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Techno-Economic Analysis of the Use of Wind Power Plants and Battery Energy Storage Systems as an Alternative to Lower the Cost of Diesel Power Plants

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ABSTRACT:
The supply of electrical energy in Indonesia is predominantly reliant on fossil fuels due to their abundant availability, ease of extraction, and lower cost. However, the continued use of fossil fuels increases CO2 emissions, contributing to the greenhouse effect. Additionally, fossil fuel prices are rising, their reserves are finite, and they require extensive replenishment time. Consequently, a transition from fossil fuels to renewable energy sources is imperative. The Indonesian government has designated Sumba Island as a pilot project under the Sumba Iconic Island (SII) program. Waingapu in East Nusa Tenggara (NTT) is notable for its significant Diesel Power Plant (PLTD) capacity of 9,450 kW, supplemented by a 2,000 kWp Solar Power Plant (PLTS). This study presents a techno-economic analysis of implementing Wind Power Plants (PLTB) and Battery Energy Storage Systems (BESS) to reduce reliance on PLTD operations. The HOMER software is utilized for system optimization, allowing for design, optimization, and evaluation from both technical and economic perspectives. Sensitivity analysis assesses the impact of fuel price increases on the optimal system configuration under current and future conditions, with a total daily energy demand of 115.6 MWh/day. The economic analysis reveals that the existing scenario has a Levelized Cost of Energy (LCOE) of $0.254/kWh. Incorporating wind turbines and BESS reduces the LCOE to $0.136/kWh. Achieving 100% renewable energy penetration with a PV-Wind-BESS configuration generates an LCOE of $0.221/kWh.

Keywords: Renewable energy, Energy transition, wind turbine, diesel power plant.

INTRODUCTION

Energy has become a primary need for the global community to support various daily activities (Ceglia et al., 2020). Most of the world's energy needs are supplied from fossil fuels such as coal, petroleum, and natural gas. Indonesia is an archipelagic country with a population of 278.74 million people and is located across the equator, so it has abundant natural wealth potential (Badan Pusat Statistik, 2024). The geographical condition of an archipelago makes Indonesia have challenges in electricity generation, distribution, and distribution.

The provision of electrical energy in Indonesia is still dominated by utilizing fossil energy sources because of their abundant availability, ease of obtaining, and cost (Pambudi et al., 2023; Sidik & Akbar, 2021). Along with the growth of the economy, the demand for electricity supply is also increasing, so a larger and more reliable electric power system is needed (Ramelan et al., 2021). Meanwhile, fossil energy sources will be depleted if continuous exploration results in increased CO2 pollution from the combustion process, which can increase the risk of the greenhouse effect (Sutikno et al., 2022). In addition, the price of fossil energy continues to increase, and its existence is limited and takes a very long time to be able to produce new fossil energy, so it is necessary to take special steps to transition from the use of fossil energy to renewable energy sources whose existence can be renewed continuously, such as; solar energy, wind, water, biomass, and so on.

The use of new and renewable energy (NRE) as a source of electrical energy is one of the government's programs to reduce dependence on the use of fossil fuels through the national energy mix program (Dar & Asif, 2023; Sunitiyoso et al., 2020). The Indonesian government targets the national energy mix in 2024 to be 19.49% and in 2025 to 23% (IESR, 2022). In 2022, the achievement of the national energy mix will reach 31.4% for petroleum, 13.92% for natural gas, and 42.38% for coal, while NRE is 12.3%. In the electricity sector, the electrification ratio in Indonesia is not completely evenly distributed because there are still several remote areas that have not been electrified. Based on the Ministry of Energy and Mineral Resources' work achievement data in 2023, Indonesia's electrification ratio is 99.78%, but there is still 0.22% left, which is targeted to be achieved in 2024. The main source of electricity is total electrification; 98.32% comes from PLN, while 1.46% comes from non-PLN or the private sector. The Indonesian government continues to strive to increase the electrification ratio in several regions, one of which is in East Nusa Tenggara (NTT) (Pamella, 2019).

East Nusa Tenggara Province is mostly dominated by the ocean, which has many fragments of small islands. The development of the power grid in NTT has several challenges, such as the distribution of residential areas that are not close to each other, the high cost of electricity generation, the difficulty of licensing in building transmission networks that pass through forest areas, and the high poverty rate. The power generation system in NTT is mostly sourced from the Litsrik Diesel Power Plant (PLTD) so the generation cost is relatively expensive. The government continues to use NRE to reduce PLTD's operating costs and support the national energy mix program. The government's seriousness is evidenced by the determination of the island of Sumba as a pilot for the Sumba Iconic Island (SII) program with the issuance of the Decree of the Minister of Energy and Mineral Resources No. 3051k/30/MEM/2015, which aims to realize the availability of energy from NRE by 95% in 2020. The electricity system of the island of Sumba is divided into 3 electricity systems, namely, the Waingapu system, the West Sumba system, and the East Sumba system, where each has not been interconnected with the electricity system in NTT. (Pamella, 2019)

One of the regions in NTT that has a large PLTD capacity is Waingapu Regency, located on the island of Sumba, with a total PLTD capacity of 9,450 kW with an additional solar power plant (PLTS) of 2000 kW. Seeing that the price of diesel fuel is quite expensive and continues to increase, it is necessary to accelerate the construction of NRE plants that are able to reduce the use of PLTD. NRE plants have intermittent properties that depend on natural conditions and have high variability and uncertainty, so policy regulation is needed to choose the right type of NRE (Das et al., 2020; Rúa et al., 2021). It is necessary to know the right power plant capacity and type so that the balance between supply and demand is maintained and the production costs are economical.

This research addresses the unique challenges of East Nusa Tenggara (NTT) Province, focusing on optimizing the energy mix in a region characterized by fragmented islands and dispersed residential areas. The study's novelty lies in its approach to interconnecting isolated systems, transitioning from costly diesel power (PLTD) to renewable energy sources (NRE), and analyzing the effectiveness of the Sumba Iconic Island (SII) program. It proposes tailored policy and regulatory frameworks to ensure a reliable and cost-effective energy supply, considering NTT’s geographic and economic constraints.

The research aims to assess NTT’s current energy landscape, particularly in Waingapu Regency, to understand PLTD reliance and initial solar integration. It evaluates the economic and environmental impacts of reducing diesel use through NRE, identifies suitable renewable energy types and capacities, and develops policies to support renewable energy adoption. Ultimately, the study aims to enhance energy security and accessibility in NTT, contributing to regional and national energy goals while addressing local challenges.

RESEARCH METHODS

This study explains the Techno-Economic Analysis in terms of the application of wind power plants and battery energy storage systems as power supplies to reduce the operation of diesel power plants in the Waingapu region, East Nusa Tenggara so that it is expected that the cost of electricity supply will be more affordable. The research scenario used is to compare the evaluation of optimization results between the existing power plant from PLN in Waingapu and after the entry of the wind + BESS plant.

Homer is software that is used as a means to carry out the system optimization process. By using Homer, a system can be designed, optimized and evaluated both from a technical and economic point of view (Fathurrachman et al., 2022). Homer can determine the optimal range of capacity and number of components and ensure the lowest possible energy costs (Baghta, 2021) (Rahmawati & Dalimi, 2023). In the optimization process, Homer uses a derivative-free optimization algorithm so that the system can find the lowest cost of energy (COE) (Baghta, 2021).

Design Models

This study used a scenario of changes in diesel fuel prices and discount rates. However, the current discount and inflation rate data inputs are still considered using Bank Indonesia's accounting data. The discount rate in April 2024 is 6.25%, while the inflation rate in 2023 is 3%, with a project duration of 25 years.

The existing system in Waingapu

Waingapu's electricity system uses 9 diesel plants and 1 solar plant to meet the power demand. The existing schema is shown in Figure 1.

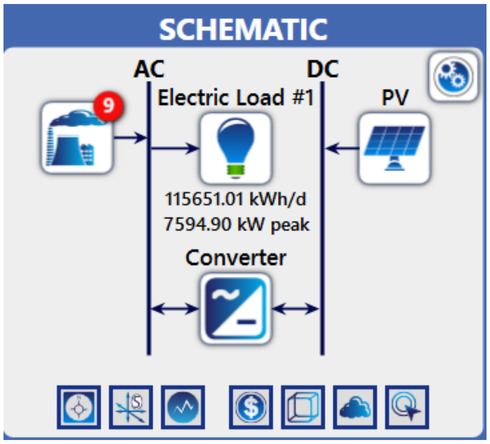


Figure 1. Schematic system existing

The diesel generator used is an existing extension of PLN, so in this simulation, the initial capital and replacement costs are assumed to be $0. For maintenance and operational costs, consideration is obtained from other researchers, namely $0.03/hour (Shezan et al., 2021), an operational lifetime of 15,000 hours, and a minimum load ratio of 25% (Ramasamy et al., 2023). Then, the price of diesel fuel is based on the official price of non-subsidized Pertamina bio-diesel in 2024.

The solar panels used in the simulation are generic flat PV plates with a capacity of 2000 kW. The reference used can be input data on Initial capital cost, replacement and O&M sourced from catalog data technology published by the Ministry of Energy and Mineral Resources in 2024 (KESDM, 2024). In the initial capital, the researcher considered the price of PV alone, excluding inverters, with a reference from NREL, namely the price of the EDSM catalog minus 2.42%. Catalog data technology is also used as a data source for converters. Details of the specifications of the existing system can be seen in Table 1.

The LCIA stage aims to make the results of LCI analysis easier to understand and relate to the environmental impacts that occur. The impact category, indicators, and characterisation model selected are the ReCiPe 2016 (H) Method. In the ReCiPe 2016 method, indicators are divided into two levels, namely, 7 (seven) midpoint indicators and 2 (two) endpoint indicators.

Table 1. Existing system specifications

Parameter	value	unit
Diesel Plant		
O&M cost	0.03	$/kW/year
Minimum load ratio	25	%
Operational life time	15,000	hours
Fuel price	0.89	$/L
Minimum runtime	1.3	minutes
PLTS		
Initial capital	780.64	$/kW
Replacement	120	$/kW
O&M	7.5	$/kW/year
Operational life time	25	Years
Derating factor	80	%
Converter		
Capital	648	$/kW
Replacemet	324	$/kW
O&M	5.5	$/kW/year
Lifetime inverter	15	years
Efiesiensi	95	%

Scheme after the addition of PLTB + BESS

The scheme of adding pltb+Bess is used to support the Sumba iconic islan program. In this simulation, the researcher used an LTW80 wind turbine with a capacity of 1000 kW and a 1 MWh lithium-ion generator battery. The input data source comes from the 2024 MEMR catalog data technology. The schematic circuit can be seen in Figure 6, while the details of the wind and BESS specifications can be seen in Table 2.

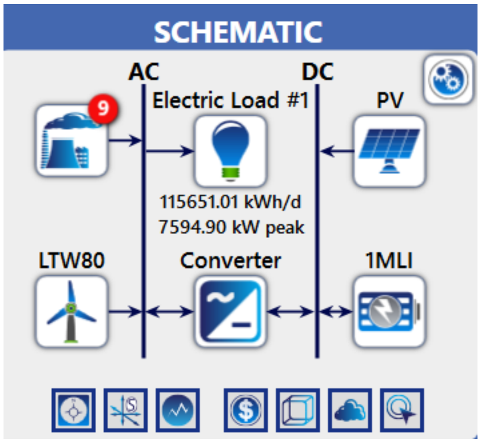


Figure 2. Schematic of the entry of pltb and bess

Table 2. Specification of wind turbine and BESS

Parameter	Value	Unit
Battery		
Capacity per unit	1000	kW
Initial capitalcost	500,000	$
Replacement cost	250,000	$
O&M	15,000	$/year
Operational lifetime	15	years
Throughput	3,000	kWh
Initial SOC	95	%
Minimum SOC	20	%
Wind turbine		
Capacity per unit	1000	kW
Initial capital	1,650,000	$
Replacement	577,500	$
O&M	4000	$
Operational lifetime	25	years
Hub height	80	meter

100% renewable energy scheme

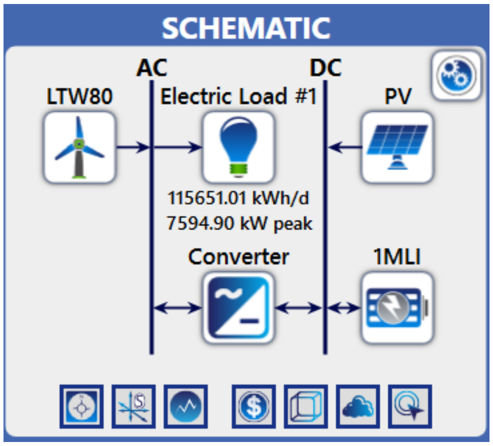


Figure 3. Schematic 100% renewable energy

The 100% renewable energy scenario by deactivating 9 diesel plants in the existing Waingapu system aims to support the Sumba iconic island program. This program aims to make Sumba a pilot island in Indonesia for the use of renewable energy (Kuswardono, 2023). This initiative aims to provide clean and sustainable energy and improve local communities' quality of life through more reliable and cheaper access to electricity. By not using diesel plants will reduce carbon emissions, improve air quality, and reduce dependence on expensive and unsustainable fossil fuels.

Economic optimization parameters

The economic analysis used in this study focuses on the COE and NPC values from Homer's optimization results. The optimum value produced by the Homer simulation of the hybrid system combination is based on the net present cost (NPC) which can be calculated using the following equation (Aziz et al., 2022):

$$NPC = \frac{C_{ann,tot}}{CRF\ (i, T_p)}$$

Where Cann,tot is the total annual cost ($/year) while i is the real interest rate, Tp lifetime of the project (year). CRF (capital recovery factor) is a ratio used to calculate the amount of annual costs needed to recover the value of the initial investment or also known as the capital closure factor. The CRF equation is as follows (Aziz et al., 2022):

$$CRF\ (i, N) = \frac{i(1+i)^n}{(1+i)^n - 1}$$

COE, or cost of energy, is the average cost per kWh to produce electrical energy. The following equation calculates the COE value (Aziz et al., 2022).

$$COE = \frac{C_{ann,tot} - C_{boiler} H_{served}}{E_{served}}$$

Where Cboiler is the marginal cost of the boiler ($/kWh), Hserved is the total thermal load served (kWh/year), and Eserved is the total electricity load served (kWh/year).

RESULTS AND DISCUSSION

Optimization result

In this study, the price of diesel fuel is a consideration because world energy prices tend to increase every year, affecting PLTD's operational costs. The main goal of this study is to reduce the production cost of electricity supply by using three combinations of scenarios: existing systems, the addition of wind turbines and BESS, and a 100% renewable energy system.

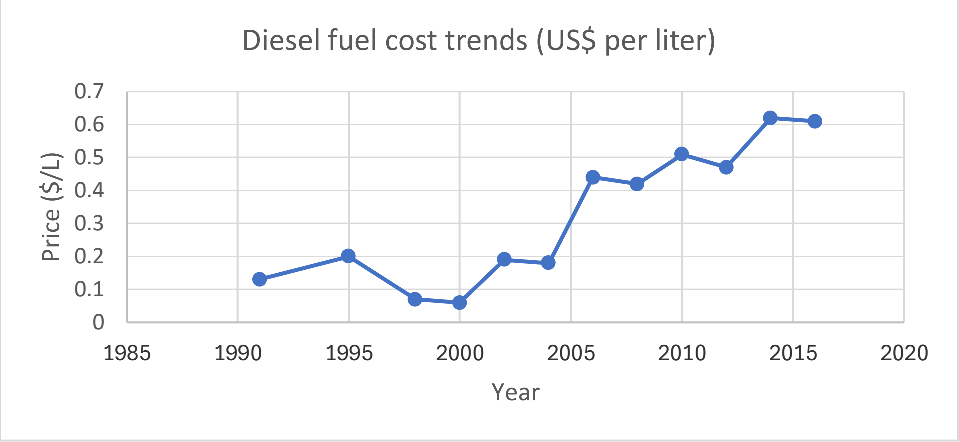


Figure 4. Trends in diesel fuel costs in Indonesia in 1991-2016

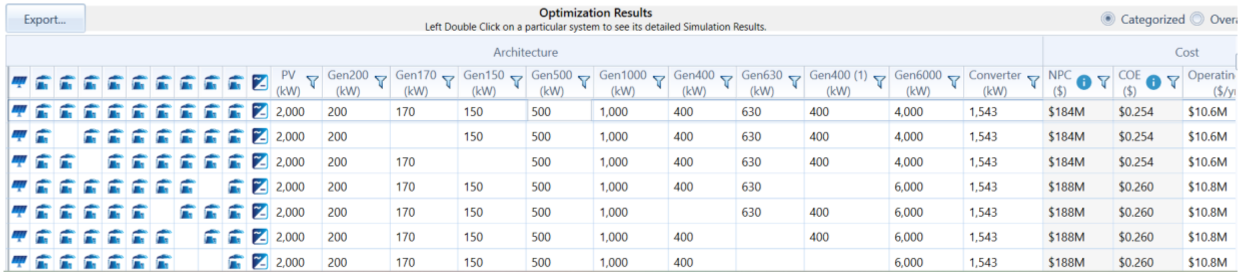
Based on historical data from the World Bank, diesel fuel prices fluctuate and tend to continue increasing, as shown in Figure 8. The average increase from 2010 to 2021 shows that diesel fuel prices increased by 3.75% yearly (Baghta, 2021).

1. The first model for an existing power generation system, shown in Figure 5, shows an optimized cost of energy (LCOE) of $0.26 and a net cost of capital (NPC) of $187.83 million.
2. The second model, after the addition of wind turbines and Bess to the power generation system shown in Figure 6, has a result with an LCOE of $0.136 and an NPC of $98.6 million. The ratio value between energy produced from renewable energy sources to total energy produced by the entire energy system or Renewable Fraction (RF) is 74.7%. Based on the optimization results, the existing system will add 18 units of wind turbines and 15 units of batteries.
3. The third model, which has a renewable fraction of 100% on the power generation system shown in Figure 7, has a result with an LCOE of $0.22 and an NPC of $157.64 million. The results of Homer optimization show that this system uses 16 wind turbines and an increase in solar panel capacity to 44,533kW, as well as 113 battery units.

Table 3. Comparison of simulation results of 3 scenarios

No	Scenario	COE ($)	NPC($)	Operating Cost ($)	Initial Capital ($)
1	Existing (Diesel+PV)	0.254	184M	10.6M	2.56M
2	Existing + Wind dan BESS	0.136	98.6M	3.38M	40.7M
3	RF 100%	0.221	158M	2.21M	120M

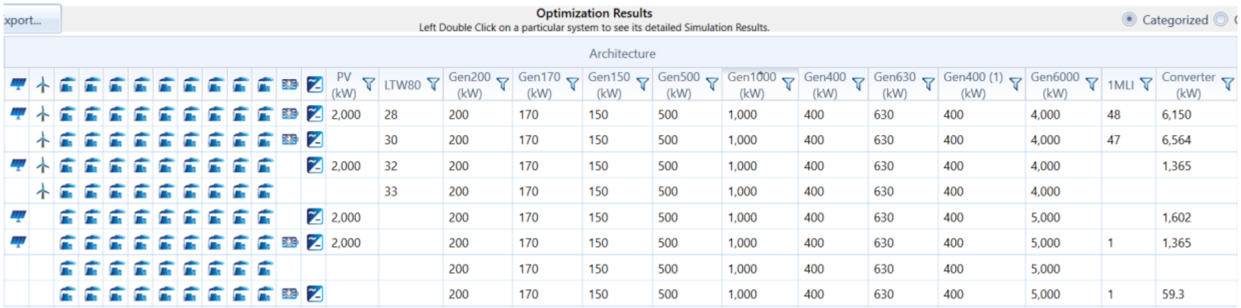
The best scenario optimization of the three models tested is the second scenario: adding wind and bess to the power generation system in Waingapu.



Optimization Results
Left Double Click on a particular system to see its detailed Simulation Results.

Architecture											Cost		
PV (kW)	Gen200 (kW)	Gen170 (kW)	Gen150 (kW)	Gen500 (kW)	Gen1000 (kW)	Gen400 (kW)	Gen630 (kW)	Gen400 (1) (kW)	Gen6000 (kW)	Converter (kW)	NPC ($)	COE ($)	Operatin ($/y
2,000	200	170	150	500	1,000	400	630	400	4,000	1,543	$184M	$0.254	$10.6M
2,000	200		150	500	1,000	400	630	400	4,000	1,543	$184M	$0.254	$10.6M
2,000	200	170		500	1,000	400	630	400	4,000	1,543	$184M	$0.254	$10.6M
2,000	200	170	150	500	1,000	400	630		6,000	1,543	$188M	$0.260	$10.8M
2,000	200	170	150	500	1,000		630	400	6,000	1,543	$188M	$0.260	$10.8M
2,000	200	170	150	500	1,000	400		400	6,000	1,543	$188M	$0.260	$10.8M
2,000	200	170	150	500	1,000	400			6,000	1,543	$188M	$0.260	$10.8M

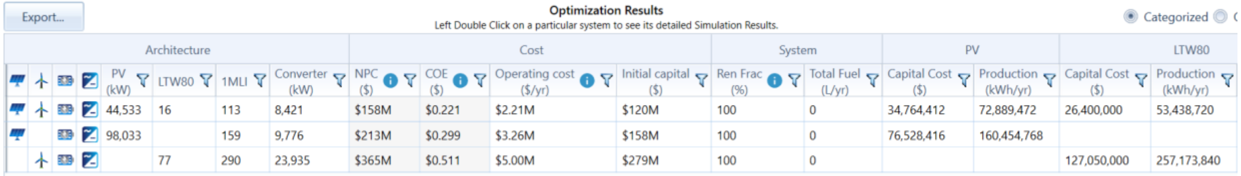
Figure 5. Optimization results of scenario 1-existing system



Optimization Results
Left Double Click on a particular system to see its detailed Simulation Results.

Architecture												
PV (kW)	LTW80	Gen200 (kW)	Gen170 (kW)	Gen150 (kW)	Gen500 (kW)	Gen1000 (kW)	Gen400 (kW)	Gen630 (kW)	Gen400 (1) (kW)	Gen6000 (kW)	1MLI	Converter (kW)
2,000	28	200	170	150	500	1,000	400	630	400	4,000	48	6,150
	30	200	170	150	500	1,000	400	630	400	4,000	47	6,564
2,000	32	200	170	150	500	1,000	400	630	400	4,000		1,365
	33	200	170	150	500	1,000	400	630	400	4,000		
2,000		200	170	150	500	1,000	400	630	400	5,000		1,602
2,000		200	170	150	500	1,000	400	630	400	5,000	1	1,365
		200	170	150	500	1,000	400	630	400	5,000		
		200	170	150	500	1,000	400	630	400	5,000	1	59.3

Figure 6. The results of the optimization of the 2-existing scenario are added by wind and bess

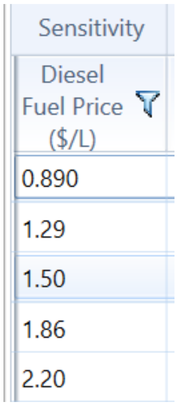


Optimization Results
Left Double Click on a particular system to see its detailed Simulation Results.

Architecture				Cost				System		PV		LTW80	
PV (kW)	LTW80	1MLI	Converter (kW)	NPC ($)	COE ($)	Operating cost ($/yr)	Initial capital ($)	Ren Frac (%)	Total Fuel (L/yr)	Capital Cost ($)	Production (kWh/yr)	Capital Cost ($)	Production (kWh/yr)
44,533	16	113	8,421	$158M	$0.221	$2.21M	$120M	100	0	34,764,412	72,889,472	26,400,000	53,438,720
98,033		159	9,776	$213M	$0.299	$3.26M	$158M	100	0	76,528,416	160,454,768		
	77	290	23,935	$365M	$0.511	$5.00M	$279M	100	0			127,050,000	257,173,840

Figure 7. Optimization results of 3-renewable fraction scenario 100%

Sensitivity analysis is performed to see the impact of various input parameters on the optimal system configuration, both for current conditions and for the next few years (Baghta, 2021; Mutiah, 2023). In this study, the price of diesel fuel is used as a sensitivity parameter which is tested with an average increase rate of 3.75% per year. The researcher divided the diesel fuel price sensitivity parameters by price projections for the 1st, 10th, 15th, 20th and 25th years, as shown in Figure 12. However, this analysis can only be applied to scenarios 1 and 2 that have diesel plants.



Sensitivity
Diesel Fuel Price ($/L)
0.890
1.29
1.50
1.86
2.20

Figure 8. Sensitivity parameters

Table 4. Sensitivity Optimization Results

Fuel Price	Year	Scenario 1		Scenario 2		Scenario 3	
		LCOE ($)	NPC ($)	LCOE ($)	NPC ($)	LCOE ($)	NPC ($)
0.89	2024	0.254	184M	0.136	98.6M	0.221	157,64M
1.29	2034	0.352	254M	0.159	115M		
1.5	2039	0.403	291M	0.168	121M		
1.86	2044	0.491	355M	0.181	131M		
2.2	2049	0.574	415M	0.192	139M		

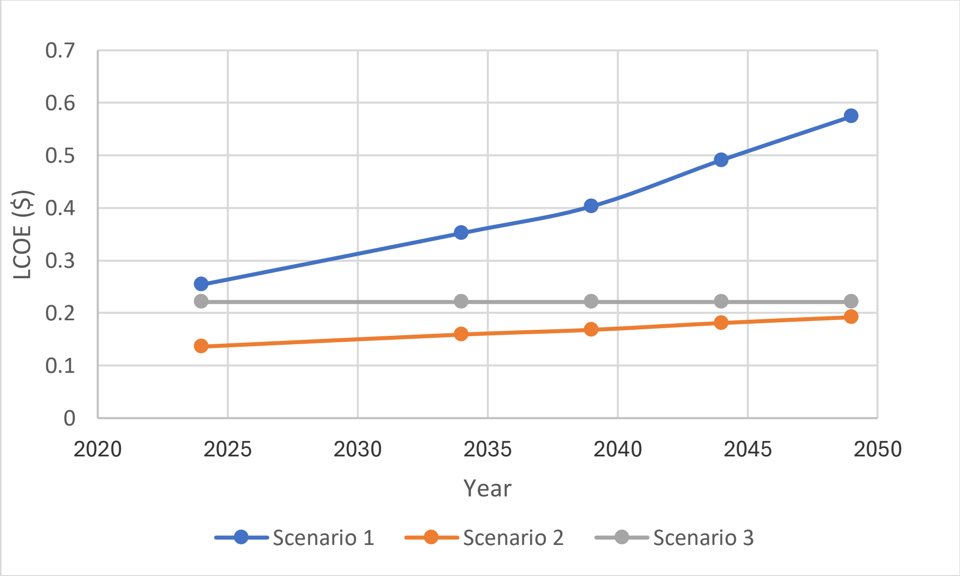


Figure 9. Diesel fuel price sensitivity test result curve

From the results of the sensitivity test, the effect of diesel fuel costs on the operational and efficiency of the electrical system can be analyzed, with the following description:

1. Scenario 1 (System Existence)
   The chart shows a sharp increase in line with the increase in diesel fuel costs. This is due to diesel generators' dependence on fuel availability.
2. Scenario 2 (Sistem Existent + Wind + BESS)
   On the graph, there is an increase but not as high as the existing system.the combination of wind turbines and BESS helps reduce the use of diesel fuel. When fuel prices rise, the system will also experience an increase but be more controlled.
3. Scenario 3- RF 100%
   Solar and wind energy sources do not require fuel costs, so operational costs remain stable even if fuel prices rise. This proves that the renewable energy system is the most stable and efficient in the long term.

CONCLUSION

This study aimed to optimize the use of renewable energy and energy storage systems to minimize reliance on diesel power plants in Waingapu Regency, East Nusa Tenggara, with a total daily energy demand of 115.6 MWh/day. The economic analysis of the current diesel-dependent scenario shows a Levelized Cost of Energy (LCOE) of $0.254/kWh. Incorporating wind turbines and Battery Energy Storage Systems (BESS) reduces the LCOE to $0.136/kWh, while achieving 100% renewable energy penetration with a PV-Wind-BESS configuration results in an LCOE of $0.221/kWh. Sensitivity analysis on diesel fuel prices indicates that the wind-BESS scenario (scenario 2) offers better economic stability than the current scenario (scenario 1), with scenario 3 optimized for 100% renewable energy, not requiring sensitivity testing. Thus, implementing wind turbines and BESS in Waingapu's energy system can significantly reduce diesel generator usage and improve economic efficiency.

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