reactions using alkaline solutions are hazardous to handle, especially at high concentrations, and the reaction is difficult to control (Jung et al., 2008). Alternatively, pretreatments with ball-milling or melting can be used to activate aluminum debris. Given that ball-milling or melting is an energy-intensive process, activating aluminum debris using 2–5% of gallium and indium proposed by Slocum (2017) seems appropriate for safe, simple, and less required energy power generation. Moreover, Slocum’s method can provide several years of shelf life, being suitable for disaster response.

When aluminum fuel (Al) reacts with water (H₂O), it produces hydrogen (H₂), boehmite (aluminum oxyhydroxide, AlO(OH)), and heat (Q) according to the following reaction:

\[ 2\text{Al}(s) + 4\text{H}_2\text{O}(l) \rightarrow 3\text{H}_2(g) + 2\text{AlO(OH)}(s) + Q \]  

(1)

This reaction releases energy (859 kJ/mol Al) in thermal energy and chemical potential energy of hydrogen in approximately equal proportions (Godart et al., 2020). The obtained hydrogen is then fed to a fuel cell that converts hydrogen into electricity at an efficiency of 40–70% (Jung et al., 2008). Besides electricity, the fuel cell also produces water, fed back to the reactor to reserve water consumption. Furthermore, boehmite is obtained. Boehmite is a valuable by-product of aluminum debris power generation that can be used in surface coating, polymer additives, binding for catalysis, and refractory materials.

### 2.3. Aluminum debris power generator

Godart et al. (2020) developed a system that uses aluminum debris to generate electricity at a scalable capacity of 3 kW. This system is aimed for power generation comparable with that of a diesel generator while improving storage and transportation to remote locations for practical support to disaster response. The aluminum debris power generator has a size and weight similar to those of a 3-kW diesel generator. As we only used some information from Godart et al. (2020) particularly on the main components of the system to estimate the cost of the generator for the potential implementation in Indonesia, hence, this study does not associate with any analysis of the system developed by Godart et al. (2020).

The aluminum debris power generator consists of a reactor module, a hydrogen conditioning module, a power generation module that includes a Proton Exchange Membrane Fuel Cell (PEMFC) and electrical components, and a structure module (Godart et al., 2020). The reactor module consists of a reaction chamber where the aluminum–water reaction takes place. Each batch reactor requires 30 g of aluminum per minute and 40 mL of water per minute. As shown in Eq. (1), the reaction produces hydrogen, boehmite, and heat. The reaction chamber must be resistant to embrittlement by hydrogen minute. As shown in Eq. (1), the reaction produces hydrogen, boehmite, and heat (Q) according to the following reaction:


godart et al.

![Table 1. Bill of materials for aluminum debris power generator.](image)

We analyzed both the aluminum debris power generator’s economic feasibility and environmental impact to provide electricity using aluminum to easy construction, lightweight requirement, and strength requirement. Air-ride casters are equipped for safe transport. Additionally, soft rubber spacers are used for fuel cells and a reactor to minimize vibration during operation and transport.

According to the main components presented by Godart et al. (2020), the bill of materials of the aluminum debris power generator is presented in Table 1. The table does not show an exhaustive list but the major generator components. The quantity and price of other components, such as nuts and bolts, are roughly estimated. Based on the bill of materials, the assembly of the components and additional supporting work is estimated as 15% of the purchased equipment cost.

### 3. Methods

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![Table 1. Bill of materials for aluminum debris power generator.](image)
debris from disaster areas. Specifically, the NPC, LCoE, and NPV were determined to analyze the economic viability, whereas an LCA according to the ISO 14040 standard was performed to assess the environmental impact.

The Indonesian National Disaster Management Agency (BNPB) has developed a national contingency plan that specifies the equipment required before a disaster occurs to mitigate risks and facilitate a prompt response. To generate power in the aftermath of a disaster, BNPB considers diesel generators, which were the reference for our economic analysis. Specifically, we compared the diesel generator with the aluminum debris power generator as a potentially better alternative. Disaster response operations for two weeks were used to estimate the electricity consumption. On average, an earthquake occurs every two years within a province in Sumatera, the most affected area and the one with the highest likelihood of disaster occurrence in Indonesia, according to a risk assessment conducted by BNPB. Considering the earthquake frequency in this region and the generator lifetime, we set the time horizon for the economic analysis to twelve years.

### 3.1. Economic analysis

The economic analysis considered the government’s viewpoint responsible for handling and coordinating disaster response, noting that the analysis and decision-making in governments notably differ from those in the private sector due to their different objectives. Public sector projects aim to maximize the benefits to most of the population while minimizing adverse consequences and costs to the government. Therefore, we determined the economic feasibility of the aluminum debris power generator from the NPC, LCoE, and NPV. The NPC represents the system life cycle cost, whereas the LCoE measures the average cost per unit of generated electricity. The LCoE allows comparing power generation methods. The NPC and LCoE have been widely applied to economic analyses of various power generation technologies, like in the study by Wiranarongkorn et al. (2020). Due to the potential gain from the boehmite by-product, the NPV representing the system life cycle value was also used as a profitability measure (Newnan et al., 2019). As the diesel generator is commonly deployed in disaster areas, we used it as a reference for analyzing the aluminum debris power generator regarding the NPC, LCoE, and NPV. An analysis on the Benefit/Cost (B/C) Ratio frequently used in public sector projects was also conducted to complement the mentioned economic measures. Figure 1 shows the workflow of the economic analysis applied to the aluminum debris power generator.

The NPC, which reflects the total cost of the project, is given by

\[ NPC(i, n) = \sum_{t=0}^{n} \frac{A_{op}}{(1+i)^t} + TCC \]  

where TCC is the total capital cost and \( A_{op} \) is the annual operations and maintenance cost. The total capital cost comprises direct costs (purchasing cost of each component and total installation cost) and indirect costs. The purchasing costs of the generator components are listed in Table 1. The annual operations and maintenance costs include fixed costs (e.g., costs related to storage) and variable costs (e.g., fuel cost).

The LCoE is calculated as

\[ LCoE = \frac{A_{total}}{E} \]  

where \( A_{total} \) (IDR/year) is the annualized cost (annualized capital cost and operations and maintenance cost) and \( E \) (kWh/year) is the total electricity generated over lifetime.

The NPV, which reflects the value of the net cash flow over the entire life, which is discounted to the present, is given by

\[ NPV(i, n) = \sum_{t=0}^{n} \frac{C_t}{(1+i)^t} \]  

where \( C_t \) is the net cash flow at time \( t \).

In public sector projects, the interest rate can be considered as an opportunity cost. Thus, the interest rate is set as the best future project for which funding is not available. According to Newnan et al. (2019), the interest rate used in any city’s public sector can be estimated as 8%. Concerning diesel generators, we considered the carbon tax of IDR 141, 560 per ton of CO2 implemented by the Directorate General of Climate Change Control, Indonesian Ministry of Environment and Forestry (2020) as the environmental cost. The parameters for the economic analysis are listed in Table 2.

We also considered three scenarios for the economic analysis of aluminum debris power generators. In the base scenario (Scenario 1), the government allocates a budget to provide electricity to the population affected by a disaster without considering any revenues. In Scenario 2, the value of the boehmite by-product resulting from the aluminum debris power generator is considered an economic incentive. In the European market, the price of boehmite is 30–300 EUR/kg (equivalent to 519,087–5,190,873 IDR/kg) depending on its purity/quality (Hydratherma, 2020). Our economic analysis considered a minimum price of impure boehmite of 30,000 IDR/kg. An intangible benefit of providing electricity to the population during the disaster was considered in Scenario 3. The intangible benefit was estimated using the value of lost load (value of supply security) by de Nooij et al. (2007), which was scaled using the Indonesian cost of living index to represent the Indonesian context. The basic assumption of Scenario 3 is that aluminum debris power generation could provide electricity one day earlier than the diesel generator because the fuel supply of aluminum debris is already available.

![Figure 1. Workflow of economic analysis in this study.](image)
in the disaster areas, on the other hand, it takes time to get diesel fuel in the areas due to infrastructure damage. One day earlier providing electricity to the population is corresponding to the intangible benefit of 137,423,596 IDR.

### 3.2. Environmental assessment

We assessed the environmental impact of the aluminum debris power generator through an LCA according to the ISO 14040 and 14044 standards. The LCA allows avoiding problem shifting, identifying whether the generator does not create problems to other processes or disregarded environmental issues. We used the LCA to evaluate the environmental impact of the generators through all its stages, including materials, manufacturing, use, and end of life. According to the ISO 14040 standard, the LCA comprises of four steps: 1) goal and scope definition, in which the objective of the analysis, scope of the study, and functional unit are established; 2) life cycle inventory analysis, which focuses on modeling the inventory and collecting the required data; 3) life cycle impact assessment, which includes the evaluation of the selected impact factors; and 4) interpretation, which allows to summarize the findings, discuss relevant issues, and provide recommendations.

We applied the LCA to 1 kWh of electricity generated by an aluminum debris power generator as the functional unit. The LCA was implemented on the GaBi ts software, which contains the ecoinvent database and GaBi professional database developed by ThinkStep. The system boundary starts from the extraction and supply of raw materials, followed by manufacturing of the aluminum debris power generator based on the bill of materials provided in Table 1, aluminum fuel production, operation, and end of life. The system boundary of the generator is shown in Figure 2.

We obtained the data required to build the life cycle inventory from empirical evidence whenever available and existing studies for modeling the foreground processes (see Table 3). The GaBi professional database was used for modeling background processes for materials such as steel, rubber, and aluminum. For the end-of-life processes, we considered landfilling as recycling data are neither available nor accessible. Table 3 presents life cycle inventory and associated data sources.

The LCA was based on the CML 2001 midpoint approach. We focused on seven impact categories widely adopted in LCA of power generation: abiotic depletion potential (ADP), acidification potential (AP), eutrophication potential (EP), photochemical ozone creation potential (POCP), terrestrial ecotoxicity potential (TETP), human toxicity potential (HTP), and global warming potential (GWP). The ADP indicates the depletion of fossil energy carriers, metals, and other materials. The AP measures the increase in the acidity of water and soil systems caused by anthropogenic emissions such as SO2, NOx, and NHS. The EP is an indicator of the addition of minerals to soil and water, which results in biomass formation (e.g., algae) and consequently reduces ecological diversity. The POCP specifies the increase in summer smog that is harmful to humans, ecosystems, and food crops. The TETP defines the impact of toxic substances on terrestrial, whereas the HTP relates to the impact on human health from hazardous substances in the environment. The GWP, an indicator of the environmental impact on climate change, is defined as the alteration in the global temperature caused by greenhouse gases (Baumann and Tillman, 2004).

### 4. Results and discussion

#### 4.1. Economic analysis

Table 4 lists the lifetime cost and costs per kilowatt-hour of generated electricity for both the diesel generator and the aluminum debris power generator. It is evident that the cost structure of the diesel generator and the aluminum debris power generator differ. The investment cost is the highest cost contributor for the aluminum debris power generator, whereas the operating cost is the highest cost contributor for the diesel generator. The diesel generator’s annual operating and maintenance cost is higher than that of the aluminum debris power generator. The operation and maintenance cost of the diesel generator accounts for 63% of the total cost, in contrast with that of the aluminum debris power generator of 4% of the total cost. Similar phenomena in which the investment cost of new technology is much higher than that of existing technology, on the contrary, the operation cost of the new technology is lower than that of the existing technology has also occurred for renewable power generation. Hertwich et al. (2015) have demonstrated that renewable technologies require higher initial investment costs than fossil-based power generation. High investment in renewable energy has contributed to the slow transition. Nevertheless, after two decades of deployment, new solar and wind power generation eventually undercut the cheapest existing coal-fired plants (IRENA, 2019).

The high investment cost of the aluminum debris power generator justifies the high LCoE. The investment cost of the aluminum debris power generator can be reduced through the efficient and economic development of each component in the generator. Table 1 indicates that the PEMFC accounts for 64% of the total capital cost. Although the PEMFC is the most expensive component, its technology has advanced in the last few years. The US Department of Energy (2018) predicts that the cost of PEMFCs will decrease by 10% until 2025 due to such advancements. The cost structure of PEMFCs can essentially be further reduced through mass production. The potential applications of PEMFCs should be explored and deployed to reach its large scale of application. Transportation (powered buses, electric powered bicycle, lightweight vehicle, powered leisure yachts), stationary application (residential power generator, UPS system in mobile phone station), portable computers are the potential applications of PEMFC (Whee, 2007). As more PEMFC applications are implemented, the PEMFC production increases, and subsequently, the production cost decreases. Therefore, the overall cost of PEMFCs can substantially decrease owing to both technology enhancement and economies of scale. This trend is similar to the one that occurred for solar power generation, which was initially hampered due to high costs, but its LCoE has decreased to reach levels even lower than those of combined cycle gas as the PV technology enhancement takes place and the uptake of PV adoption is increasing (Trowell et al., 2020).

Regarding the LCoE, the diesel generator provides a much lower cost than the aluminum debris power generator. Compared with the current electricity price in Indonesia (1,445 IDR/kWh), the electricity cost of the

| Parameter | Value |
|-----------|-------|
| Interest rate | 8% (Newman et al., 2019) |
| Number of years for economic analysis | 12 years |
| Salvage value | 10% of total capital cost |
| Diesel price | 9,500 IDR/L |
| Diesel generator price | 3,000,000 IDR |
| Diesel generator efficiency | 35% |
| Maintenance cost for diesel generator | 71 IDR/kWh |
| Carbon tax | 141,560 IDR/ton of CO2 |
| The lifetime of diesel generator | 6 years |
| Gallium price | 11,000 IDR/g |
| Indium price | 1,042 IDR/g |
| Boehmite price | 30 IDR/g |
| Maintenance cost for aluminum debris generator | 0.8% of total capital cost (Lipman et al., 2004) |
| Depreciation method | Straight-line depreciation |
| The intangible benefit of providing electricity for one day (used for Scenario 3) | 137,423,596 IDR |

### Table 2. Parameters for economic analysis of aluminum debris power generator.
aluminum debris power generator is two-and-half times higher. Nevertheless, the LCoE of aluminum debris power generator is comparable to electricity price in the European area during the first half of 2020, 3,983 IDR/kWh (Eurostat, 2020). The LCoE of aluminum debris power generator is slightly better than the LCoE of Indonesian household power generators using PEMFC for 3- and 5-kW systems, 4,071 and 3,999 IDR/kWh, respectively, assuming hydrogen at 2.2 USD/kg (Kuncoro, 2008).

Interestingly, when the boehmite price is considered (Scenario 2), it reduces the net present cost and eventually decreases the LCoE, providing a lower price than that disregarding boehmite (Scenario 1). The LCoE of the aluminum debris power generator considering boehmite (Scenario 2) is 1,091 IDR/kWh, much lower than the current electricity price, an indication that the aluminum debris power generator is cost-competitive. Figure 3 further indicates that when the market value of boehmite is 40 IDR/g, the net present value of the aluminum debris power generator is comparable to that of the diesel generator. It corresponds to an electricity price of 226 IDR/kWh, a lower price than that of the diesel generator. Furthermore, when the market value of boehmite is above 43 IDR/g, the net present value of the aluminum debris power generator becomes positive (i.e., the costs are covered by the revenues from the boehmite by-product sales), indicating a profitable investment.

As technology advances and the PEMFC production increases, the price of the PEMFC for the generator should reduce over time, reducing the investment cost of the generator and thus may increase its competitiveness. Similarly, the market value of boehmite seems to be influential toward the economic profile of the aluminum debris power generation. As the boehmite is currently also utilized as a Li-ion battery separator (Altech Chemicals Limited, 2020), the growth of the boehmite market is expected to increase in the near future. Due to the development of technology and potential future applications, both PEMFC price and boehmite price seem to be influential to the economic profile of the aluminum debris power generator. Hence, sensitivity analysis was carried to evaluate the economic viability of the aluminum debris power generator under various PEMFC prices and boehmite prices. Table 5 presents the effect of the percentage of PEMFC reduction price and boehmite price on the NPV and the cost of generated electricity.

It is worthy to note that we omitted intangible benefits in Scenario 1 and Scenario 2. Both scenarios have a negative NPV and B/C ratio of less than 1 for both the aluminum debris power generation and the diesel generator. Although a diesel generator appears to be the most economical option due to its low cost, the risk associated with diesel supply in the aftermath of a disaster is higher than the risk associated with aluminum debris availability for power generation. Disasters may disrupt road transportation, hindering fuel distribution to affected areas. In contrast, aluminum debris is already available in disaster areas. The aluminum debris power generator provides electricity while processing the debris. Therefore, using the value of supply security by de Nooij et al. (2007), which was adjusted to represent the Indonesian context, Scenario 3 considered that the aluminum debris power generator provides electricity one day earlier than the diesel generator. The results indicate the positive NPV and the B/C ratio of 6.1, implying that providing electricity earlier has made the aluminum debris power generator achieve its economical attractiveness.

It is important to note that intangible benefits are difficult to be quantified monetarily. Compared with the diesel generator, the aluminum debris power generator produces water instead of greenhouse gases or other toxic substances, enabling its operation indoors and corresponding applications such as indoor cooking or sterilization. Moreover, low-cost, or no-cost fuel, environmental friendliness, and energy-saving characteristics are other benefits offered by the aluminum debris power generator.

4.2. Environmental assessment

Table 6 reports the environmental impacts of 1 kWh electricity generated by aluminum debris power generator with a lifetime of 10,000 h. Figure 4 shows that manufacturing is the main contributor to the environmental impacts of the aluminum debris power generator, followed by aluminum fuel production and the end-of-life processes. In addition, the environmental impact of operation is the smallest. The aluminum–water reaction consumes the least energy and has no CO₂ emissions, especially when using aluminum scrap directly (Xu et al., 2019). These results contrast with the diesel generator, whose operation contributes to almost 94.6% of the lifetime energy demand, whereas its manufacturing contributes only 4.4% (Benton et al., 2017). Similar evidence is observed in battery electric vehicles and fuel cell vehicles compared with internal combustion engine vehicles. Although battery electric and fuel cell vehicles have much lower GWPs during use than an internal combustion engine vehicle, they have two and three times higher GWPs than internal combustion engine vehicles during manufacturing, respectively (Evangelisti et al., 2017). Therefore, a comprehensive LCA of the system (cradle-to-grave) should be conducted to avoid problem shifting. An environmental assessment relying solely on operations neglects critical differences associated with other processes, such as manufacturing in this case, and therefore it may provide misleading comparisons between generators.

The POCP, EP, AP, and GWP of the aluminum fuel production are attributable to gallium and indium consumption. Although the amount of gallium and indium is small, these rare metals are categorized as critical materials by the European Parliament (2017) according to two
Table 3. Life cycle inventory of 3 kWh electricity generated by the aluminum debris generator.

| Component | Input | Unit | Value | Output | Flow | Unit | Value |
|-----------|-------|------|-------|--------|------|------|-------|

**Generator Manufacturing**

1. Reactor module (Data sources: Widiyanto et al., 2003; GaBi professional database)

| Component | Input | Unit | Value | Output | Flow | Unit | Value |
|-----------|-------|------|-------|--------|------|------|-------|
| Generator Manufacturing | | | | | | | |
| Reactor | 316 stainless steel | kg | 16 | CO₂ | kg | 0.1087 |
| | Electricity - Indonesian mix (Widiyanto et al., 2003) | MJ | 514 | CO₂ | kg | 103 |
| | | | | CH₄ | kg | 0.6 |
| | | | | N₂O | kg | 0.0033 |
| | | | | SO₂ | kg | 0.34 |
| | | | | NOₓ | kg | 0.43 |
| Pump | Steel, low-alloyed | kg | 1 |
| Pipe | Steel-welded pipe | kg | 5 |
| | Brass | kg | 0.5 |

2. Hydrogen conditioning module (Data sources: Amatayakul and Ramnas, 2001; GaBi professional database)

| Component | Input | Unit | Value | Output | Flow | Unit | Value |
|-----------|-------|------|-------|--------|------|------|-------|
| Catalytic inverter (Amatayakul and Ramnas, 2001) | | | | | | | |
| Radiator | Aluminum oxide | kg | 0.521 | HC | kg | 0.3 |
| | Magnesium oxide | kg | 0.196 | CH₄ | kg | 0.2 |
| | Quartz sand | kg | 0.7 | CO₂ | kg | 390 |
| | Ceramic | kg | 0.5 | SO₂ | kg | 0.7 |
| | Cerium oxide | kg | 0.034 | Zn | kg | 0.001 |
| | Zirconium dioxide | kg | 0.119 |
| | Platinum | kg | 0.125 |
| | Palladium | kg | 1.75 |
| | Rhodium | kg | 0.125 |
| | Steel | kg | 5 |
| | Crude oil | kg | 66 |
| | Natural gas | kg | 9 |
| | Coal | kg | 11 |

3. Electricity generation module (Data sources: Noguera, 2014; Stropnik et al., 2019; Dhanushkodi et al., 2008; Dai et al., 2019; GaBi professional database)

| Component | Input | Unit | Value | Output | Flow | Unit | Value |
|-----------|-------|------|-------|--------|------|------|-------|
| DC-AC Inverter (Noguera, 2014) | Aluminum | kg | 0.3 |
| | Silica | kg | 0.004 |
| | Plastics | kg | 0.02 |
| | Copper | kg | 0.006 |
| PEMFC (Stropnik et al., 2018; Dhanushkodi et al., 2008) | Aluminum | kg | 3.15 | CO₂ | kg | 120 |
| | Graphite | kg | 13.5 | CH₄ | kg | 0.3 |
| | Glass fibers | kg | 0.3 | N₂O | kg | 0.015 |
| | Carbon black | kg | 0.002 | SO₂ | kg | 0.3 |
| | Chromium steel | kg | 3.6 | CO | kg | 0.06 |
| | Platinum | kg | 0.002 | NOₓ | kg | 0.21 |
| | Steel | kg | 3.6 | NMHC | kg | 0.06 |
| | Cast iron | kg | 2.4 | PM10 | kg | 0.03 |
| | Steel billet | kg | 11.1 | NH₃ | kg | 0.0042 |
| | Polyvinylidene chloride (PVdC) | kg | 3.3 | Benzene | kg | 0.000081 |
| | Polypropylene granulate | kg | 0.75 |
| | High-Density Polyethylene granulate (HDPE) | kg | 4.5 |
| | Nafion Membrane | kg | 0.208 |
| | Energy | MJ | 940 |
| Battery pack (Dai et al., 2019) | NMC powder | kg | 1.766 | CO₂ | kg | 6 |
| | Graphite | kg | 0.886 | SO₂ | g | 0.812 |
| | Carbon black | kg | 0.119 | NOₓ | g | 0.099 |
| | Binder (PVDF) | kg | 0.151 | PM10 | g | 0.049 |
| | Copper | kg | 0.822 |
| | Aluminum | kg | 1.673 |
| | LiPF₆ | kg | 0.113 |
| | Ethylene carbonate | kg | 0.316 |
| | Dimethyl carbonate | kg | 0.316 |
| | Polypropylene (PP) | kg | 0.077 |
| | Polyethylene (PE) | kg | 0.025 |
| | Polyethylene Terephthalate (PET) | kg | 0.0144 |
| | Insulation | kg | 0.033 |
| | Steel | kg | 0.043 |
| | Energy (for assembly) | kWh | 60.055 |
| | Water (for assembly) | L | 752.160 |

(continued on next page)
assessment criteria: economic importance and supply risk (Stropnik et al., 2019). Given that these metals are expensive, improving their recovery rate would increase their economic and environmental profiles.

Table 7 presents the comparison of the environmental impacts of the diesel generator and the aluminum debris power generator with a similar capacity of 1 kW. Table 7 indicates that the environmental impacts of the aluminum debris power generator are superior to those of the diesel generator. Concerning GWP, the aluminum debris power generator produces 346 kg CO₂-eq., being much below the production of the diesel generator, which releases 1,982 kg CO₂-eq./kWh (Noguera, 2014). Moreover, the energy demand of the aluminum debris power generator is much lower than that of the diesel generator, which is 8,191 MJ/kWh (Benton et al., 2017). In addition, 96.6% of the energy demand corresponds to the usage of the diesel generator (Benton et al., 2017), whereas usage accounts for only 8% of the energy demand in the aluminum debris power generator. Thus, the aluminum debris power generator provides

### Table 3 (continued)

| Component                  | Input | Unit | Value |
|----------------------------|-------|------|-------|
| 4. Structure module       |       |      |       |
| Frame                     |       |      |       |
| Extruded aluminum         | kg    | 5    |       |
| Styrene-butadiene rubber  | kg    | 1    |       |
| Aluminum fuel production  |       |      |       |
| Aluminum debris           | kg    | 5.4  |       |
| Gallium                   | kg    | 0.216|       |
| Indium                    | kg    | 0.054|       |
| Diesel                    | kg    | 90.09|       |
| Operation                 |       |      |       |
| Water                     | kg    | 7.2  |       |
| Diesel                    | MJ    | 44.59|       |
| End-of-Life (EoL) – Landfill |   |      |       |

### Table 4. Economic analysis of diesel generator and aluminum debris power generator over 12 years.

| Economic element          | Diesel generator | Aluminum debris power generator |
|---------------------------|------------------|---------------------------------|
|                           | Scenario 1 (base scenario) | Scenario 2 (valuable boehmite) | Scenario 3 (intangible benefit) |
| Total capital cost (IDR)  | 3,000,000         | 109,802,400                     | 109,802,400                     |
| Present capital cost      | 5,041,750         | 184,532,068                     | 184,532,068                     |
| Annualized capital cost   | 781,369           | 27,500,720                      | 27,500,720                      |
| Annual operating cost     | 1,434,865         | 389,787                         | 389,787                         |
| Annual maintenance cost   | 71,349            | 849,387                         | 849,387                         |
| Annualized carbon tax     | 2,248             | 0                               | 0                               |
| Net present cost – NPC (IDR) | 2,607,408       | 22,790,105                      | 22,790,105                      |
| LCoE (IDR/kWh)            | 431              | 3,768                           | 3,768                           |
| Net present value - NPV (IDR) | -19,341,443  | -168,051,832                    | -30,002,477                     |
| Benefit/Cost (B/C) Ratio  | 0.016            | 0.022                           | 0.596                           | 6.1

![Figure 3](image-url)  
Figure 3. Effect of boehmite value on the net present value of aluminum debris power generator.
better usage performance than the diesel generator. Nevertheless, the manufacturing of the aluminum debris power generator is a critical phase that requires further improvement.

We also conducted a contribution analysis to identify the primary source of environmental impact during the manufacturing of the aluminum debris power generator. Figure 5 shows that generator modules have varying contributions to the environmental impact. The hydrogen conditioning module and electricity generation module contribute most of the environmental impacts. The hydrogen conditioning module contributes to ADP, whereas the electricity generation module contributes the most to the HTP.

The highest contributors to the POCP are using aluminum ingot for the PEMFC in the electricity generation module and catalytic converter in the hydrogen conditioning module. The aluminum ingot for the PEMFC and stainless steel for the reactor chamber also contribute to the EP and AP. The catalytic converter dominates the impact in the ADP due to the use of rare metals such as palladium, platinum, and rhodium. The catalytic inverter and PEMFC cause a substantial environmental impact with consequences related to climate change. Nevertheless, Hertwich et al. (2015) has shown that the environmental impacts caused by higher material requirements of the technologies of renewable power generation are small compared with direct emissions from fossil-based power generation.

According to the European Parliament (2017), metals such as palladium, platinum, rhodium, are critical materials, which have the most considerable environmental impacts. Therefore, the end-of-life phase of these materials should be carefully considered. Stropnik et al. (2019) demonstrated that with proper recycling of these critical materials, the environmental impact could be reduced by 24% on average throughout the life cycle for a 1 kW PEMFC. Given that most environmental impacts of the aluminum debris power generator are caused by using critical materials including gallium, indium, palladium, platinum (categorized as high criticality), aluminum, stainless steel, and lithium (categorized as high criticality), aluminum, indium, palladium, platinum (categorized as high criticality), aluminum, stainless steel, and lithium (categorized as high criticality), aluminum, indium, palladium, platinum (categorized as high criticality), aluminum, stainless steel, and lithium (categorized as high criticality), aluminum, indium, palladium, platinum (categorized as high criticality), or high criticality, aluminum, stainless steel, and lithium (categorized as medium criticality), we suggest the proper substitution of critical materials without compromising electricity outcomes and efficiency and recycling such critical materials. Therefore, generator manufacturing could be redesigned to reduce the usage of critical materials. As most of the critical materials are expensive and have a high environmental impact, reducing their usage can improve the economic benefits and mitigate the environmental impacts of aluminum debris power generators.

The aluminum debris power generation has uncertainty when it comes to its lifetime. The key sources of uncertainty are the variability in materials used, manufacturing quality, operating conditions, maintenance (from daily checks, weekly cleaning, yearly decarbonization, five-year overhaul), and duty application, leading to inconsistent environmental impacts. Uncertainty analysis evaluating the effect of a lifetime on the environmental impacts was conducted. Because the PEMFC is a critical component that determines the lifetime of the portable aluminum debris power generator, the uncertainty analysis was based on the PEMFC technical lifetime ranging from 5,000 to 40,000 h according to Ahn et al. (2002). Figure 6 shows the probability distribution of the aluminum debris power generator, represented by the mean value and the standard deviation of the environmental impacts. The lowest uncertainty is shown in POCP, indicating some degree of robustness, whereas the highest uncertainty lies in GWP, followed by TETP and AP, respectively. When the lifetime of 10,000 h, the aluminum debris power generation contributes to 0.0349 kg CO2-eq./kWh, but this value may vary from as low as 0.00528 kg CO2-eq./kWh to as high as 0.0566 kg CO2-eq./kWh, dependent on its actual lifetime.

4.3. Comparison with other electricity generations in Indonesia

Various efforts have been conducted to explore pathways to reduce GHG emissions to mitigate climate change, investigating the replacement of fossil sources by seeking cleaner electricity generation sources, including renewable ones, and reusing waste. The most recent studies on electricity generation in Indonesia have contributed to power generation using biomass from agro-industrial waste or combining biomass waste with existing non-renewable power generation. The present paper presents another path by reusing aluminum debris for electricity generation. Figure 7 shows GHG emissions of various energy sources for electricity generation in Indonesia, which align with the range of GHG emissions from 167 case studies of electricity generation worldwide by Turconi et al. (2013). Hydropower, geothermal, and wind power generations contribute the three most negligible impacts on climate change. Diesel power generation (at a commercial scale) contributes 25 times higher to the climate change impact than portable aluminum debris power generation. It appears that the aluminum debris power generation seems to be a promising option, owing to the comparable environmental impacts with wind and solar power generations.

As sustainable Development Goals and the COP 21 Paris Agreement have stated the necessity of transitioning away from a fossil-based economy, the development of the aluminum debris power generator is of importance. However, the sustainable transition requires a radical change rather than an optimizing the existing system, which adds the lock-in of the socio-technical system. As the sustainable transition is intertwined with the social and industrial environment and the structure of energy supply and demand, building an ecosystem for the aluminum debris power generator is, therefore, necessary to speed up the transition. The results indicate that the economic attractiveness of the aluminum debris power generator can be achieved through the market deployment.

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**Table 5. Sensitivity analysis of the percentage PEMFC reduction cost and the boehmite price on the NPV in IDR and the cost per kilowatt-hour of generated electricity in IDR/kWh (in parentheses).**

| % PEMFC reduction price | Boehmite price (IDR/g) |
|-------------------------|-----------------------|
| 0% (base)               | -168,051,832 (3,768)  |
| 10%                     | -156,192,305 (3,502)  |
| 20%                     | -144,332,778 (3,235)  |
| 30%                     | -132,473,251 (2,969)  |
| 40%                     | -120,613,724 (2,703)  |
| 50%                     | -108,754,197 (2,436)  |

**Table 6. Environmental impacts of electricity generated by the aluminum debris power generator.**

| Environmental impact indicator | Value |
|-------------------------------|-------|
| Abiotic Depletion Potential (ADP) [kg Sb-eq./kWh] | 4.28 × 10⁻³ |
| Acidification Potential (AP) [kg SO₂-eq./kWh] | 8.10 × 10⁻³ |
| Eutrophication Potential (EP) [kg Phosphate-eq./kWh] | 1.00 × 10⁻³ |
| Photochemical Ozone Creation Potential (POCP) [kg Ethene-eq./kWh] | 8.47 × 10⁻³ |
| Terrestrial Ecotoxicity Potential (TETP) [kg DBCP-eq./kWh] | 1.49 × 10⁻³ |
| Human Toxicity Potential (HTP) [kg DBCP-eq./kWh] | 9.42 × 10⁻³ |
| Global Warming Potential (GWP) [kg CO₂-eq./kWh] | 3.49 × 10⁻³ |
of the by-products, technology enhancement, increased uptake of the aluminum debris power generator or its components (e.g., PEMFC, Li-ion battery) to various other applications. When it comes to increasing the uptake, expanding the aluminum debris power generator to the other fields should be encouraged. For instance, the aluminum debris power generator can be used for essential processes such as water desalination/purification in disaster areas (Godart and Hart, 2020). In addition, the PEMFC, one of the main components of the generator, can be used in residential power generation and transportation. Wee (2007) highlighted that the application of PEMFC in transportation was competitive and promising. When the scale of the aluminum debris power generator reaches its critical mass, the smallest share needed for a sustained uptake, the investment cost can hence be reduced significantly. It is worth noting that the life-cycle perspective plays a role in developing the ecosystem of the generator. The results demonstrate the necessity to consider the life cycle of the materials, i.e., boehmite and critical materials, to offset the aluminum debris power generator's costs. The environmental assessment has further confirmed that reducing or reusing materials of the aluminum debris power generator improves the environmental performance and increases economic benefits. Consequently, understanding the market of the materials is required because the price of the materials depends on supply and demand and socio-political structures (Blomberg and Soderholm, 2009).

Finally, the present study suggests some practical implications. The outcomes from this research will guide the government in taking appropriate decisions on the economically viable and environmentally sounding power generation from aluminum debris, and assist decision-making in redesigning electricity matrices, in which significant changes would occur in developing countries rather than developed countries (Barros et al., 2020). The results of the present study also practically

| Environmental impact indicator | Diesel generator (Noguera, 2014) | Aluminum debris power generator |
|--------------------------------|----------------------------------|---------------------------------|
| Abiotic Depletion (ADP) [kg Sb-eq.] | 13.04                           | 0.42                            |
| Acidification Potential (AP) [kg SO2-eq.] | 21.46                           | 0.80                            |
| Eutrophication Potential (EP) [kg Phosphate-eq.] | 3.85                            | 0.10                            |
| Photochemical Ozone Creation Potential (POCP) [kg Ethene-eq.] | 1.39                            | 0.08                            |
| Terrestrial Ecotoxicity Potential (TETP) [kg DCB-eq.] | 5.14                            | 1.47                            |
| Human Toxicity Potential (HTP) [kg DCB-eq.] | 1,322                           | 93                              |
| Global Warming Potential (GWP) [kg CO2-eq.] | 1,982                           | 346                             |
| Energy demand [MJ] | 8,191 (Benton et al., 2017) | 3,850                           |

Figure 4. Normalized environmental impacts for 1 kWh of electricity generated by the aluminum debris power generator.

Figure 5. Normalized environmental impacts for 1 kWh of electricity generated by the manufacturing of the aluminum debris power generator.
imply that the formal recycling system, which is still non-existence in Indonesia, should be established to further support the economic and environmental viability of the aluminum debris power generation and other green power generations, particularly those waste-based power generations, which appear to be promising to be developed in Indonesia.

5. Conclusions

The present study has addressed the aluminum debris power generator as a new path in achieving sustainability goals. Aluminum debris can be used as both an energy source and carrier. We evaluated the use of aluminum debris in the aftermath of a disaster for power generation in Indonesia. We aimed to analyze the economic and environmental feasibility of the aluminum debris power generator to support disaster response. Although the aluminum debris power generator is inferior to its diesel counterpart regarding the NPC and LCoE, when the monetary value of the boehmite by-product is considered, the aluminum debris power generator increases its economic attractiveness. An investigation of the secondary materials in a dynamic supply-demand market may examine the price volatility of aluminum products toward improved economic benefits. The expansion of the aluminum debris power generator to other fields such as residential power generation and transportation facilitates economies of scale, thus reducing the investment cost. In addition, fully recycling critical materials would further improve the economic benefits and mitigate the environmental impacts of the generator.

Figure 6. The probability distribution of the environmental impacts for 1 kWh of electricity generated by the aluminum debris power generator.

Figure 7. GHG emissions comparison of the portable aluminum debris power generation with other energy sources of electricity generation in Indonesia. Note: (a) Wiloso et al. (2020); (b) Siregar et al. (2020); (c) Widiyanto et al. (2003); (d) Hanafi and Riman (2015); (e) Arsyad and Setiadi (2020).
The aluminum debris power generator outperforms the diesel generator regarding the environmental impacts, primarily related to climate change. Given that manufacturing dominates the environmental impact due to the usage of the critical materials and the technology of the aluminum debris power generator is still at an early stage of development, further studies are then required to enhance the generator by adopting measures such as manufacturing redesign to substitute or minimize the use of critical materials. Such materials should also be recycled to obtain more environmental credits. To accelerate the transition, further studies should be conducted to devise an ecosystem facilitating the sustainability of the aluminum debris power generator. Potential avenues for future research include exploring technical improvements, expanding the scale of the generator for commercial use as residential power generation, expanding other applications for the generator such as transportation, and exploring recycling scenarios to improve its economic and environmental performance, leading to its sustainable use, and fully leveraging its potential.

Declarations

Author contribution statement

Bertha Maya Sopha: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Sholeh Ma’mun: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Data availability statement

Data included in article/supp. material/referenced in article.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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References

Ahn, S.-Y., Shin, S.-J., Ha, H.Y., Hong, S.-A., Lee, Y.-C., Lim, T.W., Oh, L-H., 2002. Performance and lifetime assessment of the kW-class PEMFC stack. J. Power Sour. 106, 295–303.

Altech Chemicals Limited. 2020. The Global High Purity Alumina market.” White Paper. March 2020. Accessed online (30th April 2021): https://www.altechadvancedmaterials.com/sites/default/files/Doc%20ATC%20HP%20Market%20White%20Paper%20Final%20Mar%202021.pdf.

Amatayakul, W., Rammas, O., 2001. Life-cycle assessment of a catalytic converter for passenger cars. J. Clean. Prod. 9, 395–403.

Arsyad, M., Setiadi, 2020. Gate to gate life cycle assessment coal power plant in Indonesia. APCORISE. June 16–17, 2020, Depok, Indonesia.

Barros, M.V., Salvador, R., Piekarcki, C.M., de Fransisco, A.C., Freire, M.F.S.C., 2020. Life-cycle assessment of electricity generation: a review of the characteristics of existing literature. Int. J. Life Cycle Assess. 25, 36–54.

Baumann, H., Tillman, A.M., 2004. The Hitch Hiker's Guide to LCA. Studentlitteratur, Lund.

Benton, K., Yang, X., Wang, Z., 2017. Life-cycle energy assessment of a standby diesel generator set. J. Clean. Prod. 145, 265–274.

Blomberg, J., Soderholm, P., 2009. The economics of secondary aluminium supply: an econometric analysis based on European data. Resour. Conserv. Recycl. 53 (8), 455–463.

Dai, Q., Kelly, J.C., Gaines, L., Wang, M., 2019. Life cycle assessment of lithium-ion batteries for automotive applications. Batteries 5 (48), 1–15.

de Nooij, M., Koopmans, C., Bijvoet, C., 2007. The value of supply disruption: the costs of power interruptions: economic input for damage reduction and investment in networks. Energies. Econ. 29 (2), 277–295.

Dhanuskodi, S.R., Mahinepy, N., Srinivasan, A., Wilson, M., 2008. Life-cycle analysis of fuel cell technology. J. Environ. Inf. 11 (1), 36–44.

Directorate General of Climate Change Control, Indonesian Ministry of Environment and Forestry, 2020. Carbon Tax for Indonesia: Time to Act Now. http://ditjenppi.menlh.k.go.id/dari-media/1090-carbon-tax-for-indonesia.html. (Accessed October 2020).

European Parliament, 2017. Critical Raw Materials for the EU, third ed. Brussels.

Eurostat, 2020. Electricity Price Statistics.https://ec.europa.eu/eurostat/statistics-explained/index.php/Electricity_price_statistics. (Accessed December 2020).

Evangelisti, S., Tagliferri, C., Brett, D.J., Lettieri, P., 2017. Life-cycle assessment of a polymer electrolyte membrane fuel cell system for passenger vehicles. J. Clean. Prod. 142, 4339–4355.

Franzoni, F., Milani, M., Montorsi, L., Golovitchev, V., 2010. Combined hydrogen production and power generation from aluminium combustion with water: analysis of the concept. Int. J. Hydrogen Energy 35 (4), 1548–1559.

Godart, P., Hart, D., 2020. Aluminum-powered climate change resilience: from aluminum debris to electricity and clean water. Appl. Energy 275, 115316.

Godart, P., Fischman, J., Hart, D., 2020. Kilowatt-scale fuel cell systems powered by recycled aluminum. ASME J. Electrochem. Energy Conver. Stor. 18 (1), 011003.

Hanafi, J., Riman, A., 2015. Life-cycle assessment of a mini-hydropower plant in Indonesia: a case study in Kariar river. In: The 22nd CIRP Conference on Life Cycle Engineering, 29, pp. 444–449.

Hervich, E., Gibson, T., Bouman, E.A., Avenes, A., Suh, S., Heath, G.A., Bergesen, J.D., Herrera, A., Vega, M.I., Shi, L., 2015. Integrated life-cycle assessment of electricity-supply scenarios confirms global environmental benefit of low-carbon technologies. Proc. Natl. Acad. Sci. U. S. A. 112 (20), 6277–6282.

Ho, C.Y., Huang, C.H., 2016. Enhancement of hydrogen generation using waste aluminum cans hydrolysis in low alkaline deionized water. Int. J. Hydrogen Energy 41 (6), 3741–3747.

Hydrotherma, 2020. Boehmte and Hydrogen Production. http://www.swiss-ecotech.ch /boehmte-and-hydrogen-production/. (Accessed December 2020).

IESR, 2019. Levelized Cost of Electricity in Indonesia. Institute for Essential Services Reform (IESR), Jakarta.

IRENA (International Renewable Energy Agency), 2019. Renewable Power Generation Costs in 2019. https://www.irena.org/publications/2020/Jun/Renewable-Power-Costs-in-2019. (Accessed December 2020).

Jung, C.R., Kundu, A., Ku, B., Gil, J.H., Lee, H.R., Jang, J.H., 2008. Hydrogen from aluminum in a flow reactor for fuel cell applications. J. Power Sources 175 (1), 490–494.

Kuncoro, D.D., 2008. Proton Exchange Membrane Fuel Cell (PEMFC) as Residential Power Generation. Universitas Indonesia, Indonesia (in Indonesia).

Lipman, T., Edwards, J.L., Kammen, D.M., 2004. Fuel cell system economics: comparing the costs of generating power with stationary and motor vehicle PEM fuel cell systems. Energy Pol. 32, 101–125.

Markard, J., Raven, R., Truffer, B., 2012. Sustainability transitions: an emerging field of research and its prospects. Res. Pol. 41, 955–967.

Newman, D.G., Enichenbach, T., Lavelle, J.P., Lewis, N., 2019. Engineering Economic Analysis, fourteenth ed. Oxford University Press, London.

Noguer, E.O., 2014. Comparative LCA of Stand-Alone Power Systems Applied to Remote Cell Towers. Thesis. Purdue University, US.

Portugal-Pereira, J., Lee, L., 2016. Economic and environmental benefits of waste-to-energy technologies for debris recovery in disaster-hit Northeast Japan. J. Clean. Prod. 112, 4419–4429.

Setiani, P., Watanabe, N., Sondari, R.R., Tsuchiya, N., 2018. Mechanisms and kinetic model of hydrogen production in the hydrothermal treatment of waste aluminum. Mater. Renew. Sustain. Energy 7 (2), 1–13.

Shkolnikov, E.I., Zhuk, A.Z., Vlaskin, M.S., 2011. Aluminum as energy carrier: feasibility analysis and current technologies overview. Renew. Sustain. Energy Rev. 15 (9), 4611–4623.

Siregar, K., Macshun, A.L., Sholihati, S., Alamsyah, R., Ichwana, I., Siregar, N.C., Syaufiandri, S., Sofiah, I., Miharza, T., Nur, S.M., Anne, O., Setyobudi, R.H., 2020. Life cycle impact assessment on electricity production from biomass power plant system through life cycle assessment method using biomass from palm oil mill in Indonesia. E3S Web Conf. 188, 00018.

Siregar, Y.D.I., 2012. Produksi Gas hidrogen Dari limbah alumunium dan uji daya listrik dengan fuel cell. Valensi 2 (5), 573–580.
Slocum, J.T., 2017. Characterization and Science of an Aluminum Fuel Treatment Process. Dissertation, MIT, US.

Stropnik, R., Lotrič, A., Montenegro, A.B., Sekavčnik, M., Morì, M., 2019. Critical materials in PEMFC systems and an LCA analysis for the potential reduction of environmental impacts with EoL strategies. Energy Sci. Eng. 7 (6), 2519–2539.

The Indonesian National Disaster Management Agency (BNPB), 2018. Tsunami Lunge at Palu beach, Emergency Management Continues (accessed September 2020). https://bnpb.go.id/berita/tsunami-terjang-pantai-palu-penanganan-darurat-terus-dilakukan.

The Indonesian National Disaster Management Agency (BNPB), 2020a. Disaster Data and Information. http://dibi.bnpb.go.id/. (Accessed August 2020).

The Indonesian National Disaster Management Agency (BNPB), 2020b. Indonesian National Disaster Management Agency. http://bnpb.go.id/. (Accessed August 2020).

Trowell, K.A., Goroshin, S., Frost, D.L., Bergthorson, J.M., 2020. Aluminum and its role as a recyclable, sustainable carrier of renewable energy. Appl. Energy 275, 115112.

Turconi, R., Boldrin, A., Astrup, T., 2013. Life cycle assessment (LCA) of electricity generation technologies: overview, comparability, and limitations. Renew. Sustain. Energy Rev. 28, 555–565.

US Department of Energy, 2018. 2018 Cost Projections of PEM Fuel Cell Systems for Automobiles and Medium-Duty Vehicles. https://www.energy.gov/eere/fuelcells/2018-cost-projections-pem-fuel-cell-systems-automobiles-and-medium-duty-vehicles. (Accessed December 2020).

van Bier, L., 2020. Solid Oxide Fuel Cells for Ships: System Integration Concepts with Reforming and thermal Cycles. Doctoral Dissertation. The Delft University of Technology.

Wang, H.Z., Leung, D.Y., Leung, M.K.H., Ni, M., 2009. A review on hydrogen production using aluminum and aluminum alloys. Renew. Sustain. Energy Rev. 13 (4), 845–853.

Wee, J.-H., 2007. Applications of Proton Exchange membrane fuel cell systems. Renew. Sustain. Energy Rev. 11, 1720–1738.

Widiyanto, A., Kato, S., Maruyama, N., 2003. Environmental impact analysis of Indonesian electric generation systems: development of a life cycle inventory of Indonesian electricity. JSME Int. J. 46 (4), 650–659.

Wiranarongkorn, K., Patcharavorachot, Y., Panpranot, J., Anabhumongat, S., Arpornwichanop, A., 2020. Hydrogen and power generation via integrated bio-oil sorption-enhanced steam reforming and solid oxide fuel cell systems: economic feasibility analysis. Int. J. Hydrogen Energy (in press).

Xu, S., Yang, X., Tang, S., Liu, J., 2019. Liquid metal activated hydrogen production from waste aluminum for power supply and its life cycle assessment. Int. J. Hydrogen Energy 44 (33), 17506–17514.