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The biogas development in the Indonesian power generation sector

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ABSTRACT

Climate change, pollution, and energy insecurity are currently critical worldwide problems. To improve worldwide energy security and supply, new policies regarding renewable energy and new infrastructure should be developed. Since 2006, Indonesia's dependency on oil imports has been increasing significantly. Recent policies on renewable energy have been issued to cope with the issue. This study focuses on describing the feasibility of using biogas for energy production in Indonesia. Biogas contains 50–70% methane and 30–50% carbon dioxide and has a calorific value of 21–24 MJ/Nm^3. Therefore, it can be potentially altered to contain 97% methane prior to injecting into natural gas networks. The prospective derivation of biogas from cattle, pig, and chicken waste in Indonesia could reach approximately 79 Trillion Watt-hours (TWh). In order to use biogas for power generation, two scenarios were created. The electricity demand, the environmental impact and the reduction of GHG emissions were considered over the next 20 years. The first scenario depended on current energy policy and the second scenario depended on biogas as a substitute for the fossil fuel that is still used for generating power. The carbon dioxide (CO_2), carbon monoxide (CO), sulfur dioxide (SO_2), nitrogen oxides (NO_x), particulate matter (PM), and volatile organic compounds (VOCs) were estimated for each scenario. A resource analysis of the biogas derived from animal wastes was estimated and the economics of biogas production were described. Finally, the most recent renewable energy policies were described to promote the development of this sector.

1. Introduction

Energy security could be defined as the impartial establishment of availability, affordability, reliability, efficiency, environmental benevolence, proactively governance and socially acceptability of energy services to end–users (Sovacool et al., 2011). However, energy security regarding oil depletion has not been addressed intensively. This new pattern concerns three critical periods that include natural resource depletion, climate change, and technology development as well as its demonstration and deployment (Nuttall and Manz, 2008). Therefore, the definition of energy security is continuously developing to become more complete and to cover wider dimensions. The more comprehensive definitions are aimed at decreasing fossil fuel reserves and at increasing energy supplies and security to meet energy consumption demands. In addition, the same timeframe is used to reduce emissions that contribute to climate change and the environment.

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Table 1
Calorific value of several fuels.

Fuel	Higher heating value, MJ/kg
Hydrogen	142[a]
Methane	56[a]
Biogas	21–23[c,d,e]
Biomethane (97% CH_4)	36.6 MJ/m^3[b] (~ 54.7 MJ/kg)[f]
Natural gas	54[a]
Gasoline	47[a]
Diesel	45[a]
Ethanol	30[a]
Methanol	23[a]
Coal (anthracite)	27[a]
Wood	15[a]

[a] Lam and Lee (2011).
[b] Power and Murphy (2009).
[c] Afcioglu and Turker (2012.
[d] Trisace and Lombardi (2009).
[e] Murphy et al. (2004).
[f] At pipeline condition (10 bar, 20 °C).

Biogas is an alternative and clean energy that can be used to replace fossil fuels and to enhance energy security worldwide. Biogas is comparable to natural gas and is a potentially prominent energy source for heat, electricity and fuel production. Biogas can be generated from at least five different biomass resources worldwide, including sewage and waste water, landfills, livestock manure, organic waste, and energy crops (Budzianowski, 2012). Biogas is one of the most promising and plentiful resources and is easily found throughout countries. Thus, for many cases biogas utilization was well developed and organized by governments that were involved in the subsidy, planning, design, construction, operation and maintenance of biogas plants. For instance, in EU 15 countries, the biodegradable portion of urban waste produced each year in the zootechnical sector could theoretically generate approximately 174 TWh of power from biogas by 2020. However, among the countries, France, Germany and Great Britain have the highest future production capabilities (Trisace and Lombardi, 2009).

Biogas typically consists of 50–60% methane (CH_4), 38–48% carbon dioxide (CO_2), and 2% of other trace components (i.e., hydrogen, hydrogen sulfide, NMVOC, and halo carbons) (IEA, 2000). Methane has general calorific values of approximately 21–24 MJ/N m^3 (~ 6 kWh/m^3). Therefore, biogas is often applied for cooking, heating, lighting or for the production of electricity. Larger plants can deliver biogas into gas supply networks (Bond and Templeton, 2011). Table 1 demonstrates the calorific value of biogas, compared to other fossil and renewable fuels.

Bacterial communities are playing vital role for the biochemical chain that releases methane. During hydrolysis, organic polymers (carbohydrates, proteins and lipids) are hydrolyzed to their respective organic monomers. For example, carbohydrates are converted to sugars or alcohols, proteins are converted to amino acids and lipids are converted to fatty acids. This conversion is carried out by several hydrolytic enzymes, including cellulase, cellobiase, xylanase, amylase, lipase and protease, which are secreted by hydrolytic microbes (Weiland, 2010). These organic monomers will be used as substrates by fermentative organisms (amino acids and sugars) and anaerobic oxidizers (fatty acids) (Demirel and Scherer, 2008). Next, acidogenesis (or fermentation) takes place when hydrolyzed products are further degraded to simpler organic products, such as acetate, hydrogen (H_2) and carbon dioxide (CO_2). These final fermentation products will eventually become precursors for biomethane formation. The next step, acetogenesis, which occurs during the acidogenesis process, produces acetate, H_2 and CO_2. In addition, complex intermediary products, such as propionate, butyrate, lactate and ethanol, are simultaneously produced. In this step, the intermediary products will be converted to simpler organic acids, such as CO_2 and H_2, by acetogenic bacteria. The final anaerobic digestion step is methanogenesis, in which methane is produced by two groups of bacteria (methanogens), including acetotrophic and hydrogenotrophic methanogens. Acetotrophic methanogens convert acetate to biomethane (CH_4) and CO_2. In contrast, hydrogenotrophic methanogens use H_2 as an electron donor and CO_2 as an electron acceptor to produce biomethane. In addition, many methanogens that use H_2 can use formate as an electron donor for the reduction of CO_2 to biomethane. These bacteria are highly sensitive to oxygen, which is a deadly poison that kills all methanogens even at low concentrations (Demirel and Scherer, 2008; Lam and Lee, 2011). Meanwhile, anaerobic digesters are typically designed to operate in the mesophilic (20–40 °C) or thermophilic (above 40 °C) temperature zones. Sludge produced from the anaerobic digestion of liquid biomass is often used as a fertilizer (Bond and Templeton, 2011).

In the power generation sector, the total installed power capacity in Indonesia was accounted for 31,453 MW, consisting of 25.6%, 10.7%, and 9.5% combined cycle, gas, and diesel power generation, with approximately 77% of the total energy produced in the Indonesian power generating system occurs on the Islands of Java, Madura, and Bali (JAMALI), which are the most populated areas in Indonesia (PLN, 2015). These regions use natural gas as a primary energy resource and continue to use fossil oil to support their operations, which continues to cause pollution e.g. CO_2, CO, SO_2, NO_x, PM, and VOCs. Although Indonesia had natural gas reserve that accounted for 1.7% of those worldwide and was the largest producer in the Asian pacific region in 2009, this situation indicates that its supply to the power generation sector remains inadequate (BP, 2010). Moreover, due to fossil fuel use in 2008, Indonesia released 406.03 million tons of carbon dioxide (Mt CO_2) into the atmosphere, of which 36.6% and 29.3% were emitted from the industry and power generation sectors, respectively (BP, 2010; CDIAC, 2011; MEMR, 2008).

The present article investigates the potential and feasibility of biogas use in the Indonesian power generation sector on the JAMALI. An alternative scenario was projected over the next 20 years. This scenario was evaluated with an environmental analysis, by quantifying pollutant reductions covering CO_2, CO, SO_2, NO_x, PM_{10}, and VOCs and projecting the regional potential biogas production. Likewise, GHG mitigation costs were estimated by considering the costs that could emerge from both scenarios during the analysis period. Next, the resource potential of animal waste was estimated and a biogas production cost projection was conducted. In addition, recent policies that support biogas development were presented.

2. Methods

The power generating system that is referred to this work is on the Islands of Java, Madura, and Bali (JAMALI). Around 77% of the Indonesian total power production is generated in these regions; the infrastructure covering distribution and transmission network have been well developed and reached the rural areas (PLN, 2010a, 2010b).

Two scenarios were created. The first scenario is a baseline scenario that refers to fossil fuel use. The fossil fuel used is mainly based on petroleum diesel. The second scenario was developed to evaluate the feasibility of large-scale biogas use in the Indonesian power generating system. Scenarios were built and simulated with the LEAP (Long–range Energy Alternative Planning System). The LEAP system is a scenario based energy–environment modeling tool that allows for energy policy analysis over a long-term planning horizon (Heaps, 2011). A Windows based version of the LEAP system was developed by the Stockholm Environment Institute at the Boston Center (SEI – Boston).

The most recent complete available data were taken from the calendar year of 2010, where those are still relevant to current situation (PLN, 2015). Thus, in this work the year of 2010 was selected as the base year, while an analysis period of 20 years was used.

The key indicators and the projected government power generations were extended until the end of the analysis period. The key indicators cover elasticity, energy intensity, GDP growth and electricity demand. In addition, other power sources, such as solar and wind energy, are introduced to support the mixed energy system.

Electricity consumption was obtained and environmental loadings of CO_2, CO, SO_2, NO_x, PM_{10} and VOCs were calculated for each of the analyzed scenarios. The emission factors refer to Tiers 1, which is equipped with the LEAP software. The biogas emission factor refers to natural gas. To complete the environmental analysis, the external and mitigation costs of the biogas scenarios were calculated. The biogas potentially generated from animal waste was calculated by considering technology advancements in biogas production. In addition, the process of upgrading the biogas into the biomethane was considered as a primary stage before injecting the biogas into the natural gas network. Finally, a biogas economics analysis was conducted to promote massive scale biogas production and its use in power generation.

2.1. Baseline scenario construction

Approximately 77% of the total power and electricity generated in Indonesia is produced on JAMALI. Several different reasons can account for the power generation on JAMALI. The islands represent the most populated region in the country. The urban and infrastructure development, including the development of roads, ports and electricity networks, are also concentrated on these islands. Major industrial estates and residential areas that are located in this region contribute to a higher electricity consumption than areas, which are outside of the JAMALI.

In 2010, steam coal power plants were responsible for the majority of power production on JAMALI. Steam coal, natural gas, and diesel power plants contributed approximately 47%, 16% and 15%, respectively, to total power production (PLN, 2010a, 2010b). Conventional steam power plants produce more pollutants, which are emitted into the atmosphere. IPCC Tiers 1 indicated that the direct emission of carbon dioxide from coal power was 66% higher than from natural gas power plants. However, diesel power plants contribute 30% more CO_2 than natural gas power plants (IPCC, 1996).

Therefore, alternative, cleaner, and renewable fuel sources are necessary to reduce emissions and increase electricity supply security in national level. Power plants mainly use diesel fuel because natural gas supplies are lacking and most of the gas turbines used have capability to run in dual fuel operation. Thus, natural gas power plants still consume diesel fuel to sustain their operation and to maintain a reserve margin for the regional grid, which is about 30% (PGN, 2010).

2.1.1. Power generating system

The power generation development and electricity demand projections in this study refer to the Electricity Provision Guide ("RUPTL")[1] and the National Energy Policy towards 2025 that was declared in Presidential Decree No. 05/2006 (PLN, 2010a; IEA, 2010a). The plan and the electricity demand are also still relevant to the latest situation based on recent report (PLN, 2014).

The power generating system refers to the RUPTL, which mainly consists of coal steam, natural gas, hydro, geothermal, diesel, and oil power plants. In 2010, the installed capacity and the actual generated power from the power plants in the region of JAMALI

[1] Electricity Provision General Plan ("RUPTL"), which was approved by the Decree of Minister of Energy and Mineral Resource No. 2026.K/20/MEM/2010 dated July 8, 2010, contains a strategic plan for national electricity provisions for the next ten years. The RUPTL provides information regarding the estimation of electricity demand growth, and the generation, transmission and distribution of development plans, which will be annually updated.

was accounted for 26,592 MW and 165 TWh, respectively. In addition to the power plants mentioned above, we also propose the use of solar, wind and biomass energy to promote the use of renewable energy in the near future. The use of these energy sources is encouraged because they are not currently used in the Indonesian power generating system. In addition, these resources are abundant and easy to locate throughout the regions. Moreover, these technologies have been applied without much concerns regarding their reliability (Jacobson and Delucchi, 2011).

During service, the generation of power can be performed in a merit order, which suggests that power generation can be operated for base, intermediate and peak loads. Here, we consider steam coal, geothermal, hydro, combined cycle gas, solar, wind and biomass power plants in the first group (merit order 1), gas turbine power plants in the second group (merit order 2), and diesel gas turbine and diesel power plants in the third group (merit order 3).

In addition, two other parameters that impact the generation of power, process efficiency and maximum availability, are considered. The process efficiency is the energy content of the output fuels divided by the energy content of the feedstock fuel and is expressed as a percentage. The maximum availability describes how much energy can be produced by the power plant in a specific time frame in comparison with the total energy produced during full capacity. Diesel power plants are the main focus of this study. Besides, combined cycle power plants (CCPP), gas turbines (GT), and diesel generators are also covered (with detail in Appendix A). Due to its fuel flexibility, GTs and CCPPs can run on natural gas, diesel fuel or a mixture of these fuels. In this study, we replaced diesel fuel with biogas in the biogas scenario.

2.1.2. Proposed electricity mix

The construction of the electricity mix system towards the end of the analyzed timeframe referred to the following:

- 2010–2025: Electricity General Provision Plan (RUPTL), Green Energy Policy (Ministerial Decree No.2/2004), The National Energy Policy and its Blueprint of National Energy Management 2005–25 (Presidential Decree 5/2006).
- 2025–2030: Our own projection based on: 1) the potency of renewable energy sources and the cost of generating electricity referring to the technology used, and 2) key indicators including the GDP growth, the electricity demand, and the number of consumers, which were then expressed as electricity elasticity and electricity intensity and considered constant until the end of the analysis period in 2030. For example, in 2010, the electricity demand in the JAMALI power generation system and the GDP grew by 7.6% and 6%, respectively. Therefore, the electricity elasticity reached 1.27.
- The planning reserve margin was maintained at a minimum of 30% in the power generating system.

As aforementioned above, in addition to coal, natural gas, hydro, and geothermal energy, we propose solar, wind and biomass energy for future power generation. However, we do not consider nuclear power in the future for several reasons. First, the growth of nuclear energy has historically increased the ability of nations to obtain or enrich uranium for use in nuclear weapons. Second, nuclear energy results in 9–25 times more carbon emissions than wind energy. These carbon emissions are due in part to emissions from uranium refinement and transportation and the reactor construction. In addition, a long period of time is required between the planning and operation of nuclear plants relative to the use of wind and other renewable energy sources. Third, accidents at nuclear power plants have indicated that the nuclear industry needs to improve the safety and performance of reactors and propose new reactor designs that are safer (Jacobson and Delucchi, 2011). Catastrophic accidents, such as accidents in the Fukushima in 2011 and the Chernobyl in 1986, or damaging accident, such as that of Three Mile Island in 1979, have triggered policymakers to review current energy policies (Jacobson and Delucchi, 2011).

2.1.3. Key indicators and electricity demand

Electricity elasticity and electricity intensity are two parameters that impact the power generating systems used in the model. These parameters include the electricity demand, the GDP growth, and the total number of consumers. Electricity elasticity is defined as the ratio between the growth of electricity demand and the gross domestic product while electricity intensity is the ratio between the electricity demand and the total number of consumers during a specified time frame (kWh/consumer). The electricity intensity can also be defined as the average electricity consumption of some devices or as the end use per unit of activity (Heaps, 2011). In 2010, the JAMALI power generation system had a total electricity demand of approximately 115.1 thousand GWh and approximately 28.5 million customers. Therefore, the electricity intensity was 0.004. The detailed key indicator parameters are presented in Appendix B.

Regarding the electricity demand, we considered that the growing electricity demand of each sector constantly corresponds to the RUPTL, where industrial, commercial, residential, and public growths of 9%, 9.5%, 9%, and 10%, respectively, occurred.

2.1.4. Emission and externality analyses

Recent projections from the IEA indicate that the power generation sector causes more pollution than industry, transportation and other sectors. This large amount of pollution, which is generated from the power sector results from the dominance of coal power, approximately 44% worldwide in 2050 and 42% in 2007 (IEA, 2010a). Moreover, according to the IPCC assessment, the main global warming gasses, which are generated in the power sector include carbon dioxide (CO_2), sulfur dioxide (SO_2) and nitrous oxide (N_2O) (IPCC, 2007). The emissions of CO_2 and SO_2 mainly result from coal and fossil power, while the emissions of CO result from the use of diesel generators.

The emissions in each scenario can be defined as follows:

Table 2
Implied emission factors from electricity and power generation, kg/kWh.
Sources: [a] (IPCC 1996), [b] (IEA 2000); [c] (Widiyanto et al. 2003).

Power plant	CO_2	CO	SO_2	NO_x	PM_{10}	VOCs
Coal steam	[a]0.334	[a]7.19×10^{-5}	[a]0.0015	[a]0.00108	[c]6.69×10^{-4}	[a]1.79×10^{-5}
Oil steam	[a]0.276	[a]5.39×10^{-5}	[a]0.0117	[a]0.00072	[c]2.88×10^{-4}	[a]1.79×10^{-5}
Oil CCPP/GT	[a]0.261	[b]0.09×10^{-9}	[a]8.37×10^{-4}	[a]0.00072	[c]1.04×10^{-4}	[a]1.79×10^{-5}
NG CCPP/GT	[a]0.201	[a]7.19×10^{-5}	[a]negligible	[a]0.00054	[ac]negligible	[a]1.79×10^{-5}
Diesel-Gen	[a]0.261	[a]1.26×10^{-3}	[c]0.00201	[c]0.00864	[c]3.24×10^{-4}	[a]7.2×10^{-4}
Biogas PP	[a]0.201	[b]0.49×10^{-5}	[a]negligible	[b]1.48×10^{-5}	[a]negligible	[b]9.83×10^{-7}

$$Emissions_{t,y,p} = EC_{t,y,p} \times EF_{t,y,p} \quad (1)$$

where EF is the emission factor, t is the type of technology (fuel used), y is the year, and p is the type of pollutant. Regarding N_2O, here we consider NO_x, which can include NO and NO_2 nitrogen oxides. Greater NO_x control tends to increase N_2O emissions (Lipman and Delucchi, 2007). Table 2 contains the emission standards in the Indonesian power generating system that we used in a previous study (Indrawan et al., 2017).

Moreover, these emissions potentially have negative impacts on human health and disrupt the energy supply chain, which can cause global warming, acidification, and eutrophication. These damages are given a monetary value that indicates the cost of each system, which is called the external cost (Owen, 2006; Roth and Ambs, 2004; Soderholm and Sundqvist, 2003; Schilling and Chiang, 2011; Wijaya and Limmeechokchai, 2010). Until now, any method that attempted to assess the environmental externalities was subject to uncertainties. However, it is better to approximate the externalities than to ignore them. Finally, the impact assessment is based on the Impact Pathway Approach (IPA) that was developed in the ExternE (Externalities of Energy) project, which was funded by the European Commission (Bickel and Friedrick, 2005).

The externality cost projection associated with emissions can be calculated as follows:

$$Xi = Yi \times Zi \quad (2)$$

where

Xi = external cost of pollutant i (USD/MWh),
Yi = emission of pollutant i (kg pollutant i/MWh), and
Zi = unit external cost of pollutant i (USD/kg pollutant i).

The unit external costs used in this study for the carbon dioxide (CO_2), carbon monoxide (CO), sulfur dioxide (SO_2), nitrogen oxide (NO_x), particulate matter (PM_{10}), and volatile organic compound (VOC) emissions are 19 euro's per ton, 1.06 euro's per kg, 6 euro's per kg, 5 euro's per kg, 25 euro's per kg and 1 euro per kg, respectively (Bickel and Friedrick, 2005; Roth and Ambs, 2004; Wijaya and Limmeechokchai, 2010). In addition, the exchange rate used in this study is 1 euro to 1.4 USD.

2.1.5. Diesel fuel

As previously described, fossil fuels are still used in the Indonesian power generation system and account for approximately 15% of the total power generation in JAMALI. The dominant fossil fuel used was diesel fuel. Fig. 1 shows the evolution of fossil fuels and of its trends until 2019. These trends show that fossil fuel use decreased between 2010 and 2017, but then again increased. The power sector still depends on fossil fuels for the primary energy supply because the lack of natural gas supply for power generations, consequently affecting the gas turbines, which have capability to operate in dual fuel operation mode for producing power. Therefore, the impact of substituting diesel fuel with biogas must be investigated. Biogas is similar to natural gas and produces low

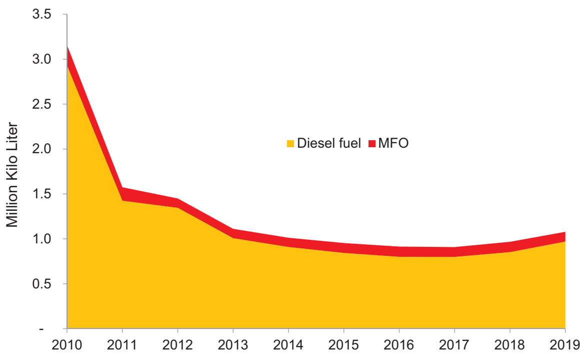

Fig. 1. Fossil fuel consumption trends in the JAMALI power generating system. It was observed that the diesel fuel still contributes substantially to power plants for upcoming years (PLN, 2010a, 2010b).

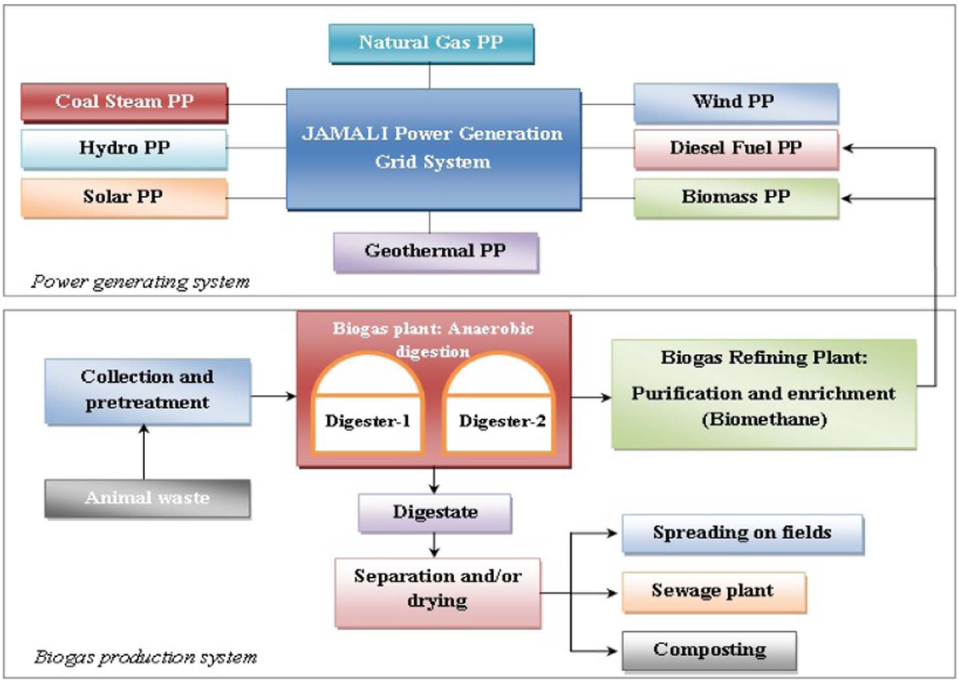

Fig. 2. Study boundary of the biogas scenario within the analyzed period to substitute diesel fuel.

emissions during the combustion process.

2.1.6. *Cost of generating electricity*

One of the fundamental objectives of projecting electricity is to measure electricity costs. To accomplish this task, the lowest cost mixture of the available electricity generating options was determined. The cost of generating electricity consists of fixed and variable costs. The fixed costs include the capital costs and fixed operation and maintenance costs. The variable costs include the fuel and variable operation and maintenance costs. Several factors, including the lifetime of the power plants, the load factor, and the discount rate must be estimated to project the fixed cost per unit of electricity generation. Similarly, the fuel costs, the heat rate, and the discount rate must be estimated to project the variable costs (Sathaye and Phadke, 2004).

2.2. *Construction of the biogas scenario*

The biogas scenario considers biogas produced from animal wastes on a large scale. In addition, this scenario accounts for aspects, which are related to biogas production and potential resources. This scenario considers the same evolution that was generated in the JAMALI power generation system and aims to identify the main parameters, which are related to the substitution of fossil oil (mainly diesel fuel). These aims coincide with policies that promote the use of biofuels and renewable energy in Indonesia.

Thus, the biogas scenario considers the use of biogas until 2030 in the JAMALI power generation system. Combined cycle power plants (CCPP – a Brayton cycle plus a Rankin cycle), which can be operated by either natural gas or diesel fuel, were the main objects of this study. Additionally, all requirements, such as those for animal farm and production infrastructures and for the distribution of biogas, were assumed to be developed at a regional level during the analyzed period. Fig. 2 shows the study boundary of the biogas scenario.

2.2.1. *The emission reduction factor*

Biogas is a promising alternative fuel in the power generation, especially for gas turbines. Biogas is similar to natural gas and produces lower carbon monoxide (CO), nitrogen oxide (NO_x), and volatile organic compounds (VOCs) emissions than diesel fuel. The massive scale use of biogas can potentially inhibit climate impacts and help to achieve the targeted 2 °C increase in temperature by the end of the century. Other impacts include human health, food, water, coast, industry, settlement, and society; the large scale disruption may result in a partial loss of ice sheets on polar land that eventually implies metres of sea level rise and large-scale and persistent changes in the meridional overturning circulation (MOC) of the Atlantic Ocean that could cause various changes to ocean behavior (Van-Vuuren et al. 2011; IPCC, 2007). In addition, the life cycle assessment (LCA) of agrobiogas to Combined Heat and Power (CHP) results in a 'negative net' CO_2 emission of approximately 414 kg CO_2/MWh. This value is lower than the values from any other types of power (Budzianowski, 2012).

The fundamental reaction that releases the majority of the energy from biogas is the combustion of methane.

$$CH_4+2O_2 = CO_2+2H_2O$$

Stoichiometrically, to achieve complete oxidation, the combustion of methane requires 9.6 volumes of air per volume of methane. For the typical biogas composition given above, this ratio is approximately 5.7:1. Similarly, the energy release by pure methane is from 36 to 37 MJ/m^3 (gross calorific value). However, this value is reduced to the range of 21–22 MJ/m^3 for rough biogas (IEA, 2000). Therefore, the refinement of biogas is essential to enhance its calorific value and achieve a higher combustion efficiency.

Accordingly, designs should aim to maximize the conversion of methane that can lead to minimize the release of unburned methane and other byproducts of incomplete oxidation, such as CO, which is typically formed when the methane is not completely oxidized. A complete oxidation of methane occurs when temperatures are above 850 °C and the residence time is longer than 0.3 s, Thus, a complete oxidation of methane is difficult to achieve and CO emissions are inevitable (IEA, 2000).

NO_x is formed at temperatures greater than 1200 °C from the oxidation of nitrogen, which is commonly referred to as the Zeldovich mechanism. In the Zeldovich mechanism, NO_x emissions result from high temperature dissociation and the chain reaction of elemental nitrogen and oxygen in the post–combustion engine (Sarathy, 2010). In addition, NO_x is formed within the flame from the oxidation of a nitrogenous non-methane volatile organic compound (IEA, 2000). These NO_x emissions account for approximately 18% of the total NO_x emission worldwide. Motor vehicles are the only source with higher NO_x emissions, which account for approximately 64% of the total emissions worldwide (Kansal, 2009).

VOCs are compounds that contain hydrocarbon and aldehydes, ketones or carboxylic acids. These components are oxidation products from the reaction of hydrocarbons with oxygen (OOMPH, 2012).

These emissions are basically unwanted byproducts of biogas combustion. In addition, other species may be formed depending on the air/fuel ratio, the temperature and the combustion reaction kinetics (IEA, 2000). However, in this study, the only emissions of concern were CO_2, SO_2 and PM emissions. As observed in Table 2, a number of studies presenting biogas emission standards is still limited. Therefore, we consider the UK's proposed biogas emission concentration limits, which were released by the IEA Bioenergy (IEA, 2000). However, the standards described were only for CO, NO_x, and VOC emissions. Therefore, we considered other pollutants that are emitted from biogas combustion are similar to those emitted from natural gas combustion. The combustion of natural gas refers to the IPCC (1996), and has been commonly used in emission projection studies (IEA, 2010a, 2010b; EPA, 2012).

2.2.2. Biogas production system

As forementioned, there are at least three steps in biogas production, including hydrolysis, acidogenesis (include acetogenesis), and methanogenesis. During these processes, several process conditions should be considered because they determine the biogas yield. These conditions include temperature, pH, retention time, volumetric loading, deployed technology, degree of pretreatment feedstock, C/N ratio and feedstock type (Poschl et al., 2010; Yadvika et al., 2004). Among these process conditions, temperature is one of the most important factors that determines biogas yield. Since Indonesia resides on the equator, the biogas production will be ideal because optimum yields are achieved at meshopilic and thermophilic temperatures, which are close to typical average temperatures in equator (30 °C). In contrast, several inhibitors can decrease yields, including lipids in waste streams from abattoirs and the presence of oxygen (even at low concentrations) (Demirel and Scherer, 2008; Lam and Lee, 2011).

The state-of-art biogas power generation can be classified into three categories, which are biogas production process, power generation, and gas cleaning system. Biogas production typically uses anaerobic digestion (AD), which can be divided into wet (total solid content less than 10 wt%) and dry fermentation (total solid content are from 15 to 35 wt%) (Weiland, 2010), which both are common practice in Germany (Stolze et al., 2015) that has total biogas plants of over 8000 plants in the early of 2015 (Achinas et al., 2017). To increase the yield of biogas, compared to single stage reactor, a multiple reactor configuration can improve process stability and generate a higher rate of biogas (Achinas et al., 2017). In addition, using a high pressure up to 100 bar can produce the biogas, which has methane content of 90% (Achinas et al., 2017). Considering the use of multiple reactor, most large-scale biogas plants also co-digest between three and five different feedstocks and have a production rate of more than 1.8 million m^3 of biogas per year. Single feedstock digestion is considered unsustainable for large-scale plants. Previously, co-digestion was estimated to be approximately 10% higher than the single feedstock digestion yield (Poschl et al., 2010). Kaparaju et al. (2009) reported that to optimize biogas production, digesters can be used in series. Digesters or reactors were fit with a stainless steel top plate, which supported the vertical low speed mixer, mixer gear motor, gas sampler, safety and pressure valves and safety valve switch. The feed valve, effluent valve, temperature probe and sampling ports were fit to the reactor wall. The process temperature was maintained at 54 ± 1 °C by pumping hot water with an electric flow heater and circulation pump through a stainless steel coil that was fit inside the reactor. However, it was more difficult to control the post–digester temperature than the main reactor.

For power generation, the gas engines are typically used to generate power and electricity. The efficiency using gas engine can reach up to 43% (Weiland, 2010). Besides, Microgas turbines are also typically used, however, it generates a lower efficiency (25–31%) compared to the gas engine (Weiland, 2010). Moreover, fuel cells are also applicable for power generation using biogas, however, current developmental stages are still developing especially to improve its tolerance from gas impurities (Weiland, 2010).

Biogas can be further transformed into compressed biogas, biomethane, biohydrogen and syngas. These products can be used to generate electricity or CHP and can be used in gas engines, gas turbines, solid–oxide fuel cells and thermally integrated biogas power plants. However, biogas must be cleaned from impurities. Among other techniques, water scrubbing (WATS), pressure swing adsorption (PSA), and chemical scrubbing (CHEMS), are the most prevailing technologies in the biogas cleaning system (Niesner et al., 2013). WATS is employed at around 40% of total biogas plants in Europe, while PSA and CHEMS have both around 25% share (Niesner et al., 2013).

Here, we consider a medium sized biogas plant (~ 6000 m^3/day) (Trisace and Lombardi, 2009; Chen et al., 2010). At this plant,

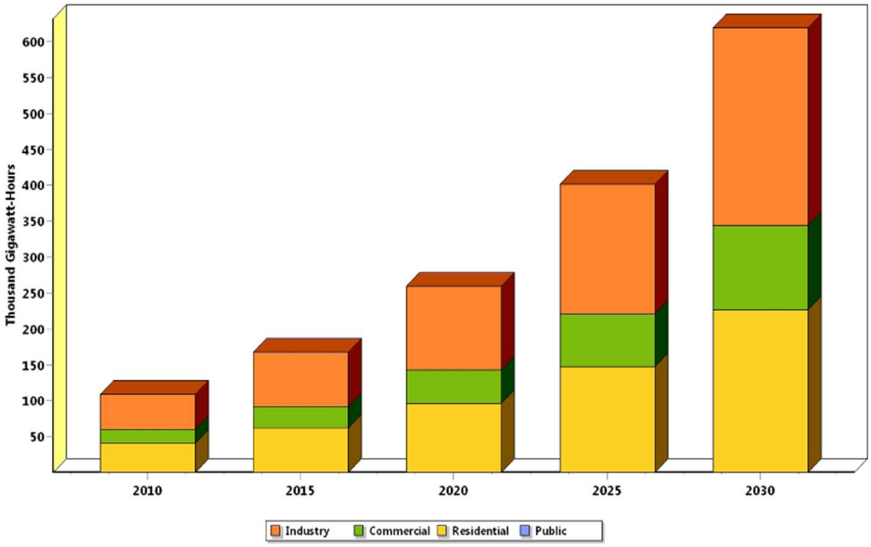

Fig. 3. The projected electricity demand shows that industrial and residential consumers are dominant in Indonesia (Source: Own calculation based on PLN (2010b).

the biogas will be transformed into biomethane before connecting to the natural gas grid and being used in the power generation. The potential electricity, which is generated from the biogas production system can be used locally to fulfill the energy needs of the plant.

2.2.3. Biogas potential resource

Many factors impacting the amount of waste and biogas can be obtained from livestock operations. These factors include the type of animal, body weight, total solids ratio, volatile solids ratio, waste availability and biogas yields (Afcioglu and Turker, 2012).

In order to meet the biogas scenario, the biogas energy potential in this study was determined for the provinces that are located in JAMALI. The JAMALI consists of seven provinces, including West Java, Banten, DKI Jakarta, Central Java, Yogyakarta, East Java and Bali. Among the different livestock populations in these provinces, the populations of cattle, chickens and pigs are the largest. Thus, we mainly consider biogas production from the waste of these animals.

Because these livestock are dominantly found large farms on the JAMALI islands, we considered primary feed stocks of cattle, pig, and chicken wastes, which have a conversion rate of 0.32, 1.43, and 0.01 m^3/animal/day, respectively. These values were calculated by considering the daily waste production, percentage of dry matter and biogas yield per weight of dry matter (Bond and Templeton, 2011).

3. Results and discussion

3.1. Electricity demand and the proposed electricity mix

Fig. 3 represents the electricity demand trends according to its estimated average annual growth rate for each consumer category. As it can be seen, although this study applies the year of 2010 as the base year, however, the projection generated still approximately represents the latest situation of the power generation in the JAMALI Islands. As it was observed, the electricity demand of 2014 generated from this study is about 163 thousand TWh (detailed in Appendix A), whereas the actual situation presents it as of around 173 thousand TWh in the early of 2015 (PLN, 2015).

Industrial consumers require more electricity to support their operations than residential, commercial, and public consumers. The total amount of electricity required until the last analysis period is 620 thousand GWh, which corresponds to 44.5% industrial, 36.6% residential, and 18.8% commercial requirements. Meanwhile, the public consumers require very small amounts of electricity. By 2030, the industrial, residential, commercial, and public consumers will require 276.3, 226.8, 116.7, and 0.1 thousand GWh of electricity, respectively. Thus, industrial activity plays an important role in the economic development of Indonesia.

In the mixed electricity system, diesel fuel is projected to contribute 2.7% in 2030. This contribution is less than the 12.2% contribution in 2010 (PLN, 2010a, 2010b; MEMR, 2010). The potential biogas, then, can replace the use of diesel fuel under biogas scenario. Whereas, coal energy will continue to provide a higher energy share than the other energy types by accounting for more than 54% of the energy production in 2020 and decreasing to 41% in 2030. This decrease is mainly caused by the introduction of solar and wind power in the power generating system. Fig. 4 shows the entire proposed electricity mix that is used in the present scenario where biogas energy is proposed to replace the use of diesel oil that still accounts from 2.5% to 6% of total electricity mix up to 2030. Until the end period of analysis, compared to other types of generation, coal power plants will dominantly contribute (approximately 41–57%) to the total electricity generation in the JAMALI of Indonesia. In addition, Table 3 shows the gross potential of the renewable energy reserves in Indonesia, which is essential and can be massively developed to support this scenario.

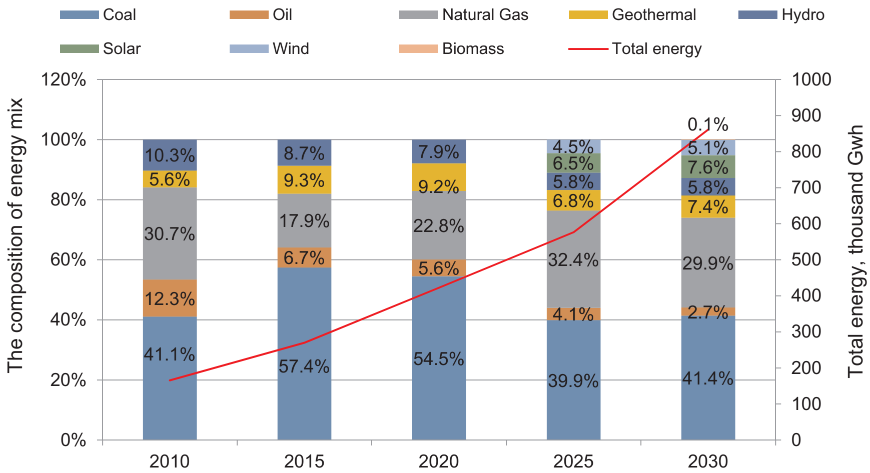

Fig. 4. Proposed electricity mix for 2030; oil represents diesel fuel.

Table 3
Potential power generation from renewable energy in Indonesia, including JAMALI.

Energy technology	Power Indonesia, GWh	Current power delivered as electricity, GWh
Coal	133.5 million[a]	68,041[i]
Natural Gas	31.7 million[b]	50,863[i]
Oil	6.7 million[c]	7827[i]
Geothermal	246.8 thousand[d]	9305[i]
Solar	204 million[e]	< 100[i]
Wind	968.3 million[f]	< 100[i]
Biomass	154.66 thousand[g]	< 100[i]
Hydro	402 thousand[h]	17,032[i]

[a] The coal reserve in Indonesia is 21.1 billion tons and consists of sub-bituminous (66%), bituminous (14%), and lignite (20%) (MEMR, 2010). Detail are provided in Appendix A.
[b] Natural gas reserves currently account for 108.4 TSCF (MEMR, 2010).
[c] Some estimations predict that the oil reserve in Indonesia may only last 10 years. However, 4.23 thousand MMBOE were accounted for in 2010 (MEMR, 2010).
[d] Having 40% of the global geothermal resource, the geothermal source was estimated at over 28,180 MW in 2010 (MEMR, 2010; Anderson et al., 2011).
[e] Over 4.8 kWh/m^2/day of sunlight intensity occurs in most of Indonesia, which has a land percentage of approximately 37.1%. Thus, this potential energy source accounted for 204 thousand TWh. In addition, Jacobson and Delucchi (2011) predicted that the solar energy reaches 6500 TW across the worlds land and ocean surfaces.
[f] The average wind velocity in Indonesia depends on the region and ranges between 4 and 7 m/s. Generally, the southern area of Java Island and some other areas have higher wind velocities. The power density of onshore and offshore wind was determined to equal 150 and 200 W/m^2, respectively. These values were based on the Geographic Information System that was provided by the Solar and Wind Energy Resource Assessment (SWERA) (2005). In addition, the global reserves reach 1700 TW (Jacobson and Delucchi, 2011).
[g] Potential biomass in Indonesia reaches 50,000 MW (Anderson et al., 2011). This study considers biomass power plants that only use solid biomass and agricultural residues, such as bagasse, sawdust, straw, empty fruit bunches, and wood waste. Biogas is only used as a substitute for the fossil power plants.
[h] It is estimated that more than 45.9 GW of hydroelectricity can be produced across Indonesia (WEC, 2010).
[i] Handbook of Energy (CDIEMR, 2010).

3.2. Emissions reduction

In this study, we found that using biogas in the Indonesian JAMALI power sector can potentially reduce pollutant emissions including CO_2, CO, SO_2, PM_{10}, NO_x and VOCs. Fig. 5 shows the potential reduction of pollutants and the external cost in the biogas scenario. In the biogas scenario, the potential emission reductions occur for all pollutants as biogas is a carbon neutral way of energy supply. Thereby, biogas can effectively reduce GHG emissions and is a promising and cleaner fuel for the power sector.

Biogas can potentially reduce CO_2 emissions by approximately 1.6% (~ 92.8 million tons) in comparison with the baseline scenario. This finding agrees with those from previous studies, in which potential emission reductions from biogas are caused by the continued consumption of the diesel fuel in the JAMALI power generating system. Moreover, the substrates from plants and animals only emit the carbon dioxide they have accumulated during their life cycle; on the whole, electricity produced from biogas generates much less carbon dioxide than conventional energy. 1 kW of electricity produced by biogas prevents 7000 kg CO_2 per year (Mateescu et al., 2008).

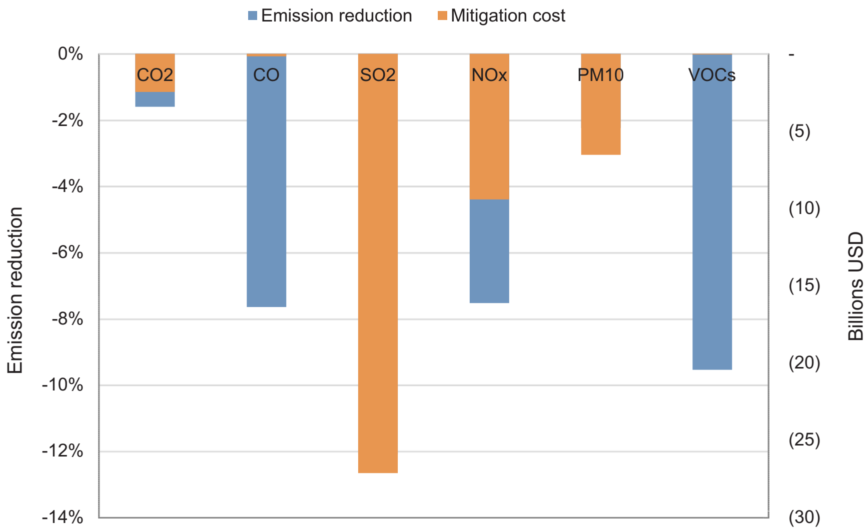

Fig. 5. Avoided emissions and costs under the biogas scenario showed major reductions in SO_2 emissions.

Large scale use of biogas in power generating systems can potentially reduce CO emissions by 7.7% (equivalent to approximately 110.7 thousand tons of CO_2) in comparison with the baseline scenario (Fig. 5). Reducing CO emissions may significantly alter the tropospheric chemistry, which can shorten its atmospheric lifespan (Wang and Prinn, 1997).

Sulfur oxide emissions strongly depend on the sulfur contained in the fuel, the cover ratio of the desulfurizers in the power stations and on their efficiencies. Sulfur oxide emissions from combustion systems are predominantly in the form of sulfur dioxides (SO_2). Because biogas contains no sulfur, the use of biogas produces lower amounts of SO_2. In fact, SO_2 pollution is reduced by approximately 12.1% (~ 3.2 million tons) during the analysis period.

Particulate matter can cause varnish deposits and sediment accumulation in the combustion chamber. To reduce PM_{10}, new engines are equipped with filters that capture particles as small as 2–10 µm (Van-Gerpen and Knothe, 2005). During the analyzed period, approximately 2.2% (~ 187 thousand tons) of PM_{10} emissions were avoided in the biogas scenario.

NO_x emissions can be present in the atmosphere and have a global warming potential that is 289 times higher than that of CO_2. NO_x is formed in combustion processes through thermal fixation or through the combustion of air that contains atmospheric nitrogen, which converts the chemically bond nitrogen in the fuel. Relative to the baseline scenario, it was observed that NO_x pollutants were reduced at the end of the biogas scenario analysis period by 7.5% (~ 1.3 million tons).

Most VOCs have a shorter atmospheric lifespan of between 10 and 11 years. VOCs were also considered in the CO_2 calculation in the Global Warming Potential (GWP) (IPCC, 1996). In the biogas scenario, VOC emissions slightly decreased by 9.6% (~ 35.3 thousand tons) from the baseline conditions during the analysis period.

3.3. Externality analyses

Using biogas in the power generation of JAMALI will considerably reduce environmental pollutant emissions. Biogas is a renewable energy source that has negative net CO_2 emissions relative to fossil fuels. In addition, biogas can easily be sustained and upgraded with technological advancements. Indonesia is the largest gas producer in Asian-Pacific region, accounting for 3.18 TSCF or 20% of the total natural gas reserves in 2009 (BP, 2010; PGN, 2011). However, as previously mentioned, an inadequate supply of natural gas to industrial customers, including power plants, still occurs. This inadequate supply causes these power plants to use diesel fuel to support their operations, which ultimately increases the environmental pollutant emissions. Increasing the direct emission of pollutants into the air will cumulatively enhance on the deterioration of human health, buildings, the ecosystem, and other aspects of life.

Thus, converting the external effects into monetary units can provide a mitigation outlook. This monetary value can cumulatively reach 45.8 billion USD, as described in Fig. 5. Therefore, using biogas in the power generation sector will significantly reduce atmospheric emissions, will help mitigate climate change and will help achieve the international climate negotiation temperature increase of 2 °C by the end of the century, as targeted by Copenhagen Accord in 2009 (Jacobson and Delucchi, 2011).

3.4. Biogas resource analysis

Considering a biomethane calorific value of 36.6 MJ/m^3 (Table 1) and the number of livestock, which were domesticated throughout the region of JAMALI, exceeding 7.6 million cattles, 1.1 million pigs, and 734 million poultries in 2010 (MA, 2011), the potential biogas production in JAMALI reaches a total of 33.8 TWh. Whereas, considering that the power produced from diesel may reach 23.6 TWh in 2030 and that the process efficiency of the existing combined cycle power plants is typically 35%, the potential biogas energy in JAMALI can replace 50.1% of the total energy produced by diesel fuel in 2030.

In the national level, there was 16.1 million cattles, 7.5 million pigs, and 1.1 billion chickens domesticated in 2010 (MA, 2011); Indonesia has an endogenous biogas capacity to account for approximately 79.4 TWh of power in 2010, which is more than sufficient to replace totally diesel fuel in the power sector by 2030.

3.5. Cost – benefit analysis

To analyze the benefits of the biogas scenario relative to the baseline scenario, we describe the analysis from five different aspects, including economics, technological advancements, environmental, social and supporting policies. Economic analysis (especially the production cost), technology advancement, and mitigation of emissions are directly related to the biogas refining process. However, the social aspects, such as job creation, and the supporting policy (including tax and incentives) are indirectly related to biogas refinement. However, these aspects play strategic and important roles in supporting and achieving the projected target in the biogas scenario.

3.5.1. Biogas production costs

In the biogas refinement process, which aims to inject biogas into the natural gas grid, two primary processes are addressed. These processes include biogas production and the upgrading process of biogas (e.g. methane content of 50–70%) into biomethane (e.g. methane content of 95–99%).

In this study we consider the cost of biogas production in terms of dollars per million BTU (MMBtu). This method provides a direct comparison of the supply between biogas and conventional natural gas. In Indonesia, the natural gas prices commonly depend on State Gas Company (PGN), which have reached a value of 10.2 USD/MMBtu since the 2012 fiscal year (MI, 2011). PGN is a major gas transmission and distribution supplier that operates distribution and transmission pipeline networks of more than 3750 and 2100 km, respectively (PGN, 2011). In addition, PERTAGAS, another gas transmission and distribution supplier, is a subsidiary of the National Oil Company (PERTAMINA), which has a transmission pipeline network of 1589 km and approximately 60% locations on JAMALI (PERTAGAS, 2012).

Here, we use a medium-sized biogas plant in this biogas scenario that considers the large-scale animal husbandry farms located throughout the islands of JAMALI. Here, we refer to a projection that was estimated by Trisace and Lombardi (2009)for a plant having a capacity of 6000 m^3 per day. The variable cost includes the material and utility costs and the fixed cost include the capital costs (depreciation, maintenance, insurance and tax) and personnel costs. More maintenance will be needed in the digester plant, which is incorporated into the main plant. Moreover, the cost estimation refers to the local situation, which includes labor and equipment costs. With the typical transport cost of 4.2 USD/t/year for loading the substrat, the total substrate needed of 1000 t/year, the engine size of 43 kW with the specific fuel consumption of 193 g/kWh and density of 0.832 kg/l, the total variable cost will be about 58,000 USD/year. Meanwhile, with the calculated fixed cost, including depreciation, maintenance of the digester, and insurance, of about 15,000 USD/year and the typical labor cost across regions in Indonesia of 2000 USD/year, the total biogas production cost was achieved at approximately 74,985 USD/year or 0.04 USD/m^3.

Furthermore, before injecting the biogas into the natural gas grid, the biogas should be purified to remove carbon dioxide (CO_2), trace concentrations of hydrogen sulfide (H_2S) and other impurities. The typical content of CO_2 and H_2S in the biogas should be reduced from the range of 30–48% to the range of 1–3%, and from the range of 50–3000 ppm to less than 16 ppm, respectively. Whereas, the CH_4 content should be increased from the range of 50–70% to the range of 97–99% (IEA, 2000; Chen et al., 2010). In addition, the water content and odor should be within the range of maximum 7 lbs/MMSCF and 5–30 mg/m^3, respectively. Thereby, to attain this levels, in this study we use the Selexol process, which can remove these three impurities simultaneously and is assumed to cost approximately 0.0051 USD/ft^3 (Chen et al., 2010). As previously mentioned, the projected biogas production cost will reach 74,985 USD/year or 0.04 USD/m^3 (0.0011 USD/ft^3) when considering operational hours of 7500 h/year, a 30% subsidy related to government support and a 10% annual discount rate. Therefore, the cost of total biomethane production will reach 0.0062 USD/ft^3. As tte corresponding calorific value of biomethane is 36.6 MJ/m^3, Thus, biomethane production will cost 6.3 USD/MMBtu.

However, the above estimation still relies on imported energy (i.e., diesel) to energize the plant. The actual biogas plant can energize its operation by transforming gas into electricity. In this case, the energy component will be neglected and the total biomethane production cost will be approximately 5.5 USD/MMBtu.

In comparison, Chen et al. (2010) attempted to calculate the biogas production cost based on data from twenty farms in the United States. These authors considered the daily biogas production volume, the capital cost of the digester, operation and maintenance costs, the cost of running a facility at full capacity, and a 20-year digester lifespan. Overall, these authors found that the cost of biogas production decreased significantly with increasing production volume. The average cost was 2.11 USD per 1000 ft^3, and the costs of the smallest and largest production rates were 6.38 USD (production of 11,333 ft^3/day) and 0.376 USD per 1000 ft^3 (production of 232,681 ft^3/day). These authors found that the correlation between the biogas production rate and the biogas cost agreed with the following equation:

$$y = 3.7967x^{-0.748} \text{ with } R^2 = 0.62981 \quad (3)$$

where x = biogas production rate (ft^3/day), and y = biogas plant cost (USD/ft^3).

Therefore, assuming that a plant were in capacity of 200,000 ft^3/day, the biogas plant cost would be 0.00041 USD/ft^3 or 0.41 USD per 1000 ft^3. The Selexol process was selected for upgrading to biomethane and corresponded to a calorific value of 36.6 MJ/Nm^3. Therefore, the total biomethane production will reach 0.0055 USD/ft^3 or 5.6 USD/MMBtu, which agrees with the projections described above. Therefore, the cost of biogas production based on the cost of animal manures will be highly competitive and much lower than the current average market price, which reaches 10.2 USD/MMBtu (MI, 2011).

Finally, the following parameters were considered; a diesel fuel contribution was 2.7% (~ 23,252.6 GWh) of the total power output in the final year, a diesel fuel price was 0.6 USD/lt (~ 0.7 USD/kg[2]), a diesel heating value was 45 MJ/kg, a natural gas or biogas price was 10.2 USD/MMBtu, a combined cycle heat rate was 7050 Btu/kWh, a combined capital cost cycle was 948 USD/kW, a lifetime was 30 years, a discount rate was 10%, a plant loading factor was 42%, an auxiliary consumption was 3.5%, a fixed O&M cost was 11.4 USD/kW/year, a variable O&M cost was 0.003 USD/kWh, and total generation costs of diesel CCPP and biogas CCPP were 0.153 and 0.114 USD/kWh, respectively. Therefore, in comparison with using diesel, the large-scale use of biogas can reduce the cost of generating electricity by 0.039 USD/kWh (~ 906.8 million USD) in 2030.

3.5.2. Technology advancement

The most important and costly parameter in biomethane production is the upgrading process (Chen et al., 2010). The upgrading process can account for approximately 80% of the total biomethane production cost. As mentioned earlier, we use the Selexol process as the biogas cleaning system. Thereby, technological advancements in biomethane must be continuously investigated to support the biogas scenario in order to reduce the production cost of biomethane, therefore, it can be more competitive in the commercial market.

3.5.3. Mitigation of emissions

The environmental aspect of the biogas projection achieves the mitigation of emissions. The potential emission reduction can cumulatively reach 42.8 billion USD. Specifically, the SO_2, VOCs, CO, NO_x, PM and CO_2 emissions were reduced by 12.1%, 9.6%, 7.7%, 7.5%, 2.2%, and 1.6%, respectively.

Some emerging concerns of promoting the use of biogas across the region of JAMALI are listed below.

a. The plant can be effectively developed in areas that are close to large farms or husbandries, where it will also improve sanitation.
b. The plant can provide independent electricity to local communities and decrease their dependency on the national electrical grid supply. If the use of biogas plants is simultaneously conducted across regions, it will significantly reduce emissions, which are currently resulted from coal power generation. In addition, biogas plants can increase the power reserve margin of the electrical network at a regional level.
c. The local communities can receive benefits from the clean development mechanism (CDM) because they can preserve the environment with access to biogas power plants.
d. Other factors related to environmental issues include odor and noise levels, potential increases in traffic, and concerns regarding potential damage to landscapes.

3.5.4. Social aspect

A massive biogas production can be socially advantageous for rural development. These advantages include job opportunities, accelerated technology transfer and penetration, and increased energy security for rural communities. Potential jobs can be estimated by the energy demand, the potential reserves, and the plant capacity. The annual biogas potential reaches 33.8 TWh, which accounts for 50.1% of the total alternative fuel that is needed to replace the diesel fuel in 2030. With capacity of 6000 m^3/day and a biogas calorific value of 36.6 MJ/m^3 (~ 982.3 Btu/ft^3), 1518 biogas units would be needed to satisfy the energy demand in the JAMALI. It is estimated that one person is needed to manage each plant (Trisace and Lombardi, 2009) and that 3 workers are needed to upgrade the biogas into the biomethane. Thus, the total number of workers that are needed for all biomethane plants in the region of JAMALI could reach 6072. However, the number of workers only satisfies the demand of the biomethane plant and does not include transportation and other related processes that will require additional manpower.

Introducing biogas in rural development can provide local people with more exposure to the latest current technology in the renewable energy sector. In addition, the utilization of biogas may enrich the understanding of local population about GHG emissions and enhance their efforts for reducing the emissions and for mitigating CO_2 in the future.

Finally, regional energy security is prone to increase, especially in the rural areas. People will no longer depend on fossil fuel and its derivatives when renewable energy sources are used. Understanding energy efficiency in relation to energy savings will also definitely increase the population's awareness regarding the energy and environmental issue.

3.5.5. Policy implications

As explained above, regions located on the equator with a tropical climate (such as Indonesia) are highly suitable for the development of the biogas production. These areas have more stable and higher temperatures than northern regions, such as Europe countries.

Thus, we propose several recommendations associated with biogas development strategies that could be used to accelerate the development of biogas production across all regions.

a. Provide Feed-In-Tariffs (FITs) for all investments in renewable energy, including biogas. Although drawbacks, such as a slow

[2] Density diesel fuel as 0.85 kg/lt.

response to innovation by investors, may occur, this policy will be effective in the beginning stage of the biogas production.

b. Promote incentives and tax exemption. Incentives can be aimed at the plants, which exhibit the highest energy conversion (Poschl et al., 2010). Meanwhile, tax exemption or tax relief could be used to compensate for shortfalls between the production costs and market prices.
c. Promote researches on biogas feedstocks, biogas production technologies, including anaerobic processes, which can enhance biogas production efficiency. The supports can be initiated by local and central governments. In addition, it is necessary to develop a collaborative research throughout research institutions in Indonesia, including the Indonesian Institute of Science (LIPI), the Agency for the Assessment and Application of Technology (BBPT), the universities, and other external research agencies.
d. Provide multitude of low interest loans that are directed at protecting the environment, soil, water and air, and at using renewable energy resources for small scale biogas plants.
e. Injecting biogas into the natural gas grid is the most efficient delivery system because it avoids the cost of conversion (Poschl et al., 2010). Therefore, a special support policy is needed. For example, natural gas network payments could be regulated. This regulation should encourage biogas development and may accelerate the formation of the biogas network grid across regions.
f. Deliver grants and loans to agricultural producers and rural small businesses for the implementation of renewable energy and energy efficiency programs.
g. Since biogas can capture methane, a greenhouse gas with a heat trapping power 25 times that of CO_2, the CDM registration process is highly recommended with investor owned utilities (IOUs). In this way, the Certified Emission Reduction (CER) can be measured and properly issued.
h. Involve more private sector in developing the biogas plants by continued socialization and promotion of certain supporting policies.

4. Conclusions

This study indicated that biogas is plentiful enough (under the good resource assumption) to meet the needs of the alternative scenario, which presently introduces biogas into the power generation sector, through 2030. During the entire analysis period, sulfur dioxide, nitrogen oxides, particulate matter, carbon monoxide, volatile organic compounds and carbon dioxide cumulative emissions were reduced by 12.1% (~ 3.2 million ton), 7.5% (~ 1.3 million tons), 2.2% (~ 187 thousand tons), 7.7% (~ 110.7 thousand tons), 9.6% (~ 35.3 thousand tons) and 1.6% (~ 92.8 million tons), respectively, relative to the baseline scenario. External costs can potentially be avoided by using biogas in the power generation sector, which cumulatively reached 45.8 billion USD within the analysis period.

The potential biogas generated from cattle, pig, and poultry wastes on the JAMALI islands and on a national scale accounted for 33.8 and 79.4 TWh, respectively. Based on the biogas scenario, the biogas on the JAMALI islands could satisfy 50.1% of the total energy demand in 2030. This energy demand corresponds to a diesel contribution of 23.6 TWh in 2030 in a power plant with a process efficiency of 35%. The potential biogas generated from cattle, pig and poultry wastes on the JAMALI islands and nationally accounted for 31.65 and 75 TWh, respectively. The minimum amount of power necessary to satisfy the energy demand in the biogas scenario was 25.5 TWh.

An economic analysis was conducted to support the biogas scenario. Biogas produced from animal manure was highly competitive with the price of diesel and natural gas. It was found that the biogas production cost would vary between 5.5 and 6.3 USD/MMBtu, while the current natural gas price reaches over 10.0 USD/MMBtu.

In social perspective, the biogas scenario could generate approximately 1518 new plants and 6072 jobs. These jobs exclude the transportation, collection and other process that could also be generated in association with biogas production process. Biogas substantially enhances the energy security in local communities especially in rural areas by decreasing their dependency on fossil fuels as well as the electrical grid. Finally, incentives, tax exemptions, FITs, and regulations can encourage the participation of private sector in constructing biogas plants in order to achieve the target energy mix by 2030.

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Appendix A. Power generating system characteristics and the proposed energy mix in the power generating system

As forementioned, the Indonesian power generating systems in the JAMALI region currently consist of coal, natural gas, fossil, hydro, and geothermal power plants. Toward the end of the analysis period (2030), we propose that solar, wind, and biomass power plants should be added as a substitution for fossil fuel power plants. Therefore, some considerations have been made to determine the parameters to consistently use throughout the projection within the analysis period, including the maximum availability, process efficiency, and merit order, which was based on references (Heaps, 2011; Jacobson and Delucchi, 2011; Wijaya, 2009). While the capacity and type of power plants refers to the Electricity Provision General Plan (PLN, 2010b; MEMR, 2011), the configuration of the power generating system that is used in JAMALI region was described in Table A.1.

Table A.1
Power generation configuration characteristics.
Sources: 1) (PLN, 2010a; PLN 2010b); 2) (Wijaya M.E. 2009); 3) (Jacobson and Delucchi 2011); 4) Own determination based on average solar intensity 4.8 kWh/m^2/day (LIPI 2006) and wind average power density onshore and offshore as 150 and 200 W/m^2 (SWERA 2005); 5) Own determination based on (IEA 2007)

Type	Fuel	Current capacity, MW[1]	Life time (year)		Process Efficiency		Max. Availability
			Existing	New	Existing	New	
Steam PP	Coal	12,360	25	30	32% [2]	39% [3]	90% [2]
Steam PP	Diesel oil	1,500	25	30	32% [2]	39% [3]	90% [2]
CCPP	Natural gas	4,215	25	30	35% [2]	51% [3]	80% [2]
GT	Natural gas	858	25	30	22% [2]	40% [3]	80% [2]
GT/CCPP	Diesel oil	4,077	25	30	as CCPP & GT above		80% [2]
Geo PP	Geo	1,045	25	30	80% [2]	100% [3]	90% [2]
Hydro PP	Hydro	2,536	25	30	80% [2]	100% [3]	80% [2]
Solar PP	Solar	negligible	-	30	-	100% [3]	30% [4]
Wind PP	Wind	negligible	-	30	-	100% [3]	100% [4]
Diesel PP	Diesel oil	76	25	-	37% [2]	-	70% [2]
Biomass PP	Straw, Sawdust	-	-	20	-	35% [5]	80% [5]

Appendix B. Key indicator

A key indicator used in this work refers to the Electricity Provision General Plan 2010–2019 (PLN, 2010b). This plan consists of GDP growth (%), electricity elasticity, and electricity intensity. In addition, electricity demand is used to determine the energy that is required during the analysis period. Details are described in Table A.2.

Table A.2
Key indicator of JAMALI power generating system (PLN, 2010a).

Year	Electricity growth, %	GDP growth, %	Elasticity	Electricity demand, GWh				Total consumers			
				Industry	Commercial	Residential	Public	Industry	Commercial	Residential	Public
2010	7.60	6.00	1.27	49,292.1	18,997.2	40,468.9	6340.6	41,571	1,196,508	26,633,702	582,625
2011	8.80	6.30	1.39	53,600.2	20,708.8	43,909.7	6980.7	43,680	1,274,275	27,922,367	622,511
2012	9.30	6.30	1.47	58,661.2	22,663.4	47,788.2	7694.2	45,907	1,358,157	29,283,901	666,064
2013	9.40	6.30	1.48	64,251.0	24,834.5	52,041.7	8490.4	48,259	1,448,601	30,722,387	713,666
2014	9.40	6.30	1.49	70,351.5	27,246.9	56,708.9	9380.9	50,744	1,546,119	32,242,338	765,757
2015	9.40	6.30	1.48	76,958.1	29,909.7	61,811.9	10,373.0	53,367	1,650,692	33,844,261	822,632
2016	9.10	6.00	1.51	83,896.8	32,749.6	67,229.7	11,438.2	56,001	1,757,658	35,454,003	883,774
2017	9.10	6.00	1.50	91,425.1	35,864.4	73,112.1	12,618.8	58,774	1,871,639	37,144,149	950,552
2018	9.00	6.00	1.49	99,358.3	39,281.5	79,609.5	13,917.3	61,694	1,993,099	38,730,877	1,023,620
2019	8.80	6.00	1.46	107,741.7	43,008.1	86,434.2	15,363.6	64,770	2,122,533	39,895,207	1,103,719

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