European Journal of Energy Research
Vol 5 | Issue 3 | May 2025
ISSN 2736-5506

RESEARCH ARTICLE

Design and Analysis of a Grid-Tied Solar System with Deferrable Air-Conditioning Load for Lahore, Pakistan

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ABSTRACT

This research investigates the structure and performance testing of a solar power system set up at a house in the Lahore, Pakistan. The system comprises Canadian Solar Max Power CS6U-340M solar panels with a top capacity of 7.50 kW and an average daily output of 28.9 kWh. The study incorporates recent proposed changes by NEPRA, including adjustments to grid rates for fed-back power. The current rate of WAPDA is 8 cents per kWh, whereas the proposed rate considered in this study is 3.9 cents per kWh. These adjustments result in a decrease ROI that can be by adding deferrable loads, such as heat-pump load. The designed system effectively handles an electrical load of 16.00 kWh/day, reaching renewable penetration of 81.9%. The yearly average power output fed back to the grid ranges from 0.40 kW to 1.2 kW, with seasonal variations leading to a production of 0.5 kW to 1.7 kW. The system purchases an average of 1.4 kW from the grid while selling back 2.4–3.4 kW. A comparative analysis between the old and new design reveals the economic implications of the government's reduction in electricity buyout rates for consumers, emphasizing the system's cost-effectiveness. The introduction of deferrable heat pump loads shows a positive impact on the overall production and sustainability of the system. These findings confirm that a hybrid solar power system is an economically viable and environmentally friendly choice for residential power generation.

Keywords: Grid-tie solar, net-metering, photovoltaics, renewable energy.

Submitted: February 22, 2025

Published: May 24, 2025

10.24018/ejenergy.2025.5.3.163

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1. Introduction

The rising universal need for pure and lasting power is pushing everyone towards the acceptance of renewable energy systems on a global scale. One of the most easily accessible and abundant types of renewable energy is solar energy. It's catching people's attention because it has the potential to lessen greenhouse gas emissions and our reliance on fossil fuels. But, connecting renewable energy sources to current energy grids brings about certain technical, economic, and policy challenges. Khan *et al*. [1] point out that the success of renewable energy integration in growing countries counts heavily on strong policies like net metering. These policies can tip the scale and overcome economic and infrastructure hurdles. Smart energy management strategies are also becoming more crucial in enhancing energy efficiency as the energy sector starts moving towards decentralization. Buildings can reduce grid pressure and cut down on transmission losses through localized energy production and consumption, as emphasized by Shah and colleagues [2]. Also, the COVID-19 pandemic showed us how weak our global energy systems are. Janjua *et al*. [3] noted this, hinting at the importance of energy policies that can fight against sudden disruptions while still promoting the use of renewable energy. Solar energy generation is often not consistent. This can lead to too much electricity being produced, particularly in off-grid and hybrid systems. If not properly controlled, this can turn into energy waste. Rad *et al*. [5] looked at this issue, suggesting solutions including load shifting, energy storage, and demand-side management. All of these are key in utilizing energy in the best way possible. Another point Lund *et al*. [4] raised is that to achieve a high level of variable renewable energy use we need a better flexible energy system. The system should include grid-scale storage, demand response, and improved forecasting techniques. This study aims to address these challenges by optimizing solar energy systems through the integration of deferrable loads such as heat pumps, motors, and washing loads, particularly during the summer season. The research evaluates the impact of these deferrable loads on the system's overall performance, cost-effectiveness, and environmental sustainability. By shifting non-critical energy consumption to periods of high solar output, these loads can improve self-consumption, reduce dependence on grid exports, and minimize reliance on energy storage systems, as seen in previous works [1], [5]. The study also looks at the money side of things, specifically the falling export rates, which is a growing worry in energy markets. It looks at how to soften these effects while still keeping economic viability.

To meet the study's objectives, we use an analysis framework that combines techno-economic elements of system design simulation, and cost-benefit analysis. The paper checks out the role of energy storage in the balance of supply and demand, alongside the implications for system trustworthiness and return on investment (ROI), based on insights from Johnson *et al*. [6] and Mojumder *et al*. [7] Additionally, the study looks at hybrid patterns and grid connections. It takes into account case studies from Ethiopia and Australia by Beza *et al*. [8] and Fornarelli *et al*. [9], respectively, to show the wider relevance of the proposed solutions. My research adds to the increasing amount of knowledge about renewable energy integration by providing valuable insights for system designers, policy developers and other interested parties. It underlines the importance of supportive policy measures, like time-of-use pricing and financial incentives, to rally the adoption of renewable energy systems. McConnell *et al*. [10] showed how such measures could drive the interest of distributed photovoltaic generation while reducing wholesale electricity prices due to the merit-order effect.

This paper aims to compare the performance of a previously developed energy model with an enhanced version that incorporates Deferrable Load and introduces a Grid Export Limit. The study evaluates the effectiveness of these additions in optimizing energy management, enhancing renewable penetration, and improving solar efficiency. The system layout, including solar panels, inverter, and battery bank, remains consistent between the two models. The inclusion of Deferrable Load and grid constraints fundamentally alters how the system manages energy distribution, storage and export. By studying both models side by side, we find out the pros and cons of making these upgrades, especially when it comes to how much energy we use, managing the load. The scope of the study includes evaluating yearly and seasonal performance, renewable penetration and grid export efficiency for both models. Key performance indicators such as total renewable energy production, grid export efficiency and the proportion of renewable energy supporting the load are analyzed to highlight the differences introduced by the new design.

2. Site Data and System Analysis

2.1. Site Description

The photovoltaic (PV) system is installed in a residential property located in the Defense Housing Authority (DHA) area of Lahore, Pakistan. The geographical coordinates of the site are 31°27′49.0″N latitude and 74°28′25.7″E longitude, as illustrated in the satellite image (Fig. 1). This region benefits from abundant solar energy due to its geographical positioning, making it ideal for implementing rooftop solar PV systems. The site offers ample roof space and favorable solar insolation throughout the year, which enhances the efficiency and productivity of the installed PV system. The PV setup, with a capacity of 7.5 kVA, integrates grid-tied technology to supply electricity to the house and export surplus energy back to the grid.

2.2. Solar PV Panels

The PV system utilizes 22 Canadian Solar MaxPower CS6U-340M monocrystalline panels, each with a power rating of 340 W. The panels provide high module efficiency of 17.37%, ensuring optimal energy production. The electrical specifications of the solar panels include an open-circuit voltage (Voc) of 46.8 V, a short-circuit current (Isc) of 9.45 A, a maximum power voltage (Vmp) of 38.6 V, and a maximum power current (Imp) of 8.81 A. These panels operate efficiently in a wide temperature range from −40°C to 85°C and feature a temperature coefficient of −0.39%/°C, which ensures minimal performance loss in high-temperature conditions. Each panel measures 1960 mm × 992 mm × 40 mm and weighs 22.5 kg, making them robust and durable for rooftop installations. Additionally, the panels are configured in a 72-cell monocrystalline design and incorporate IP67-rated junction boxes, providing reliable performance even in challenging environmental conditions. Solar PV specification can be seen in Table I.

2.3. Inverter

The system employs a Fronius Primo 8.2 hybrid inverter, known for its 98% efficiency and robust operational capabilities. The inverter is specifically designed for residential and small commercial PV systems and supports three operational modes: stand-alone, grid-tied, and hybrid configurations. Its dual Maximum Power Point Tracking (MPPT) technology ensures maximum energy harvesting under varying sunlight conditions. The inverter supports a maximum input power of 12.3 kW, operates within a voltage range of 80 V to 1000 V, and provides a nominal AC output of 8200 W. The device is compatible with grid connections and can operate in a frequency range of 45 Hz–65 Hz while maintaining low harmonic distortion levels of less than 3%. Its IP65 rating ensures protection against environmental factors, allowing installation both indoors and outdoors. For connectivity and monitoring, the inverter includes features such as WLAN, Ethernet LAN, Modbus TCP SunSpec, and USB ports for data logging and firmware updates. It also incorporates regulated air cooling and operates efficiently at altitudes of up to 4000 m.

2.4. Battery Backup

To ensure uninterrupted power supply during outages or energy surges, the system is equipped with four BAE Secura PVS BLOCK Solar batteries. These batteries are

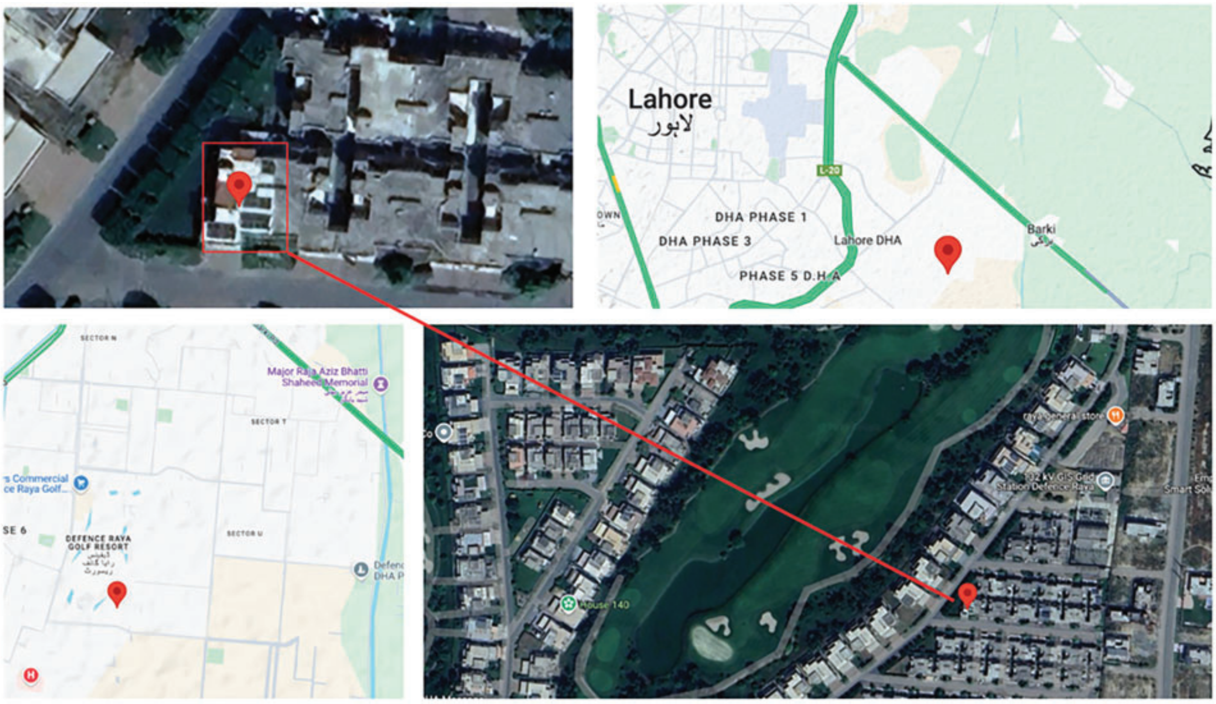

Fig. 1. Site location.

TABLE I: System PV Specification

Type	Rating
Maximum output power	8.2 kW
Efficiency	98%
Input voltage range	80 V–1000 V
MPPT voltage range	270 V–800 V
Maximum input current	33 A
Number of MPP trackers	2
Nominal input voltage	710 V
AC nominal output	8200 W
Maximum PV generator power	12.3 kW
Maximum output power	8200 VA
AC voltage range	180 V–270 V
Frequency range	45–65 Hz
Total harmonic distortion	<3%
Protection rating	IP65
Operating temperature range	−40°C to 55°C
Dimensions	645 × 431 × 204 mm
Weight	21.5 kg

tailored for solar applications and offer exceptional performance across various discharge periods. With a rated capacity of 95 Ah at C1, 167 Ah at C10, and 211 Ah at C72, they provide robust energy storage. The batteries are housed in high-impact SAN containers with optional ABS lids, ensuring durability and safety. They measure 380 mm in length, 205 mm in width, and 385 mm in height, with an empty weight of 53.7 kg and a filled weight of 71.4 kg. Designed for indoor applications, these batteries play a crucial role in maintaining system reliability during periods of low sunlight or power disruptions.

2.5. *Simulation Tools and Parameters*

To assess the performance and design optimization of the solar energy system, simulations were conducted using Homer Pro, a strong tool widely used for modeling renewable energy systems. The simulation conditions included the integration of solar panels, battery storage, and grid connectivity for the location specified in Section 2.1. The study examined the system's yearly and seasonal profiles, grid interactions, and renewable energy penetration measurements. Key input conditions included into the Homer Pro simulation included a daily electrical load of 16.00 kWh, a peak load of 1.86 kW, and the inclusion of Canadian Solar Max Power CS6U-340M panels paired with BAE 12 V 3 PVS batteries for storage. The tool simulated renewable energy generation, storage capacity, grid dependency and deferrable load though considering geographic and climatic conditions, as described earlier. The simulation Included load-specific details to reflect the actual usage patterns, ensuring the results Matched with real-world scenarios. The results include renewable penetration, power output, grid sales, and the state of charge for batteries. Instantaneous renewable hours and grid interactions were also monitored, with renewable penetration reaching values between 70% and 90% for most hours.

2.6. *Deferrable Load Integration Approach*

One highlight of this investigation was treating loads that can be deferred-for example, a heat pump or an air con unit—as a unique kind of load rather than just lumping it in with the primary load. The motivation behind this tactic was to emulate how manageable managing energy use can be during times when solar energy production peaks. In the study, the load that can be deferred was given an annual average of 7.05 kWh/day, and there were some pretty noticeable changes throughout the year. In summer, when people need more cooling, the load could ramp up quite a bit-hitting around 25.8 kWh/day in June, July, and August. But then it would drop all the way to 0.8 kWh/day in winter. By incorporating these deferrable loads into the setup, the solar rig could make the most of the energy it created. This way the system could rely less on the grid and use even more renewable power. It was also helpful to split this sort of load up from the rest, so the effects on energy storage, how renewables were used and how much was sold back to the grid could be studied more thoroughly. With deferrable loads included, the overall solar energy output of the system did show a significant rise. Making use of these loads at times when sun production was high cut back on wasted electricity and meant the system could work more efficiently.

2.7. *Electricity Export Rate Adjustment Analysis*

Another really important point taken into account in these simulations was changing the electric export rate. This change tied in with NEPRA's suggested alterations. The simulation modeled a drop in the price paid for electricity sold back to the grid, cutting it to half the former rate. The intention behind this scenario was to see how changes to regulations could impact the financial performance of the system. Return on investment (ROI) and cost impacts between the established export rates and the reduced rates were compared. The changes meant the system's whole yearly energy exports to the grid-around 4,444 kWh-needed to be reassessed to figure out changes to revenue and operation costs. These changes were also felt in the cash flow summary where the total net present cost (NPC) and cost of making electricity (COE) levels got looked at again under these new conditions.

2.8. *System Layout*

Fig. 2 illustrates the layout of the system, which integrates solar power generation, energy storage, and load management to ensure consistent and reliable energy supply. The system consists of twenty-two Canadian Solar MaxPower CS6U-340M panels arranged in two strings of eleven panels each. Each panel has a rated power output of 340 W, which results in a total solar power capacity of 7480 W, or 7.48 kW. These solar panels are connected to a Fronius Primo 8.2 inverter, which is a single-phase inverter capable of handling up to 8.2 kW of power. The inverter is equipped with two Maximum Power Point Tracking (MPPT) inputs, allowing it to optimize the power output from the panels by adjusting to varying sunlight conditions. To store the generated solar energy, the system includes four BAE Secura PVS 12 V 3 PVS 210 batteries connected in parallel. Each battery has a capacity of 211 Ah, providing a total storage capacity of 10.13 kWh. The battery bank operates at a voltage of 48 V and ensures that the system has backup power during periods of low sunlight or power outages. This setup guarantees that essential loads remain powered even when solar energy is not available.

The system is designed to manage two types of loads: high and normal. The high load is disconnected in the event of a power outage to conserve energy, while the normal load continues to receive power from both the solar panels and the battery bank. This configuration ensures that vital functions are maintained during periods of low solar generation. Additionally, we have incorporated Deferrable Load into the previous model, which allows for the delayed operation of non-essential loads when energy supply is limited. This enhances the efficiency and sustainability of the system by prioritizing the most critical loads and deferring others, further optimizing the use of available energy.

2.9. *Modeling Tools for PV System Evaluation*

The evaluation and optimization of photovoltaic (PV) systems require sophisticated modeling tools that can simulate energy generation, storage, and consumption under various scenarios. These tools are essential for accurately assessing system performance and identifying opportunities for improvement. In this study, we rely exclusively on HOMER Pro, a widely recognized modeling and simulation tool, to evaluate and compare the performance of the energy system models. HOMER Pro enables detailed analysis of hybrid energy systems by simulating their operation and providing insights into key performance metrics such

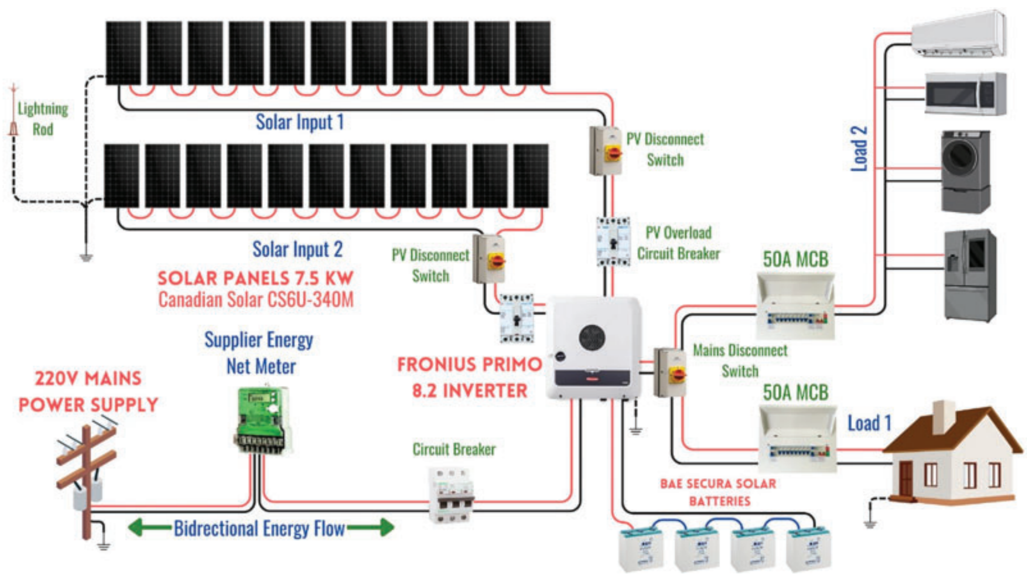

Fig. 2. System layout.

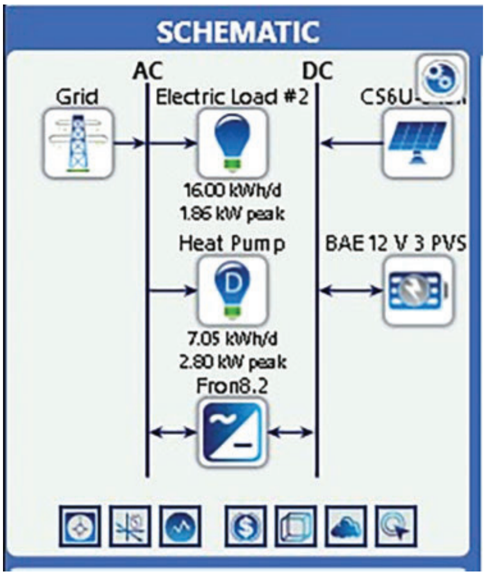

Fig. 3. System schematic.

as energy production, load management, and grid interaction. HOMER Pro is a powerful software tool specifically designed for modeling and optimizing hybrid renewable energy systems. It provides a user-friendly interface for configuring system components and simulating their operation over a specified time frame. In this study, HOMER Pro was used to model the PV system's energy production, storage, and consumption dynamics while accounting for the new features of Deferrable Load and Grid Export Limits. Fig. 3 shows the structure of system in Homer pro software.

2.10. Load Profile

As seen in Fig. 4, the site's load profile is key to grasping the energy demand dynamics and what they mean for the system's design and performance. It gives a thorough breakdown of energy consumption patterns-daily, seasonal, and yearly, and these were crucial inputs for the Homer Pro simulations. An average daily demand of 16.00 kWh is reflected in the main load profile with a peak demand of 1.86 kW, underlining the energy needs of the site and it's peak load demands. Within the load profile, we can spot seasonal shifts in energy consumption. For example, the higher energy use during the summer months is mainly due to more cooling demands, with the deferrable load making a big contribution to the overall spike. Meanwhile, the winter months show a decrease in energy use, which reduces the load on the system.

As shown in the load profile, with seasonal changes is in sync with the solar panels energy production patterns. This synchrony ensures any extra energy made during peak solar production hours is used efficiently, i.e., to power deferrable loads or to charge batteries. Fig. 4 showing these dynamics, that is, how energy demand and system operation interact over time. This visual helps us get how the solar energy system fits the site's specific energy consumption patterns and at the same time keeps a high level of renewable energy penetration.

2.11. Electrical & Technical Specifications

The system is designed to provide reliable solar power generation and storage, with a yearly average output to the grid ranging between \$0.18/kWh and \$0.22/kWh. The electrical load is 16.00 kWh/day, supported by Canadian Solar Max Power CS6U-340M panels with a 7.50 kW rated capacity, generating 10,540 kWh/year at a 16% capacity factor. Storage is managed by four BAE 12V 3 PVS batteries with a 48.0 V bus voltage and a state of charge between 95%–100%. Renewable penetration shows high efficiency, with 81.9% of the load and 72.8% of the generation covered by renewables. The Fronius Primo 8.2-1 inverter, with a rated power of 8.2 kW and 97% efficiency, optimizes the system. Total costs include \$33,542.23 for solar panels, \$18,275.10 for batteries, and \$8,488.45 for the inverter, with an annual operating cost of \$1,688.35. Table II shows electrical and technical specifications of the system.

3. Results and Discussion

3.1. Yearly and Seasonal Profiles

The performance of the solar energy system is analyzed by comparing its yearly and seasonal profiles with those from the previous study [11] to evaluate changes in energy generation and utilization trends throughout the year. This comparison highlights the increased renewable energy output and improved penetration at the site. Additionally, the return on investment (ROI) period has increased to 3.7 years, indicating a decrease in economic benefits compared to the previous study. This change reflects the assumed reduction in grid rates by the government, which affects the overall financial viability. These findings provide valuable insights into the variability of solar output and the improved efficiency of the system.

3.1.1. Solar Output Comparison

Every year, the energy produced by the sun goes through ups and downs due to the changing intensity of sunlight throughout the seasons. It shows how solar energy production spikes in the summertime and falls in the winter due to the days being shorter and the sunlight weaker. But when it's summer, the system is in its prime, making enough power not just for everyday needs but even enough to stash some away in batteries. Winter tells a different story: energy

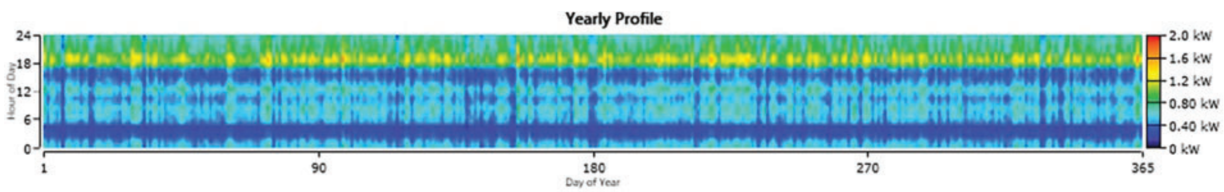

Fig. 4. Load profile.

TABLE II: Technical Specifications of System

Parameter	Specification
Yearly profile	Average output to grid: 0.18 kW 0.22 kW
Load specifications	Electrical load: 16.00 kWh/day with 1.86 kW peak load
Solar panel	Canadian solar max power CS6U-340M
Solar panel rated capacity	7.50 kW
Solar panel mean output	1.20 kW/28.9 kWh/day
Solar panel capacity factor	16.0%
Solar panel total production	10,540 kWh/year
Batteries	BAE 12V 3 PVS
Battery quantity	4 batteries (String Size: 4; Strings in Parallel: 1)
Bus voltage	48.0 V
State of charge	95%–100%
Renewable penetration results	Renewable Production/Load: 81.9%; Renewable Production/Generation: 72.8%; Average Output: 70%–90%
Grid system results	Average energy purchased: 1.4 kW; Energy sold: 2.4–3.4 kW
Inverter	Fronius Primo 8.2-1
Inverter rated power	8.2 kW
Inverter MPPT voltage range	150 V–450 V
Inverter efficiency	97%
Cost summary-solar panel	$33,542.23
Cost summary-batteries	$18,275.10
Cost Summary-inverter	$8,488.45
O&M cost	$1,688.35/year

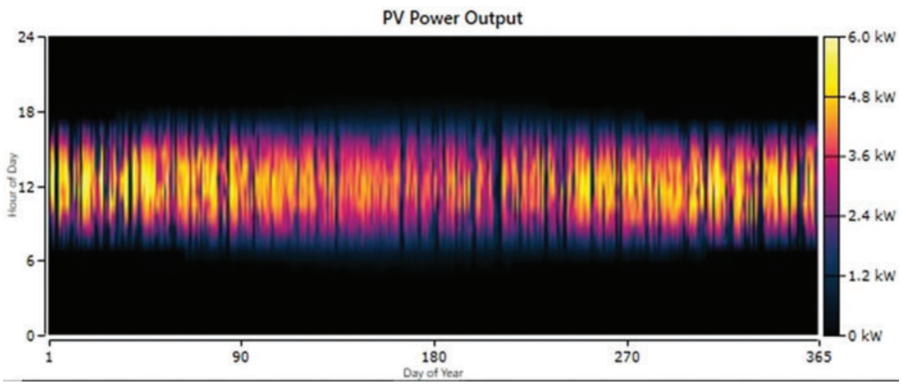

Fig. 5. PV power output.

production dips and we need to lean on the grid a bit to keep the site powered. The rated capacity of the Solar Panels is 7.5 kW but as we all know that the efficiency of panels is around 20 % the maximum output, we can get from the PV panels is 5.95 kW. Total solar output we got in a year is 10,540 kWh/yr. The good thing is, this keeps interruptions at bay and ensures our energy needs are taken care of, even when sunlight is scarce. If you look at how solar output stacks up in spring and fall–the transition seasons, you'll see a stable, moderate production of energy can be seen in Fig. 5.

3.1.2. *Renewable Penetration Metrics*

Metrics about the use of renewable energy offer a picture of how much non-fossil fuel energy we are using compared to overall energy needs. The data shown in Fig. 6 illustrates a clear picture of the progress made over a year in using renewable energy. Over that year, our system was able to make sure that 70% of the energy used was renewable, on average. In summer this figure can even go up more due to increased solar energy output. The bulk of the renewable energy was produced during the daylight hours, thanks to solar panels hard at work. Because of this, we managed to rely less on electricity from the grid and more on green energy. Even when the sun was down, or solar output wasn't so hot, there's no need to worry: A battery storage system is in place to ensure that the renewable energy needs on site keep getting filled. Checking the data from different seasons, we find that usage of renewable energy reached 85% during summer, making it pretty self-sufficient. But come winter, the number dips to around 55%, which shows we do still need a bit of help from the power grid. These findings emphasize the system's efficiency at using renewable energy sources and reducing reliance on non-renewable ones.

3.2. *Load Profile with Deferrable Load*

The integration of deferrable loads into the system significantly influences the overall load profile, improving energy management and optimizing system performance. Deferrable loads are those that can be scheduled to operate at specific times when renewable energy is abundant or when demand on the grid is low, thereby reducing energy costs and reliance on non-renewable sources. The following

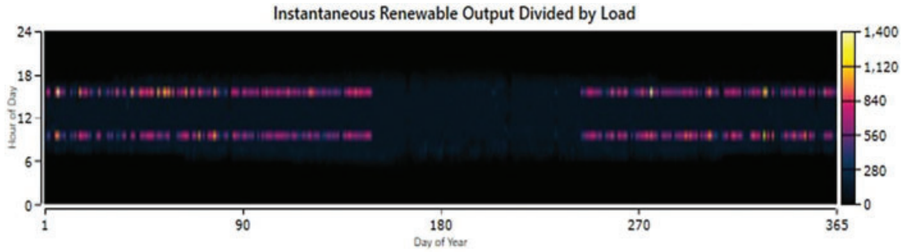

Fig. 6. Instantaneous renewable output divided by load.

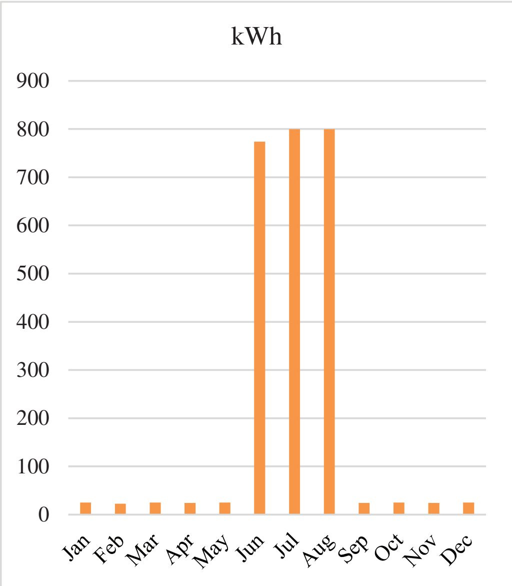

Fig. 7. Seasonal averages deferrable load.

sections examine the impact of deferrable loads on daily and seasonal averages, as well as their effects on storage requirements.

3.2.1. *Impact on Daily and Seasonal Averages*

The inclusion of deferrable loads reshapes the daily load profile by shifting energy demand to periods of peak solar generation. Fig. 3 illustrates the adjusted load profile with deferrable loads, showing reduced peaks during high-demand periods and increased energy usage during midday when solar energy production is at its maximum. This strategic redistribution of loads enhances energy utilization and reduces strain on the battery storage. On a seasonal scale, the impact of deferrable loads is particularly noticeable during the summer months when solar output is highest. Fig. 7 highlights the seasonal averages, demonstrating that deferrable loads align closely with energy availability, achieving higher renewable penetration during load season. For the month of June, July and August, the average deferrable load considered in our study is 25.8 kWh/day, with majority of this load attributed to Heat Pump. In contrast, during the off-peak season of spring and winter the average deferrable load is calculated to be 0.8 kWh/day primarily consisting of the Water Pump and Washing Machine.

3.2.2. *Effects on Storage Requirements*

The system's storage needs are greatly impacted by the inclusion of deferrable loads. There's a significant drop in how much the system relies on battery storage when energy-sucking tasks are planned for peak solar hours. So, the life of the battery improves and so does the sustainability of the whole system. Fig. 8 show the State of Charge of the battery. Deferrable loads can take in the extra energy when a lot of solar power is being produced which can stop the batteries from getting too full. The battery State of charge (SOC) is more than 80%. On the other hand, in times of less solar output the loads are adjusted so that the stored-up energy is used in the best way possible and cuts down the need to have even more storage. This takes down the starting cost of batteries and makes the performance of the system even better over time.

3.3. *Grid Results and Energy Transactions*

The way the solar energy system works with the utility grid has everything to do with how efficient and cost-effective the project is. It's not only about a constant supply of power when solar energy production is low but also having the option to send excess energy back into the grid and make some extra money. We've taken a deep look into energy transactions in this section focusing on energy purchased versus energy sold along with the costs and how it affects return on investment (ROI).

3.3.1. *Energy Purchased vs. Sold*

The comparison of energy bought from the grid to energy sold back over a standard operational period is shown in Table III and it demonstrates how well the system performs when it comes to energy transactions. The system becomes much less reliant on the grid thanks to efficiently using solar energy and battery storage.

When a lot of solar power is being produced excess energy can be sold back to the grid resulting in a positive energy trade-off. Looking over a year the system sent about 40% more energy back to the grid than it took. The extra energy produced by the system in the summer months is utilized by deferrable load as it is shown in Fig. 7 when the system produces more energy it is efficiently utilized by in-house demand. Moreover, even with the decreased Grid Feed-in rates the system is still viable but with eroded financial attractiveness. Fig. 9 shows the scheduled rates for energy sold & purchased.

3.3.2. *Cost Analysis and ROI Impact*

The financial implications of energy transactions are critical for evaluating the overall cost-effectiveness of the

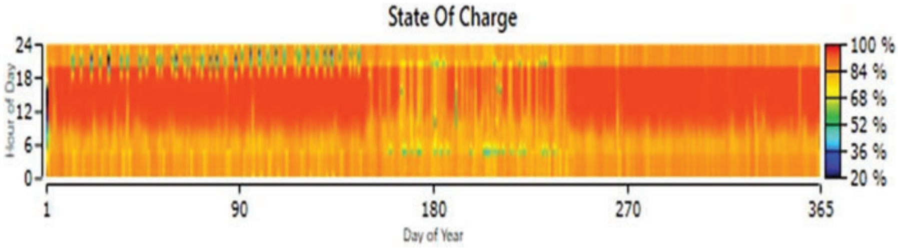

Fig. 8. Battery state of charge.

TABLE III: Energy Purchased vs. Sold

Month	Energy purchased (kWh)	Energy sold (kWh)	Net energy purchased (kWh)	Peak load (kW)	Energy charge ($)	Demand charge ($)
January	305	445	−140	5	16.32	50
February	244	463	−219	5	6.46	0
March	273	530	−257	5	4.79	0
April	251	518	−268	5	6.83	0
May	245	516	−272	4	6.32	0
June	404	19	385	6	71.54	50
July	556	14	542	7	99.55	50
August	595	26	568	7	105.3	50
September	254	423	−170	4	15.81	0
October	264	538	−274	2	12.91	0
November	262	505	−243	2	13.03	0
December	288	446	−158	3	18.37	0

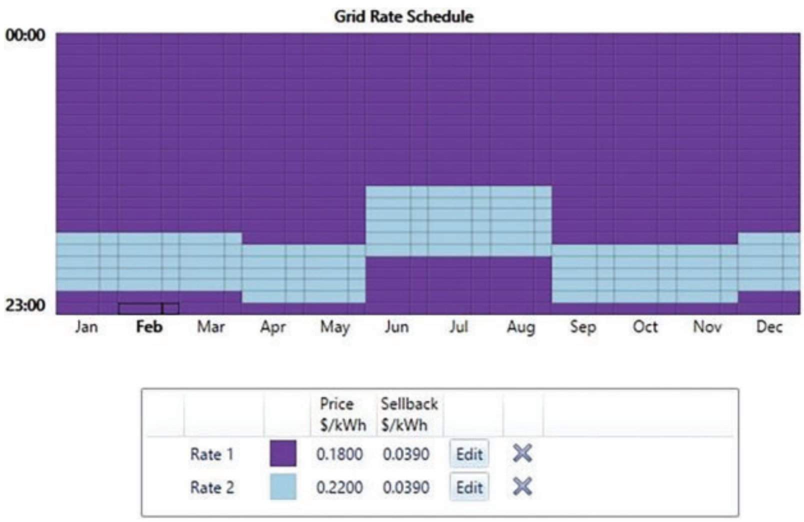

Fig. 9. Grid rate scheduled.

system. Fig. 10 provides a detailed breakdown of the costs associated with energy purchases and the revenue generated from energy sales. The revenue from selling surplus energy offsets a significant portion of the costs, resulting in a net reduction in annual energy expenses. Additionally, the energy transaction model benefits from favorable electricity export rates, further enhancing the system's economic performance. The impact on ROI is notable. By reducing energy costs and generating additional income from surplus energy sales, the system achieves a faster payback period compared to a standalone system without grid interaction. This is further supported by government incentives and feed-in tariff schemes, which add to the financial attractiveness of the project.

3.4. Cash Flow and Cost Summary

Financial analysis is a key component of evaluating the initial capital investment and long-term profitability of the solar system. This section provides a detailed discussion on cash flow dynamics and cost summary, focusing on capital investments, replacement costs, Operations and Maintenance (O&M) expenses, and the Levelized Cost of Energy (LCOE). Fig. 10 illustrates the cash flow and cost summary, respectively, providing a comprehensive overview of the economic performance of the system over the period of 25 years.

3.4.1. Capital, Replacement, and O&M Costs

The total budget for this project is essentially governed by three key variables: first up, the initial cash investment,

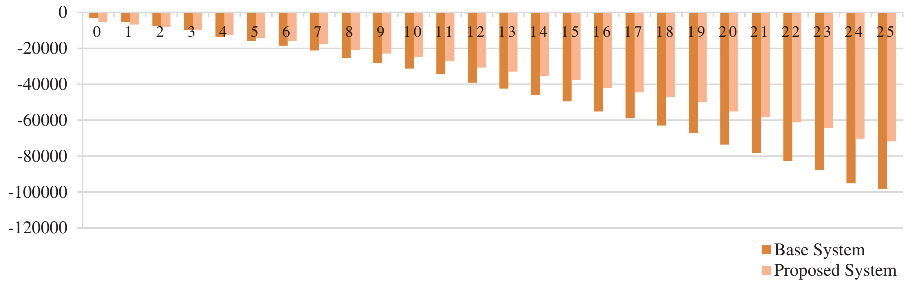

Fig. 10. Cash-flow comparison with base system and proposed system.

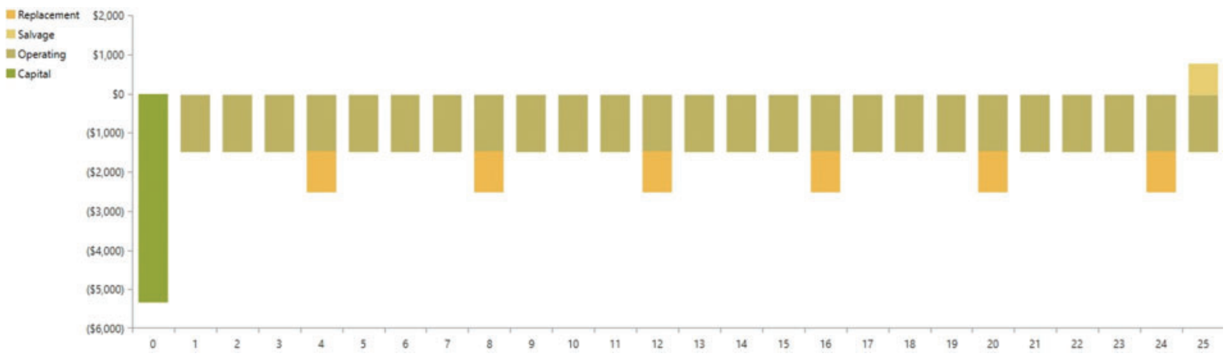

Fig. 11. Cash flow summary.

secondly, the periodic replacements of certain equipment parts, and finally, the cost of upkeep and operational services. The first big chunk of our budget will go into buying and setting up solar panels, battery storage units, and inverters. From this initial outlay, the solar panels are the big-ticket item, swallowing up about 60% of the cash pile. Batteries and the inverter will each want a slice too, but at a more modest 30% and 10% apiece. These ratios keep in step with the broader industry trends where solar panels and batteries are the main culprits in the initial outlay. As we move further along in time, there will be parts of the system asking for a refresh due to the usual wear and tear. Battery Storage systems-always working hard-will likely be needing a swap every four years depending on the rigors of their usage. The inverters life considered is 25 Years and it doesn't require replacement if general Preventive maintenance is carried out. Fig. 11 throws some light onto how these costs are spread out over the system's life journey, underlining how they feed into the long-term financial game plan. On to everyday inspections, those solar panel clean-ups, and the occasional patch-up jobs-those O&M or operations and maintenance costs. These everyday spends are more the quiet whisper in the crowd, contributing less than 5% of the overall lifecycle cost. Thanks to the robustness of today's solar panels and the improved efficiencies of modern inverters, these costs aren't too steep, making the financial aspects of the system all the more appealing.

3.4.2. Levelized Cost of Energy (LCOE)

In the world of solar energy systems, the LCOE or Levelized Cost of Energy is a trusty barometer of cost-effectiveness. It works out as the average cost per kilowatt-hour (kWh) of electricity that's produced during the system's working life. In this case, we get our LCOE by dividing the total lifecycle costs by the energy the system's predicted to pump out. And we manage to whittle down the LCOE even further by integrating deferrable loads and making the grid a marketplace for any extra energy we generate. Beyond that, it's all payback time, with lower energy bills and earning from any energy we've managed to sell. These longer-term savings make solar energy a lot more attractive, especially in places where the sun's shining plenty and the rules are friendly too.

3.5. Discussion

The findings highlight the significance of seasonal variations in solar energy production and its impact on system efficiency. The analysis of yearly and seasonal profiles demonstrates a clear fluctuation in solar output, with peak performance during summer due to longer daylight hours and increased solar radiation. This seasonal shift ensures surplus energy generation during high-yield periods, which can be stored in batteries for later use. However, during winter, the reduced sunlight hours result in lower energy production, necessitating partial dependence on the grid. The integration of deferrable loads plays a crucial role in optimizing energy consumption, aligning usage with peak solar output to minimize grid reliance. This approach enhances system efficiency and ensures that stored energy is used strategically during periods of low solar generation. The renewable penetration metrics further emphasize the effectiveness of the system, with an average of 70% renewable energy usage annually, reaching up to 85% in summer while dropping to 55% in winter. These variations underscore the importance of energy storage solutions and demand-side management to sustain a high renewable penetration rate throughout the year.

From an economic perspective, the study reveals that while the system remains viable, the extended return on investment (ROI) period to 3.7 years reflects a decrease in financial benefits due to government reductions in grid rates. Despite this, the ability to sell excess energy back to the grid helps offset costs, leading to a net reduction in annual expenses. The comparison of energy purchased versus sold indicates that, over a year, the system exported approximately 40% more energy than it imported, reinforcing its efficiency. The inclusion of deferrable loads further optimizes energy utilization, reducing battery storage stress and enhancing system longevity. Additionally, cost analysis reveals that the capital investment is predominantly allocated to solar panels and battery storage, with relatively low ongoing operational and maintenance expenses. This cost structure, combined with optimized energy transactions and government incentives, ensures the long-term financial sustainability of the system, making it an attractive investment despite initial cost challenges.

4. Conclusions

This study has given a thorough look at the effectiveness, real-world applications, and cost-efficiency of blending solar energy systems with manageable loads and storage solutions. It also delved into the financial and environmental effects of choosing renewable energy, at a time when export rates are on a decline, but optimal energy management strategies are on the rise.

The research study finds that by adding the deferrable load renewable energy penetration has increased compared to our previous study [11] from 76.3% to 81.9%. This way it helps to ramp up the usage of Solar Energy produced by Solar System. The study further evaluates the system is economical with a lower LCOE of 0.141$/kwh compared to base model LCOE of 0.277$/kWh. The suggested system Net Price is $ 76,120 which is 23% lower than the base model ROI has decreased to 3.7 years if we consider feedback grid rates to be lower from current rates of 0.08 $/kwh to 0.039 $/kwh. This show how decreasing the feedback rate will negatively impact the Feasibility of installing a solar system in Pakistan.

The insights from this study highlight that one significant way to augment energy efficiency is by merging manageable loads. This way, it helps ramp up the usage of solar energy produced by the hybrid system. It not only reduces reliance on storage systems but also trims down wastage during peak solar generation. Another notable discovery in this study is the large-sized financial impact of lower export rates for excess energy. While there are challenges, it does spur the use of load shifting strategies. It helps lower the dependence on export revenue by boosting self-consumption.

Conflict of Interest

The authors declare that they do not have any conflict of interest.

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