Techno-Economic Feasibility Study of a Combined Cycle Power Plant Utilizing Natural Gas and Biogas from Cattle Manure Co-firing in South Central Timor

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Abstract

The low electrification ratio in East Nusa Tenggara, particularly in South Central Timor Regency, poses a significant issue. Despite reaching an electrification rate of 92.33%, efforts to achieve 100% are ongoing. South Central Timor as one of the largest cattle farming areas in Indonesia, with its large grasslands and dry climate ideal for cattle farming, has substantial biogas potential from beef cattle manure through anaerobic digestion. Biogas from beef cattle manure has a net calorific value of 18.36 MJ/kg. Based on projections for 2027 using best fit regression, the average daily manure production capacity from 260,217 cattle in South Central Timor is 7.55 kilotons, which is equivalent to approximately 301,852 m^3 of biogas. A small-scale combined cycle power plant (CCPP) is proposed to capitalize on this, with a capacity of 20.73 MW and a net thermal efficiency of 55.33%. The plant's fuel mix will consist of 30% biogas and 70% natural gas by mass, with a fuel mass flow rate of 1 kg/s. The levelized cost of electricity (LCOE), internal rate of return (IRR), and net present value (NPV) obtained from the economic calculations are Rp1,126.76/kWh, 9.62%, and 222 billion IDR with assumptions of a 20-year plant lifetime, an electricity selling price of Rp1,352/kWh, and a discount rate of 6%. The plant is expected to reduce carbon emissions by 61 kilotons annually, while creating new job opportunities in the energy, livestock, and logistics sectors.

Keywords: anaerobic digestion, beef cattle manure, biogas, co-firing, combined cycle power plant

1. Introduction

Rural electrification is a difficult issue to tackle in numerous developing countries, Indonesia being one of them. Although the country is shown to be making substantial progress in improving

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electricity supply, still some areas, particularly those called "Daerah 3T - Daerah Tertinggal, Terdepan, dan Terluar (3T Regions - Underdeveloped, Frontier, and Outermost Regions)", continue to face challenges regarding this. East Nusa Tenggara is one of the provinces whose share of electricity increased more slowly than the national average level [1]. According to Perusahaan Listrik Negara (Indonesian National Electricity Company), the electrification ratio in East Nusa Tenggara has reached 92 33%, well below the targets set by the government of 100% [2]. Some of the relative difficulties in achieving fully electrified rural areas are important factors such as geographical isolation, low population density, and economical limitations [3]. In addition, reliance on diesel generators as the main electricity source in the region also entails great operating costs and leads to issues related to carbon emissions. Despite efforts to improve energy access, simply increasing the electrification ratio does not guarantee a sustainable, reliable, and clean energy supply, especially in an isolated microgrid [4].

To address both electrification and sustainability issues, alternative energy sources are being explored. The exploration shows that biogas from cattle manure presents a relatively promising solution. South Central Timor is a region that is rich in livestock. It is home to approximately 260,217 cattle according to projections for 2027 [5]. Anaerobic digestion of cow waste has the potential to produce a combustion gas known as biogas, which is a clean and renewable source of energy that can be used to produce electricity. The amount of manure in the region is approximately 7.55 million kg per day, which will result in the production of approximately 327,618 kg of biogas per day. This biogas is supplied as an additional fuel in a combined cycle power plant (CCPP) where it is used together with natural gas [6].

Indonesia benefits from a strong natural gas infrastructure that allows the implementation of co-firing natural gas and biogas in power plants. As one of the largest natural gas producers in Southeast Asia, Indonesia has built an extensive network of gas pipelines and LNG (liquefied natural gas) terminals [7]. This infrastructure not only serves to supply natural gas throughout the country to different regions but also offers the necessary flexibility to accommodate the use of biogas as an additional fuel. By then, the switch to cleaner energy will be less problematic.

In addition to its extensive natural gas infrastructure, Indonesia's energy system is supported by a network of substations, including 70 kV substations. These substations play a crucial role in distributing electricity to various regions across the area [7]. These substations are also connected to the existing grid that will ensure that electricity generated from conventional and renewable sources can be transmitted to consumers, obviously using some technical steps [8]. This existing electrical infrastructure is key to facilitating Indonesia's energy transition, as it ensures that the power generated from a combination of biogas and natural gas can be efficiently distributed and contribute to the nation's growing energy demands while supporting the shift toward cleaner, more sustainable energy solutions [9]. The new generation system in power flow also improves grid stability and reduces the probability of load loss [10].

2. Literature Review

In areas with abundant organic waste, biogas is suggested as an eco-friendly energy source. Biogas production through anaerobic digestion of organic material, such as agricultural and livestock waste, generates energy with a potential reduction of waste [11]. Biogas is mainly made up of methane (CH_4) and carbon dioxide (CO_2). Methane is highly calorific, which means it is ideal for electricity generation due to its high energy density [12]. Cattle farming in South Central Timor produces a significant amount of manure that can be used to make biogas due to its agriculture and livestock industries. Previous research has shown that it is possible to use cow manure as a biogas source, especially in areas with a large number of livestock [13,14].

Combined Cycle Power Plants (CCPPs) are kind of power plants that combine a gas turbine and a steam turbine in a single system. CCPPs achieve higher efficiency compared to traditional power plants. The possibility of biogas as part of CCPP has been investigated in terms of effectiveness and cleaner emission of GHG during electricity generation [15]. Co-firing means burning two or more different types of fuel simultaneously, biogas and natural gas being examples. The reduction of operational costs in CCPPs has been shown when using biogas because it has a low thermal gas price compared to that offered by the main constituents of natural gas [16, 17].

The CCPP operates using both a gas turbine and a steam turbine. The combustion of natural gas within the gas turbine is used to create electrical power, and excess energy in the form of heated gas expelled from the turbine is used to create steam in a heat exchanger that will turn the steam turbine to produce electricity. This two-stage operation greatly improves the general effectiveness. Current advanced CCPP designs can achieve overall gas turbine cycle efficiencies of 60% or more [18]. Typical single-cycle plants have the range of efficiencies around 30% and 40% [19].

Current research shows the great potential of using cattle manure biogas as a renewable energy source, but there are still many gaps in understanding how it could be used as the main fuel in combined-cycle power plants. For example, Arshad et al. looked at the potential for electricity generation from cattle manure biogas in Pakistan, estimating that it could supply up to 20% of the country's energy needs. Although this study highlights the energy potential of cattle manure biogas, it remains mainly theoretical and does not explore practical applications where biogas is the main fuel for power generation [20]. In parallel, Zare et al. examined ways to optimize the co-firing of renewable gas fuel from biomass with natural gas in combined heat and power (CHP) systems, showing that adjusting the mix could improve performance and reduce costs. However, this study focuses mainly on general optimization and does not address regional needs, such as the challenges faced in rural or emerging areas, nor the use of biogas from beef cattle manure [21]. There is a need for a focused techno-economic feasibility study on utilizing biogas from cattle manure as supplementary fuel in a combined cycle power plant tailored to local conditions, such as those in South Central Timor. Such research would explore optimal fuel ratios, infrastructure requirements, and economic models, contributing to the development of sustainable energy solutions for regions with limited infrastructure but abundant natural resources.

The co-firing of biogas with conventional fossil fuels, such as natural gas, in CCPPs has been explored as a strategy for reducing reliance on non-renewable resources while minimizing emissions. Co-firing biogas not only reduces the carbon footprint of electricity generation, but also improves the overall efficiency of the combustion process due to the lower nitrogen content of biogas compared to coal or other solid fuels [22]. Several studies have investigated the technical feasibility of co-firing biogas in gas turbines and combined cycle systems, with results indicating that biogas can be an effective supplementary fuel in these plants [23, 24]. Figure 1 shows the overview of co-firing CCPP system that is being proposed. It combines biogas from cattle manure and natural gas from the gas network as previously explained.

By incorporating a CCPP into the already established network, there are many advantages in terms of reliability, efficiency, and sustainability of the grid. The power system becomes less sensitive to changes and disconnections. The flexibility of CCPPs allows them to quickly increase power generation to meet peak demand, reducing the risk of blackouts due to the ability of CCPPs to add megawatts to the grid at short notice [25].

The economic feasibility of biogas as a fuel source for electricity generation is also a critical consideration for its large-scale adoption. There are multiple elements that impact the economic efficiency of biogas projects, including the availability of feedstock, the size of the plant, the biogas production technology, and the conditions in the market in which biogas projects operate [26].

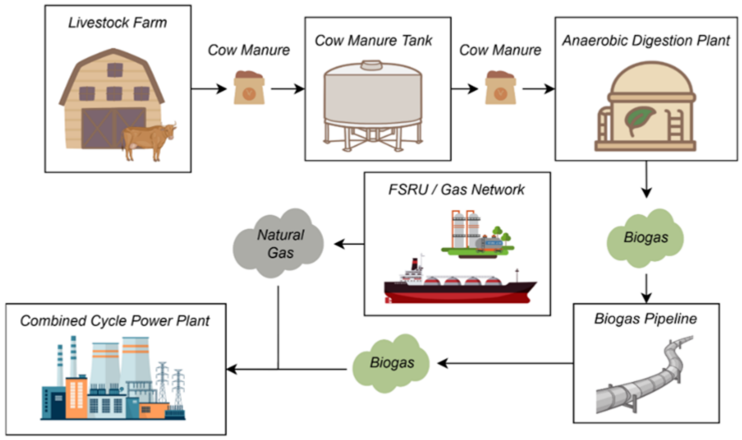

Figure 1: *Overview of co-firing CCPP system*

In many cases, especially in rural settings where infrastructure and capital are often limited, the case for commercial biogas and many other renewable power generation is strengthened by the provision of government support and incentives [27]. For example, in Indonesia and several other countries, policies have been implemented to increase renewable energy sources, including biogas, in the energy mix through feed-in tariffs and tax and other subsidies [28]. In addition, the development of biogas projects is often associated with other socioeconomic advantages such as the development of agriculture, livestock, and energy industries, which creates more jobs [29].

The environmental advantages of using biomass gas for power generation by means of electricity are resources. In fact, biogas is also considered a carbon-free fuel, as most of the methane produced during biogas combustion would have been released into the air in the process of decomposing organic waste. This leads to a great decrease in greenhouse gas emissions, particularly in areas occupied by cow breeding [30]. In addition to that, the use of manure for biogas production reduces waste and protects water and land from pollution, which is beneficial to the environment and the health of the public [31]. In South Central Timor, biogas-generated energy can also provide a sustainable solution to waste management.

Beyond environmental impacts, the social implications of biogas utilization are equally important. In areas with low electricity uptake, for example, there is the possibility of biogas projects that improve the economic status of the areas, helping with the overall rural development. These schemes, for example, improve local economies by creating jobs in biogas plants, livestock rearing, and power line development [29]. However, employment opportunities from biogas initiatives encourage agricultural practices along with the recognition of renewable energy sources in rural regions.

The successful implementation of biogas power generation projects is highly dependent on supportive policies and regulations. In Indonesia, for example, the federal government has made a policy change to support renewable resources, including biogas, due to the huge potential and set realistic targets within which increased use of renewable resources is a proportion of the country's energy portfolio. As a result, the country's policy framework promotes the development of incentives such as feed-in tariffs and renewable portfolio standards for renewable energy projects [27]. However, more political and financial support is needed for South Central Timor, particularly for its small-scale and community-based energy projects [32].

3. Methodology

The primary objective of this study is to evaluate the potential of using raw biogas from cattle manure in a CCPP as a resource for co-firing. The study relies on a combination of data regressions to inform its findings. Data regressions were performed to predict the future population of cattle, the daily production of manure, the biogas yield through anaerobic digestion, and the local energy demand. These data were combined with other secondary data from the existing literature on biogas energy content, environmental impacts, power plant efficiency, and government policies on renewable energy. Data on cost structure, including capital expenditure (CAPEX), operational expenditure (OPEX), and local electricity pricing, were also collected to perform an economic analysis.

The technical feasibility focuses on estimating the biogas production potential, calculating its energy output, and evaluating the thermal efficiency of the power plant using a biogas and natural gas co-firing system. Economic feasibility involves calculating the Levelized Cost of Electricity (LCOE), analyzing the payback period, and assessing financial viability over a 20-year plant lifespan. Additionally, environmental feasibility assesses the reduction in carbon emissions from co-firing compared to a natural gas-only plant.

This feasibility study uses MATLAB, Microsoft Excel, and EBSILON Professional as primary software tools. MATLAB and Microsoft Excel will help to analyze, process and arrange large data sets such as cattle dung, calculate biogas production, and conduct economic studies. The configuration, simulation and optimization of the CCPP with co-firing was analyzed and predicted using EBSILON Professional. EBSILON Professional's simulation capabilities will enable a detailed evaluation of thermal efficiency, fuel usage, and energy production to effectively improve plant operations.

4. Results and Discussion

4.1. Site selection

The most important factor in choosing the location of a CCPP is proximity to the fuel supply and infrastructure. CCPPs primarily rely on natural gas as their fuel, so being near natural gas sources ensures a consistent and cost-effective fuel supply. Since gas refineries are not found on Timor Island, natural gas as the main fuel will probably be supplied from liquified natural gas (LNG) through the gasification process. LNGs will be delivered by an oceangoing LNG ship. In addition, there should also be transmission lines and electrical grids available so that the power generated can be consumed. Other factors such as the availability of cooling water, land for the building of the plants, and the distance from the market to the nearest electricity transmission facilities are also critical. The site will only require a small area of land, and from the location selection, a land area of 70,000 m2 is available as seen in Figure 2.

4.2. Beef cattle manure prospect

Data regarding the beef cattle population in South Central Timor have been collected from 2016 to 2022. From the trend, it indicates that the data increased linearly with R^2 of 97.4%. Therefore, using linear regression, the projected population curve is illustrated in Figure 3 with a total potential of 260,217 cattle in 2027.

Beef cattle can produce up to 29 kg of manure per day [33]. This is due to the abundance of meadows in South Central Timor that support the ideal growth of beef cattle [34]. To determine the

Figure 2: *Satellite image of the proposed site (Google Earth)*

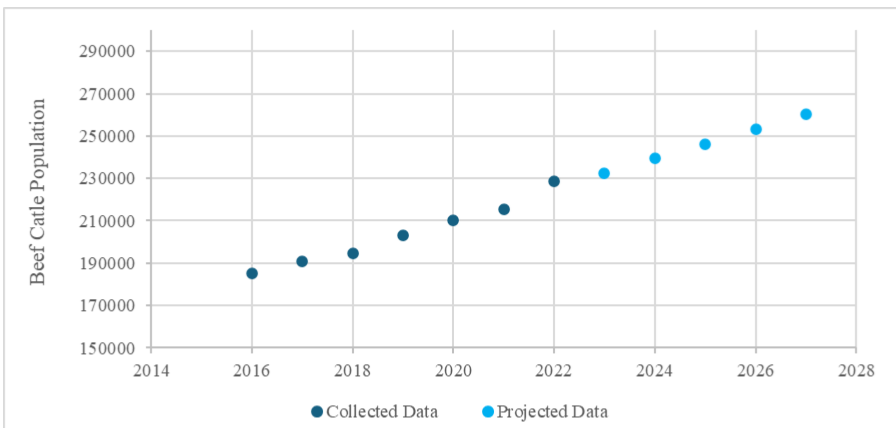

Figure 3: *Data projection of beef cattle population*

utilization factor of the cattle manure, the cattle manure produced per day in kg must be converted to its equivalent biogas, as biogas is the substance that is used to generate energy through a combined cycle power plant. Using a conversion factor of 0.04 m^3 biogas/kg manure [35], the total biogas production per cattle is 1.16 m^3/day. With a projected population of 260,217 beef cattle in 2027, it is predicted that per day, South Central Timor has a total potential of 301,851.72 m^3. The manure produced then converted into biogas using the conversion steps shown in Figure 4.

With a calorific value of 21 MJ/m^3 for biogas [36], the predicted thermal power potential (assuming 100% heat efficiency) is 73 MW. This result indicates that biogas is a promising renewable energy source in South Central Timor. A high calorific value allows more energy to be generated per unit of fuel, thereby reducing the total fuel consumption by mass and accordingly the total operational costs.

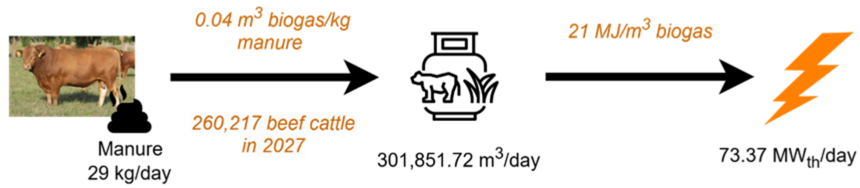

Figure 4: *Simplified conversion steps from cattle manure to biogas*

4.3. Load forecasting

The forecast of loads is important for the calculations of the feasibility study. Load forecasting provides a perspective on future electricity demand that helps determine the generating capacity of the power plant design. Based on this, load forecasting can also help in economic feasibility analysis because it allows better calculation of operating and investment costs that lead to the conclusion whether the power plant construction plan is feasible or not. In addition, load forecasting can also be a benchmark for how many energy sources are needed, in this case a combination of natural gas and biogas from beef cattle manure.

Actual data on energy demand in South Central Timor are still limited, so load forecasting with certain methods must be done. South Central Timor electricity demand in 2016 was approximately 84 MWh a day [37]. This figure is derived from the fact that the peak load is 5 MW and the load factor is about 70%. However, actual data for other years could not be obtained. Since the region's Gross Domestic Regional Product (GDRP) data are publicly available, it is possible to predict electricity demand by correlating the GDRP and the electricity demand parameters [38]. GDRP can be used as a reference in load forecasting because there is a correlation between economic growth and energy consumption in general, including electrical energy [39]. Looking at social cases in society, an increase in GDRP reflects an increase in economic activity both on an industrial and household scale, both production and consumption, and even distribution. All of these economic activities require energy, including electricity. Although this phenomenon is more pronounced in urban areas, a direct proportional correlation is also observed in rural areas [40,41].

The method used to predict electricity demand in year n is just multiplying the electricity demand n-1 by a multiplication factor in the form of a comparison of GDRP between year n and GDRP in year n-1. Thus, this is the same as assuming that electricity demand is linearly proportional to GDRP. Equation (1) explains the method used.

$$ED_n = \left(\frac{GDRP_n}{GDRP_{n-1}}\right) \times ED_{n-1} \tag{1}$$

For the feasibility study, it is assumed that the year zero for the design power plant is 2024. So, it is also necessary to project the GDRP of South Central Timor based on actual GDRP data in 2023 and earlier years. The projections were performed for 20 years, which is the assumed lifespan of the power plant [42]. We assumed construction to take 2 years starting from the beginning of 2025 until the end of 2026 [43]. Furthermore, it is assumed that the project will start running in 2027 until 2047. The projection is carried out using linear regression by making the year as the independent parameter (x) and GDRP as the dependent parameter (y). Table 1 and Table 2 show the linear regression results obtained based on the observations of the South Central Timor GDRP from 2011 to 2023.

Table 1: *Regression statistics*

Regression Parameter	Value
Multiple R	0.9949
R Square	0.9898
Adjusted R Square	0.9889
Standard Error	203.5022

Table 2: *Regression statistic results*

Parameter	Intercept	Year
Coefficients	-987,896.88	493.03
Standard Error	30,425.66	15.08
t Stat	-32.47	32.68
P-value	2.82×10^{-12}	2.62×10^{-12}
Lower 95%	-1,054,863.30	459.83
Upper 95%	-920,930.47	526.24

The equation obtained is as follows:

$$\text{GDRP} = 493.03 \times \text{Year} - 987896.88 \tag{2}$$

This equation can be said to be quite statistically representative because it has multiple R, R Square, and adjusted R-Squared that is close to +1, showing a strong positive correlation. In addition, the P-value is significantly lower than 0.05, confirming a significant correlation [4]. This good correlation allows us to make accurate projections later on.

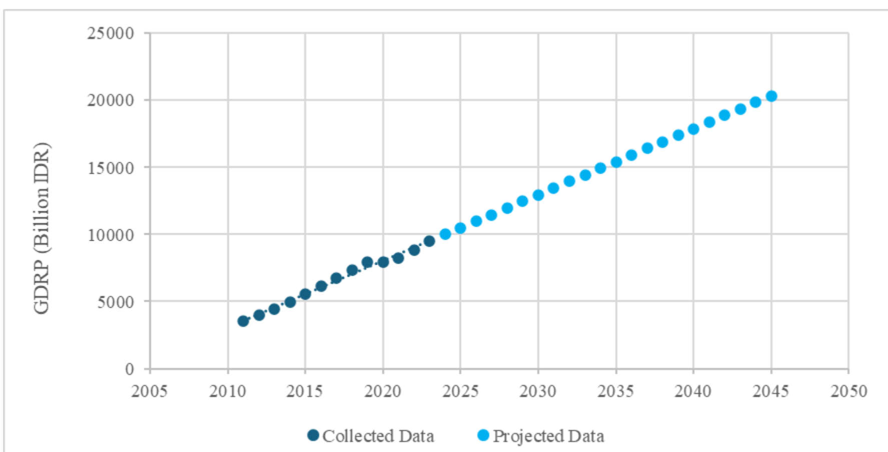

Figure 5: *Projection of gross regional product (in billion IDR)*

GDRP of South Central Timor is predicted to always increase every year based on the equation of linear regression results [45]. Based on these projections, electricity consumption in South Central Timor is also predicted to increase (Figures 5 and 6).

Based on typical load curves for Indonesia, the hourly load can also be projected for each year of the assumed life expectancy (Figure 7). The peak load time is at 8 p.m., which is mainly contributed by residential loads such as air conditioners, refrigerators, lights, and entertainment electronics while the lowest load time is at 8 a.m. [46].

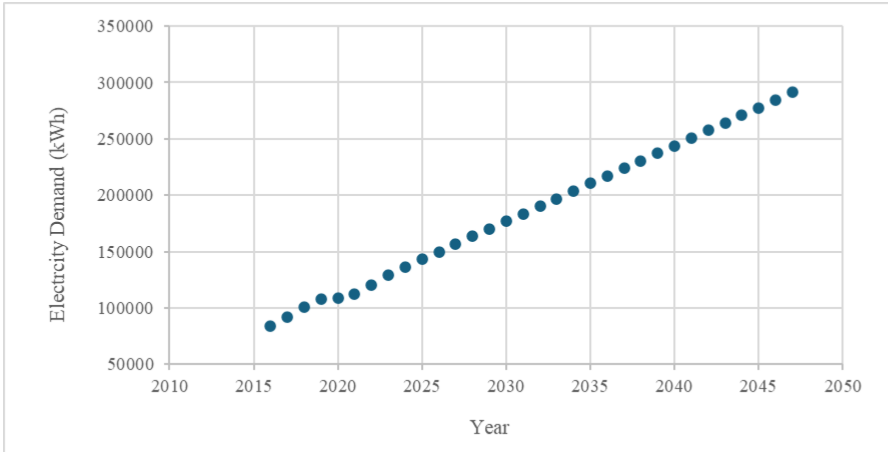

Figure 6: *Projection of electricity demand (in kWh)*

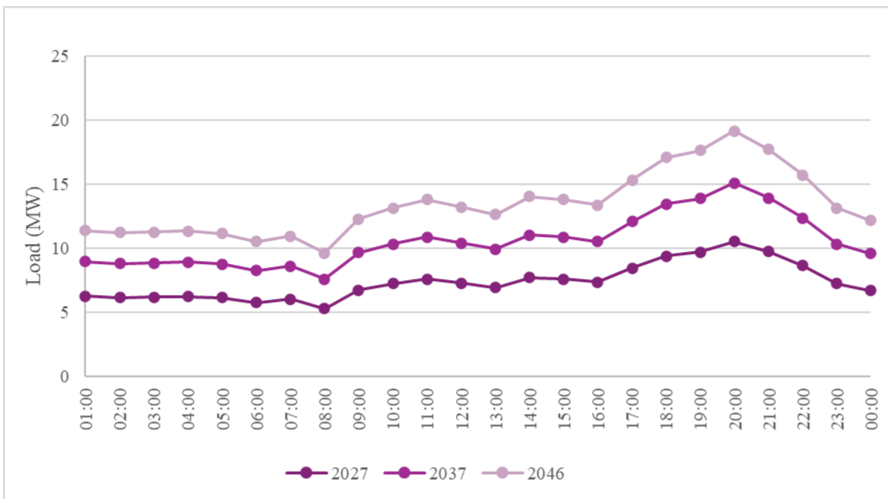

Figure 7: *Projection of typical daily load profile/curve in South Central Timor*

4.4. Power plant type and size determination

A CCPP will be used to supply the electricity demand in South Central Timor for 20 years, according to the typical small-scale technical lifetime of the CCPP. CCPP is known for its high reliability due to operational flexibility, particularly in terms of ramping rate and startup time. The quick start time allows CCPPs to provide power faster compared to conventional thermal plants. In addition, its high availability is indicated by the low forced outage rate (FOR), which ensures consistent power generation with fewer unscheduled downtimes. Based on the Indonesian Power Sector Technology Data document prepared by the Ministry of Energy and Natural Resources, the ramping rate, warm start-up time and FOR of CCPP are 20%, 2 hours, and 5%, respectively. These values are quantitatively better than most other power plants [47].

According to the calculation of the load forecast, the peak load of the power system in the last year of the power plant operation time is approximately 16.93 MW. Using 80% as the maximum load value, 21 MW of plant capacity is chosen [48]. In fact, the exact capacity of the power plant cannot be determined without setting the fuel flow rate. Thermodynamic simulations are conducted to obtain a suitable fuel composition for both biogas and natural gas. Table 3 and Table 4 show the typical composition of biogas from beef cattle manure and natural gas, especially in Indonesia, respectively.

Table 3: *Compositions of biogas from beef cattle manure [49, 50]*

Compositions	%Volume	Mass Fraction
CH_4	61.5	0.36718
CO_2	38.5	0.63282

Table 4: *Compositions of natural gas [50, 51]*

Compositions	%Volume	Mass Fraction
CH_4	80.93	0.06755
CO_2	7.98	0.01834
N_2	6.21	0.00905
C_2H_6	2.32	0.00313
C_3H_8	1.39	0.00324
n-C_4H_{10}	0.32	0.23618
i-C_4H_{10}	0.34	0.24131
n-C_5H_{12}	0.08	0.06451
i-C_5H_{12}	0.16	0.12695
C_6H_{14}	0.27	0.22974

The CCPP used for the simulation consists of one gas turbine generator (GTG) and one steam turbine generator (STG), both operating as single-stage units, as shown in Figure 8. In this configuration, the GTG burns fuel to generate electricity, while the waste heat from the gas turbine is utilized by the heat recovery steam generator (HRSG) to produce steam, which drives the STG for additional electricity generation. This single stage arrangement is typical for small-scale CCPPs to simplify the design and operation of the plant [52].

Based on simulations, the fuel flow rate of 1 kg/s with the 3:7 biogas to natural gas co-firing ratio is suitable for the designed capacity, resulting in the capacity of the 20.73 MW plant. Biogas co-firing with natural gas is technically feasible as a result of the similar combustion characteristics of both gases, which allows them to be blended and used in existing natural gas-fired power plants with minimal modifications. Biogas, primarily composed of methane, can be injected into natural gas pipelines or directly co-fired in gas turbines or combined cycle power plants [53]. Figure 9 shows a biogas to fuel ratio sensitivity analysis to assess its impact of variance on power plant capacity, capacity factor, and lowest loading, simulated with a constant fuel flow rate (1 kg/s).

As the biogas-fuel ratio increases from 10% to 50%, the capacity of the power plant decreases marginally, while the capacity factor shows a slight but consistent increase. The lowest loading, which reflects the minimum power output of the plant within its operational hours, also demonstrates a growing trend with the biogas-to-fuel ratio. This sensitivity analysis implies that, at higher biogas-to-fuel ratios, the system becomes more fuel-efficient in terms of capacity factor, but the trade-off is a lower overall power plant capacity. However, a higher capacity applied to the system could lead to higher overall operational costs due to inefficiencies in fuel usage, especially under fluctuating load conditions.

It is also important to note that the co-firing ratio should consider the feasibility of manure transportation. From a geographical study, it takes 10 hours to complete a trip around the province with 400 km distance, assuming 40 km/h of truck speed. If two trips are made every day to collect manures from the farmer and feed them to the plant, 33 trucks will be needed to maintain

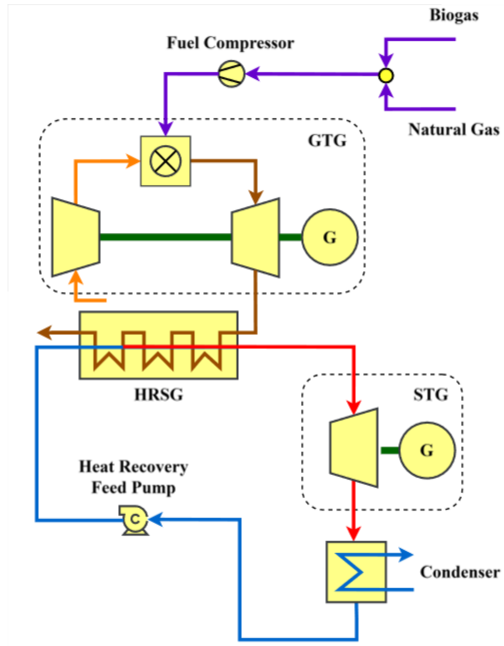

Figure 8: *Combined cycle power plant (CCPP) schematic*

feedstock requirements. This calculation is based on the truck load specifications of 5 tons. Manure collection trips will vary depending on the locations of the cattle farms, so a 400 km distance is just a worst-case scenario taken. The number of trucks departing each trip from the calculation results is sufficient and realistic, with the note that two trips each day are carried out by different trucks, so there are 66 of them in total. Increasing the biogas-to-fuel ratio will increase the number of trucks needed proportionally, making it less realistic to run and uneconomical in terms of investment costs.

4.5. Thermodynamic simulation and technical constraints

Thermodynamic simulation is conducted to determine the efficiency of the power plant and to verify that the design could be successfully implemented. This was achieved by validating the phase changes and the composition of the working fluid throughout the system [54]. The simulation tracked the thermodynamic behavior of the fluid as it passed through different components of the plant, such as the gas turbine, the heat recovery steam generator (HRSG), and the steam turbine. By ensuring accurate modeling of phase transitions and the correct composition of the working fluid, the simulation confirmed that the power plant design is feasible and capable of operating efficiently. The successful validation through this thermodynamic analysis ensures that the plant can perform as expected under real-world conditions. To make the simulation represent the real condition, some key assumptions used in the simulation related to component specification are listed in Table 5.

The calorific value calculation using ISO6976 standard shows the gross calorific value (GCV) and net calorific value (NCV) for both natural gas and biogas. The GCV of natural gas is 48.32 MJ/kg, while its NCV is 44.51 MJ/kg, reflecting the high energy content of natural gas. In comparison, the GCV of biogas is 20.43 MJ/kg, and its NCV is 18.36 MJ/kg, showing a significantly lower energy content than natural gas. These values highlight the difference in energy potential

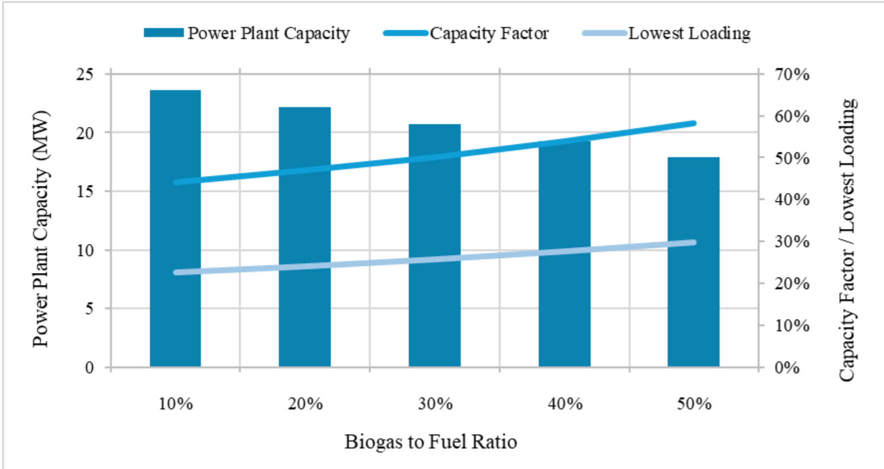

Figure 9: *Sensitivity analysis of biogas-to-fuel ratio*

Table 5: *Key assumptions for thermodynamic simulation*

Components	Parameters	Value
Compressor	Isentropic Efficiency	85% [55]
	Mechanical Efficiency	99% [56]
Electric Motor	Electrical Efficiency	95% [57]
	Mechanical Efficiency	99% [57]
Turbine	Isentropic Efficiency	88% [58]
	Mechanical Efficiency	99% [59]
Generator	Generator Efficiency	97% [60]

between the two fuels, with natural gas providing approximately double the calorific value of biogas.

Based on a thermodynamic simulation, 55.33% of net thermal efficiency achieved by also including fuel compressor as one of plant auxiliaries consumption. Energy conversion through gas turbine contribute to 13 MW electrical capacity. On the other hand, heat recovery using a Rankine cycle with water as the working fluid resulting in 7.73 MW additional capacity. In full capacity operation, the specific fuel consumption (SFC) of the power plant is 0.17 kg/kWh by mass and 2.08 m^3/kWh by volume with a fuel pressure of 15 bar.

The modeling of efficiency changes in relation to power plant loading will utilize a typical curve of combined cycle. This curve illustrates the relationship between the load level and the plant's thermal efficiency. Generally, the efficiency of a CCPP increases as the load approaches optimal capacity, then tends to stabilize or slightly decrease at very high load levels [61]. By using this typical curve, the modeling will provide insights into how variations in load impact the overall efficiency of the plant. Furthermore, this model will be employed for both economic and environmental analysis, helping to determine the real financial projection and greenhouse gas emission. Figure 10 shows the efficiency characteristic used.

While the efficiency of the power plant improves as the load increases, there is a point of saturation where further increases in loading do not significantly enhance efficiency. After reaching around 55% efficiency at near full load, the curve begins to flatten, indicating that the system has reached its maximum efficiency. From Figure 10, it can be seen that thermal efficiency improves progressively over the years. However, despite the improvements, there is also a visible saturation effect, particularly during the peak operational hours in the middle of the day, where efficiency

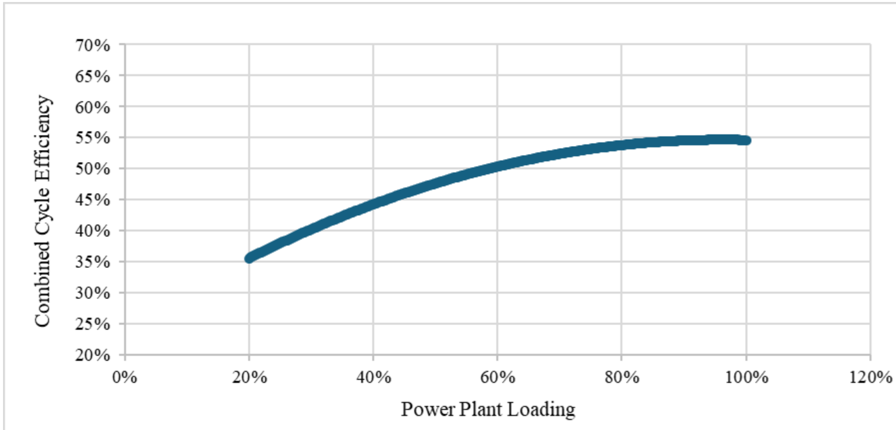

Figure 10: *Combined cycle efficiency and power plant loading relation*

reaches a plateau. This suggests that even with technological advancements over time, there are limitations to how much the thermal efficiency can be improved, especially during high-demand periods.

4.6. Economic analysis

The economic analysis of the designed power plant is crucial to evaluating its financial viability and long-term sustainability. In this analysis, key parameters such as the levelized cost of electricity (LCOE), the internal rate of return (IRR), and the net present value (NPV) are calculated to assess the cost-effectiveness, profitability, and attractiveness of the plant. investment. LCOE provides a standardized measure of the cost per unit of electricity generated over the lifetime of the plant, factoring in capital, operating, and maintenance expenses. The IRR, on the other hand, represents the expected rate of return on investment, helping to gauge the project's financial performance relative to market benchmarks. Finally, NPV determines the overall value of future cash flows discounted to current terms, providing information on whether plant revenues outweigh its costs. These metrics provide a comprehensive understanding of the economic feasibility and potential returns of the power plant, enabling informed decision-making for investors.

Table 6 provides key economic parameters for the designed power plant, specifically detailing the cost components for a combined cycle power plant, a biogas plant, and transportation. The parameters will affect the capital expenditure (CAPEX) and the operating expenditure (OPEX) of the project. These detailed cost components are essential inputs for calculating the overall economic performance of the power plant, specifically in determining metrics. The key assumptions are based on the typical experimental or theoretical values of previous relevant research, as well as the price of the product at the time this paper was published.

In addition to the primary cost components, the price of manure, which will be purchased from local farmers, is set at Rp50,000 per quintal. The decision to source manure from local farmers not only supports the local economy but also ensures a reliable supply of feedstock. For baseline condition, by assuming a USD exchange rate of Rp15,200 and a 6% discount rate, the LCOE, IRR, and NPV of the biogas co-firing combined cycle power plant are Rp1,126.76/kWh, 9.62%, and 222 billion IDR, respectively [71,72]. The electricity sales price is assumed to be Rp1,352/kWh, adjusting for the electricity cost for the R-1/TR class with 900 VA electric power capacity [73].

For an overview of financial projection over time, a cumulative discounted cash flow for the

Table 6: *Key assumptions for economic analysis*

Components	Parameters	Value
Combined Cycle Power Plant	Capital Expenditure	1,215 USD/kW [62]
	Fixed O&M Cost	26,800 USD/MW [47]
	Variable O&M Cost	2.6 USD/MWh [47]
	Natural Gas Price	13.2 USD/MMBtu [63]
	Lifetime	20 years [64]
Biogas Plant	Capital Expenditure	1000 USD/m^3/day [65]
	Overall O&M Cost	2.5% of CAPEX/year [66]
	Lifetime	20 years [67]
Transportation	Trucks Purchase	IDR 580,000,000/truck (66 trucks) [68]
	Driver Salary	IDR 3,000,000/driver/month (66 drivers) [69]
	Fuel Cost	IDR 6,800/liter [70]
	Fuel Consumption	7 km/liter [68]

project is presented in Figure 11. With a capital expenditure (CAPEX) of 608 billion IDR, the project shows a moderate internal rate of return (IRR), slightly above the assumed discount rate. While the NPV is positive, indicating that the project will generate more revenue than its costs over its lifetime, the relatively modest IRR suggests that the economic attractiveness of this investment depends on the investor's risk tolerance and financial goals.

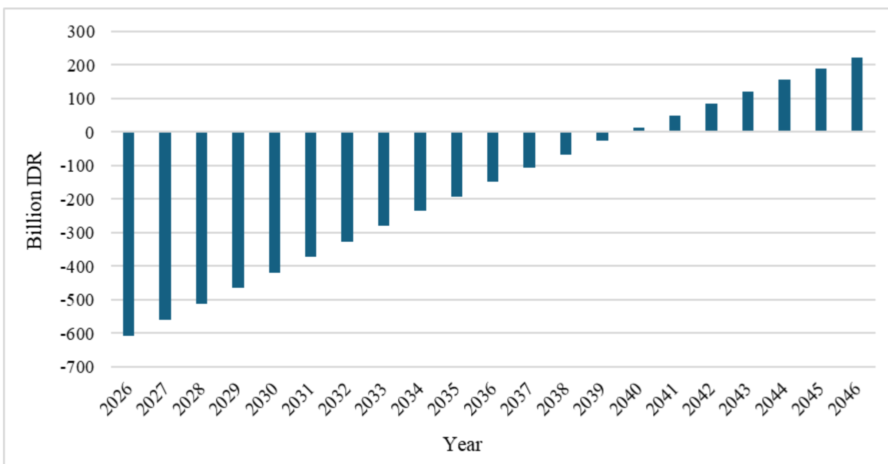

Figure 11: *Cumulative discounted cash flow of investment*

Since beef cattle manure is a key input for the biogas plant, changes in its price can have a big impact on economic metrics, both the LCOE and the IRR. The sensitivity analysis in Figure 12 will show how different prices of manure affect these financial measures.

As the price of manure increases from 1 to 10 USD per quintal, the LCOE (represented by the blue bars) remains relatively stable but shows a slight upward trend, indicating that higher manure prices result in increased electricity production costs. However, the IRR (represented by the light blue line) decreases consistently as the manure price increases. The maximum IRR occurs at the lowest manure price of 1 USD per quintal, where the IRR is slightly above 10%. At this price, the lowest LCOE is also achieved, just below Rp1,100/kWh. This highlights the importance of maintaining low manure prices to maximize profitability and cost efficiency in the project. That is why a systemized method is needed to collect cattle manure while also maintaining a reasonable incentive for farmers.

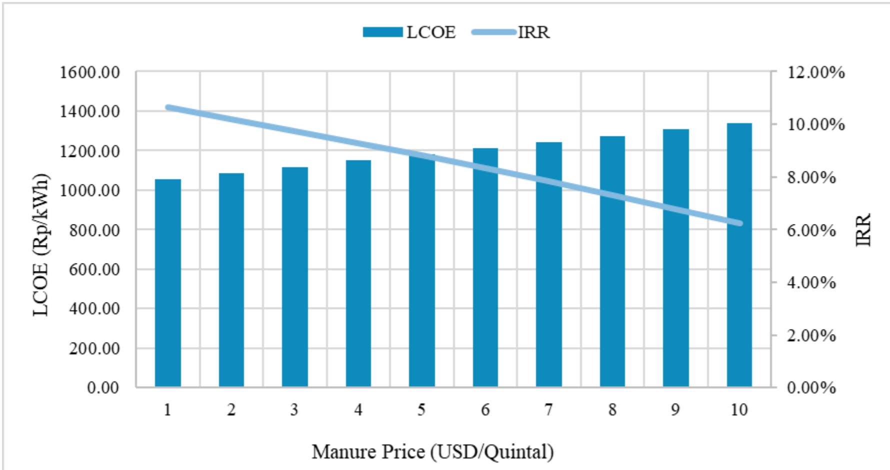

Figure 12: *Sensitivity analysis of beef cattle manure price*

4.7. Environmental impact

Stoichiometrically, on the basis of thermodynamic simulations, the expected emission factor of the power plant is 0.49 $kgCO_2/kWh$. Based on these data, considering the efficiency characteristic, which is shown in Figure 12, the total greenhouse gas emitted by the power plant is approximately 1,037 kilotons annually. However, if a diesel power plant is used, as it is in existing condition, the total emissions would be 2,316 kilotons. This value is obtained based on the assumption that the diesel power plant emits 1.27 $kgCO_2$ every 1 kWh of electricity generated [74].

To estimate the emissions from manure transportation, it is assumed that the trucks travel an average distance of 400 kilometers per trip, making two trips per day. This distance is based on the assumption that manure is collected from farmers across the regency, with the truck covering the same distance to return to the power plant. The feasibility of completing two trips per day is supported by an average truck speed of 40 kilometers per hour, ensuring that daily manure transport remains efficient and within operational capabilities. The trucks are assumed to use solar fuel, with a combustion factor of 2.22 kg CO_2 per liter of fuel or 10.1 kg CO_2 per gallon [75]. Based on these assumptions and the total fuel consumption of the trucks during the 20-year operating period of the plant, the cumulative GHG emissions from manure transportation are calculated to be approximately 61 kilotons of CO_2. This estimate provides insight into the environmental impact of transportation in the overall lifecycle emissions of the biogas co-firing power plant.

In conclusion, the implementation of the biogas co-firing combined cycle power plant design can result in a significant reduction of greenhouse gas emissions, amounting to 61 kilotons of carbon emissions annually. This reduction is achieved through the combined effects of lowering emissions from the power plant itself and transporting beef cattle manure as a renewable fuel source to the plant. The transportation of manure, while contributing to some emissions, is outweighed by the overall decrease in carbon emission output from the plant's operation, highlighting the environmental benefits of this sustainable energy solution.

The implementation of the biogas co-firing combined cycle power plant not only offers economic benefits but also significantly contributes to reducing the environmental impact of power generation. Using beef cattle manure as a renewable fuel source and optimizing transportation logistics, the plant helps reduce greenhouse gas emissions, aligning with global efforts to combat climate change. This project supports several Sustainable Development Goals (SDGs) of the United

Nations, especially SDG 7 (Affordable and Clean Energy), SDG 12 (Responsible Consumption and Production) and SDG 13 (Climate Action). The reduction of carbon emissions through the use of renewable resources and improved energy efficiency underscores the potential of the plant to contribute to a more sustainable and environmentally friendly energy system.

5. Conclusion

The feasibility study of co-firing biogas from cattle manure in a combined cycle power plant (CCPP) in South Central Timor offers a promising solution to address local energy needs while reducing environmental impacts. There are adequate areas rich in cattle manure that could present good opportunities for biogas production, a renewable energy source that could be quickly and effectively integrated with the existing natural gas infrastructure. By specifically assessing the projected biogas yield from the local cattle population and connecting it to regional energy demands and growth, the study results reflect the improved energy efficiencies while co-firing with biogas and reductions in greenhouse emissions that provide a stronger push toward obtaining a sustainable energy future for the region.

In 2027, South Central Timor's combined cycle power plant is scheduled to begin operations, supported by a threshold of 260,217 projected to beef cattle populations, producing an estimated 301,851.72 m^3 of biogas per day. This abundant biogas resource indicates the potential of cattle manure as a renewable energy source for the region. With an anticipated peak load of 16.93 MW in the final operational year of the plant, the biogas fusion plant is designed to meet energy demands with a load factor of 70%.

A techno-economic analysis, assuming a USD exchange rate of Rp15,200 and a 6% discount rate, projects the levelized cost of energy (LCOE) at Rp1,126.76/kWh, an internal rate of return (IRR) of 9.62% and a net present value (NPV) of 222 billion IDR. These indicate a financially viable solution that balances renewable energy production with economic returns. The economic sensitivity analysis conducted also shows that the purchase price of cow manure for local farmers can be optimized to improve both the profitability of the project and also the welfare of farmers.

From an environmental standpoint, thermodynamic simulations show an expected emission factor of 0.49 $kgCO_2/kWh$ for the plant, which proves that this power plant will contribute significantly to greenhouse gas reductions. The plant's operation is projected to lower annual carbon emissions by approximately 61 kilotons. Then, although manure transportation generates minor emissions, the overall reduction in carbon output from the plant will offset this emissions.

More mature planning, incentives, and policies will certainly help in the implementation of related projects in the future. In the coming years, technological development in the production, storage and distribution of biogas will be very important in the establishment of biogas as the main source of energy. In addition to that, the combination of biogas with other renewable sources, such as solar or wind, provides certain opportunities for the development of more resilient and diversified energy systems in rural areas, which, in turn, can be useful for meeting the goals of sustainable development.

Indonesia can reflect on the experience of China, which has successfully implemented several programs to accelerate the implementation of renewable energy that prioritizes local resources in the rural context [76]. China's multilevel governance approach that integrates both national and local entities can serve as a model for Indonesia's decentralized governance [77]. With this model, the local government, in this case South Central Timor, can be empowered to customize energy solutions based on specific regional needs and potentials, allowing flexibility and adaptation in implementing policies, even within a highly centralized framework [78]. Besides the multilevel governance approach, China's experience also shows the importance of top-down policy approaches and financial subsidies, all of which can be insightful for Indonesia.

Declaration of interest: The authors declare no conflicts of interest.

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