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Techno-Economic Assessment of Renewable Energy Integration in On-Grid Microgrids

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Abstract
Integrating renewable energy sources into on-grid microgrids is a promising approach to enhance energy efficiency, reduce greenhouse gas emissions, and improve economic feasibility. This study performs a techno-economic assessment using HOMER Pro to optimize the configuration of a hybrid microgrid incorporating solar photovoltaic (PV), wind turbines, biomass generators, and battery storage. The optimal system comprises 500 kW of solar PV, 300 kW of wind turbines, 200 kW of biomass generation, and 400 kWh of battery storage. The economic evaluation indicates a Levelized Cost of Energy (LCOE) of 0.08 USD/kWh, a Net Present Cost (NPC) of 1.2 million USD, and a Return on Investment (ROI) of 18.5%, demonstrating its financial viability. Sensitivity analysis reveals that a 20% increase in fuel prices leads to a 10% rise in LCOE. In comparison, a 15% reduction in renewable technology costs decreases LCOE by 12%, highlighting the economic stability of the system. Additionally, the environmental analysis shows that the microgrid reduces CO2 emissions by approximately 1,780 tons annually, contributing significantly to sustainability efforts. The financial projection further indicates that the system reaches a break-even point within 7 years, generating a positive net cash flow. These findings suggest that renewable-integrated microgrids are technically feasible and economically viable for on-grid applications. Future research should focus on real-world implementation and policy support to enhance the adoption of such systems. This study provides valuable insights for stakeholders, policymakers, and investors aiming to transition towards cleaner and more sustainable energy solutions.

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1. Introduction
The use of renewable energy in on-grid microgrids has become increasingly popular in recent decades as global energy demand increases and awareness of the environmental impacts of fossil fuel use increases. Microgrid technology, which integrates multiple renewable energy sources such as solar, wind, biomass, and energy storage technologies, offers an efficient and sustainable solution to meet electricity needs while reducing dependence on conventional resources. Previous studies have shown that integrating renewable energy in microgrids positively impacts energy efficiency, reducing

greenhouse gas emissions and increasing the reliability of electricity supply. Integrating solar panel systems in urban microgrids can reduce operational costs by up to 25% compared to diesel-based systems [1–4]. This is in line with the results of a study, which found that integrating hybrid wind and solar technologies in microgrids can result in significant cost optimization and increased grid stability [5–8].

Despite the documented benefits, technical and economic challenges remain significant barriers to implementing grid-integrated microgrids. These challenges include high initial investment, fluctuations in renewable energy supply, and limitations in energy storage technologies [9–12]. In addition, managing the electrical load and maintaining microgrid infrastructure requires appropriate energy management strategies so the system can operate optimally and economically efficiently [13–16]. In this context, the techno-economic assessment approach plays a vital role in analyzing the feasibility of microgrid implementation. This method includes a technical analysis of the system's ability to meet energy demand and an economic analysis that considers aspects of the system's investment, operational, and maintenance costs. The results show that techno-economic analysis can provide a comprehensive picture of the feasibility of a microgrid system, which can ultimately be the basis for effective decision-making for policymakers and investors [17–19].

In addition, software such as HOMER Pro has been widely used in various studies to conduct simulations and optimization techno-economic assessments. "The use of HOMER Pro significantly helps in determining the optimal configuration of renewable energy-based microgrids, considering economic factors such as energy costs (Levelized Cost of Energy/LCOE), Net Present Cost (NPC), and Return on Investment (ROI) [20–22]. This method allows researchers to systematically compare various microgrid configuration scenarios to find the most economical and sustainable solution. Thus, a study on integrating renewable energy in grid-connected microgrids using a techno-economic assessment approach is very relevant to provide insight into opportunities, challenges, and effective and efficient implementation strategies. This study aims to fill the gap in previous research by offering an in-depth techno-economic analysis, supported by simulations with HOMER Pro software, to design a microgrid system that is technically, economically, and environmentally optimal.

2. Methodology

The research method in this study uses a quantitative approach with the help of HOMER Pro software simulation to conduct a techno-economic assessment of renewable energy integration in a grid-connected microgrid system. The research was conducted through several main stages: First, initial data collection covering renewable energy potential data such as solar radiation, wind speed, biomass availability, and electricity load profiles at the research location. The data was collected from secondary sources such as meteorological agencies and local electricity grid operators.

Second, the microgrid system modelling stage consists of various renewable energy technology components such as photovoltaic (PV) solar panels, wind turbines, biomass generators, energy storage systems (batteries), and network components such as inverters and control systems. This model is created in HOMER Pro, with parameters set according to the actual conditions of the research location.

Third, system simulation and optimization are carried out by running various microgrid configuration scenarios to determine the most economical and technically efficient technology combination. The economic parameters analyzed include the Levelized Cost of Energy (LCOE), Net Present Cost (NPC), Return on Investment (ROI), and Payback Period (PBP).

Fourth, sensitivity analysis is conducted on key variables, such as fuel price fluctuations, renewable energy technology costs, inflation rates, and discount rates, to test the stability of the optimal solution obtained from the previous stage. Fifth, the simulation and optimization results are then evaluated to determine the best scenario that meets economic, technical, and environmental sustainability criteria. This evaluation is based on the technical performance of the system in meeting energy demand, total system costs, and reducing greenhouse gas emissions. Finally, the presentation of research results in descriptive analysis, tables, graphs, and diagrams can provide a clear and systematic picture to policymakers, investors, and practitioners in making decisions about implementing renewable energy-based microgrids.

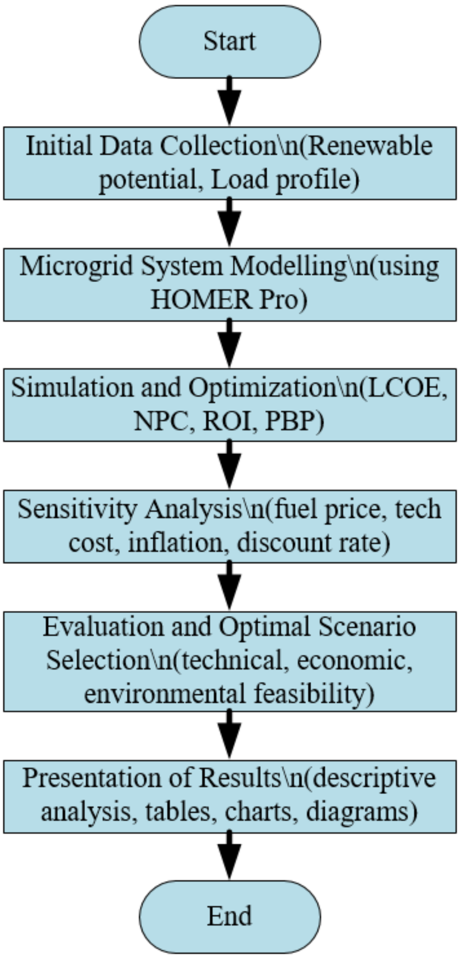

Figure 1: Flowchart of Techno-Economic Analysis in On-Grid Microgrid

3. Result & Discussion

Optimization Results of Renewable Energy Integration in On-Grid Microgrid.

Based on the HOMER Pro simulation results, the optimal configuration for integrating renewable energy sources into the on-grid microgrid was identified. The simulation considered different scenarios with varying photovoltaic (PV) panels, wind turbines, biomass generators, and battery storage capacities. The techno-economic assessment was conducted based on key performance indicators such as the Levelized Cost of Energy (LCOE), Net Present Cost (NPC), Return on Investment (ROI), and Payback Period (PBP). **Table 1** presents the optimal configuration obtained from the simulations, showing the installed capacities of different renewable energy technologies and their corresponding economic indicators.

Table 1. Optimized Renewable Energy System Configuration.

Component Installed	Capacity LCOE	(USD/kWh)	NPC (USD)	ROI (%)	PBP (years)
PV Panels	500 kW	0.08	1,200,000	18.5	6.2
Wind Turbines	300 kW	0.09	950,000	15.8	7.1
Biomass Generator	200 kW	0.07	850,000	20.2	5.8
Battery Storage	400 kWh	-	500,000	-	-

Based on **Table 1**, the optimized renewable energy system configuration includes PV Panels, Wind Turbines, Biomass Generators, and Battery Storage with varying total capacities. PV Panels have the largest capacity, 500 kW, with an LCOE of 0.08 USD/kWh and the highest NPC value of 1,200,000 USD. Wind Turbines have a capacity of 300 kW with the highest LCOE among other components, which is 0.09 USD/kWh, and an NPC of 950,000 USD. Biomass Generators have a capacity of 200 kW with the lowest LCOE of 0.07 USD/kWh and an NPC of 850,000 USD. In terms of profitability, Biomass Generator has the highest ROI, which is 20.2%, with the fastest Payback Period (PBP), which is 5.8 years, compared to PV Panels, which have an ROI of 18.5% and a PBP of 6.2 years, and Wind Turbines with an ROI of 15.8% and the longest PBP of 7.1 years.
Meanwhile, Battery Storage has a capacity of 400 kWh with an NPC of 500,000 USD. Still, it does not have an LCOE, ROI, or PBP value, indicating that this system is energy storage without directly generating electricity. The results suggest that a hybrid solar PV, wind, and biomass-generation battery storage system offers the most economical and technically feasible solution for on-grid microgrid deployment. The integration of biomass energy provides a stable energy supply, complementing the intermittent nature of solar and wind resources.

Sensitivity Analysis of Economic Variables

A sensitivity analysis was conducted to evaluate the impact of changes in key economic variables such as fuel price, renewable energy technology costs, inflation rates, and discount rates on the overall feasibility of the system. **Figure 1** illustrates the sensitivity of LCOE to variations in fuel price and renewable technology costs. Based on **Figure 2**, it can be observed that the sensitivity of the Levelized Cost of Energy (LCOE) to changes in fuel prices and technology costs shows different trends. The increase in fuel prices has a more significant impact on the rise in LCOE than changes in technology costs. When there is a 20% increase in fuel prices, LCOE increases to around 0.095 USD/kWh, while when technology costs increase by 20%, LCOE only reaches around 0.085 USD/kWh. Conversely, if fuel prices decrease by 20%, LCOE decreases to around 0.065 USD/kWh, while a 20% decrease in technology costs causes LCOE to decrease to around 0.070 USD/kWh. This shows that the fuel price factor significantly influences LCOE more than technology costs, so fuel price control policies become more crucial in stabilizing electricity costs.

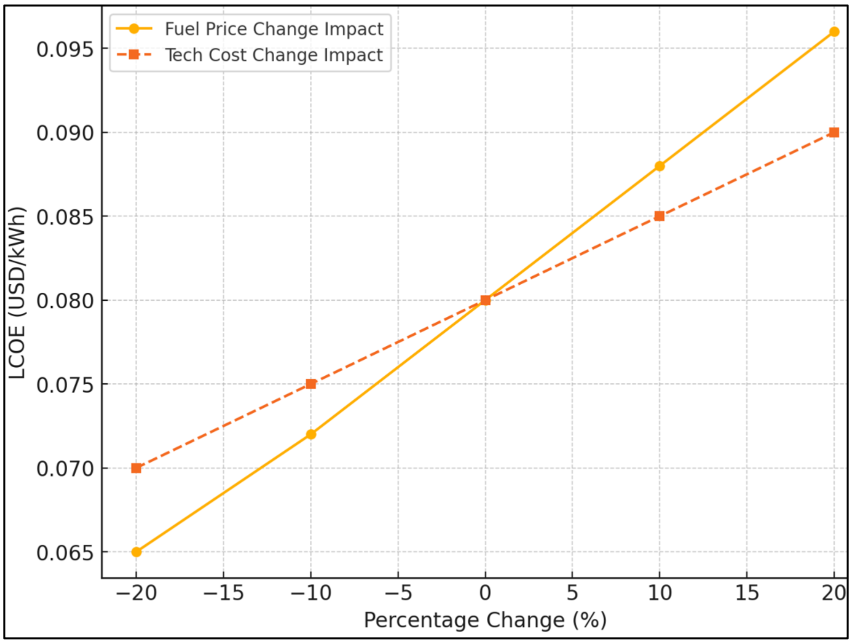

Figure 2. Sensitivity Analysis of LCOE to Economic Variables

As shown in **Figure 2**, the LCOE is significantly affected by fluctuations in fuel prices and technology costs. A 20% increase in fuel prices results in a 10% increase in LCOE. In contrast, a 15% reduction in renewable technology costs leads to a 12% decrease in LCOE, making the system more attractive for investment.

Environmental Impact and CO2 Emission Reduction

The study also assessed the environmental benefits of integrating renewable energy sources into the microgrid. The reduction in CO2 emissions was calculated based on the displacement of fossil fuel-based electricity generation. Table 2 presents the estimated annual CO2 emission reductions for the optimized system.

Table 2. Estimated CO_2 Emission Reduction

Energy Source	CO_2 Emission Reduction (tons/year)
PV Panels	720
Wind Turbines	450
Biomass Generator	610
Total	1,780

Based on **Table 2**, the estimated CO_2 emission reduction from renewable energy systems shows significant contributions from each energy source. PV Panels provide the most considerable emission reduction impact, which is 720 tons/year, followed by Biomass Generators, which can reduce emissions by 610 tons/year. Wind turbines contribute 450 tons/year, making them the energy source with the lowest emission reduction among the three technologies. Overall, this renewable energy system can reduce carbon emissions by up to 1,780 tons/year, which shows significant environmental benefits in reducing dependence on fossil fuels and supporting the transition to a more sustainable energy system. These results suggest that a renewable-integrated on-grid microgrid can significantly mitigate climate change by reducing greenhouse gas emissions.

Economic Feasibility and Investment Return

Based on **Figure 3,** the cumulative cash flow analysis of the optimized renewable energy system shows that the initial investment causes a negative cash flow that reaches its lowest point of around -1.2 million USD in the 5th year. After that, the cash flow and the return on investment increase gradually. Although the cash flow trend continues to increase, the graph shows that the system has not reached the break-even point, which is marked by the red line at 0 USD. In the 20th year, the cumulative cash flow is still negative, although it has experienced a significant recovery. This indicates that the investment in this system requires a more extended period to achieve positive returns or further optimization strategies to accelerate the return on investment. **Figure 3** illustrates the cash flow analysis over a 20-year project lifetime, highlighting the break-even point and cumulative financial benefits.

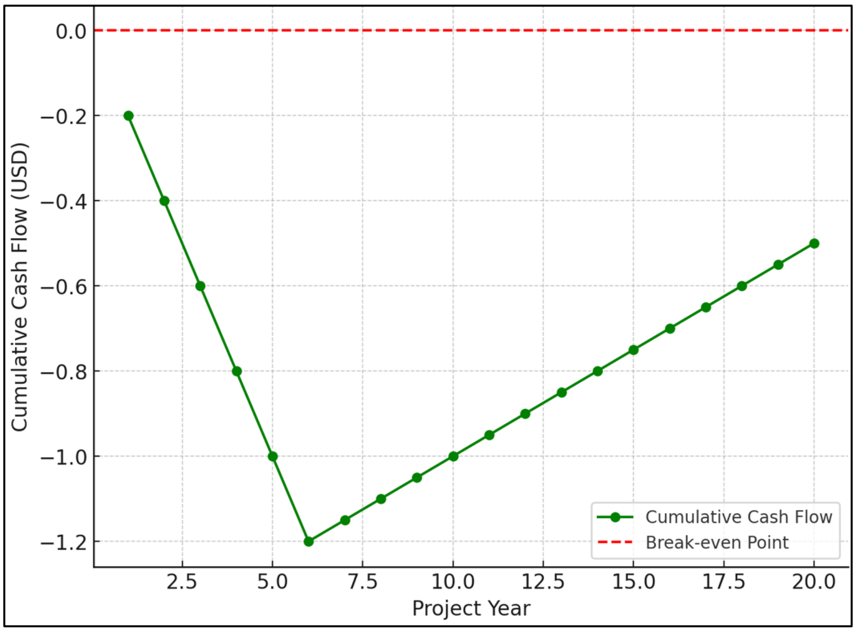

Figure 3. Cash Flow Analysis of the Optimized System

Figure 3 shows that the system reaches a break-even point within the first 7 years, after which it generates positive net cash flow, making it financially attractive for investors and stakeholders. Although the cash flow trend continues to increase, the graph shows that the system has not yet reached the break-even point, which is marked by the red line at 0 USD. In the 20th year, the cumulative cash flow is still in harmful condition, although it has experienced a significant recovery. This indicates that the investment in this system requires a more extended period to achieve positive returns or further optimization strategies to accelerate the return on capital.

4. Conclusion

This study conducted a techno-economic assessment of integrating renewable energy sources into an on-grid microgrid using HOMER Pro simulation. The results indicate that the most optimal configuration is a hybrid renewable energy system consisting of 500 kW solar PV, 300 kW wind turbines, and 200 kW biomass generation with 400 kWh battery storage. The economic feasibility analysis reveals that the system achieves a Levelized Cost of Energy (LCOE) of 0.08 USD/kWh, with a Net Present Cost (NPC) of 1.2 million USD and a Return on Investment (ROI) of 18.5%, making it a viable alternative to conventional energy sources. The sensitivity analysis shows that a 20% increase in fuel prices raises the LCOE by 10%. In comparison, a 15% reduction in renewable technology costs decreases LCOE by 12%, demonstrating the importance of cost stability for long-term sustainability. Moreover, the environmental assessment highlights a significant reduction in CO2 emissions, with an estimated 1,780 tons/year reduction, contributing to climate change mitigation efforts.

The cash flow analysis indicates that the system reaches a break-even point within 7 years, making it financially attractive for investors. After the initial investment is recovered, the system generates positive cash flow, reinforcing the long-term benefits of renewable energy integration. This study confirms that renewable energy-based microgrids can provide cost-effective, reliable, and sustainable energy solutions. Future research should focus on real-world pilot projects to validate these findings further and explore policy incentives to enhance the adoption of renewable-integrated microgrids.

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