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Technical and Economic Feasibility of Integrating Energy Storage System in to Grid Connected PV System - Case Study Approach

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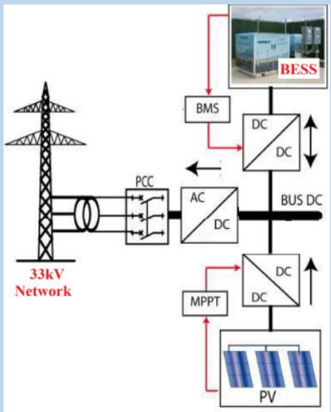
Abstract: This study investigates the technical and economic impacts of integrating energy storage systems (ESS) into grid-connected photovoltaic (PV) systems using the electrical network of a Palestinian village as a case study. Four different configurations of PV and sizes of ESSs are compared to assessing their impact on the most critical grid performance parameters, including voltage regulation, energy loss reduction, and dynamic load control. Utilizing ETAP for simulation, the study also analyzes actual grid behavior under real conditions, total harmonic distortion due to the PV inverter, and reverse power flow when there is high PV penetration. Harmonic distortion was found to be moderate in Case 0 and to increase in Cases 1 and 3, with Case 3 showing the highest distortion at low-voltage buses. Case 3 showed reverse power flow with very little export to the upstream grid, underscoring the significance of control mechanisms at high penetration levels. Economic efficiency is assessed considering the System Advisor Model (SAM) with high focus on main indicators like payback period, net present value, and levelized cost of energy. In all cases, Case 1 is the most efficient and feasible with the smallest levelized cost of energy of 17.4 cents/kWh and a payback period of 8.2 years. Case 2 and Case 3 indicate the best performance; the increased investment cost reduces their economic efficiency. The conclusion is that Case 1 has the optimal trade-off between technical effectiveness and economic viability, and it is an acceptable solution for grid stability, power quality management, and peak-shaving in small- to medium-size applications. The report wraps up by recommending longer-term investigation of hybrid energy storage technology, predictive algorithms, and long-term service reliability of energy storage under the conditions of diverse grids.



Keywords: Energy Storage System, Grid-Connected Photovoltaic System, Sustainable Energy, Technical Feasibility, Economic Benefits, Voltage Regulation.

Introduction

Palestine face a persistent lack of conventional energy resources, depending completely on imports to meet their petroleum demand and approximately 90% of their electricity needs, mainly through procurements from Israeli energy companies (IEC) (1-3). This dependence has resulted in raised energy prices, marked by variations, which harmfully impact energy security and economic stability (1, 4) With no original fossil fuel resources and only one operational power plant in Gaza (which is insufficient to meet local demand) Palestine remains extremely vulnerable to energy disruptions (1, 5).

To lessen this weakness, renewable energy (RE) particularly solar photovoltaic (PV) systems has gained strategic importance. Palestine benefits from an average solar radiation of 5.4 kWh/m²/day and about 3000 sunshine hours annually, which is considered as high potential for solar energy exploitation (6). Because of government incentives and lower technology costs, the use of grid-connected systems has increased significantly in recent years. These systems have been adopted not only in residential buildings but also in schools, municipal facilities, and private sector establishments (1).

Still, the widespread use of PV systems brings up new technical and economic problems. Because solar energy is not always available, it causes voltage and regular changes, which makes it harder to keep the grid stable, especially when there aren't strong regulations and the systems don't have a lot of technical capacity (7). These problems get worse because of political limits on the supply of electricity and a distribution network that is already under a lot of stress (8).

Many studies have looked into how to combine Energy Storage Systems (ESS) with PV installations to solve these problems. ESS makes it possible to store excess energy produced when the sun is shining and release it later when demand is higher or generation is lower. This increases system reliability, reduces grid stress, and enhances power quality. For example, Suyanto et al. demonstrated that increasing the proportion of renewable energy and decreasing the use of fossil

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fuels did not impact system stability when a 10 MWac PV system with 4 MWh of storage was added to the Baubau grid (9).

Research has demonstrated the technical and economic advantages of incorporating storage. Tran et al. discussed the challenges of utilizing photovoltaic systems in weak grids and how energy storage can enhance grid performance (7). According to Peprah et al., well sized residential PV systems in reduce power losses and keep voltage levels within permissible limits (10). Rehman et al. determined that relying solely on grid-connected batteries during frequent outages was less reliable and cost-efficient compared to utilizing grid supply in conjunction with photovoltaic (PV) systems and battery storage (11). The authors in (12) studies the previous researches about techno-economic issues of PV integration on smart grid mainly the intermittency, voltage fluctuations, and grid congestion and tensions. The authors in (13) presented that joint PV system with ESS systems can already produce improved net present values than standalone PV. Kumar et al. looked at the feasibility of a 1 MWp PV system in Malaysia and found that it could produce a lot of energy and save money (14), Rallabandi et al. looked at multi-megawatt PV plants with utility-scale batteries and found that they could respond better to changes in power and keep the frequency stable (15). The authors in (16) suggests a novel adaptive control policy to progress BES efficiency while confirming a steady power supply to the electrical network.

Balint et al. looked at different ways to discharge BES, and they found that adaptive algorithms made self-consumption better during times of high load (17).

Maria et al. (18) looked at a hybrid storage design for residential PV systems that used batteries and supercapacitors, they focused on how to control the system precisely and keep the AC stable Masoume et al. talked about the costs of battery aging and the lifecycle of batteries. They suggested management strategies based on models to improve self-sufficiency and economic performance in residential solar applications (19).

In short, the research shows that adding ESS to grid-connected PV systems not only makes them more reliable, but it also makes deploying renewable energy more cost-effective, especially in areas like Palestine where energy is scarce and politics are unstable.

While numerous studies have examined the integration of PV systems with energy storage to enhance grid stability and economic feasibility, most have been conducted in contexts marked by strong regulatory frameworks, resilient grid infrastructures, or at a large utility scale. The Palestinian electrical network relies heavily on electricity from other countries, has poor grid infrastructure, and can't generate enough electricity locally. The unique conditions necessitate a tailored analysis that considers the specific technical and economic constraints faced by rural communities in Palestine. This study's originality lies in its comprehensive techno-economic assessment of ESS integration within a real village-scale distribution grid in the Jenin governorate, employing detailed load flow and time-domain simulations in conjunction with financial modeling in SAM. This study uniquely evaluates grid performance metrics (voltage stability, peak shaving, losses, harmonic distortion, and short-circuit levels) in conjunction with financial indicators (LCOE, payback period, and total installed cost), enabling a thorough comparison of technical feasibility and economic viability.

Methodology

This paper conducts a thorough techno-economic analysis to assess the incorporation of ESS into a grid-connected PV system, utilizing the electrical grid of a Palestinian town in the Jenin governorate as a case study. The aim is to assess the technical and economic feasibility of diverse Energy Storage System configurations across various photovoltaic penetration scenarios.

This study involved the installation of the photovoltaic plant and energy storage system at bus situated near the feeder's terminus and in proximity to local loads. This decision exemplifies standard implementation in Palestinian villages, bolstered by technical and logistical considerations: proximity to medium-voltage lines, access to municipally-owned land, and elevated solar radiation coupled with appropriate site conditions. Co-locating photovoltaic systems and energy storage systems at this juncture optimizes local self-consumption, diminishes feeder losses, and directly alleviates evening demand peaks. Siting is recognized to influence outcomes. Deployment at the substation would mitigate voltage elevation and fault currents, yet offer diminished efficacy in peak shaving. The adopted downstream siting enhances local demand management, although it may lead to increased reverse flows and harmonics.

This study defines the penetration level (PL) as the ratio of the total apparent power produced by the PV system (SDG) to the total apparent power required by the system (S_{Load}), expressed as a percentage, as delineated in Equation (1):

$$PL = \frac{\sum S_{DG}}{\sum S_{Load}} \times 100\% \quad (1)$$

This statistic indicates the percentage of the system's load that can be covered by photovoltaic power and is a crucial factor in assessing renewable integration into the grid. The current network setup with a 1 MW PV system without any ESS, results in a penetration level of 17%. This value considered as the foundation for Case 1, in which ESS is integrated without changing the PV capacity. In scenarios with more penetration, the photovoltaic system size is augmented to attain 50% penetration level in Case 2 and 100% penetration level in Case 3.

Four scenarios are considered:

– 1 MW PV system without any ESS (PL = 17%) in case 0
– 1 MW PV system with ESS (PL = 17%) in case 1
– 3 MW PV system with ESS (PL = 50%) in case 2
– 6 MW PV system with ESS (PL = 100%) in case 3

In many studies, the ETAP program is used for technical analysis of electrical networks. The efficiency of the network during operation is evaluated by simulating steady-state load flow, while the efficiency of the network during dynamic load fluctuations, particularly the effectiveness of the ESS system in reducing peak loads, shifting loads, and stabilizing the network, is evaluated in time-domain simulations.

The economic study was undertaken using the System Advisor Model (SAM) (20), which evaluates capital investment, operational and maintenance costs, as well as possible economic benefits. Essential financial metrics which are: the payback period, net present value, and LCOE, were computed to assess the system's cost-effectiveness.

This methodology integrates technical and economic assessments to determine the ideal design of ESS and provides actionable insights to improve energy security and sustainability in similar rural environments.

Case Study

This study focuses on a Palestinian village which located in the Jenin Governorate. Figure 1 illustrates the load demand of the village, while the electrical grid consists of components including generators, buses, and cables that heavily distribute electricity to different areas. The variable capacities of the transformers ranging from 400 to 630 kVA. These components play a pivotal role in transferring power from the main grid to intra-grid distribution.

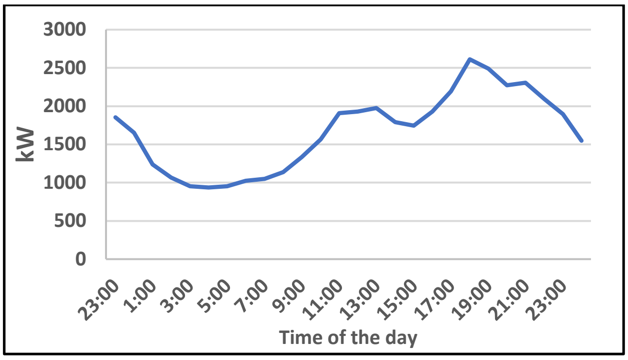

Figure (1): Load Demand of the Village.

A lithium-ion battery energy storage system (ESS) was modeled to make sure that the storage part was shown correctly in all three integration scenarios. Table 1 shows the specifications and operational assumptions. The ESS capacities were decided based on how well each PV system size worked with the penetration levels, and the power ratings were set to make peak shaving easier. Round-trip efficiency near 91%, the system was expected to last 10 to 12 years, which is about 4000 to 6000 cycles at 80% depth of discharge (DoD) [17].

The operation of the ESS in this study was regulated by a peak-shaving control strategy aimed at reducing grid demand during evening hours. The controller charges the battery during PV surplus or low grid demand and discharges during peak demand periods. This guarantees optimal use of locally produced solar energy while diminishing dependence on external sources. The control strategy prioritizes maintaining the battery's state-of-charge (SOC) within safe operational limits to mitigate efficiency losses and extend battery lifespan. This framework, initially designed for peak shaving as the primary control objective, can be modified for alternative strategies such as self-consumption maximization or frequency regulation in subsequent research.

Table (1): Specifications of the modeled ESS.

Case	PV Capacity (KW)	ESS Capacity (MWh)	Round-trip Efficiency (%)
1	1,020.41	7.61	90.65
2	3,024.55	22.84	91.06
3	6,049.11	45.67	91.14

According to industry standards for stationary grid applications, the lithium-ion energy storage system was expected to last 10 to 12 years. This estimate was based on a standard cycle life of about 4000 to 6000 full cycles at 80% depth of discharge (DoD) under controlled operating conditions. In the simulations, the battery had a maximum depth of discharge of 80% and a round-trip efficiency of about 90%. This is a common way to get the most out of the battery's capacity and life.

Battery lifespan is significantly influenced by usage patterns, such as the frequency of charge-discharge cycles, ambient temperature, and the implemented control strategy. This study assumed a conservative nominal lifetime; however, future research should explicitly incorporate degradation models into the techno-economic analysis to account for the influence of operational conditions on replacement schedules and long-term expenses.

Results and Discussion

In this section, the technical and financial implications of incorporating photovoltaic generation and energy storage systems into the village distribution network are thoroughly examined. Various levels of renewable integration are used to investigate critical performance aspects, including power flow dynamics, harmonic distortion, short-circuit currents, peak load reduction, and economic feasibility, across diverse scenarios. The subsections that follow offer a comprehensive analysis of the simulation results and their implications for grid stability, power quality, equipment safety, operational efficiency, and cost-effectiveness.

This study's analysis utilized the maximum load day profile supplied by the regional electricity distribution company. This date was chosen as it epitomizes the most critical operational condition for the network, characterized by maximum system stress, voltage reductions, and peak demand. Assessing system performance under these conditions guarantees that the proposed PV–ESS configurations are examined against the most demanding scenario. Although seasonal or annual simulations offer comprehensive insights, the maximum load day encapsulates the worst-case performance scenario, which is crucial for assessing grid stability and the efficacy of storage integration. Subsequent research will broaden this analysis to encompass various seasonal and annual profiles to further validate the findings' robustness.

1. Load Flow Analysis

This section presents a simulation-based analysis of the present performance of the electrical network of the village through ETAP. The study focuses on the operational effects of the presently operational 1 MW grid-connected solar photovoltaic system. By simulating the grid under normal operating conditions, this study aims to evaluate the efficiency of voltage regulation, power distribution patterns, and losses resulting from fluctuations in solar electricity production throughout the day. Load flow analysis evaluates the voltage distribution across the network, measuring how well voltage levels are maintained within standard limits across multiple transmission lines. The study aims to assess to what extent the PV system supports voltage and whether specific parts of the network are confronted with significant deviations from nominal values. Such simulations give a complete analysis of energy transfer efficiency and capability of existing infrastructure for integrating variable renewable generation. The results from this analysis are that voltage levels throughout the majority of the network are within acceptable limits, and this suggests a well-controlled system by and large. There are tiny anomalies at certain buses, however, which may perhaps need closer inspection considering future innovations or in the introduction of storage possibilities.

The unbalanced load flow results for Case 0 give a notion of phase-wise voltage magnitudes, active/reactive power, and power factor at the essential buses. Bus 1, being near the principal utility source, has a balanced three-phase voltage of 100% magnitude, generates 1.68 MW, and operates at a power factor of 99.9%. The delivered power at downstream nodes has a high-power factor in all the phases, representing nearly purely active power flow with insignificant capacitive nature as per Table 2.

However, Bus 39, which is the closest to the PV, has a voltage magnitude of 102.13%, which is marginally higher than Bus 1. And the power factor on Bus 38 is 100%.

This assessment provides a foundation for evaluating the improvements that energy storage systems achieve in subsequent chapters, particularly in terms of operational efficiency and grid stability.

For Case 1, the ESS modes of operation at Bus 39 being considered are charging and discharging. These scenarios reflect how the ESS affects grid power flow, voltage level, and generation in the upstream zone. Under ESS charging, Bus 1 has increased generation to 2.66 MW, with power going to downstream loads. The voltage level remains 100%, while power factor is 99.7%, which is efficient power transfer. At Bus 39, the voltage is 99.88%. Although no load or generation is directly allocated to Bus 39 in this mode, power injection to the storage system can be clearly observed. When it discharges, Bus 1 generation drops to 1.94 MW, reflecting reduced grid demand. Bus 39 voltage rises to 101.65%, and power flows out from the ESS to Bus 38. The system again reflects almost perfect power factor conditions. The results for case 1 are summarized in Table 1.

In Case 2, the ESS at Bus 39 operates in both charging and discharging modes to subject the system response to more dynamic power transfer conditions. As previously stated, charging in Case 2 is more stringent than in Case 1, Bus 1 sends out 2.66 MW with a power factor of 99.5%, and Bus 39 witnesses a slight rise in voltage to 100.26%. The ESS back feeds 0.489 MW per phase onto the grid at Bus 39, resulting in a local rise in voltage to 100.63%, the highest to date. Upstream generation at Bus 1 reduces to 1.2 MW, and current passing to Bus 3 reduces in proportion. The power factor at Bus 1 is still good at -99.1% despite such back feeding, whereas system balance is maintained. This bidirectional operation reflects the function of the ESS in flattening the load profile and supporting grid efficiency.

The ESS and PV system are entirely operative in Case 3, and the system is operating in maximal penetration mode. Two modes of operation are considered: charging and discharging. This provides a valuable perspective on the bidirectional power flow and its impact on grid stability. There is a significant amount of power consumption at the low-voltage node Bus 39 due to ESS charging. Each phase consumes 1.205 MW through Con1, while the grid provides 1.975 MW per phase through Con2. The system is operating at a near-perfect power factor (±100%), and the voltage at Bus 39 increases to 100.64%.

In contrast, Bus 1 contributes only 0.359 MW, suggesting that the majority of the demand is being met locally from distributed sources. In discharge mode, the power generation at Bus 1 is negative (-0.013 MW), indicating that the upstream source is currently absorbing power. The power factor at Bus 1 also drops to about 68.6%, reflecting greater reactive exchange — a far cry from the quasi-ideal situation when in charging mode. To additionally evaluate the behavior of the interaction between the PV system and the main grid, particularly with regards to the potential for reverse power flow, generation values at Bus 1 were analyzed under different operating conditions. The results are shown in Table 2.

Table (2): Power Flow Evaluation at Bus 1 for All Cases.

Case No.	ESS Mode	Generation @ Bus1	Status	Power Factor @ Bus1
Case 0	-	1.665 MW	No rejection	99.9%
Case 1	Charging	2.66 MW	No rejection	99.7%
	Discharging	1.94 MW	No rejection	99.8%
Case 2	Charging	1.71 MW	No rejection	99.5%
	Discharging	1.2 MW	No rejection	99.1%
Case 3	Charging	- 0.005 MW	Minor rejection	89.1%
	Discharging	- 0.014 MW	Minor rejection	68.6%

2. Harmonic Analysis

Total Harmonic Distortion of Voltage (THDV) or Total Harmonic Distortion of Current (THDI) can be used to describe harmonic distortion in power systems. THDV measures how much the bus voltages are distorted compared to the fundamental component, while THDI measures how much the current waveforms are distorted compared to the fundamental current. This study monitored both indices; however, THDV was prioritized in the performance evaluation due to its direct impact on overall power quality experienced by consumers, rendering it a more practical system-level indicator than current distortion, which is frequently confined to specific feeders or loads.

The choice of THD over Total Demand Distortion (TDD) was shaped by the specifics of the case study. TDD normalizes harmonic currents relative to the maximum demand load current, which is especially beneficial in systems with substantial industrial non-linear loads. In the simulated Palestinian village grid, most of the loads are residential and small commercial users. There are some non-linear loads, but they are not very common. So, THD was thought to be good enough to measure the harmonic effect at both the distribution bus and system levels.

ETAP simulation framework used to to model the loads with both static and dynamic demand profiles. This method made sure that harmonic distortion could be measured under real-world conditions, including changes in load over a 24-hour period. The reported THD values show how PV injection, ESS operation, and load-induced distortions all work together to affect system performance.

To evaluate the impact of PV integration with the ESS on power quality, harmonic distortion was examined at Bus 1 (medium voltage) and Bus 39 (low voltage) across all scenarios. Results shown in Table 3, Bus 39 is the most vulnerable grid point, consistently exhibiting higher Telephone Interference Factor (TIF) and THD values than Bus 1. In Case 0, Bus 39 showed THD = 2.87%, TIF = 94.63, while Bus 1 indicates negligible distortion since the THD = 0.06%, and TIF = 2.18. The distortion in case 1 increased, with Bus 39 recording the highest THD = 5.68% and TIF = 186.87 due to the inverter components. While the propagation of inverse frequencies started to appear with increasing THD (0.33%) and TIF (11.79) at Bus 1, Case 2 showed a slight decrease in distortion at Bus 39 (THD = 2.82%). Bus 1 reached its peak in THD (0.59%) and TIF (21.08) in Case 3, indicating increased harmonic propagation to the inverse grid, while Bus 39 continued to exhibit significant distortion (THD = 3.22%, TIF = 107.34). The results highlight the necessity of harmonic mitigation strategies, especially at lower voltage levels, with the increasing deployment of renewable energy, even while all values remained within the IEEE 519-2014 limits (21).

Table (3): Harmonic Distortion Metrics for All Cases.

Case	Bus	RMS Voltage (%)	THD	TIF	Bus
0	1	100.00	0.06	2.18	0.06
	39	96.18	2.87	94.63	2.87
1	1	100.00	0.11	4.00	0.11
	39	90.32	5.68	186.87	5.68
2	1	100.00	0.33	11.79	0.33
	39	96.35	2.82	93.75	2.82
3	1	100.00	0.59	21.08	0.59
	39	95.76	3.22	107.34	3.22

3. Short-Circuit Analysis

Short-circuit analysis is crucial for evaluating fault current magnitudes and ensuring that all equipment within the grid can operate safely under such stress. Using IEC 60909 standard methodologies (22, 23), Three-phase short-circuit simulations were conducted at Bus 1 (medium voltage) and Bus 39 (low voltage) to assess the effect of increasing PV and ESS penetration on fault current behavior. Results show stable fault levels at Bus 1 in all cases, and minor fluctuations in peak current (ip), initial symmetrical current (I″k), and steady-state current (Ik). For instance, ip increased from 22.187 kA in Case 0 to 22.309 kA in Case 3. However, Bus 39 experiences a dramatic rise in fault stress as renewable penetration increases. While the ip at Bus 39 is 29.937 kA in both Cases 0 and 1, it escalates to 159.635 kA in Case 2 (+433%) and surges further to 252.154 kA in Case 3 (+742%). Similarly, the Ik grows from 14.793 kA (Case 0) to 125.342 kA (Case 3), far exceeding conventional breaker and cable tolerances. These findings shown in Table 4 highlight the growing risk of equipment overstress and the urgent need to upgrade protection systems, especially at low-voltage levels, to ensure safe and reliable operation as the grid absorbs more distributed energy resources.

Table (4): Short-Circuit Simulation Results for All Cases.

Case	Bus ID	ip (kA)	I"k (kA)	IK (kA)
0	1	22.187	8.765	9.063
	39	29.937	14.780	14.793
1	1	22.187	8.765	9.063
	39	29.937	14.780	14.793
2	1	22.236 (+0.22%)	8.800 (+0.4%)	9.098 (+0.39%)
	39	159.635 (+433%)	78.133 (+428.6%)	78.517 (+430.7%)
3	1	22.309 (+0.55%)	8.748 (-0.19%)	9.150 (+0.96%)
	39	252.154 (+742%)	116.017 (+684.9%)	125.342 (+7473%)

4. Peak-Shaving

A 24-hour simulation was conducted in the time domain for each scenario to evaluate the effectiveness of integrating an energy storage system in improving instantaneous load dynamics. The primary objective was to determine the ability of a photovoltaic energy storage (ESS) system to relieve pressure on the grid during periods of high demand. The study compared the original grid load to the net demand after integrating the photovoltaic (PV) and storage systems (ESS) into the grid.

For clarity, the results and figures refer to two key terms. The first is the local distribution grid demand (P-grid), which is the total load before storage is used and represents the actual load curve that the grid would handle in the absence of a storage system. While the net energy demand (P-net) is the amount of energy that is drawn from the outside source. The difference between the two figures at any given moment represents the power delivered from the ESS to the grid. This helps to reduce the need for the external source at peak periods.

PV system in case 0 without any storage. Peak load demand hours range from 6:00 to 9:00 a.m., reaches approximately 2,700 kW. This increases stress on distribution components and reduces system efficiency, as a large portion of the daytime PV production remains unused.

An energy storage system was added with a penetration rate of 17% was added in case 1, resulting in a significant reduction in peak demand. The storage system shown in Figure 2 illustrates the dynamic Load Profile for Case 1 at 1 MW PV with 17% penetration and ESS. This resulting in reducing peak demand from 2,700 kW to 1,800 kW. The system is charged during the early morning and midday hours, when the PV production is higher than the demand. The addition of EES contributed in stabilizing the load curve and improving energy balance during peak periods.

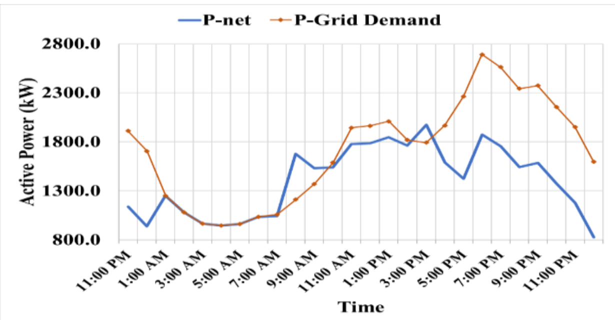

Figure (2): Dynamic Load Profile for Case 1 at 1 MW PV with 17% Penetration and ESS.

The PV capacity goes up to 3 MW and ESS penetration reaches 50% in case 2. Figure 3 shows the dynamic load profile for case 2 at 1 MW PV with 50% Penetration and ESS. The net load drops a lot during the day as the ESS charges up when there is extra PV power. The peak load demand was 1,350 kW which is a 51% peak shaving. Also, short periods of energy export happen when PV output is higher than both local consumption and ESS charging limits. This shows that the system is more self-sufficient and could help the grid.

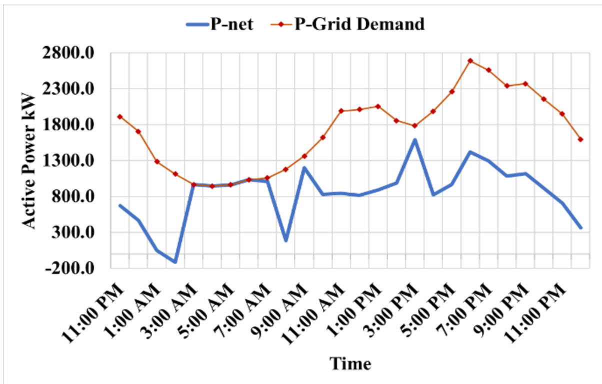

Figure (3): Dynamic Load Profile for Case 2 at 1 MW PV with 50 % Penetration and ESS.

6 MW of PV and 100% ESS are used in case 3. Figure 4 shows that the dynamic load profile for case 3 has a lot of export events and not much need for the grid. The ESS is used to its full potential during the day, and excess generation leads to ongoing power exports. More importantly, the evening peak demand drops from 2,700 kW to less than 1,000 kW, which is a 63% drop. The net load profile seems flat and stable which means more reliably.

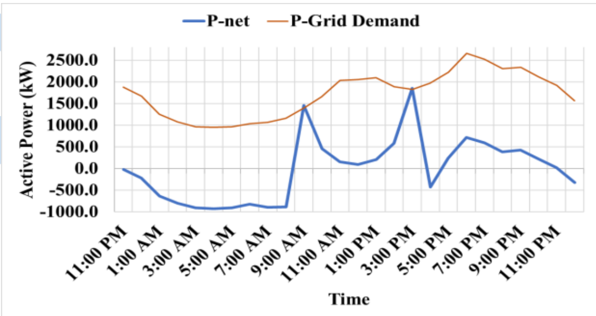

Figure (4): Dynamic Load Profile for Case 3 – 6 MW PV with 100% Penetration and ESS.

The results indicate that peak shaving is more effective with bigger capacities of PV systems and ESS. The benefit from ESS to store electricity and discharge it at peak demand is crucial for reducing grid stress, enhancing load factors, and promoting the utilization of renewable energy sources.

5. Economic Analysis

The integration of PV system and EES has not only technical benefits but also economic benefits. The Levelized Cost of Electricity (LCOE), Payback Period, and Total Installed Cost shown in Table 5 for each case. The base system (grid-only) does not generate pertinent economic indicators as a result of the absence of capital investment. Conversely, hybrid configurations exhibit financial returns that fluctuate based on the integration of renewable sources, as demonstrated. The LCOE for each configuration was calculated using equation (2):

$$LCOE = \frac{\sum_{n=0}^{N} \frac{C_n}{(1+d)^n}}{\sum_{n=1}^{N} \frac{Q_n}{(1+d)^n}} \tag{2}$$

where:

N/: Analysis period in years.

C_n: The annual project costs in Year n.

d: The discount rate.

Q_n: Electricity delivered by the system to the grid (and/or load if applicable) in year n.

Table (5): Short-Circuit Simulation Results for All Cases.

Metric	Case 1	Case 2	Case 3
Nominal LCOE (cents/kWh)	17.4	18.6	18.8
Payback Period (years)	8.2	9.8	9.9
Total Installed Cost	$1,609,835	$5,953,514	$12,246,799

Total costs include capital investment, operation and maintenance, and replacement costs, while Total Lifetime Energy Output represents the total energy delivered to the load over the project's lifetime. The Payback Period (PBP) was determined by dividing the total installed cost by annual savings as shown in equation (3)

$$PBP = \frac{C_0}{S_{annual}} \quad (3)$$

Where:

C_0: Total initial investment.

S_{annual}: Annual savings.

The four cases help us understand the technical and economic trade-offs of solar systems with built-in energy storage that are linked to the grid. Increasing the size of the PV and ESS systems improves the grid performance from technical point of view but it also has very expensive when increasing the PV capacity. Case 1 emerges as the most cost-effective configuration, offering the lowest LCOE (17.4 cents/kWh) and shortest PBP (8.2 years), while still achieving significant voltage regulation improvement, peak load reduction, and energy loss minimization. Although Cases 2 and 3 deliver higher annual savings and additional grid support benefits, their elevated investment requirements reduce economic viability. From a technical standpoint, Case 1 also maintains manageable short-circuit levels, acceptable harmonic distortion (with potential for basic filtering), and strong voltage stability—making it the optimal choice for village-scale grids seeking to increase renewable penetration at a reasonable cost.

Conclusion

This study assessed the effects of incorporating ESS and PV systems into a village-scale electric distribution network, concentrating on voltage stability, power losses, peak shaving, and overall system efficiency.

The simulation results indicated that the incorporation of ESS significantly enhanced voltage stability across the system. Even the most minimal design in Case 1 markedly diminished voltage fluctuations relative to the baseline condition. Despite Cases 2 and 3 had greater ESS capacities their performance enhancements were not very reliable because of the increased investment needed.

The adoption of ESS significantly reduced power loss, especially with reactive power. Case 1 demonstrated the minimal overall losses owing to optimal synchronization of charging and discharging with demand patterns. Although Cases 2 and 3 demonstrated ongoing enhancements, the cost-benefit analysis favored the more compact, targeted ESS implementation of Case 1.

Among the several advantages of ESS integration, peak shaving has emerged as the most crucial. In Case 1, the ESS efficiently discharged during peak demand periods, reducing strain on the central grid and normalizing the load profile. This not only diminished the probability of outages but also prolonged the longevity of current infrastructure and deferred the necessity for costly modifications.

Although Case 1 proved to be the most economically advantageous option due to its reasonable investment cost, brief payback period, and low LCOE, it is essential to recognize the enhanced technical performance of Cases 2 and 3. The increased capacities of PV and ESS in these scenarios facilitated improved voltage stability, enhanced peak shaving (up to 63%), and elevated levels of renewable integration. Cases 2 and 3 significantly minimized dependence on external energy sources, advancing the system toward energy self-sufficiency. Despite the substantial initial expenses that currently restrict their practicality, these configurations signify strategic avenues for future energy autonomy. Consequently, Case 1 presents the most equitable immediate solution, whereas Cases 2 and 3 underscore the long-term prospects for expanding renewable energy and storage to attain enhanced autonomy and resilience.

A comprehensive framework is suggested for modeling both existing and prospective ESS technologies to enhance the outcomes of this study. This framework needs to include three main parts: Technical performance, which includes load flow, charging and discharging dynamics, and efficiency; Economic outcomes, which include LCOE, and payback period; and Practical issues, such as battery degradation, load fluctuations, and regional tariff structures. The framework gives planners, utilities, and policymakers clear instructions on how to size and run Energy Storage Systems in village and distribution-scale grids by including these parts. This would help stakeholders look at different scenarios, judge technologies, and make better decisions about future energy investments.

In conclusion, the results demonstrate that the first scenario represents the most effective and suitable option for small and medium-sized village electrification applications, especially in areas where financial constraints limit the possibility of establishing large-scale storage systems or photovoltaic installations. The results also indicate that limited investments in distributed energy resources can provide significant operational benefits and enhance grid reliability, making them a strategic option for enhancing energy resilience in rural areas.

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- **Ethics approval and consent to participate:** Not applicable
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