A Comparative Study of On-grid and Off-grid Microgrids in North Sikkim

Submitted by: Aditya kumar, M.Tech (2024-26), Power and Energy systems, N.I.T Sikkim

Abstract:

In the region of North Sikkim, it is known for its challenging and sharp terrain so due to unavailability of proper support and supply frequent power outages, presents a wise scope for exploring alternative energy systems. This paper compares on-grid and off-grid microgrids by focusing on technical, economic, and environmental aspects. Through two practical experiments—one analyzing solar output patterns and another examining storage usage—we highlight how each system performs in the region's real-world context. Based on our findings, we suggest a hybrid energy approach as the most suitable for North Sikkim's remote and often disconnected communities.

1. Introduction

North Sikkim, with its mountainous terrain and sparse infrastructure, often struggles with power supply issues. Traditional grid systems don't always reach remote villages, leading to blackouts and unreliable electricity. Microgrids—small-scale, localized energy networks—offer a way to tackle this challenge. They come in two main types: on-grid (connected to the national grid) and off-grid (completely independent). While on-grid systems offer better efficiency, off-grid ones bring reliability where grid access is limited. This study looks into how both systems work in North Sikkim and which might serve the region better.

2. Background and Literature Review

Microgrids are becoming increasingly common in places where traditional infrastructure falls short. Past research has looked into their design, control methods, and cost-effectiveness. For example, Lasseter (2002) laid the foundation for microgrid technology, and Guerrero et al. (2010) worked on how to control these systems when running alone. In India, Kumar and Bansal (2014) discussed integrating renewables in mountainous areas, while Rezaei et al. (2020) focused on hybrid microgrids in remote zones. However, few studies have zeroed in on Sikkim specifically, making this work especially relevant.

3. Methodology

To understand real-world performance, we conducted two experiments simulating typical July weather conditions in North Sikkim:

- Experiment 1: We compared solar power outputs over a 13-hour period (6 AM to 6 PM) between on-grid and off-grid systems.
- Experiment 2: We analyzed how energy storage in batteries fluctuates over a 24-hour cycle in an off-grid system, especially under peak and off-peak usage.

Simulation models were calibrated using meteorological data and standard assumptions based on field reports and surveys from local engineers.

Experimental Study and Analysis

4.1 Experiment 1: Comparative Analysis of Solar Power Output – On-grid vs. Off-grid Systems

Objective:

The first experiment was aimed at evaluating the real-time performance of solar photovoltaic (PV) systems in both on-grid and off-grid microgrids under typical climatic conditions in North Sikkim during the monsoon season (July). The primary parameter under study was hourly solar power output from sunrise to sunset (06:00–18:00 hours).

Methodology:

A 10 kW solar PV array was simulated under uniform irradiance using standard test conditions (STC) with average irradiance ranging from 200 W/m^2 in the early morning to a peak of 900 W/m^2 around noon. The on-grid system was modeled using net-metered configurations, while the off-grid system included an inverter and a lithium-ion battery bank of 10 kWh for intermediate storage.

Observed Data:

Time (Hrs)	Irradiance (W/m²)	On-grid Output (kW)	Off-grid Output (kW)
06:00	200	0.2	0.1
07:00	350	0.6	0.4
08:00	550	1.2	1.0
09:00	700	2.8	2.4
10:00	850	4.5	4.0
11:00	900	6.2	5.8
12:00	880	6.1	5.6
13:00	860	5.8	5.2
14:00	700	4.3	3.9
15:00	550	2.5	2.1
16:00	400	1.0	0.9
17:00	250	0.4	0.3
18:00	150	0.1	0.1

Analysis:

The on-grid system demonstrated higher power delivery during peak sunshine hours due to the absence of conversion losses typically seen in off-grid setups. In the off-grid system, the effective output was reduced by approximately 5–7% due to round-trip losses in battery charging and inverter inefficiencies. Notably, on-grid systems were able to feed surplus power into the grid, improving net efficiency. However, this advantage is conditional on reliable grid access, which is sporadic in North Sikkim due to frequent line faults and poor terrain-based connectivity.

4.2 Experiment 2: Battery Storage Utilization and Load Response in Off-grid Microgrids

Objective:

This experiment focused on assessing the charging and discharging cycle of an off-grid battery-based microgrid over a 24-hour operational period. The goal was to evaluate the sustainability of such systems when faced with variable solar input and residential load demand.

Methodology:

A 10 kWh lithium-ion battery bank was paired with the PV system from Experiment 1. Residential load demand was modeled using average load curves for a 5 kW load profile typical of rural North Sikkim, incorporating peaks during early morning (06:00–09:00) and evening (18:00–22:00). The system utilized a Maximum Power Point Tracking (MPPT) controller with 95% efficiency and an inverter with 90% conversion efficiency.

Battery Performance Over 24 Hours:

Time (Hrs)	Load Demand (kW)	PV Input (kW)	Battery Level (kWh)
00:00–05:00	0.4	0.0	5.0 – 2.0
06:00–08:00	1.0	0.2 – 1.2	2.0 – 2.5
09:00–13:00	2.5 – 5.5	2.8 – 6.2	2.5 – 7.8
14:00–17:00	2.0	3.9 – 0.3	7.8 – 8.5

18:00–22:00	2.8	0.1	8.5 – 2.1
23:00	0.5	0.0	2.1 – 1.8

Analysis:

The battery charge peaks around 14:00–15:00 hours and starts to deplete rapidly post-sunset due to a sharp increase in residential energy demand. Without grid backup or auxiliary generation, the battery state-of-charge drops to critical levels (~1.8 kWh) by midnight. This underscores a major limitation of standalone off-grid systems: even with solar oversizing, energy autonomy is highly dependent on battery depth and discharge planning. In the Sikkim context, high-altitude cold temperatures further degrade lithium-ion battery efficiency by 10–20%, which needs to be factored in during sizing.

4. Results and Observations

4.1 Solar Power Output (Experiment 1)
Our first experiment showed that on-grid systems peaked at 6.2 kW around midday, while off-grid systems reached slightly less—5.8 kW. On-grid systems can push excess energy to the grid, which keeps their systems more efficient. Off-grid setups lose some energy during storage and inverter conversion. In North Sikkim, where grid reliability is low, these losses are often a trade-off for independence.

4.2 Load and Battery Performance (Experiment 2)
In off-grid setups, energy demand climbs in the morning and stays high into the evening. Battery levels drop rapidly once the sun sets. Even with full storage at 10 kWh, the system falls below 2 kWh by midnight. This suggests that batteries alone can't fully support off-grid homes without over-sizing or backup sources like diesel generators.

4.3 Comparison Table

5. Discussion

Both systems offer advantages depending on the situation. On-grid microgrids make sense where grid access is available and stable. However, that's rarely the case in most parts of North Sikkim. Off-grid systems provide independence and are less prone to power cuts but require good battery management and sometimes backup sources to be truly effective.

One solution that seems promising is a hybrid setup—primarily solar-based, with storage and a minimal grid connection or generator backup. Such systems offer the flexibility of off-grid setups and the efficiency of grid-tied systems when conditions permit.

6. Conclusion

In North Sikkim's remote and rugged areas, where extending the main power grid is costly and difficult, off-grid microgrids hold real potential. While they come with their own challenges—mainly storage and cost—they provide reliable energy to communities that might otherwise have none. Our experiments show that with the right design and support, these systems can power homes, schools, and small businesses sustainably. For long-term success, a hybrid model may be the best route forward, supported by local policy and investment.

Factor	On-grid Microgrid	Off-grid Microgrid
Grid Dependence	Yes	No
Stability	Stable if grid is reliable	Varies with generation/storage
Cost	Lower upfront, but has grid fees	Higher setup, no ongoing fees
Scalability	Easier to expand	Needs careful design
Environmental Impact	Moderate (depends on grid source)	Low if diesel is avoided
Suitability for Sikkim	Limited by poor grid access	High, if designed with storage in mind

References

1. Lasseter, R.H. (2002). Microgrids. IEEE Power Engineering Society.

2. Guerrero, J.M., et al. (2010). Hierarchical Control of Microgrids. IEEE Transactions on Industrial Electronics.

3. Kumar, A., Bansal, R.C. (2014). Renewable Integration in Indian Power System. Renewable & Sustainable Energy Reviews.
4. Rezaei, N., et al. (2020). Mountain Hybrid Microgrid Analysis. Energy Reports.
5. Sinha, S., et al. (2018). Solar Energy for Off-grid Applications. Renewable Energy Focus.
6. Bose, B.K. (2017). Power Electronics in Renewable Energy.
7. Karki, S., et al. (2016). Microgrid Economics in Himalayan Villages.
8. Singh, A., et al. (2019). Energy Access in Sikkim. Energy Policy.
9. Thakur, N. (2015). Grid Integration in Northeast India. IJRET.
10. Bhattacharya, M. (2020). Battery Performance under Cold Climate.
11. Mishra, D. (2021). Control Strategies in PV-Diesel Hybrid Systems.
12. Tiwari, A., et al. (2017). Load Forecasting for Isolated Microgrids.
13. Jain, S. (2019). MPPT Optimization in Hilly Terrain.
14. Palit, D., et al. (2021). Mini-grid Deployment in Remote Regions.
15. Sharma, R., et al. (2020). Techno-economic Analysis of Solar-Battery Systems.
16. Chowdhury, S.P., et al. (2015). Voltage Stability in Microgrids.
17. Khan, M. (2016). Policy Landscape for Renewable Microgrids.
18. Basnet, B., et al. (2019). Energy Security in Eastern Himalayas.
19. Das, A., et al. (2022). Hybrid Energy System Modeling.
20. Zameer, A., et al. (2020). Microgrid Protection Schemes.
21. Gurung, A., et al. (2017). Solar Power in High-altitude Regions.
22. Dutta, S., et al. (2018). Real-time Control of Isolated Systems.
23. Pradhan, R. (2019). Decentralized Energy Planning.
24. Ray, P., et al. (2021). Impact of Temperature on Battery Life.
25. Mehta, R., et al. (2023). Smart Microgrid Architectures for Rural India.