JIGE 5 (4) (2024) 3953-3962
JURNAL ILMIAH GLOBAL EDUCATION
ejournal.nusantaraglobal.or.id/index.php/jige
DOI: https://doi.org/10.55681/jige.v5i4.3672

Linear Programming Approach of Biogas Production and Cost as an Independent Energy Source

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Article Info

Article history:

Received Desember 15, 2024
Approved Desember 30, 2024

Keywords:

Biogas, COE, Linear Programming, Optimization, Renewable Energy, West Waru Village

ABSTRACT

This study aims to optimize energy allocation for West Waru Village, a village with significant electricity demands and a biogas production system, to minimize energy costs. Two simulations were conducted to evaluate different scenarios and their outcomes. Simulation 1 focused on maximizing the utilization of biogas while adhering to production constraints, monthly energy needs, and annual production limits. The results indicated that during high-demand months (July to December), energy distribution approached the maximum production capacity, optimizing biogas usage while fulfilling energy requirements. Simulation 2 targeted the minimization of total energy costs by balancing energy sourced from biogas and PLN. The optimal solution achieved a total cost of 420,000. The simulation showed that during the first two hours of the day, energy demands were partially met by biogas, with PLN contributing the rest to fulfill the demand. Throughout the remaining hours, biogas production was zero, leading to a complete reliance on PLN. The results highlighted the feasibility and effectiveness of combining biogas and PLN energy to achieve cost savings, while suggesting potential improvements to enhance biogas production or utilization efficiency to reduce PLN dependence further. Overall, the study demonstrates that effective energy management in West Waru Village can be achieved by optimizing biogas and PLN use, maintaining cost efficiency, and ensuring the fulfillment of energy demands. Future work should focus on boosting biogas production capacity and enhancing distribution strategies to further reduce operational costs.

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How to cite: Wedhasari, T. (2024). Linear Programming Approach of Biogas Production and Cost as an Independent Energy Source. *Jurnal Ilmiah Global Education*, *5*(4), 3953-3962. https://doi.org/10.55681/jige.v5i4.3672

INTRODUCTION

Energy is a basic need for human life, not only for household also for industrial, transportation, and public services. In recent decades, energy needs have continued to increase along with population growth and global economic development(Nelson & Vaughn, n.d.). However, the dominants still using fossil fuels has caused various environmental problems, including climate change, air pollution, and decreased quality of life. Therefore, the development and utilization of renewable energy sources are very important to create a sustainable energy system. Biogas is one of the renewable energy sources produced from the decomposition process of organic matter by microorganisms under anaerobic conditions. Organic materials that can be used to produce biogas include animal waste, agricultural waste, organic waste, and industrial waste.

This process produces methane gas (CH_4) as the main component, which can be used as fuel to generate electricity or heat energy. The main advantage of biogas is its ability to manage organic waste while producing environmentally friendly energy. In Indonesia, the potential for biogas is very large, especially in rural areas that have abundant biomass availability, such as cow dung. Villages in Indonesia, including West Waru Village, have a high livestock population, thus providing a great opportunity to utilize livestock dung as an alternative energy source. The use of biogas not only helps reduce dependence on electricity from the PLN network, but also provides economic benefits, such as reducing energy costs, increasing waste efficiency, and creating new jobs.

This study aims to reduce dependence on PLN electricity by increasing the contribution of biogas to meet the village's energy needs for 24 hours, so that sustainable energy independence is achieved in West Waru Village using the Linear Programming (LP) model by considering daily electricity demand data, biogas energy potential, operational and investment costs, this study aims to calculate the optimal Cost of Energy (COE) so that the energy system in the village can meet electricity needs efficiently and sustainably (Situmeang et al., 2022). The potential of biogas is expected to be a model of energy solutions for villages in Indonesia, which not only supports rural electrification but also supports national energy sustainability goals. The expected benefits of this study are the Independent Energy System optimization method that allows for the development of energy systems that can meet energy needs independently in rural areas, reducing dependence on electricity from PLN.

Indonesia, as a developing country with a growing population, faces various challenges in the energy sector. These issues are not only related to the provision of sufficient energy, but also to sustainability, equal access, and the environmental impact of the current energy system. Here are some of the main issues in the energy sector that are relevant to raising the potential of biogas as an alternative solution. Until now, more than 85% of Indonesia's energy needs still depend on fossil fuels, such as coal, oil, and natural gas. This dependence causes several negative impacts, including Environmental Pollution from the combustion of fossil fuels produces high carbon emissions, contributing significantly to climate change and decreased air quality. Depletion of Resources where even though abundant, fossil energy reserves in Indonesia will continue to decrease, especially oil, which requires the country to import fuel to meet energy needs (Rianawati et al., 2021). Fossil energy prices tend to fluctuate following the international market, which can affect electricity costs for the community.

Although Indonesia has achieved quite high electrification, with the national electrification ratio reaching more than 99% by 2023, there is still inequality in energy access in remote and rural areas. Some related problems are Infrastructure Limitations where Many remote areas, such as villages on small islands or remote areas on large islands, do not yet have adequate electricity networks. Reliability of Supply: Even though the electricity network is available, the energy supply is often unstable, especially in rural areas, which hinders the economic and social activities of the community. On the other hand, Indonesia produces millions of tons of organic waste every year, both from the agricultural, livestock, and household sectors. This waste is often not managed properly, causing various problems including environmental Pollution where unmanaged organic waste can pollute soil, water, and air, and become a source of disease. As well as Energy Inefficiency, whereas organic waste such as livestock manure and agricultural waste have great potential to be converted into renewable energy through biogas technology.

With the growth of population and economy, the energy needs in Indonesia continue to increase every year. This creates some pressures, such as the Surge in Energy Costs from Electricity costs from PLN tend to increase due to the need for additional infrastructure and fossil fuels. Environmental Burden The more energy produced from fossil fuels, the greater the impact on the environment.

Although Indonesia has great potential for renewable energy (such as solar, wind, and biomass), its utilization is still very low. Some of the obstacles faced are High Initial Costs where Many renewable energy technologies, including biogas, require quite large initial investment costs, making them an obstacle for rural communities. Lack of Awareness: Communities, especially in rural areas, are often not yet aware of the economic and environmental benefits of using renewable energy(Silaen et al., 2020). As well as the lack of Incentive Policies in the form of government support in the form of incentives or subsidies for renewable energy has not been maximized.

Biogas can be an effective solution to overcome these problems, especially in rural areas such as West Waru Village. Some of the reasons why biogas is relevant include being a source of Renewable and Sustainable Energy, Biogas comes from abundant biomass in the village, such as cow dung, so it is not used up. By managing Waste Productively from the Utilization of livestock manure for biogas helps reduce organic waste that pollutes the environment. Reducing Dependence on PLN in the form of Biogas can produce enough local energy to meet village needs, reducing electricity purchases from PLN. Low Operating Costs if After the initial investment, the operating costs of biogas are relatively cheap because the raw materials are easily obtained in rural areas. The Economic Potential of Electrical Energy from biogas can be used for community needs, and the excess can be sold to the PLN network to earn additional income.

With its potential, the use of biogas is not only able to answer energy challenges in Indonesia but also improve the welfare of rural communities and support the achievement of sustainable development goals, especially in the clean and affordable energy sector.

Linear Programming (LP) is a mathematical technique used to find the optimal value (maximum or minimum) of a linear objective function, while obeying a number of constraints that are also linear. LP is used to solve the problem of allocating limited resources efficiently, such as cost, time, energy, or raw materials (Hillier & Lieberman, 2015). The LP objective function is formulated in the form:

$$Z = c_1x_1 + c_2x_2 + \cdots + c_nx_n$$

Constraints:

$$a_{11}x_1 + a_{12}x_2 + \cdots + a_{1n}x_n \leq b_1, \ldots, a_{m1}x_1 + a_{m2}x_2 + \cdots + a_{m2}x_2 \leq b_m$$

Where $x_i \geq 0$ for all i.

Linear Programming has been widely applied in various fields, including:

Renewable Energy: LP is used to optimize mixed energy generation systems such as biogas, solar, and wind power. For example, a study by (Situmeang et al., 2022)) used LP to design a renewable energy system with minimum operating costs.

Industry: LP helps optimize raw material allocation, production schedules, and logistics transportation (Dantzig, 1951).

Agriculture: In the agricultural sector, LP is used to maximize crop yields by managing the use of fertilizers, water, and land efficiently (Hazell & Norton, 1986).

Linear programming (LP) is well suited for problems involving linear mathematical relationships, such as the cost function (COE) and energy constraints that are present in this study. Multi-Source Energy Optimization: LP allows efficient allocation of energy from biogas and PLN to meet daily energy needs at the lowest cost.

Solution Efficiency: LP is fast, accurate, and effective for problems with many decision variables, such as daily energy from biogas and PLN.

Suitability to Objectives: LP helps achieve the goal of minimizing the cost of energy (COE) while optimally meeting the village's energy demand.

Ability to Handle Operational Constraints: LP handles various technical constraints, such as biogas production capacity, daily energy demand, and a combination of operational and investment costs.

Some literature that has conducted research on biogas, including a significant influence between the variables of biogas utilization and the welfare variables of livestock farmers. So the use of biogas affects the welfare of livestock farmers, and this influence can apply generally in addition, there are factors that affect biogas production such as acidity levels, environmental temperature, and the condition of the manure used, (Wita Fidela et al., 2024) (Yudi Sobana & Yuhka Sundaya, 2024). conversion of vegetable waste into biogas by adding cow dung and making conclusions about the optimum composition of a mixture of cow dung and vegetable waste that produces the highest levels of methane gas (CH4) (Setyanansyach et al., 2023), where the use of cow dung and organic waste in biogas production as a sustainable effort to minimize the environmental impact of livestock waste and as alternative energy (Agus Indri Oktavia et al., 2016) ((Haryanto et al., 2020)). One of the biogas production processes is carried out with several processes and uses a digester tool (Annur et al., 2020) (Vilino et al., 2022). According to (Pusat et al., 2021); (Ilmiah & Teknika, 2012) biogas when examined from a sustainability aspect, biogas business which is quite good and does not have a negative impact, but is still relatively lacking in terms of marketing and distribution of biogas energy as a subsystem of business activities from products from a business, is directed at improving the mechanisms of various approaches that are generally applicable in the activities of a processing business.

METHOD

The data in this study uses data from previous researchers (Amir et al., 2023), where in their research they optimized biogas installations using HOMER. The data taken was processed using a Linear program and simulated using CPLEX with the objective function of minimizing energy production costs. From these data, parameters, objective functions, decision variables and constraints were created in this study. From several aspects, a code was created to be simulated into CPLEX. So that the final result can get the desired value to be minimized and the decision variable.

Indonesia has the potential for solar energy, wind energy and biomass of 4.80 $kWh/m^2/day$, 3-6 m/second, and 50GW (Ministry of Energy and Mineral Resources, 2008). In this study, electricity from biogas was obtained from cow dung, there were 26 cows and 19 buffaloes, for 1 cow producing 9 Kg/day of dung and buffalo 12 Kg/day, for cows it can produce 204 m3/ton of biogas with a dry matter content of 0.18 and an organic matter content of 0.86. From these results, every 1 m3 of biogas can produce 3.8 kWh of electricity. The location used as a case study is West Waru Village, Waru District, Pamekasan Regency. Based on the BPS Pamekasan Regency in 2021, Waru Barat Village is located about 26 Km from Pamekasan City. There are 4,044 households and 13,714 residents. Most houses in West Waru Village have electrical equipment such as TVs, fans, lights, water pumps and refrigerators and most are still in simple houses with typical rural areas. As much as 15 kg of cow dung can be converted into 0.036 m^3 of biogas per day (Silaen et al., 2020). West Waru Village has 4,000 cows, considering the number of cows, the potential for biogas in West Waru Village is 2,160 m^3/day which can be produced and converted into electrical energy. Biogas consists of 50-70% CH_4, 30-50% CO_2, and a small amount contains H_2S.

Table 1. Data from Nizar Amir et al., 2023.

Equipment	Total Unit	Power (W)	Duration (Hour)	Energy/day (kWh)
TV	4044	100	3	1213.2
Fan	8088	85	5	3437.4
Lamp	28308	20	4	2264.64
Refrigerator	4044	175	24	16984.8
Water pump	4044	200	4	3235.2
HP charger	4044	20	6	485.28

Installation Cost for rural biogas generator technology Rp 12,742,800,000. In 1 year, the electricity energy of West Waru village is supplied by biogas generator of 7,205,220 kWh and PLN 1,882,152 kWh and peak power of 2,225 kW. In 1 year, the biogas generator is able to work more than 18 hours a day, and the rest is supported by electricity from the PLN network. From previous research, mentioned the price per kWh was Rp 1,168 while the price per kWh from PLN was Rp 1,550. In previous research, the biogas generator specifications were used with a maximum working hour of 20,000 hours and a minimum load ratio of 30%. Capital costs of Rp 9,117,156 / kW and installation costs of Rp 6,837,866.59 / kW. Operating or maintenance costs of Rp 379.8 / hour, this figure was used by previous researchers. West Waru Village has 4,000 cows, considering the number of cows, the biogas potential in West Waru Village is 2,160 m3/day which can be produced and converted into electrical energy.

Raw data from previous research (Amir et al., 2023) The renewable energy source used is biogas produced from cow dung. Based on previous research, each cow produces around 15 kg of dung per day which can be converted into 0.036 m^3 of biogas per day. With 4,000 cows in Waru Barat Village, it is estimated that the potential biogas energy that can be produced is 2,160 m^3 of biogas per day and the average calorific value of biogas assuming methane is 60%. The biogas produced is converted into electrical energy through a biogas generator with a maximum energy production capacity of 7,205,220 kWh per year. In addition, the need for electrical energy in this village is estimated at 10,081,300 kWh per year. Energy that cannot be produced from biogas can be met by purchasing energy from PLN.

Decision variable

$x_t(kWh)$: Energy from biogas allocated for month t, where t∈{1,2,…,12}

Parameters

$production\ Biogast$ =[600,550,600,580,600,600,620,620,600,620,600,610,600,550,600,580,600,600,620,620,600,620,600,610]

$production\ PLNt$= [850,750,850,850,850,850,860,890,850,850,830,830,850,750,850,850,850,850,860,890,850,850,830,830]

$Electricity\ demandt$= [300,300,300,300,400,600,1000,900,800,1000,1200,1800,1500,1300,1100,1500,1900,2100,2000,1800,1300,1200,700]

$energydemand_t\ (kWh)$: monthly energy demand for month t

$dailyproduction_{max}$: maximum daily production capacity of biogas

$daysInmonth_t$: (days) : number of days in month t

$totalyearlyproduction$: (kWh): total annual biogas production capacity.

Simulation 1

Objective function

The goal is to maximize the total energy from biogas allocated over one year.

$$maximize\ Z = \sum_{t=1}^{12} x_t$$

Constraints

$x_t \leq energyDemand_t\ \ \forall t\ \in \{1,2,\dots,12\}$

$x_t\ \leq dailyProductionMax\ x\ daysInMonth_t\quad \forall t\ \in \{1,2,\dots,12\}$

$\sum_{t=1}^{12} x_t\ \leq totalYearlyProduction$

Non negativity constraint

$x_t\ \geq 0\ \ \forall t\ \in \{1,2,\dots,12\}$

This LP model maximizes biogas energy allocation while considering monthly energy needs, daily production capacity, and total annual production capacity. The objective function aims to maximize the total distribution of biogas energy throughout the year, while the constraints ensure compliance with production and monthly demand limitations.

In the simulation results, an optimal solution with the following energy allocation was obtained:

x= [30000,30000,30000,30000,40000,60000,66960,66960,64800,66960,64800,66960]. This simulation 1 indicates that during months with higher energy demands, the allocation of biogas energy was optimized up to the daily production capacity, while still satisfying the total annual production constraint.

Simulation 2

Decision variables

$biogasProduced_t\ (kWh)$: energy produced from biogas during hour 3 where $t \in \{1,2,\dots,12\}$

$ElectricityPLN_t\ (kWh)$: energy sourced from PLN during hour t

Parameters

T=24 total number of hours in a day

CostPLN 1000 where cost per kWh from PLN (in currency units)
costBiogas 800 where cost per kWh from biogas (in currency units)
$productionBiogas_t$ (kWh) maximum biogas production capacity perhour
$DemandElectricity_t$ (kWh) hourly electricity demand.

Objective Function

$$Maximize\ Z = \sum_{t=1}^{24} (Electricitycost\ PLN.ElectricityPLN_t + costbiogas.biogasproduced_t$$

Constraints

$$BiogasProduced_t \leq productionBiogas_t \quad \forall t \ \in \{1,2,\ldots,24\}$$
$$BiogasProduced_t + ElectricityPLN_t = Electricitydemand_t \ \ \forall t \ \in \{1,2,\ldots,24\}$$
$$BiogasProduced_t \ \geq 0, ElectricityPLN \geq 0 \ \forall t \ \in \{1,2,\ldots,24\}$$

The simulation 2 result:

- Energy sourced from PLN:

Electricity PLN =[150,150,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0]

- Energy produced by biogas:

Biogas Produced = [75,75,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0]

Optimal Objective Value: The total minimized cost obtained from the simulation is 420,000 (currency units). The Feasibility from simulation 2 The solution satisfies all constraints, ensuring that energy demands are met and production capacities are not exceeded.

RESULT AND DISCUSSION

From the simulation 1 the result Objective: The model maximized the use of biogas while adhering to the daily production capacity, monthly energy demands, and the total annual production limit.

Distribution of Biogas: The simulation showed that months with higher energy needs (July to December) received a larger share of biogas distribution, approaching the maximum capacity allowed.

Capacity Utilization: The model effectively allocated energy in a way that utilized the biogas production to its fullest extent without exceeding the limits set by the daily and total production capacities.

The model prioritized using biogas in months when energy demands were higher, optimizing the energy supply to align with available production capacity and monthly needs. Energy distribution was maximized, with months in the second half of the year (July to December) using near-maximum biogas output, demonstrating efficient use of available resources.

The simulation 2 result the total minimal cost achieved was 420,000 currency units. This cost is the lowest achievable while meeting all electricity demand constraints using the combination of biogas and PLN energy. Energy Usage: The solution indicates that during the first and second hours, biogas production (75 kWh per hour) was insufficient to meet the demand of 150 kWh per hour. Therefore, PLN supplied the additional 75 kWh per hour. Cost Efficiency: The optimal solution resulted in a total energy cost of 420,000 currency units, confirming that the model achieved cost minimization by using a combination of biogas and PLN energy. Trade off from both simulation while Simulation 1 achieves maximum resource utilization and reduces dependency on PLN, it does not directly address cost efficiency. This could result in higher operational costs if PLN electricity is more affordable than biogas for certain months or hours. Simulation 2 demonstrates cost efficiency but underutilizes biogas, as seen in the results where significant energy is sourced from PLN during the simulation period. This may lead to underinvestment in biogas production infrastructure or wasted potential from existing biogas capacity.

CONCLUSION

Simulation 1 showed that biogas was distributed in a way that maximized production in line with monthly energy demands, especially in peak months. The model efficiently distributed biogas according to the monthly energy needs, utilizing the maximum production capacity without exceeding constraints. Energy Utilization Efficiency: Biogas allocation reached near-maximum capacity during high-demand months (July–December), ensuring that the total annual production capacity of 7,205,220 kWh/year was fully utilized. Biogas usage satisfied monthly electricity demand (e.g., 60,000 kWh in June when demand was higher). Daily production capacity (≈ 19,728 kWh/day) met the demand for high-demand months like December so to reduced dependency on PLN by allocating biogas energy close to daily and monthly limits. Use Simulation 1 results to align energy supply with seasonal demand fluctuations, ensuring the best use of biogas resources while maintaining cost efficiency.

Simulation 2 demonstrated a cost-minimizing strategy where biogas was used when available, and PLN electricity was used only when necessary. The model successfully minimized the total energy cost, achieving an optimal cost of 420,000 currency units by balancing the use of biogas and PLN electricity. Biogas Produced per hour: [75, 75, ..., 0 (kWh/hour)] — showing limited biogas usage to meet hourly demands. Electricity from PLN per hour: [75, 75, ..., 0 (kWh/hour)] — indicating that PLN provided a significant share of energy during early hours of the simulation. For high-demand hours, PLN supplied additional electricity where biogas production was insufficient. The results showed that all constraints were satisfied, with no issues in feasibility or cost optimization. By relying on biogas production for 75 kWh/hour during peak hours and sourcing the remainder from PLN (e.g., 75 kWh/hour), the model minimized costs to 420,000 Rp/day while satisfying demand constraints.

The operational and maintenance cost (O&M) is Rp 7,596,000,000/year, and the installation cost is Rp 12,742,800,000. These costs represent a significant financial burden, limiting profitability. The selling price of biogas (Rp 1,168/kWh) is relatively low compared to the production cost of biogas (Rp 1,000/kWh), leaving minimal profit margin for energy sales. The selling price of biogas (Rp 1,168/kWh) is relatively low compared to the cost of PLN electricity (Rp 1,550/kWh). Negotiating a higher selling price (e.g., Rp 1,300–1,500/kWh) with buyers could significantly boost revenue, especially in markets where biogas is valued as a renewable energy source.

Based on the results, the following suggestions are made for next researches such as: 1) Enhance Biogas Production Capabilities To further reduce reliance on PLN electricity and minimize energy costs, investments in biogas production facilities could be considered. This would increase the availability of biogas during peak hours and reduce the dependency on more expensive PLN electricity; 2) Optimize Biogas Usage Scheduling: Implementing a more dynamic scheduling approach for biogas utilization that aligns with fluctuating demand patterns could help ensure that energy use is always cost-effective. This would include better forecasting of energy demands and adjusting biogas output accordingly; 3) Exploration of Hybrid Energy Solutions: Combining biogas and renewable energy sources such as solar or wind power could create a more resilient and cost-effective energy system. This would further reduce the use of PLN electricity and increase the sustainability of energy supply. Invest in Efficiency Measures: Upgrading equipment and adopting energy-efficient practices in the community could lower energy consumption and make the current biogas production more effective.

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