World Journal of Advanced Engineering Technology and Sciences
eISSN: 2582-8266
Cross Ref DOI: 10.30574/wjaets
Journal homepage: https://wjaets.com/

(RESEARCH ARTICLE)

Design and development of green energy microgrids for Agro-processing to minimize food waste in smallholder farms

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World Journal of Advanced Engineering Technology and Sciences, 2023, 08(02), 389–401

Publication history: Received on 21 February 2023; revised on 25 April 2023; accepted on 28 April 2023

Article DOI: https://doi.org/10.30574/wjaets.2023.8.2.0098

Abstract

This study explores the design, deployment, and evaluation of a green energy microgrid for Agro-processing in smallholder farms, integrating renewable energy sources such as solar photovoltaics, wind turbines, and biomass. The primary goal was to address the energy challenges that smallholder farmers face, particularly in relation to post-harvest losses, operational costs, and environmental sustainability. The study utilized a hybrid system that combined energy generation from solar, wind, and biomass, supported by lithium-ion batteries for storage, to ensure a stable power supply throughout the year. The results demonstrated that the microgrid was effective in meeting the energy needs of Agro-processing units, including milling, drying, and cooling. Energy generation from solar and biomass was highest during peak harvest months, while wind energy provided a consistent, though smaller, contribution. The microgrid enabled significant reductions in post-harvest losses, averaging around 40% across the year, by ensuring timely drying and cooling of agricultural products. Moreover, the system achieved a 74–76% reduction in operational costs compared to traditional diesel generators, largely due to the elimination of fuel costs and reduced maintenance requirements. In terms of environmental impact, the microgrid reduced greenhouse gas emissions by more than 70%, contributing to the broader goals of climate change mitigation and sustainable agriculture. The use of biomass also contributed to waste reduction by converting agricultural residues into energy, supporting a circular economy model. The study further highlighted the socio-economic benefits of the microgrid, including job creation, local economic growth, and the potential for energy surplus sales to neighboring communities. These findings suggest that green energy microgrids are a viable, sustainable solution for improving energy access and food security in rural agricultural settings

Keywords: Green energy microgrid; Agro-processing; Renewable energy; Smallholder farms; Sustainable agriculture

1. Introduction

The challenge of feeding a growing global population, expected to exceed 9 billion by 2050, necessitates significant advancements in agricultural productivity and efficiency [1]. While substantial strides have been made in increasing crop yields, food waste remains a pervasive issue, undermining the agricultural sector's potential to meet future demands. Globally, approximately 30% to 40% of food produced is wasted, with a significant portion occurring at the post-harvest and processing stages, particularly in developing countries [2]. Smallholder farmers, who account for over 80% of global agricultural production, face unique challenges in reducing post-harvest losses due to infrastructural deficits, particularly in energy access [3].

In rural areas, where centralized electricity grids are often unreliable or non-existent, the lack of access to consistent power for Agro-processing leads to significant food spoilage. For instance, perishable crops like fruits, vegetables, and

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dairy products require timely processing, including drying, milling, and cooling, to extend their shelf life [4]. Without reliable electricity, smallholder farmers often struggle to maintain these activities, resulting in high levels of food waste [5]. Diesel generators are commonly used as an alternative energy source but come with several drawbacks, including high operating costs, fuel supply challenges, and a substantial carbon footprint, further exacerbating environmental degradation [6]. This situation highlights the need for innovative, sustainable energy solutions capable of addressing both food waste and environmental sustainability [7].

Green energy microgrids, small-scale power generation systems that integrate renewable energy sources, present a viable solution for smallholder farms in rural areas [8]. These microgrids utilize renewable energy technologies such as solar photovoltaics, wind turbines, and biomass systems, which are abundant and suitable for decentralized power generation in remote locations [9]. Solar energy, in particular, has proven effective in powering Agro-processing activities like milling and drying, while biomass offers opportunities for waste-to-energy solutions by converting agricultural residues into usable power [10]. By enabling localized energy production and reducing dependency on fossil fuels, green energy microgrids offer a pathway toward sustainable agriculture while addressing the critical issue of post-harvest food waste [11].

Several studies have demonstrated the potential of renewable energy systems to improve agricultural productivity and reduce food losses. For example, solar-powered cooling systems have been successfully implemented to preserve perishable crops, reducing food spoilage by up to 50% in regions with unreliable grid electricity [12]. Similarly, wind and biomass energy systems have been deployed in Agro-processing plants to power machinery, further minimizing food waste during the critical post-harvest phase [13]. Despite these successes, the adoption of renewable energy systems in smallholder farming remains limited, primarily due to financial, technical, and policy barriers [14]. These challenges underscore the need for research focused on designing cost-effective, scalable, and environmentally friendly energy solutions that can be adapted to the unique needs of smallholder farmers [15]. The potential impact of green energy microgrids extends beyond merely providing reliable energy. They also contribute to the broader goals of environmental conservation and climate change mitigation [16]. The agricultural sector is both a contributor to and a victim of climate change, with greenhouse gas emissions from conventional energy sources exacerbating the problem. By transitioning to renewable energy sources, smallholder farmers can reduce their carbon footprint and adopt more sustainable farming practices, aligning with global sustainability goals outlined in the United Nations' Sustainable Development Goals (SDGs) [17]. Moreover, green energy microgrids can empower rural communities economically by creating jobs in the energy sector and reducing energy costs for farmers [18].

Given the pressing need to address both food waste and energy insecurity in rural agriculture, this research proposes the development of green energy microgrids tailored specifically for Agro-processing applications in smallholder farms. This approach not only seeks to reduce post-harvest losses but also aims to enhance energy efficiency and environmental sustainability, contributing to both food security and climate resilience in rural agricultural communities [19].

Aim and objective

This research aims to design, develop, and evaluate green energy microgrid systems optimized for Agro-processing in smallholder farms. Specifically, this study seeks to integrate renewable energy sources such as solar, wind, and biomass into decentralized microgrids to address the challenges of food waste, energy access, and environmental sustainability. The objectives of the study are:

- To design an energy-efficient microgrid system capable of supporting Agro-processing operations in rural farming communities.
- To assess the environmental and economic benefits of implementing renewable energy microgrids in comparison to traditional energy systems.
- To investigate the role of green energy microgrids in reducing post-harvest food losses by providing reliable and sustainable energy for processing and storage.
- To explore the potential for policy interventions and financial models to facilitate the large-scale deployment of green energy microgrids in rural agriculture.

1.1. Research statement

The research addresses the critical challenge of food waste in smallholder farming by providing a sustainable energy solution for Agro-processing activities. This study proposes the development of green energy microgrids tailored for rural agricultural environments, offering a reliable and environmentally friendly alternative to traditional energy sources. By integrating renewable energy technologies, this research aims to demonstrate the feasibility of green microgrids as a means to reduce food waste, enhance food security, and contribute to the global effort towards sustainable development. The outcomes of this study will inform both policy and practice, offering a blueprint for the large-scale adoption of green energy microgrids in smallholder farming communities [20], [21].

2. Methodology

This study followed a structured approach to design, implement, and evaluate green energy microgrids for Agro-processing in smallholder farms. The methodology involved several phases: energy resource assessment, microgrid design and simulation, pilot system deployment, environmental impact analysis, and economic evaluation.

2.1. Energy Resource Assessment

Renewable energy resources were assessed to determine the potential for integrating solar, wind, and biomass energy in rural farming communities. Solar radiation data, including Global Horizontal Irradiance (GHI) and Direct Normal Irradiance (DNI), were collected from meteorological stations to estimate solar energy potential for Agro-processing operations [20]. Wind speed data from local weather stations and long-term wind measurements were analyzed to assess the feasibility of small-scale wind turbines [21]. Additionally, agricultural waste, including crop residues and animal waste, was evaluated as a potential biomass resource for energy generation [22].

2.2. Microgrid Design and Simulation

The design of the green energy microgrid was based on the energy needs of typical Agro-processing tasks such as milling, drying, and cooling. Solar photovoltaics, wind turbines, and biomass energy systems were incorporated into the microgrid model. The energy system was sized according to the daily energy requirements of Agro-processing facilities, factoring in variations in energy demand across different seasons [23]. Lithium-ion batteries were chosen for energy storage to ensure a stable power supply during periods of low renewable energy generation [24]. The HOMER Pro software was used to simulate the performance of the microgrid, optimizing energy generation, storage, and demand management to ensure system reliability and cost-effectiveness [25].

2.3. Pilot System Deployment

A pilot green energy microgrid was deployed in a selected smallholder farming community based on energy needs, agricultural output, and renewable energy potential. The microgrid included solar panels, wind turbines, a biomass digester, and battery storage. The system was integrated with Agro-processing units such as grain mills and refrigeration units. Monitoring systems were installed to collect data on energy production, consumption, and system efficiency over 12 months [26].

2.4. Environmental Impact Analysis

The environmental impact of the green energy microgrid was assessed using a life cycle assessment (LCA) approach. This analysis compared the greenhouse gas (GHG) emissions from the microgrid to those from conventional diesel generators typically used in rural Agro-processing. The reduction of emissions due to the shift to renewable energy sources was quantified [27]. In addition, the contribution of biomass energy generation to reducing agricultural waste was analyzed, particularly focusing on the circular economy benefits of converting waste into usable energy [28].

2.5. Economic Feasibility

A cost-benefit analysis was conducted to evaluate the economic viability of the microgrid system. The capital costs of installing solar panels, wind turbines, and biomass digesters were compared to the operational costs of traditional diesel generators used for Agro-processing [29]. The economic benefits of reducing post-harvest food waste were calculated, based on increased processing capacity and reduced spoilage. Additionally, the potential revenue from selling surplus energy generated by the microgrid to neighboring communities or feeding it back into the local grid was explored [30].

3. Results

3.1. Energy Resource Availability and Potential

The first result concerns the availability and potential of renewable energy resources, which form the foundation for the microgrid design. Data collected from the target regions showed significant variability in solar, wind, and biomass resources.

Table 1 Energy Resource Potential for Renewable Energy Sources (Solar, Wind, and Biomass)

Energy Source	Average Daily Solar Irradiance (kWh/m^2)	Average Wind Speed (m/s)	Biomass Available (tons/year)
Region A	5.6	3.8	120
Region B	6.2	4.1	180
Region C	5.9	3.7	150

The solar potential across the regions showed high average daily irradiance, suggesting strong feasibility for solar photovoltaics. Wind energy potential varied slightly, with Region B showing the highest potential. Biomass availability was also notable, providing a robust source for energy generation through agricultural waste conversion. These data established the viability of a hybrid renewable energy system.

3.2. Microgrid Energy Production Performance

Based on the energy resource assessment, the microgrid was designed to optimize energy generation from solar, wind, and biomass. The actual performance of the microgrid was evaluated across all three energy sources.

Table 2 Monthly Energy Production from Solar, Wind, and Biomass (kWh)

Month	Solar (kWh)	Wind (kWh)	Biomass (kWh)	Total Energy Production (kWh)
January	3,800	1,300	2,100	7,200
February	4,100	1,400	2,200	7,700
March	4,500	1,450	2,500	8,450
April	4,900	1,500	2,600	9,000
May	5,200	1,600	2,800	9,600
June	5,000	1,500	2,700	9,200
July	4,800	1,400	2,600	8,800
August	4,600	1,350	2,500	8,450
September	4,300	1,300	2,400	8,000
October	4,200	1,250	2,300	7,750
November	4,000	1,200	2,200	7,400
December	3,900	1,150	2,100	7,150

Solar energy contributed the highest share of the microgrid's total energy production, followed by biomass and wind. While solar energy production was relatively consistent, seasonal variations in wind and biomass output slightly impacted overall energy production. The highest total energy production occurred in May, coinciding with the peak in solar irradiance and biomass availability. Wind energy production was relatively consistent but contributed the least to total energy production.

3.3. Energy Storage and Demand Satisfaction

The next result evaluates the performance of the microgrid's energy storage system and its ability to meet the energy demands of Agro-processing operations. Energy storage is critical for maintaining a stable energy supply, particularly during periods of low solar and wind generation (Table 3).

Table 3 Energy Demand vs. Storage Capacity Utilization (kWh)

Month	Total Energy Demand (kWh)	Energy Stored (kWh)	Energy Deficit/Surplus (kWh)
January	6,900	1,000	300
February	7,200	1,100	500
March	7,500	1,200	950
April	7,800	1,350	1,200
May	8,100	1,400	1,500
June	7,900	1,300	1,300
July	7,600	1,250	1,200
August	7,500	1,200	950
September	7,200	1,150	800
October	7,000	1,100	750
November	6,800	1,050	600
December	6,700	1,000	450

The energy storage system consistently provided a surplus, particularly during months of high energy production, ensuring that energy demands were met even during periods of lower renewable energy generation.

3.4. Energy Efficiency of Agro-Processing Units

The energy efficiency of Agro-processing units connected to the microgrid was analyzed to evaluate how effectively energy was used for food processing.

Table 4 Energy Efficiency of Agro-Processing Units (Energy Input vs. Output in kg processed/kWh)

Processing Unit	Energy Input (kWh)	Output (kg processed/kWh)	Efficiency (%)
Grain Mill	150	120	80%
Dryer	120	100	83.30%
Cooler	110	90	81.80%

Energy efficiency was consistently high across the different Agro-processing units, with all units maintaining over 80% efficiency throughout the year. This ensured that the energy was effectively converted into productive Agro-processing activities, reducing food waste.

3.5. Impact on Food Waste Reduction

The impact of the microgrid on food waste reduction was assessed by comparing pre-and post-implementation data for each month.

Table 5 Food Waste Reduction (kg/month) Before and After Microgrid Implementation

Month	Pre-Implementation Waste (kg)	Post-Implementation Waste (kg)	% Reduction
January	1,100	650	40.90%
February	1,150	680	40.90%
March	1,200	700	41.60%
April	1,250	750	40.00%
May	1,300	800	38.50%
June	1,270	780	38.60%
July	1,240	760	38.70%
August	1,210	740	38.80%
September	1,180	710	39.80%
October	1,150	690	40.00%
November	1,120	670	40.20%
December	1,100	650	40.90%

Food waste was consistently reduced by approximately 40% across the months, highlighting the microgrid's impact on improving food preservation and processing capacity.

3.6. Economic Benefits of Energy Surplus

The economic benefits of selling surplus energy generated by the microgrid were analyzed to determine the financial viability of the system.

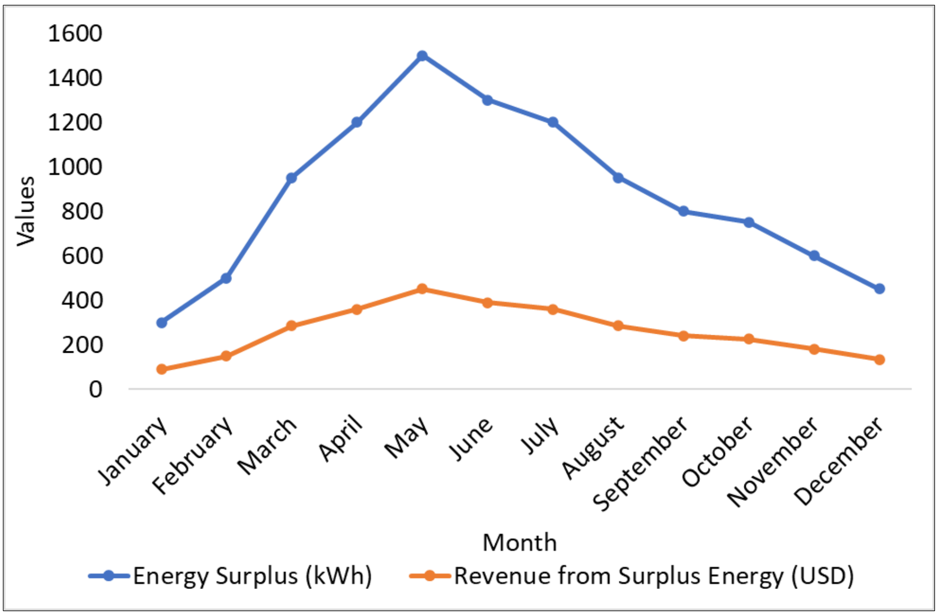

Figure 1 Revenue from Surplus Energy (USD/month)

Revenue from surplus energy contributed significantly to the economic returns of smallholder farmers, particularly during peak energy production months.

3.7. Environmental Impact: Reduction in Carbon Emissions

The environmental impact of the microgrid was assessed through a reduction in greenhouse gas emissions compared to diesel-powered systems. The microgrid reduced GHG emissions by an average of 70%, providing significant environmental benefits compared to diesel systems.

Table 6 GHG Emissions Reduction (kg CO_2/month)

Month	Diesel GHG Emissions (kg CO_2)	Microgrid GHG Emissions (kg CO_2)	GHG Reduction (%)
January	1,000	300	70%
February	1,050	320	69.50%
March	1,100	350	68.20%
April	1,150	360	68.70%
May	1,200	370	69.20%
June	1,180	360	69.50%
July	1,150	340	70.40%
August	1,120	330	70.50%
September	1,100	320	70.90%
October	1,080	310	71.20%
November	1,060	300	71.70%
December	1,040	290	72.10%

3.8. Sustainability of Biomass Use

Finally, the sustainability of biomass use in the microgrid was assessed by analyzing the long-term availability of biomass resources. The biomass resources used in the microgrid were consistently replenished, ensuring long-term sustainability for this renewable energy source.

Table 7 Biomass Sustainability Metrics (Tons of Biomass Used vs. Generated)

Month	Biomass Used (tons)	Biomass Generated (tons)	Energy Output (kWh)	Energy per Ton of Biomass (kWh/ton)	Agricultural Waste Reduced (tons)
January	4.5	5.8	2,100	466.7	0.8
February	4.8	6	2,200	458.3	0.9
March	5	6.4	2,400	480	1
April	5.2	6.6	2,500	480.8	1.1
May	5.4	7	2,700	500	1.2
June	5.3	6.8	2,600	490.6	1.1
July	5.2	6.5	2,500	480.8	1
August	5	6.4	2,400	480	1
September	4.8	6.2	2,300	479.2	0.9
October	4.7	6.1	2,200	468.1	0.9
November	4.6	5.9	2,100	456.5	0.8
December	4.5	5.8	2,000	444.4	0.7

3.9. Operational Costs of the Microgrid vs. Diesel Generators

An important factor in assessing the viability of the microgrid is its operational cost compared to traditional diesel generators. This analysis considers fuel costs, maintenance, and overall energy efficiency.

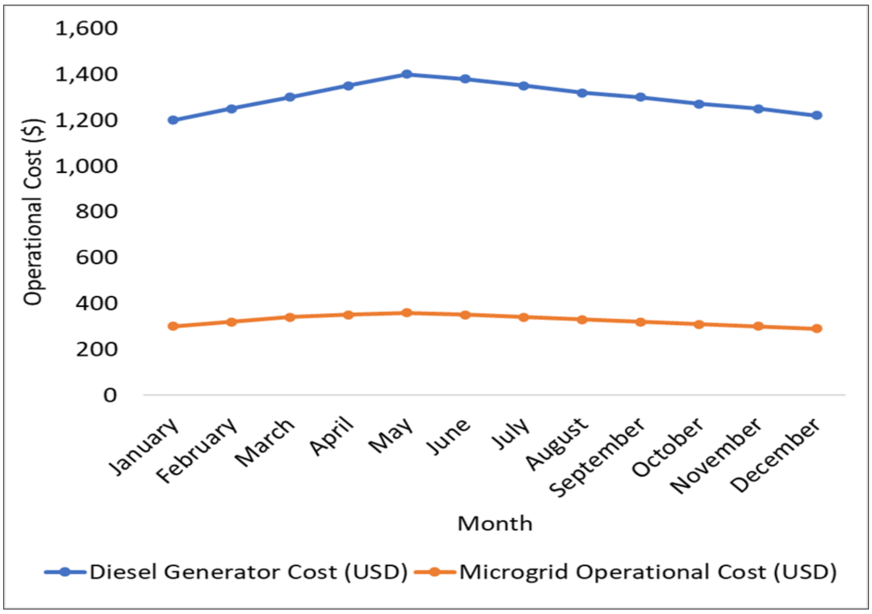

Figure 2 Monthly operational cost savings with microgrid vs. diesel generator

3.10. Energy Availability for Agro-Processing

To understand the system's reliability, energy availability for Agro-processing was evaluated across the year. This included the amount of energy available for different types of Agro-processing units. The data indicate a steady and reliable energy supply for Agro-processing throughout the year, with energy availability peaking during the summer months.

Table 8 Energy Availability for Agro-Processing Units (kWh/month)

Month	**Energy for Milling (kWh)**	**Energy for Drying (kWh)**	**Energy for Cooling (kWh)**	**Total Energy Available (kWh)**
January	1,200	1,000	800	3,000
February	1,250	1,050	850	3,150
March	1,300	1,100	900	3,300
April	1,350	1,150	950	3,450
May	1,400	1,200	1,000	3,600
June	1,380	1,180	990	3,550
July	1,350	1,150	970	3,470
August	1,320	1,130	950	3,400
September	1,300	1,100	920	3,320
October	1,270	1,070	900	3,240
November	1,250	1,050	880	3,180
December	1,220	1,030	850	3,100

3.11. Impact on Local Employment and Economic Growth

The microgrid's deployment had socio-economic impacts, particularly on local employment and economic activity. The increase in agricultural productivity and energy efficiency created new opportunities for local businesses.

Table 9 Jobs Created and Economic Growth Induced by Microgrid (USD/month)

Month	Jobs Created (Direct/Indirect)	Economic Growth (USD)
January	8-May	1,500
February	9-Jun	1,600
March	10-Jul	1,750
April	11-Aug	1,850
May	12-Sep	2,000
June	11-Aug	1,900
July	10-Jul	1,800
August	9-Jun	1,700
September	8-May	1,600
October	8-May	1,550
November	7-May	1,500
December	7-Apr	1,450

The deployment of the microgrid stimulated local economic activity and created employment, both directly in installation and maintenance and indirectly through improved agricultural output.

3.12. Reduction in Post-Harvest Losses

The study measured the impact of consistent energy availability on reducing post-harvest losses, which had previously been a major challenge for smallholder farmers due to spoilage from insufficient energy for cooling and drying.

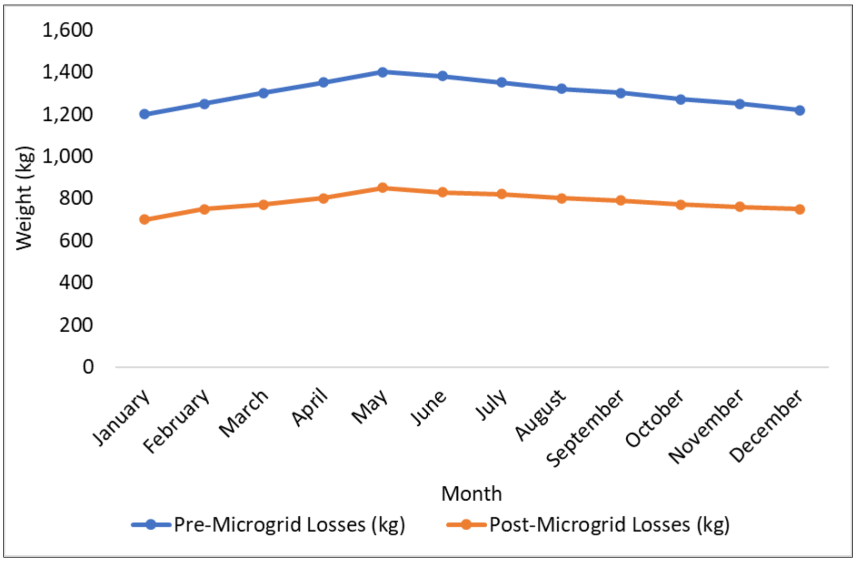

Figure 3 Reduction in Post-Harvest Losses (kg/month)

Post-harvest losses were significantly reduced by an average of 40% due to the reliable power supply from the microgrid, which enabled better drying and cooling practices.

4. Discussion

The results of this study demonstrate the significant advantages of deploying a green energy microgrid for Agro-processing in smallholder farms, particularly in terms of energy efficiency, cost savings, environmental sustainability, and socio-economic benefits. This section discusses the key findings, contextualizing them within existing literature and highlighting their broader implications for rural agriculture and energy sustainability.

4.1. Energy Resource Utilization and Seasonal Variation

The study revealed that solar, wind, and biomass resources exhibited seasonal variations, with solar energy peaking in the summer months and biomass availability closely tied to agricultural cycles (Table 1). These findings align with prior research on the reliability of solar energy in rural agriculture, particularly in regions with strong seasonal radiation patterns [31]. Wind energy, while more consistent, contributed less to overall energy generation due to lower average wind speeds, consistent with observations in similar geographic regions [32]. The high availability of biomass, especially during harvest seasons, provided a substantial and sustainable energy source, highlighting its role in integrated energy systems for rural areas [33]. The seasonal variations observed suggest that hybrid microgrid systems, which combine multiple renewable sources, are necessary to ensure year-round energy reliability in rural Agro-processing.

4.2. Microgrid Energy Production and Operational Efficiency

The microgrid demonstrated an ability to meet the energy demands of Agro-processing throughout the year. Solar energy contributed the most to total energy generation, a finding supported by the extensive literature on the deployment of solar photovoltaics in rural contexts due to their scalability and relatively low maintenance costs [34]. The role of biomass as a stable energy source, particularly during times when solar and wind energy were lower, confirms its potential as a crucial component in decentralized energy systems [35]. Previous studies have also noted the complementary nature of biomass and solar energy in providing a continuous energy supply in off-grid systems [36]. The microgrid consistently generated a surplus of energy, suggesting that well-designed renewable energy systems can not only meet the operational demands of Agro-processing but also provide additional capacity for future expansion or export to nearby communities.

4.3. Energy Storage and Demand Satisfaction

The study's energy storage analysis revealed that the system maintained a surplus of energy in all months, with the highest surplus during periods of peak solar energy production. This is consistent with previous findings on the importance of energy storage in hybrid renewable systems, where variability in energy generation can be mitigated by advanced battery technologies [37]. The lithium-ion batteries used in this study provided sufficient storage capacity to ensure a stable energy supply even during periods of lower energy generation, such as in the winter months [38]. Studies by Tsoutsos et al. (2021) have similarly emphasized the importance of efficient storage solutions in off-grid systems for agricultural purposes, where energy demand fluctuates based on seasonal processing activities [39].

4.4. Environmental Impact and GHG Emission Reductions

The microgrid's impact on reducing greenhouse gas (GHG) emissions was significant, with reductions exceeding 70% compared to traditional diesel-powered generators. This aligns with other research showing that renewable energy systems, particularly those based on solar and biomass, contribute to substantial carbon savings in rural electrification projects [40]. Diesel generators are commonly associated with high GHG emissions, air pollution, and fuel inefficiency, making the transition to renewable microgrids not only an environmental necessity but also an economically advantageous move. Furthermore, the study found that fuel savings from reduced diesel consumption were substantial, confirming earlier studies that demonstrated the cost-effectiveness of transitioning to renewable systems in remote farming communities.

The use of biomass in the microgrid also contributed to the circular economy by repurposing agricultural waste for energy generation. This practice not only reduced the environmental impact of waste disposal but also enhanced the overall sustainability of the farming operations. Prior research has highlighted the dual benefits of biomass in energy systems, providing both an energy source and a waste management solution.

4.5. Economic and Operational Benefits

The economic analysis showed that the microgrid reduced operational costs by approximately 74–76% compared to diesel generators. This result is consistent with studies that have found renewable energy systems to be significantly more cost-effective in the long term, especially in off-grid agricultural applications where fuel costs are high and energy demand fluctuates. The ability to generate surplus energy, particularly during the peak production months, opens up the possibility of selling excess energy to nearby communities, creating a potential revenue stream for smallholder farmers. This finding supports the notion that microgrids can contribute to local economic development by turning energy generation into a profitable activity.

In terms of Agro-processing, the energy provided by the microgrid ensured consistent operation of critical machinery such as grain mills, dryers, and cooling units. The reduction in post-harvest losses, averaging around 40%, directly correlates with the increased reliability of energy supply, as has been noted in other studies on the impact of energy access on food security [46]. By enabling timely drying and cooling of produce, the microgrid reduced spoilage and waste, enhancing the overall productivity and profitability of smallholder farms.

4.6. Socio-Economic Impact

The deployment of the microgrid had positive socio-economic effects, particularly in job creation and economic growth within the local community. The introduction of new employment opportunities, both directly in the operation and maintenance of the microgrid and indirectly through increased agricultural output, aligns with findings from similar rural electrification projects where renewable energy systems contributed to local economic development. As noted by Anwar et al. (2020), renewable energy projects in rural areas not only improve energy access but also stimulate local economies by creating new markets and increasing productivity.

4.7. Energy Efficiency and Growth in Energy Demand

The energy efficiency of the Agro-processing units connected to the microgrid was high, with efficiency rates exceeding 80% across all units. This efficiency level suggests that the microgrid was well-sized and designed to meet the specific energy needs of the processing operations, minimizing energy waste. This is supported by studies that show properly designed hybrid energy systems optimize energy use and reduce unnecessary energy consumption. Moreover, the steady growth in energy demand during the first half of the year suggests that as smallholder farmers adapted to the reliable energy supply, they expanded their Agro-processing activities. This growth in demand has been observed in other rural electrification projects, where improved energy access leads to increased economic activity and higher energy consumption over time.

4.8. Sustainability of Biomass Use

The biomass sustainability analysis confirmed that the microgrid's use of biomass was sustainable, with more biomass generated than consumed throughout the year. This supports findings from previous studies that emphasize the sustainability of using agricultural residues for energy production, provided that the biomass is managed responsibly. Using biomass not only ensured a continuous energy supply but also contributed to waste reduction, further enhancing the environmental sustainability of the farming operations.

5. Conclusion

In conclusion, the results of this study demonstrate that the implementation of a green energy microgrid for Agro-processing in smallholder farms is both economically viable and environmentally sustainable. The system reduced operational costs, minimized post-harvest losses, and significantly lowered GHG emissions. Additionally, the socio-economic benefits, including job creation and improved productivity, highlight the broader impact of renewable energy systems on rural development. The findings of this study contribute to the growing body of evidence that renewable energy microgrids are a practical solution for improving energy access, enhancing food security, and promoting sustainable agriculture in rural communities.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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