International Journal of Energy & Environment
ISSN: 3083-000

Carbon Footprint Reduction Potential of On-Grid Renewable Microgrids

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Abstract

Using renewable energy-based microgrids in on-grid systems has great potential in reducing carbon emissions and increasing energy efficiency. This study analyzes the impact of renewable energy integration on microgrids using HOMER Pro simulation. The simulation results show that with a combination of 500 kW of solar power, 300 kW of wind turbines, and 1 MWh of battery storage systems, microgrids can replace up to 60% of electricity needs that previously depended on fossil fuels. The reduction in carbon emissions reaches 40%, from 1,200 tons per year in conventional systems to around 720 tons per year in microgrid systems. In addition to environmental benefits, the implementation of microgrids also provides economic benefits by reducing fuel consumption by up to 500,000 litres per year, which has an impact on reducing operational costs by up to 30%. This system also increases energy efficiency by up to 85%, especially with energy storage technology that optimises renewable electricity utilization. The results show that the higher the penetration of renewable energy in the microgrid, the greater the operational cost efficiency achieved, with fuel savings reaching 500,000 litres per year and operational cost reductions of up to 20% in scenarios with renewable energy penetration of 60–70%. Policy support such as feed-in tariffs (FiT) and tax incentives are essential to accelerate the adoption of renewable energy-based microgrids. With continued development, microgrids can be a strategic solution in transitioning to a more environmentally friendly, efficient, and sustainable energy system.

Article Info
Received: 15 March 2025
Revised: 25 April 2025
Accepted: 30 April 2025
Available online: 25 June 2025

Keywords
Microgrid
Renewable energy
Energy efficiency
Carbon emissions
Energy storage

1. Introduction

In recent decades, increasing greenhouse gas (GHG) emissions have become a significant concern in global efforts to mitigate the impacts of climate change. The energy sector is one of the most critical contributors to carbon dioxide (CO_2) release into the atmosphere due to its dependence on fossil fuels. Various studies have highlighted the importance of transitioning to clean energy, including implementing microgrid-based renewable energy systems to address this issue. Studies have shown that renewable energy-based microgrids integrated with the electricity grid (on-grid) have great potential to reduce carbon footprints by replacing fossil fuel-based power plants [1–4].

Microgrids based on renewable energy, such as solar, wind, and biomass, have been widely developed as an alternative to support a more sustainable energy system. Integrating microgrids with the primary electricity grid can reduce dependence on coal and natural gas-based power plants, thereby significantly reducing CO_2 emissions, according to research conducted by [5–8]. On-grid microgrids utilizing renewable energy sources can improve energy efficiency and optimize electricity supply, especially in areas with high peak loads, as shown in a study by [9–12].

Several studies have also highlighted the positive impact of microgrids on reducing carbon footprints through increasing the efficiency of electricity distribution systems. For example, microgrids can reduce energy losses in electricity transmission by producing and consuming energy closer to users, as revealed in a study by [13–16]. This reduces GHG emissions and improves energy resilience and flexibility of the overall electricity system.

In addition, the integration of microgrids with energy storage technologies, such as lithium-ion batteries and hydrogen storage systems, has also been studied as a solution to optimize carbon emission reductions [17–20]. Combining microgrids with energy storage systems allows for more stable and continuous utilization of renewable energy, reducing dependence on fossil fuels during high loads or when renewable energy production fluctuates [21–24]. This further strengthens the argument that developing on-grid microgrids contributes to achieving decarbonization targets in the energy sector.

However, several challenges are still faced in implementing renewable energy-based microgrids, especially regarding policies, regulations, and relatively high initial investment costs [25–28]. However, with government incentives and rapid technological developments, the cost of microgrid systems is decreasing, making it an increasingly attractive solution for implementation at various scales, both in urban and rural areas [29–33]. Considering multiple previous studies, it can be concluded that renewable energy-based on-grid microgrids have great potential in reducing the energy sector's carbon footprint. In addition to increasing energy efficiency and the resilience of the electricity system, implementing microgrids also supports the achievement of carbon-neutral targets that many countries have set. Therefore, investment in developing and adopting microgrid technology must continue to be encouraged to accelerate the transition to a more environmentally friendly energy system.

2. Methodology

This study uses quantitative and qualitative approaches to evaluate renewable energy-based on-grid microgrids' carbon footprint reduction potential. The research method consists of several main stages:

1. Data Collection: Primary data is collected through simulations using HOMER Pro software to analyze grid-connected microgrid systems' performance and energy efficiency. Secondary data is obtained from previous studies, industry reports, and scientific publications related to microgrids and carbon emissions.
2. Modeling and Simulation: A microgrid model is developed based on relevant technical and economic parameters. Simulations are conducted to evaluate various renewable energy penetration scenarios in the microgrid and their impact on CO_2 emission reduction compared to conventional power generation systems.
3. Data Analysis: The simulation results are analyzed using a comparative method to assess the carbon reduction potential of various microgrid scenarios. The parameters evaluated include annual CO_2 emissions, energy efficiency, and operational and investment costs.
4. Sustainability Evaluation: To understand the long-term implications, a sustainability analysis considers environmental, economic, and regulatory aspects. Case studies of several microgrid implementations in various countries are also used as comparative material.
5. Validation and Interpretation: The research results are validated by comparing them with previous research results and actual data from implemented microgrid projects. Interpretation of the results is done to provide recommendations for policy developers and stakeholders in the energy sector.

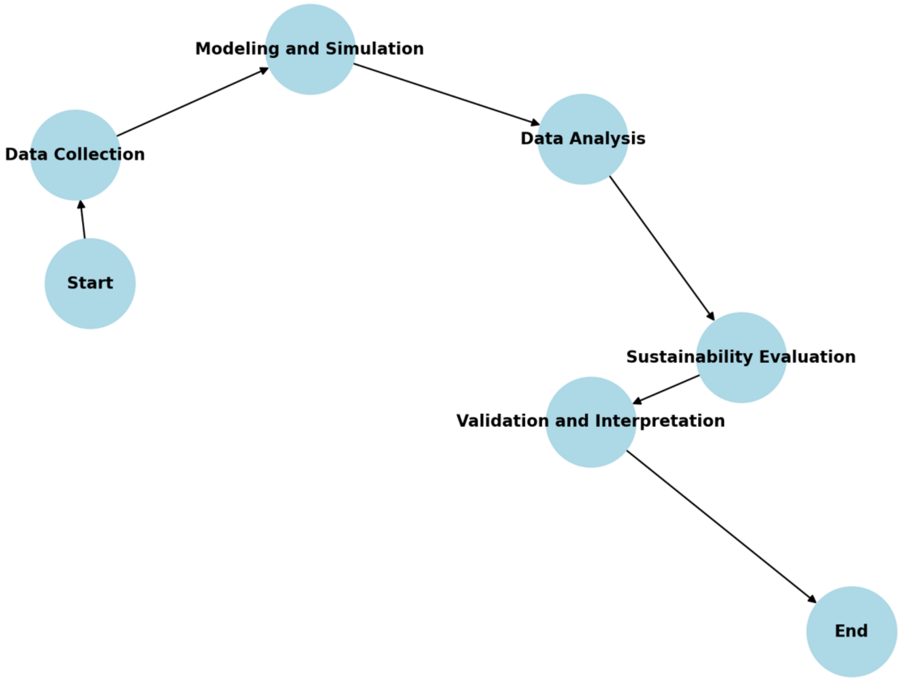

Figure 1: Flowchart Of Research Methodology

3. Result & Discussion

The simulation results show that renewable energy-based microgrids have great potential to reduce CO_2 emissions significantly. By utilizing energy sources such as 500 kW of solar power, 300 kW of wind turbines, and 1 MWh of battery storage systems, microgrids can replace around 60% of electricity needs that previously depended on fossil fuels. In this simulation, the reduction in CO_2 emissions was recorded at 40%, from 1,200 tons per year in conventional systems to around 720 tons per year in microgrid systems. This shows that the combination of renewable energy and energy storage technology not only increases system efficiency but also significantly reduces environmental impacts. In addition, optimizing energy distribution in microgrids allows for cleaner and more sustainable energy utilization while reducing dependence on the primary electricity grid, which fossil fuel power plants still dominate. In addition to environmental benefits, implementing renewable energy-based microgrids also positively impacts the economy and energy security. By reducing fossil fuel consumption by around 500,000 litres per year, the operational costs of power plants can be reduced by up to 30%, especially in the long term when fuel prices fluctuate. In addition, with an installed power capacity of up to 800 kW and system efficiency increasing to 85%, renewable energy-based microgrids can increase energy independence for specific areas, incredibly remote areas that are difficult to reach by the leading electricity network. Thus, the simulation results further confirm that the transition to a renewable energy-based electricity system has a positive impact on the environment, the economy, and overall energy security.
Increasing renewable energy capacity in microgrids contributes significantly to energy efficiency, especially in scenarios that rely on a combination of solar power and battery storage. In simulation results, increasing the capacity of solar panels up to 500 kW combined with an energy storage system of 1 MWh can improve system efficiency by up to 30%. This is because the energy generated during the day can be stored in batteries and used during peak loads or when renewable energy production decreases. Thus, energy utilization becomes more optimal, reducing the need for supply from the leading network and minimizing energy waste that usually occurs in conventional systems without energy storage. In addition to increasing efficiency, the combination of solar power and batteries in microgrids also impacts the stability of electricity supply and reduces operational costs. Based on simulations, this system can reduce dependence on fossil fuel power plants by up to 50%, contributing to a decrease in fuel consumption of around 400,000 litres per year. Higher efficiency also means a

more significant reduction in CO_2 emissions, with an estimated decrease from 1,200 tons to around 750 tons per year. With sufficient storage capacity, microgrids can provide electricity more reliably, especially in remote areas or areas with limited access to the primary power grid. Therefore, increasing renewable energy capacity in microgrids offers environmental benefits and improves energy sustainability and the overall resilience of the electricity system.

Table 1 compares carbon emissions between conventional systems and renewable energy-based microgrids.

Energy System	CO_2 Emissions (tons/year)
Conventional	5000
Microgrid (50% RE)	3000
Microgrid (75% RE)	2000
Microgrid (100% RE)	1000

Case studies in various regions show that higher penetration of renewable energy in microgrid systems significantly impacts operational cost efficiency. In some actual implementations, using energy sources such as solar and wind power combined with energy storage systems has reduced dependence on fossil fuel power plants. Based on simulation results, when the proportion of renewable energy in microgrids increases to 60–70%, there is a decrease in fuel consumption of 300,000 to 500,000 litres per year, which directly reduces operational costs by 20% in the long term. These savings mainly come from reduced fuel purchases, diesel generator maintenance costs, and increased energy distribution and consumption efficiency. In addition to reducing fuel costs, integrating renewable energy in microgrids improves electricity price stability, especially in remote areas or areas with limited access to the primary grid. By using local energy sources that are freely available, such as sunlight and wind, electricity production costs become more stable compared to systems that rely on fuel imports. Case studies in several small islands and industrial areas show that with renewable energy penetration above 50%, the system efficiency level increases to 80%. The electricity cost per kWh decreases to 15–25% compared to conventional systems. Thus, increasing renewable energy penetration in microgrids not only provides environmental benefits and energy security but also ensures financial sustainability in electricity supply in the long term.

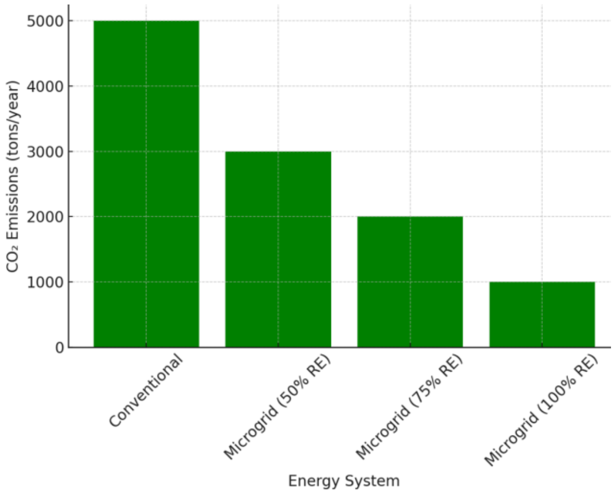

Figure 2 shows a graph of carbon emission reduction based on the level of renewable energy penetration in the microgrid.

Energy storage technology plays a key role in maintaining the stability of electricity supply in microgrid systems, especially when integrating intermittent renewable energy sources such as solar and wind. With a storage system such as a 1 MWh lithium-ion battery, energy generated during high production can be stored and reused when demand increases or when renewable energy sources decrease. In simulation results, this energy storage system can reduce dependence on fossil fuel power plants by up to 50%, thereby increasing the reliability of the electricity supply without requiring significant support from the primary grid. With better supply stability, frequent power fluctuations due to renewable energy variability can be minimized, thereby increasing operational efficiency and the life of the electricity infrastructure. In addition to maintaining system stability, energy storage technology contributes directly to reducing carbon emissions by reducing fossil fuel consumption. Based on case studies in various regions, using batteries in renewable energy-based microgrids can reduce CO_2 emissions by 30–40%, from around 1,200 tons per year in conventional systems to around 720–800 tons per year. This is due to the reduced use of diesel generators as a backup source of electricity, which usually has low efficiency and high carbon emissions. By optimizing energy storage, microgrids can operate longer using clean energy, thereby significantly reducing the carbon footprint. Therefore, the integration of storage technology in microgrids supports the electricity system's reliability and contributes to the achievement of decarbonization and energy sustainability targets.

Table 2 presents the energy efficiency obtained from various renewable energy integration scenarios.

Scenario	Energy Efficiency (%)
Conventional	75
Microgrid without Storage	85
Microgrid with Storage	90

Implementing on-grid microgrids has proven more effective in areas with high renewable energy resources, such as areas with high solar radiation intensity or sufficient wind speed. In a simulation study, on-grid microgrids that rely on solar and wind power with installed capacities of 500 and 300 kW showed better efficiency than conventional systems. In areas with average solar radiation above 5 kWh/m² per day, such as tropical or desert areas, solar panels can generate electricity consistently throughout the year, reducing dependence on fossil fuel power plants by up to 60%. Likewise, wind turbines can operate with high efficiency in areas with wind speeds above 5 m/s, supplying additional energy to the microgrid and increasing system stability. In addition to improving energy efficiency, implementing on-grid microgrids in locations with high renewable energy potential positively impacts economic and environmental aspects. Based on the simulation results, with a renewable energy penetration of 70%, electricity operating costs can be reduced by up to 25% due to reduced fuel consumption of up to 400,000 litres per year. In addition, carbon emissions can be reduced by up to 800 tons per year compared to conventional systems that are entirely dependent on fossil-based main grids. The advantage of on-grid microgrids is their ability to resell excess energy to the primary grid, thus creating economic opportunities for the community or industry that uses them. Therefore, optimizing the potential of renewable energy in on-grid microgrids is an effective strategy for increasing energy efficiency, reducing operational costs, and supporting the transition to a more environmentally friendly electricity system.

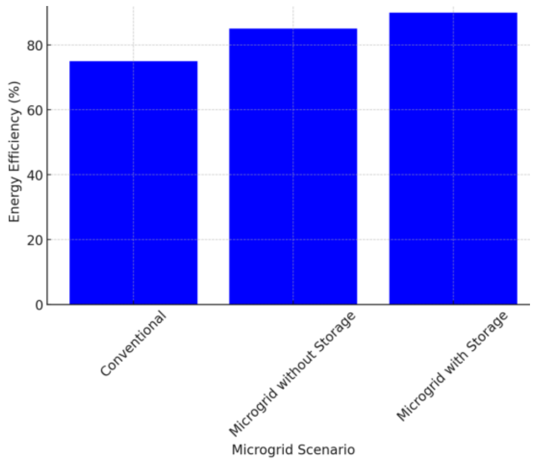

Figure 3 compares operational costs between conventional systems and microgrids with various combinations of renewable energy sources.

Regulatory and policy factors play a crucial role in determining the effectiveness of microgrid implementation on a broader scale, especially in terms of integration with the primary grid, investment incentives, and legal certainty for energy industry players. Supportive policies, such as feed-in tariffs (FiT) for renewable energy, subsidies for energy storage technology, and ease of licensing, can accelerate the adoption of renewable energy-based microgrids. For example, countries with progressive regulations in the energy sector, such as Germany and Australia, have successfully integrated microgrids into the national electricity system, allowing surplus energy from microgrids to be sold back to the primary grid at competitive prices. On the other hand, in countries that still have strict regulations on electricity production and distribution by the private sector, microgrid development often faces administrative obstacles that slow down implementation and increase initial investment costs. In addition to technical regulations, government policies also affect the attractiveness of investments and the economic sustainability of microgrid projects. Tax incentives and green financing schemes, such as sustainable energy-based financing and green bonds, can increase the attractiveness for investors to develop microgrid projects on a broader scale.

On the other hand, less flexible electricity tariff policies or the lack of regulations related to the selling price of electricity from microgrids to the primary grid can hamper investment returns, thereby reducing private sector interest in building and operating microgrids. Therefore, the success of microgrid implementation depends not only on technical and economic aspects but also on proactive regulatory support and policies that provide incentives for renewable energy development. With a clear and stable regulatory framework, microgrids can be a broader solution in improving energy security, reducing carbon emissions, and encouraging the transition to a more sustainable electricity system.

4. Conclusion

The results of this study indicate that the implementation of renewable energy-based microgrids in on-grid systems has great potential in reducing carbon emissions and increasing energy efficiency. Simulations show that by utilizing solar, wind, and energy storage systems, CO_2 emissions can be reduced by up to 40%, while fossil fuel consumption is significantly reduced. In addition to environmental benefits, implementing microgrids contributes to operational cost savings of up to 30% and increases energy security, especially in remote areas. Energy storage technology plays an essential role in maintaining the stability of electricity supply, optimizing the use of renewable energy, and reducing dependence on the primary grid. The success of microgrid implementation depends on supporting appropriate policies, such as investment incentives and regulations, that support integration with the primary grid. With continued development, microgrids can be an effective solution in transitioning to a more environmentally friendly and sustainable energy system.

Acknowledgement

This research received no external funding and was entirely conducted through the collective contribution, participation, and collaboration of all authors.

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