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Original Research Article

Optimal BESS Management for Peak Shaving Integrating Solar PV on Industrial Load

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Abstract

The industrial sector, a significant contributor to global energy demand, is experiencing a vital transition towards sustainable practices while maintaining production efficiency. The implementation of peak shaving electricity, a strategy that reduces consumption during periods of peak demand, presents a viable solution. This approach reduces greenhouse gas emissions and energy costs, benefiting both the environment and the economy. Recent advancements in the integration of solar photovoltaics (PV), battery energy storage system (BESS), and demand response programs have enhanced the appeal of peak shaving using with vendor controller and reliable communication system. This integrated approach has attracted considerable attention for its potential to optimize energy use while maintaining industrial operations, providing a pathway to responsible industrial sustainability. This paper presents application of optimal BESS management with integrating solar PV for industrial peak shaving using real-time demand response data and standard Modbus TCP/IP communication systems. This article identifies key themes, including objectives, technologies employed, and techniques for implementation. A case study of a California Waste Management facility describes the implementation of hybrid solar photovoltaic systems, a battery energy storage system, and electric vehicle (EV) charging infrastructure. These systems are capable of directly powering operations, storing solar energy in batteries, feeding excess energy into the grid, and transitioning to grid-supplied power as required. This case study demonstrated a notable 13.87% reduction in energy costs and a 22.9% decrease in CO_2 emissions. This study presents the Industrial Peak Shaving framework, designed to promote sustainable industrial practices and guide future research and implementation.

Keywords: Energy Demand, Peak Shaving, PV, BESS, EV, Modbus TCP/IP, CO_2.

1. INTRODUCTION

The global energy demand is anticipated to increase because of population growth and economic development. By 2050, the global electricity demand is projected to increase by 2.7% annually, primarily driven by the industrial and residential sectors, which account for 89% of worldwide electricity consumption [1]. The increasing usage of fossil fuels to generate energy has a major impact on the environment as it adds to the emissions of greenhouse gases. According to the World Energy Report and the IEA report, producing electricity and heat in 2021 added over 900 million metric tons (Mt) of emissions, which is 46% of the global rise. There has been a lot of research on decarbonizing the supply side of the industrial sector, but it is just as crucial to deal with the demand side, which includes energy consumption and usage patterns on the consumer side. Manufacturers and other industrial sectors can successfully decrease emissions, maximize efficiency, and optimize energy consumption by concentrating on demand-side or direct load management [2]. The increasing demand for sustainable and renewable energy sources has led to a detailed examination of sustainability-related technologies, analyzing their capabilities and possible uses [3,4]. The deployment of renewable energy not only mitigates environmental degradation but also promotes economic expansion in the top 15 emitting nations [5]. Raihan et al. reported that in the long run, a 1% increase in renewable energy use reduces CO_2 emissions by 0.3%. Additionally, CO_2 emissions are positively and statistically correlated with economic growth, with a 1% increase in economic growth being associated with a 0.9% increase in CO_2 emissions [6]. To fulfill the goals of the Paris Climate Agreement, which seeks a 45%

reduction in emissions by 2030, and net zero by 2050, numerous nations have proposed energy transition plans and strategies that reconcile environmental sustainability, energy security, and equity [7].

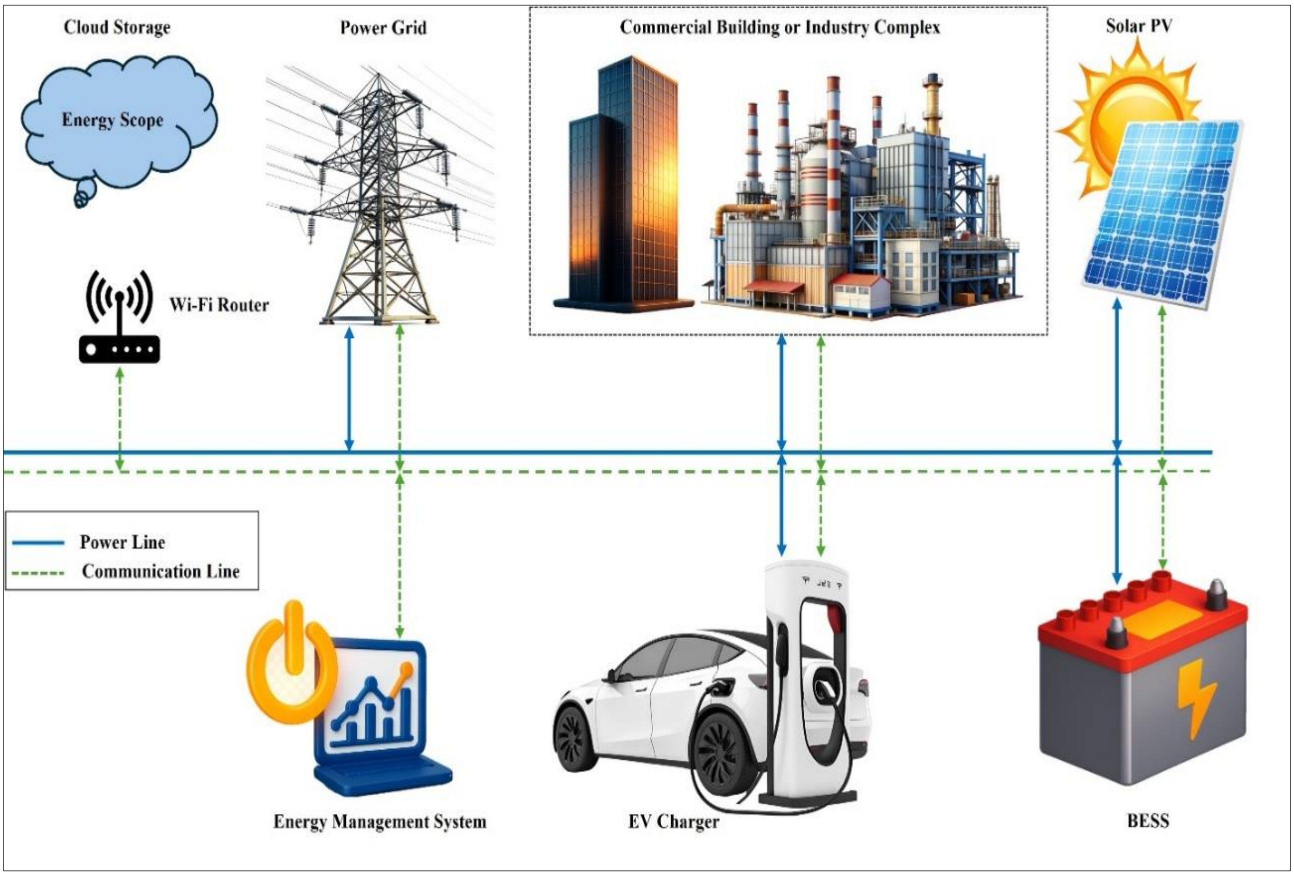


Figure 1: An Overview of a Large Power Consumer Connected to BESS, EV and Solar PV System

Throughout a single day, load demand may fluctuate periodically. Adapting to these changes, particularly during peak periods, poses a significant challenge for electric utility grids [8]. Typically, the peak demands of commercial and industrial customers significantly diverge from their normal load demands. Consequently, the optimal unit commitment strategy is necessary for utility companies to maintain a balance between supply and demand throughout the day. However, peak demand is continually rising because of the growing number of end consumers [9]. A decrease in system stability and sustainability, an increase in the marginal cost of supply, and an increase in the risk of power failure are all consequences of gradual growth at peak load. Therefore, utilities have prioritized the regulation of peak demand by balancing supply and demand [10,11]. A process known as "peak load shaving" is used to smooth the load curve by reducing the peak load amount and shifting it to lower load times [12]. The distribution network is susceptible to peak load, which occurs intermittently and accounts for only a minor portion of the day. A traditional way to deliver peak load is to boost capacity by building small gas power plants and diesel generators. However, as this method is only utilized to sustain production capacity for a few hours each day, it is not economically viable and is inefficient in terms of generator use [13]. Figure 1 shows an overview of a solar PV, BESS and EV charging system connected to a large power consumer.

2. PEAK SHAVING DEFINITION

Peak shaving is a technique that lowers the maximum power consumption at a specific time. The application of peak-shaving techniques is one promising way to attain sustainability [14]. The optimal peak shaving process using a combination of demand response, battery energy storage, and solar photovoltaic is shown in Fig. 2. The energy generated by solar panels during the day is either stored in a battery system or used for individual consumption. The stored energy is used in lieu of the power grid during periods of high demand for electricity, hence lowering the peak demand [15]. The demand response program assists in the regulation of energy consumption by prompting consumers to reduce their energy consumption during peak hours, reschedule production, or charge their batteries during low-price periods [16]. The intensity of irradiation is a critical factor in the capacity of solar PV to lower electricity consumption [17].

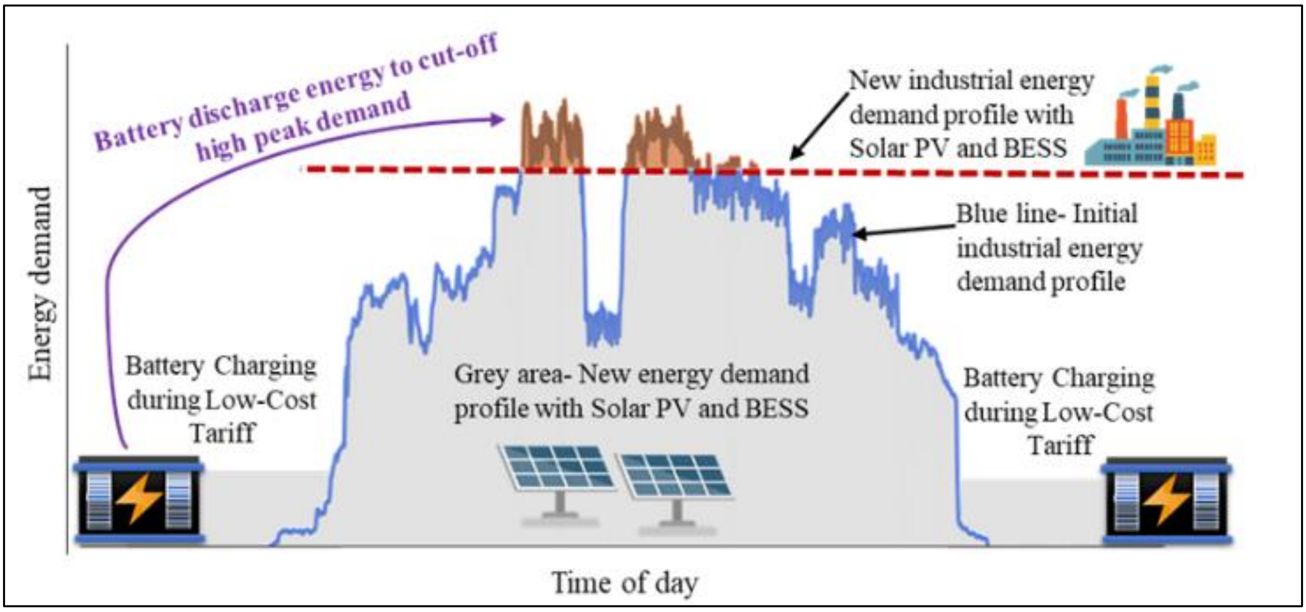


Figure 2: A Typical System of Peak Shaving Using Solar PV, BESS and Demand Response

3. IMPORTANCE OF PEAK SHAVING

The grid is very susceptible to peak load because it only happens a small fraction of the time each day. A common way to meet the peak load is by adding capacity to the generator. Nonetheless, this methodology is economically impractical and inefficient concerning the utilization of the generator, as utility providers are required to sustain the generation capacity that is operational merely for a limited number of hours per day [18]. Moreover, it presents several disadvantages, such as heightened fuel consumption and CO_2 emissions, elevated transportation and maintenance expenses, and accelerated equipment life degradation. Therefore, peak shaving may be a more effective solution for addressing the drawbacks associated with increasing capacity. Many countries, like the member states of the European Union, have already fully unbundled the power market. Because of this, it is important to understand the effects and benefits of peak shaving for people who work in the market, like energy producers, transmission and distribution (T&D) grid operators, electricity traders, and energy users [19]. Therefore, peak load shaving is a preferred method to eliminate the previously mentioned disadvantages and propose an effective solution [20]. Generally, the advantages of peak shaving include (i) grid stability and efficiency (encompassing power quality, efficient energy utilization, system efficiency, cost reduction, renewable energy integration, and grid reliability), (ii) benefits for the end-user, and (iii) reduction of carbon emissions [21].

3.1 Grid Stability and Efficiency

The following categories outline a few variables where the system's peak load optimization could significantly improve.

3.1.1 Improved Power Quality

The balance between power generation and demand is a crucial challenge, increasing day by day due to the ongoing increase in load demand. If electricity generation does not completely match the demand for power, it might cause difficulties including instability, voltage fluctuations, and total blackouts, which would affect the grid system. These issues may manifest as strain on generating equipment and compromised energy quality. Earlier studies have suggested several methods for reducing peak loads to manage the mismatch between power generation and consumer demand. These methods are mainly about making an optimal demand pattern that can contribute to better power quality [22].

3.1.2 Efficient Energy Utilization

The load factor represents an effective method for assessing the fluctuation in demand within a facility. It assesses the efficacy of electrical energy consumption. Lower load factor indicates significant variability of the consumer load. The definition of load factor (LF) represents [23].

$$LF = \frac{P_{AVG}}{P_{peak}} \quad (1)$$

Where LF is the load factor, P_{AVG} represents average load and P_{peak} represents peak load.

The economic viability of the power plant depends on having a higher load factor. According to equation (1), a high load factor means an affordable cost of electricity. Therefore, improving load factor has become essential to lowering the costs of energy and making the power plant financially profitable. Peak shaving could be a viable method to improve the load factor and affordable electricity cost.

3.1.3 Energy Cost Reduction

Typically, the public utility does not possess an energy storage system. Consequently, the amount of power generated must not exceed the amount of power demanded. Alternatively, the price of generating energy per unit will go up because of the unused electricity. This is why peak shaving is becoming more important for balancing supply and demand precisely. Such an approach will lower the cost of generating energy. But usually, the electrical network is built so that it can handle peak demand. Since peak occurs occasionally, a system larger than necessary is illogical. Furthermore, peak shaving will improve the system work, which means that the grid operator will save money on fuel and maintenance. Additionally, peak shaving ensures efficient use of the transmission and distribution (T&D) system. This procedure will delay system upgrades and make T & D infrastructure material life longer [24]. Thus, the grid operator will save money on capital costs. Peak shaving will also cut down on losses in the transmission and distribution system, which will help save even more money. To get the most money from peak shaving, industry as well as utilities need to implement it.

3.1.4 Renewable Energy Integration

The sources of clean energy are becoming more popular as an attempt to lower emissions of carbon dioxide (CO_2) in response to rising environmental consciousness. Therefore, the use of fossil fuels will continue to decrease in the generation of energy in the future. However, it is now more difficult to maintain the resilience and sustainability of the power network due to the intermittent nature of the majority of green energy sources [25].

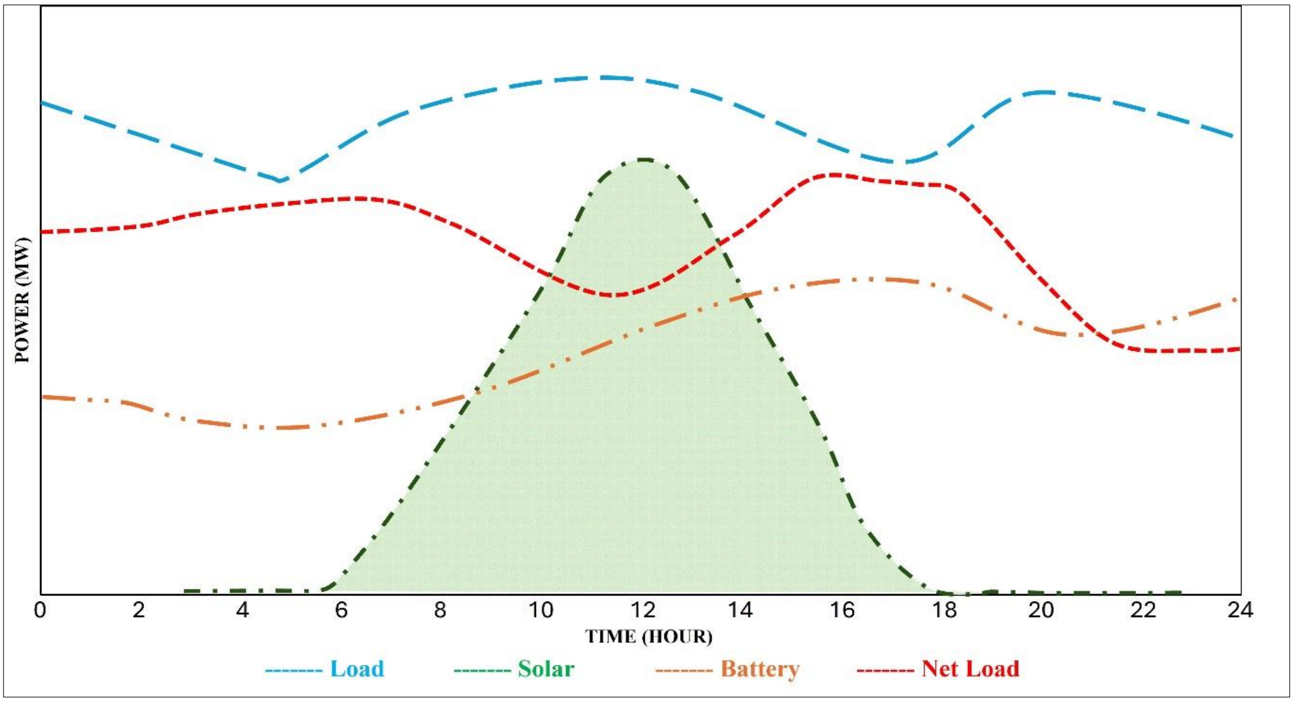


Figure 3: A Simplified Daily Net Load Profile

The net electric power (P_{net}) is vital for figuring out how much renewable energy sources like solar, wind power, and others may be used and how they impact the grid. When determining how the grid will function, the properties of (P_{net}) differ from those of traditional loads (P_{Load}). Net load (P_{net}) is defined as the traditional loads (P_{Load}) subtracted from the non-dispatchable generation, ($P_{G\,(non-dispatchable)}$). Dispatchable generators must provide a net quantity of a load. The equation of net load calculation is as follows in equation (2):

$$P_{net} = P_{Load} - P_{G\,(non-dispatchable)} \qquad (2)$$

Figure 3 shows that overall net load curves fluctuate substantially when solar energy, other renewables and battery energy storage electricity are used on an extensive scale. The design and operation of the electric grid need to consider the fact that there is more non-dispatchable generation in the grid, which makes the net load more variable [26]. When solar energy and battery power are added to the grid, the net consumption drops around noontime, and the largest peak moves to the late afternoon and evening that shows in figure 4.

3.1.5 Power Reliability and Quality

The power network system has been experiencing an enormous peak demand that progressively grows higher each single day. Such an event could make the grid less resilient and reliable. Therefore, the implementation of BESS technologies for peak shaving may increase power resiliency, sustainability, and reliability [27].

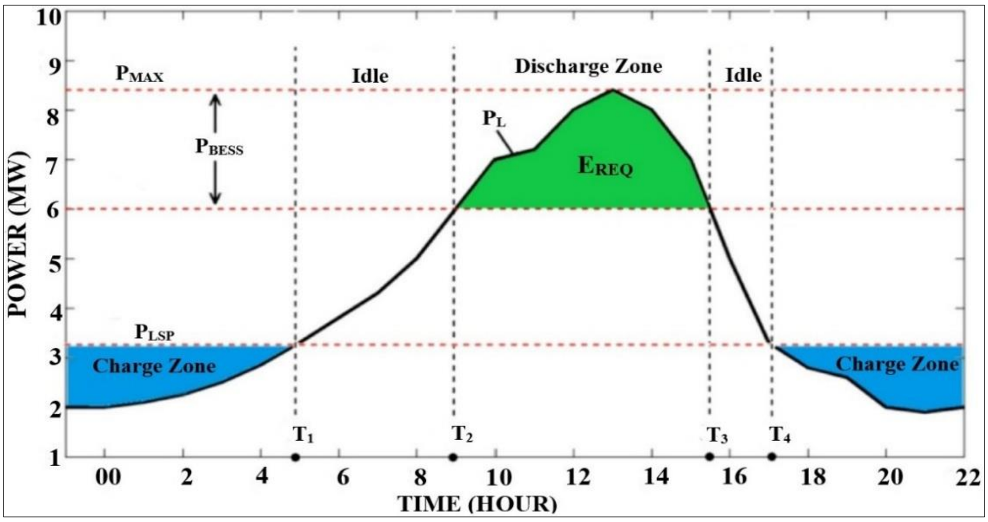


Figure 4: A Simplified Daily Load Profile with Charging and Discharging mode

3.2 Benefit of End User

To fulfil the peak demand that changes periodically, we may need peaking power stations, which are less effective for the economy and the atmosphere. Thus, the cost of generating electricity per kWh goes up during peak hour. Customers bear the increased cost of generating electricity per kWh during peak hours. Consequently, peak shaving holds significant importance for end consumers. The best way for residential and commercial clients to save money on their electricity bills is to move peak demand from the expensive peak time to the cheaper off-peak period [28]. Additionally, end users may experience a reduction in the capital costs and connection fees associated with the distribution system. Peak shaving offers essential advantages to end users, such as enhanced reliability, sustainability, and improved power quality.

3.3 Carbon Emission Reduction

Power plants use more fuel during peak demand times since the peak generator must start and stop frequently. The utilization of increased fuel consumption elevates carbon emissions. Power plants will operate more efficiently, and load fluctuation will decrease with peak load shaving. This will cut down on carbon emissions, save our environment, and provide us with economic benefits [29].

4. METHODOLOGY

To implement peak shaving using BESS and solar PV, several challenges must be addressed to ensure economical effectiveness, such as determining the optimum operation and charging/discharging strategy for BESS. In this article, we present a case study of a California-based industry load that operates year-round and is involved in waste management processing.

To maximize the economic advantages of peak shaving through battery energy storage systems (BESS) and solar PV systems, an analysis of historical load profiles, which represent the actual operational characteristics of the network, is conducted. Load profiles are gathered for various days of the week, and the average daily load variation is represented as a generalized load profile for further analysis. Figure 4 shows a simplified daily load profile. Analyzing previous load profiles estimates battery capacity. Peak shaving energy requirements can be calculated using the general load characteristics. Power demand experienced a substantial increase between the hours of t_2 and t_3, culminating in a peak value (P_{MAX}) from 12:00 PM to 2 PM. Electricity use is also very low in one place, indicating minimal consumption. The green region in the load graph shows the amount of energy needed (E_{REQ}) from the batteries to adjust the load power (P_{Load}) if the demand for electricity goes over a certain limit (P_{USP}). The upper power set point (P_{USP}) signifies the transition in power from peak to valley values, relative to the magnitude of peak reduction.

The power supplied by the BESS at a given moment in time, denoted as $P_{ESS}(t)$, corresponds to the difference between $P_{Load}(t)$ and $P_{USP}(t)$, as demonstrated by Equation (3) and (4) below:

$$P_{ESS}(t) = P_{Load}(t) - P_{USP}(t) \quad (3)$$

$$E_{REQ} = \int_{t2}^{t3} P_{Load}(t) \times dt \quad (4)$$

Another significant challenge in assessing the capacity of the BESS involves the evaluation of the state of charge (SoC) and the state of health (SoH). Typical target values for the State of Charge (SoC) in batteries should range from 20% to 95% to ensure the preservation of battery integrity.

The algorithm was developed in Python and utilizes energy balancing calculations to determine the optimal battery charging and discharging setpoints for the purpose of peak utility demand reduction. Figure 5 shows the BESS algorithm flowchart. Algorithm 1 shows its pseudocode. To determine the appropriate set-points for battery charging and discharging to lower peak load demand, the energy-balancing equation Eq. 5 below is considered, together with the limitations indicated in Eqns. 6, 7, and 8, respectively:

$$E_{Batt} = \sum_{T=0}^{T=24} |P_{SP} - P_{Load,t}| \cdot \Delta t \qquad (5)$$

$$P_{SP} = X\% \times P_{MAX} \times PF \qquad (6)$$

Where, P_{SP} is the power set point, X is a variable in an unknown set point that we can find by solving equation (1), P_{MAX} is the maximum load in MVA, PF is the power factor, and $P_{Load,t}$ is the load profile for the day ahead that corresponds to a time interval of Δt =30 min.

The battery's charging set-point during off-peak hours $P_{SP}^{(Charging)}$ and discharging set-point during peak hours $P_{SP}^{(grid)}$ is constrained by the following:

$$P_{SP}^{(Chrg)} \geq P_{load,t}^{(off-peak)} \; and \; P_{SP}^{(Chrg)} \leq P_{load\,(max)}^{(off-peak)} \qquad (7)$$

$$P_{SP}^{(grid)} < P_{load,(max)}^{(on-peak)} \; and \; P_{SP}^{(grid)} > P_{load\,(min)}^{(on-peak)} \qquad (8)$$

5. MATHEMATICAL MODEL AND ALGORITHM

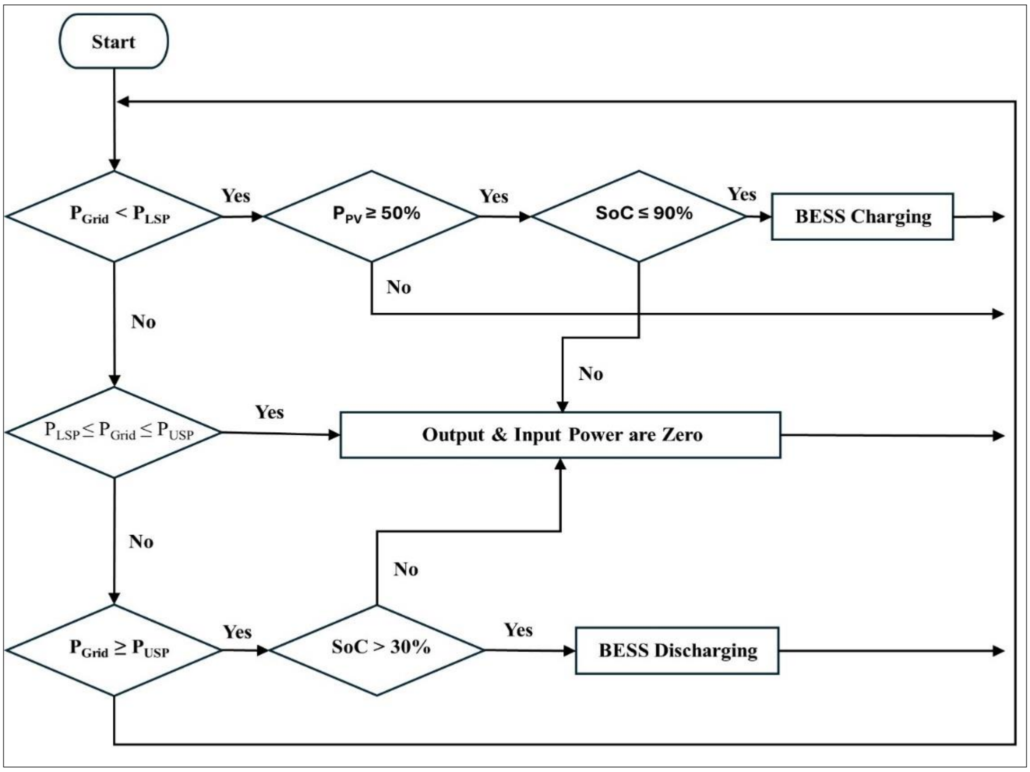


Figure 5: BESS Algorithm Flowchart

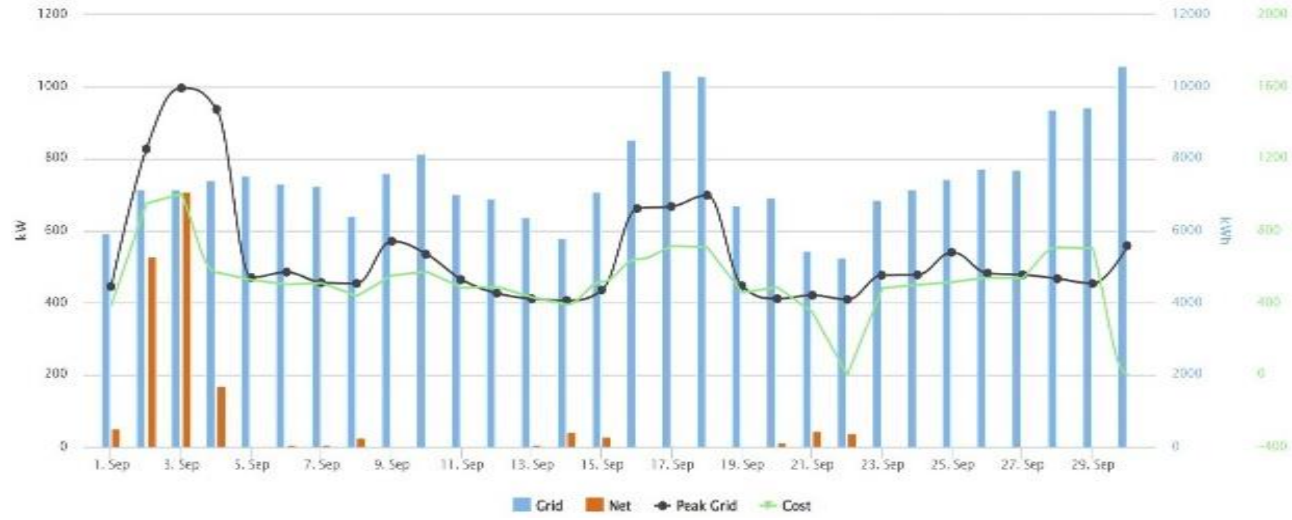
Algorithm 1. Battery Management System (BMS) Algorithm
1: Initialize: PF, E_{Batt}, SoC_{int}, SoC_{target}, P_{MAX}
2: Calculation of the energy required to charge battery:
3: Required Energy: $E_{Batt} \leftarrow (SoC_{target} - SoC_{int}) \times E_{Batt}$
4: Function to calculate the set-points:
5: **function** calculates set point (x)
6: **return** 0.01x × P_{MAX} × PF
7: Determine grid peak shaving set-point in peak hours:
8: **function** calculate l hour(x)
9: Solve Eq. 5 with constraints in Eq. 8
10: **return** Energy from right hand side of Eq. 5 (E_{Batt})
11: **for** x ∈ range (lower limit, upper limit) **do**
12: l hour value ⟵ calculate l hour(x)
13: **if** |l hour value − E_{Batt}| < min_diff **then**
14: closest_x_value ⟵ x
15: min_diff ⟵ |l hour_value − E_{Batt}|
16: **end if**
17: **end for**
18: **Return** grid Peak Shaving & Battery Charging set-point

Algorithm 2. BESS Peak Shaving Algorithm

Initialize: Load profile and update iteration
Update load profile in every 15 minutes for 24 hours
Read $SoC_{Battery}$ and set (P_{load}), (Q_{load}), PV_{load}
Grid and charging set_point from Algorithm 1
if $(SoC) < SoC_{min}$ OR $(SoC) > SoC_{max}$ **then**
    battery idle
else
    if $P_{valley\_SP} \leq PV_{load} \leq P_{charging\_point}$ **then**
        battery charging
    else
        battery idle
    end if
    if $SoC_{min} \leq (SoC) \leq SoC_{max}$ **then**
        if $P_{grid\_SP} \leq P_{load} \leq P_{load\_max}$ **then**
        battery discharge
        end if
    end if
end if

Where, $P_{load,t}^{(off-peak)}$ represents the off-peak load at time t with a 30-minute interval, $P_{load\ (\max)}^{(off-peak)}$ represents the highest demand during off-peak hours, $P_{load,(\max)}^{(on-peak)}$ represents the highest peak demand, and $P_{load\ (\min)}^{(on-peak)}$ represents the lowest demand during peak hours.

The energy balance equations for the system with respect to the grid and the BESS plant are shown in Equation 5. The summation condition, which is related to limitations in Eqns. 7 and 8, is the absolute difference between the power set points and a time-varying day-ahead load demand during off-peak hours. The total load demand and the BESS plant charging power during off-peak hours cannot exceed the maximum load demand. The battery is charged with photovoltaic energy during off-peak hours when sunlight is available. The consumer load designated peak shaving points should not be exceeded by the overall load demand, which should be minimized during peak hours by the BESS plant. Following the solution of Equation 5, the charging rate of the battery is adjusted based on the determined set point. The system will begin charging the battery if the load is equal to x% or less than. To facilitate the discharge of the battery energy storage system (BESS) plant and reduce the load during peak operating hours, the setpoint is established by solving Equation 5 and depends upon the constraint depicted in Equation 8. Algorithm 1 only displays the battery discharge approach; a similar algorithm can be added with a solar PV system for battery recharge. The second strategy, which is displayed as pseudocode in algorithm 2, reduces the maximum load demand by utilizing the BESS plant. The nested text program in SEL RTAC and a Python program in the Energy Scope SCADA panel's macro widget are also utilized for peak shaving applications. The power setpoints for charging a BESS plant and peak shaving in the designated consumer load are both determined using Algorithm 1. Algorithm 2 uses these setpoints for peak shaving operation with the Energy Scope SCADA, the EPC Power inverter, and the SEL RTAC Gridscape controller along with Modbus TCP/IP wireless communication system [30].



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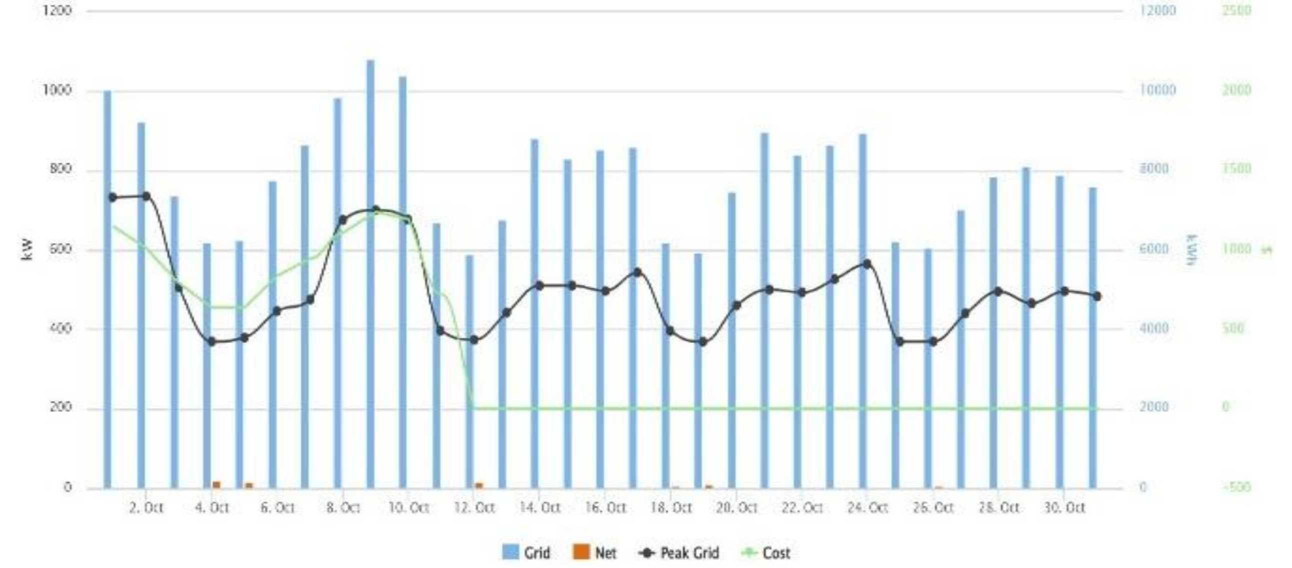

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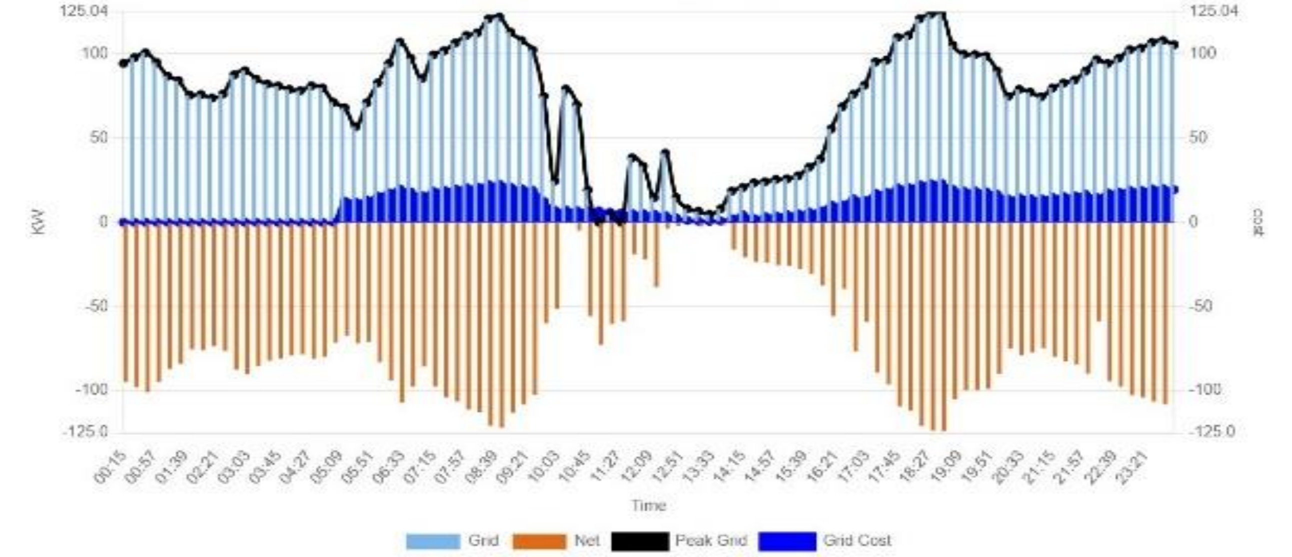

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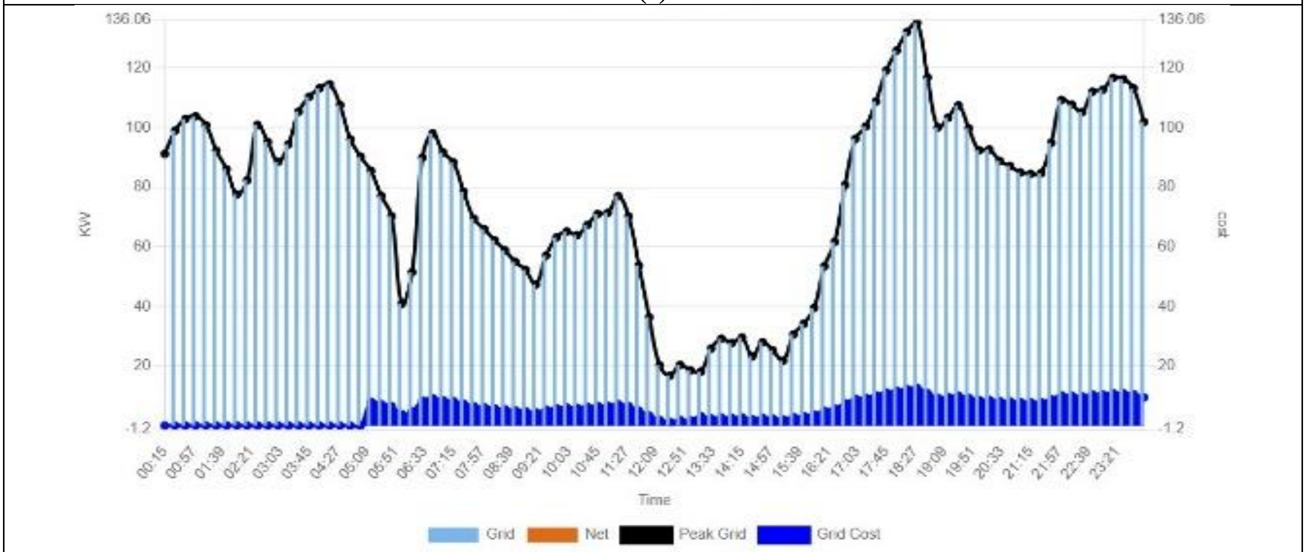


(d)

Figure 6: (a) Monthly Summer Load Profile; (b) Monthly Winter Load Profile; (c) Daily Summer Load Profile; (d) Daily Winter Load Profile

6. CASE STUDY

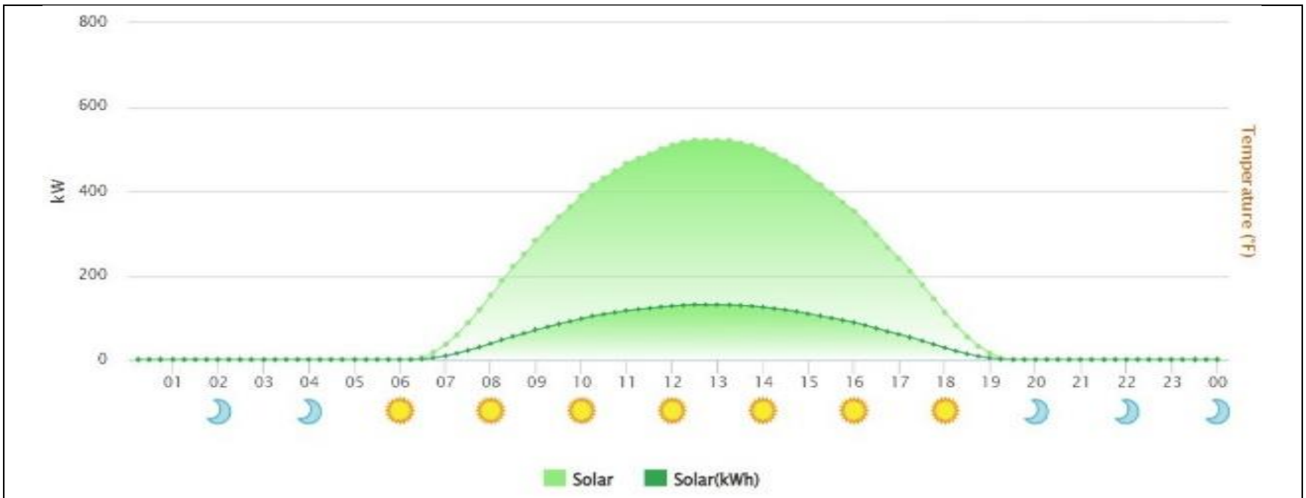
This section presents a case study employing demand data and photovoltaic (PV) power generation data from a large power industry in California, USA. The industry functions throughout the entire year and manages waste processing operations. The peak power usage for this load profile is 1,802.5 kW, and the annual energy consumption is 5,983 MWh. During daily operation hours, peak loads exceeding 1,000 kW are common. The company has a 1200 kWh lithium-ion BESS and a 1700 kWp solar PV system. We expect renewable power generation will increase 12% in the United States to 1,058 billion kWh in 2025 and increase a further 8% to 1,138 billion kWh in 2026. Renewable sources were the second-largest contributor to U.S. power generation in 2024 and accounted for 945 billion kWh, up 9% from 2023 [31]. In consideration of current trends in renewable energy generation within the United States as of 2024, a penetration rate of 50% is deemed suitable, correlating to a 1700 kWp photovoltaic installation for this case study. With the specifications listed in Table I, the investigated company is thus outfitted with a 1700 kWp/1200 kWh PV-BESS system. Since the focus of this study is on developing an effective and optimal energy management using BESS and solar PV, there is no additional discussion about optimizing system sizing. Figure 6 shows that (a) Monthly Summer Load Profile; (b) Monthly Winter Load Profile; (c) Daily Summer Load Profile; (d) Daily Winter Load Profile, of the industry.

Table I: Pv-Bess Power Circuit Parameters in Energy Scope

Objects	Descriptions	Parameters	Values	Units
Load Profile	Nominal Load	L_{nom}	10	MVA
	Annual Peak	A_{peak}	1.8	MW
	Annual Energy Consumption	A_{energy}	5983	MWh
	Time Duration	$T_{duration}$	8640	Hours
PV	System Size	KW_{DC-P}	1.7	MW
	Peak Power Watts	(W_{peak})	650	Watt
	Open Circuit Voltage	(V_{oc})	45.1	Volt
	Short Circuit Current	(I_{sc})	18.36	Amp
	Nominal Operating Temperature	Temp	43 (±2)	^{0}C
BESS	Battery Capacity	E_{batt}	1.2	MWh
	SoC Limit	SoC	5-95	%
	Nominal Voltage of battery	V_{nom_batt}	1.00	kV
	Capacity at Nominal Voltage	E_{nom_batt}	93.50	%
	Battery Inverter Capacity	INV_{batt}	9.125	MVA
	Inverter Nominal Voltage	V_{nom_inv}	0.480	kV
	Switching Frequency	f_s	2.5	kHz
	Nominal Frequency	f_{nom}	60	Hz

7. RESULTS AND DISCUSSION

The real-time data simulation outcomes demonstrate the effectiveness of the two proposed algorithms in achieving peak load shaving that reduces the energy bill and carbon emission. The case study presents a demand profile illustrating consumption patterns during adverse weather conditions, specifically cloudy and rainy days across both winter and summer seasons. The analysis is presented in alignment with the findings, and the overarching conclusions are subsequently addressed.



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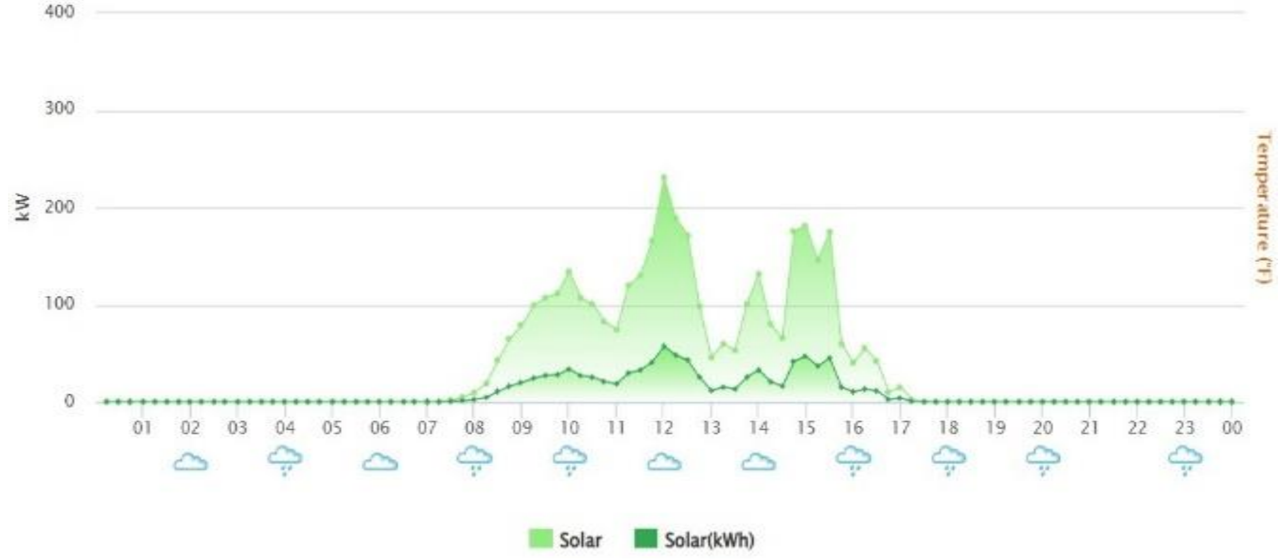
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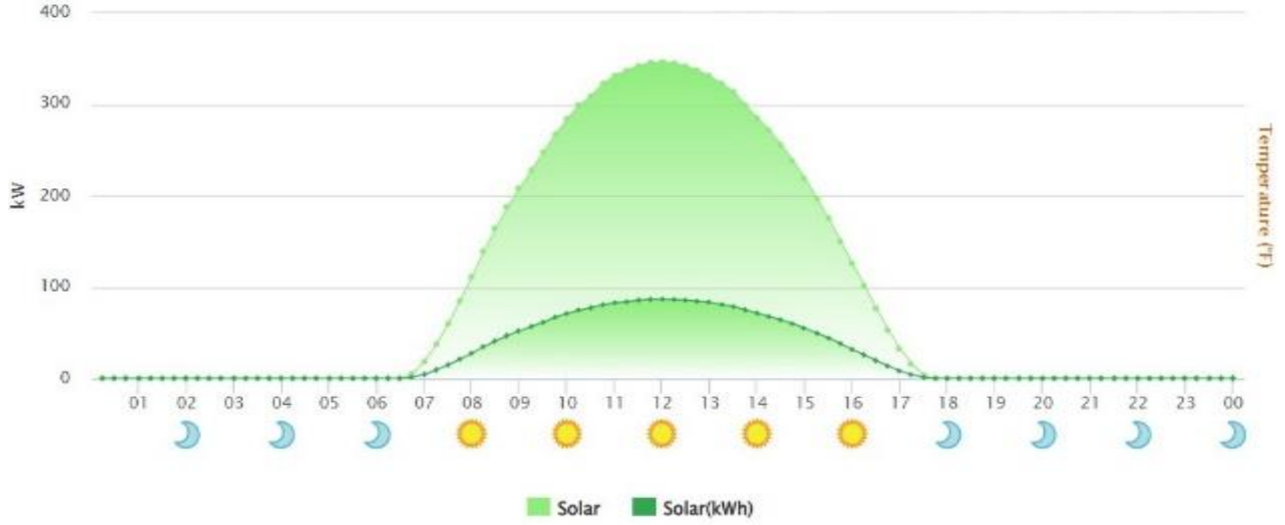
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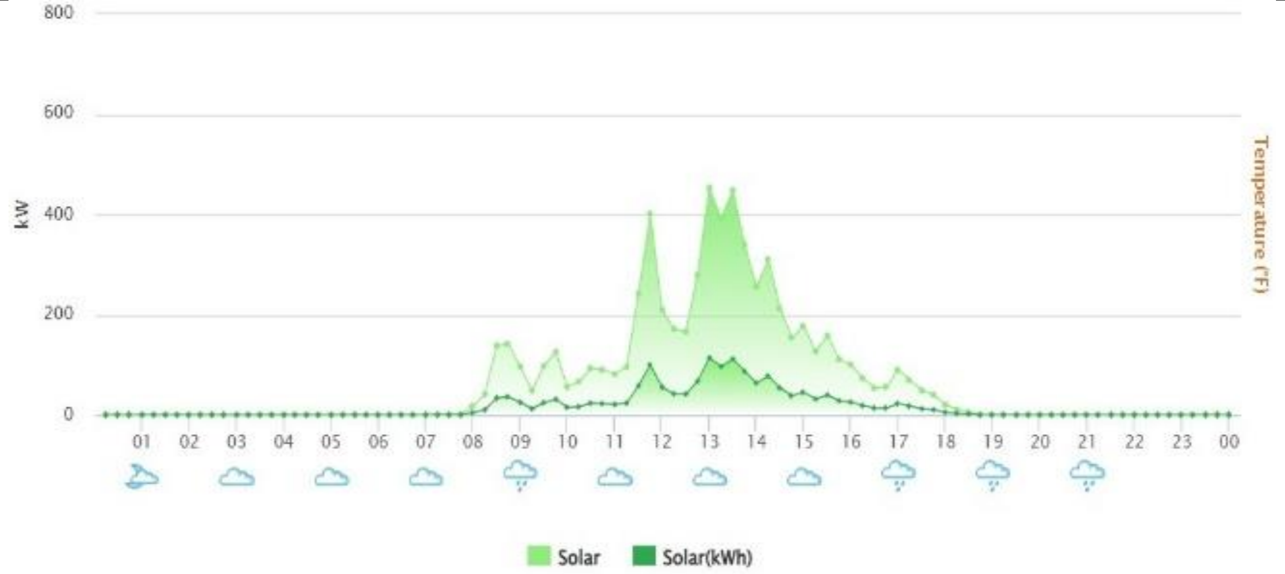
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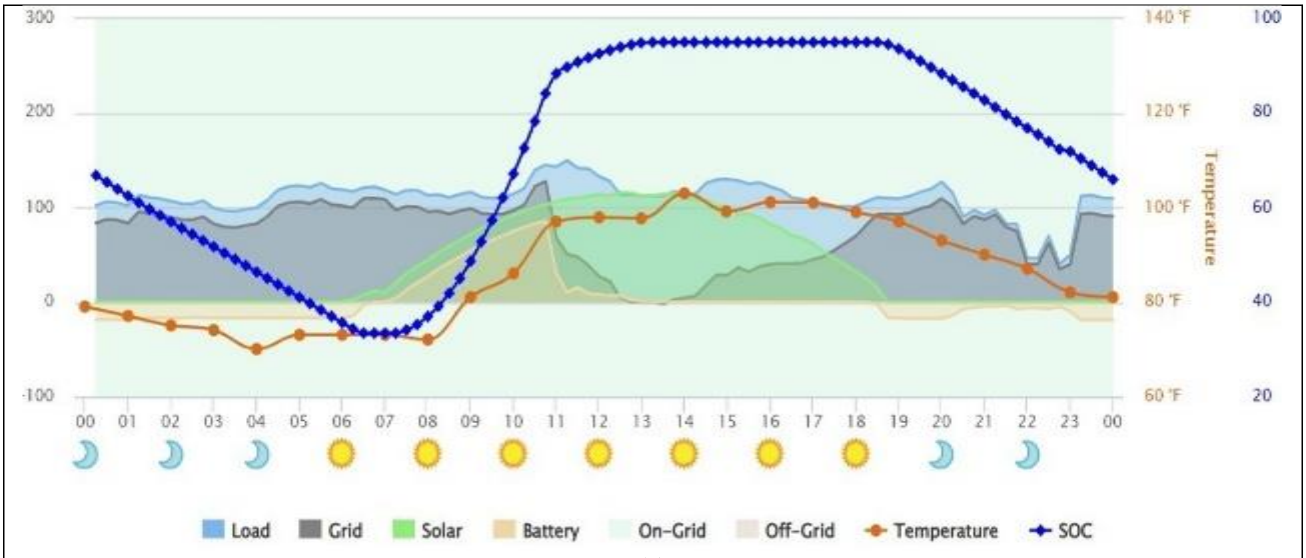

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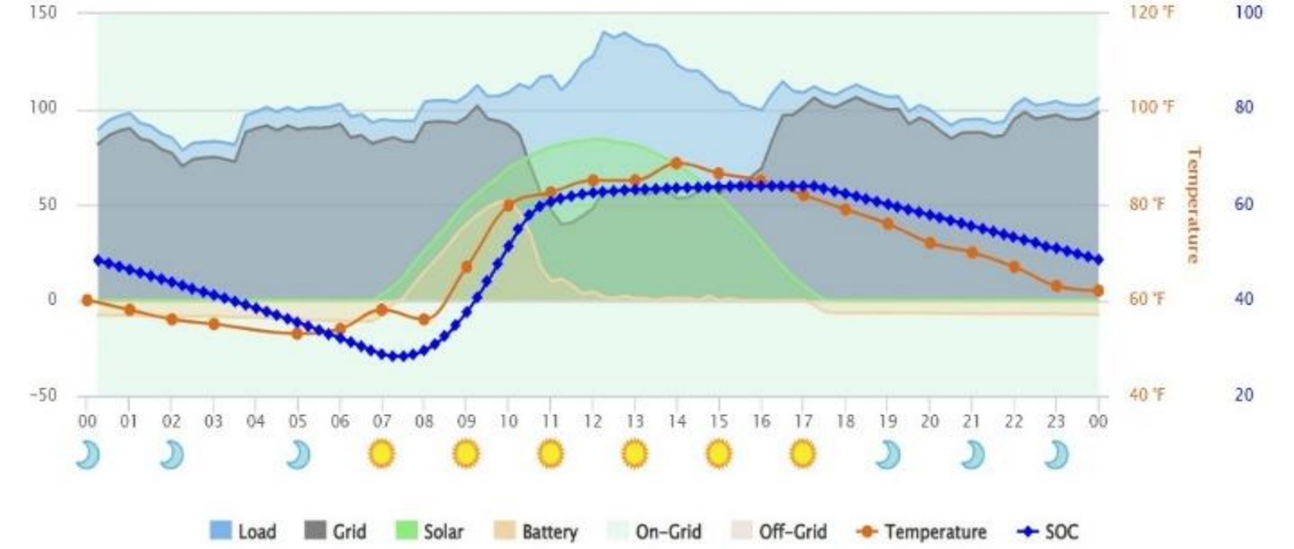

(f)

Fig. 7: (a) Solar PV Generation in Summer; (b) Solar PV Generation on Summer Rainy Day; (c) Solar PV Generation in Winter; (d) Solar PV Generation in Winter Cloudy Day; (e) Battery Discharging & Charging in Summer (SoC%); (f) Battery Discharging & Charging in Winter (SoC%).

The BESS plant obtains its power from the solar PV energy in the morning (from 7 a.m. to 12 p.m.) and sends it to the utility grid during peak hours (from 3 a.m. to 7 a.m.). The BESS facility sends 90.35 MWh of power to the electrical grid to help lower the peak shaves when demand is high. The load profile changes from winter to summer. Figure 6 shows the process by which the BESS plant is charged from PV solar and the utility grid during off-peak hours (7 am-12 pm) and then produces 100.07 MWh to be exported to the utility grid during peak demand hours (5 pm-9 pm and 11 pm-2 am), thereby lowering peak demand levels. Figure 7 displays (a) Solar PV Generation in Summer; (b) Solar PV Generation on a Rainy Day; (c) Solar PV Generation in Winter; (d) Solar PV Generation on a Cloudy Day; (e) Battery Discharging and Charging in Summer (SoC%); and (f) Battery Discharging and Charging in Winter (SoC%).

Table II: Peak Shaving Economic Analysis Using Pv & Bess Plant Two Separate Season at a Selected Month

SEASON	**Load Condition**	**Energy Consumption (kWh)/Month**	**Energy Bill ($)**	**CO_2 Emission (lb-co2/kWh)**	**% CO_2 Reduction**	**% Cost Reduction**	**Cost Reduction ($ amount)**
Summer	Without Peak Shaving	510513	86787.21	386969	---	---	---
	With Peak Shaving	420165	74749.82	318485	-17.7	-13.87	12037.39

Winter	Without Peak Shaving	438854	72522.82	332651	---	---	---
	With Peak Shaving	338786	65147.25	256800	-22.9	-10.17	7375.57

*CO_2 Emission factor 0.758 lbCO2 per kWh.

*SCE Tariff (GS-2) and (TOU-GS-2) with seasonal energy rate schedule.

Table I presents the PV–BESS power circuit parameters within the Energy Scope portal for real-time data simulation. Throughout multiple seasons, the Energy Scope simulation results for peak shaving from the BESS plant Gridscape controller are displayed in Table II. The performance indicators are the amount of energy the BESS plant supplies during peak times in MWh, the percentage of peak demand that is dropped by installing the BESS plant, and the amount of money saved by peak shaving in a month-long period in two different seasons. The result indicates that solar PV energy or power from the utility grid charges the BESS unit during off-peak hours to fill the valley. During peak hours, the unit is discharged to lessen the peak load demand. During a summer month, this initiative decreased the peak load demand by 13.87% and lowered carbon emissions by 17.7%. Conversely, during a winter month, peak shaving and carbon emission reductions amounted to 10.17% and 22.9%, respectively. The BESS draws less energy in the summer than in the winter, but the savings on utility bills are higher because the tariffs change with the seasons during peak and off-peak hours. All things considered, the BESS plant performed satisfactorily in reducing peak demand and carbon emission throughout the year. The summer months saw the most significant cost reductions, which coincided with the implementation of alternative tariff schedules.

8. CONCLUSIONS

This study addresses BESS as a distributed energy resource, particularly in the context of integrated solar energy and BESS technology. We explain the benefits and importance of BESS, focusing on how it might improve the integration of renewable energy for peak load shaving. Through this configuration, we successfully evaluated the peak-shaving control by the optimal battery energy storage system (BESS) management across diverse operational scenarios, encompassing periods of peak demand that were observed throughout the year. It is demonstrated that all connected devices and equipment are capable of communicating with each other seamlessly, enabling the real-time transmission and receiving of data and information, as well as the exchange of power signals and set points. The results demonstrated that the BESS effectively reduced peak demand, showcasing the capability of the real-time Energy Scope data simulation to evaluate BESS performance and accurately replicate realistic utility grid conditions. During the winter season, peak load demand decreased by 10.17%, and carbon emissions were reduced by 22.09%. Correspondingly, in the summer, peak load demand declined by 13.87%, and carbon emissions decreased by 17.7%. Future work will focus on using artificial intelligence to implement an automated BESS control strategy for sustainable renewable energy infrastructure development, as well as designing and building a scalable Hybrid Battery Energy Storage System (HBESS) to address energy storage challenges by integrating Li-Ion, Na-Ion, and second-life EV batteries into a unified system.

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REFERENCES

1. International Energy Outlook 2023, Global Energy Consumption By 2050 https://www.eia.gov/todayinenergy
2. S. A. B. dos Santos, J. M. Soares, G. C. Barroso, and B. D. A. Prata, “Demand response application in industrial scenarios: A systematic mapping of practical implementation,” *Exp. Syst. Appl.*, vol. 215, Apr. 2023.
3. Mears and J. Martin, “Fully flexible loads in distributed energy management: PV, batteries, loads, and value stacking in virtual power plants,” *Engineering*, vol. 6, no. 7, pp. 736–738, Jul. 2020.
4. Nastasi, N. Markovska, T. Puksec, N. Duić, and A. Foley, “Renewable and sustainable energy challenges to face for the achievement of sustainable development goals,” *Renew. Sustain. Energy Rev.*, vol. 157, Apr. 2022.
5. M. Usman, M. S. A. Makhdum, and R. Kousar, “Does financial inclusion, renewable and non-renewable energy utilization accelerate ecological footprints and economic growth? Fresh evidence from 15 highest emitting countries,” *Sustain. Cities Soc.*, vol. 65, Feb. 2021.
6. Raihan, R. A. Begum, M. N. M. Said, and J. J. Pereira, “Relationship between economic growth, renewable energy use, technological innovation, and carbon emission toward achieving Malaysia’s Paris agreement,” *Environ. Syst. Decis.*, vol. 42, no. 4, pp. 586–607, Dec. 2022.
7. Tolliver, A. R. Keeley, and S. Managi, “Green bonds for the Paris agreement and sustainable development goals,” *Environ. Res. Lett.*, vol. 14, no. 6, Jun. 2019, Art. No. 064009.
8. E. Reihani, M. Motalleb, R. Ghorbani, L. Saad Saoud, Load peak shaving and power smoothing of

a distribution grid with high renewable energy penetration, Renew. Energy 86 (2016) 1372–1379.
9. E.A. Martinez Cesena, N. Good, P. Mancarella, Electrical network capacity support from demand side response: techno-economic assessment of potential business cases for small commercial and residential end-users, Energy Policy 82 (2015) 222–232.
10. Rahimi, M. Zarghami, M. Vaziri, S. Vadhva, A simple and effective approach for peak load shaving using battery storage systems, 2013 North American Power Symposium (NAPS), 2013, pp. 1–5.
11. S. Lakshmi, S. Ganguly, Multi-objective planning for the allocation of PV-BESS integrated open UPQC for peak load shaving of radial distribution networks, J. Energy Storage 22 (2019) 208–218.
12. G.J. May, A. Davidson, B. Monahov, Lead batteries for utility energy storage: a review, J. Energy Storage 15 (2018) 145–157.
13. S. Mishra, P. Palanisamy, Efficient power flow management and peak shaving in a microgrid-PV system, 2018 IEEE Energy Conversion Congress and Exposition (ECCE), 2018, pp. 3792–3798.
14. G. Subramani, V. K. Ramachandaramurthy, S. Padmanaban, L. Mihet-Popa, F. Blaabjerg, and J. M. Guerrero, "Grid-tied photovoltaic and battery storage systems with Malaysian electricity tariff – A review on maximum demand shaving," *Energies*, vol. 10, no. 11. 2017.
15. P. E. Campana *et al.*, "Li-ion batteries for peak shaving, price arbitrage, and photovoltaic self-consumption in commercial buildings: A Monte Carlo Analysis," *Energy Convers Manag*, vol. 234, 2021.
16. J. D. Arango Castellanos, H. Dhanasekaran Velayutha Rajan, A. K. Rohde, D. Denhof, and M. Freitag, "Design and simulation of a control algorithm for peak-load shaving using vehicle to grid technology," *SN Appl Sci*, vol. 1, no. 9, 2019.
17. R. Chaurasia, S. Gairola, and Y. Pal, "Technical, economic feasibility and sensitivity analysis of solar photovoltaic/battery energy storage off-grid integrated renewable energy system," *Energy Storage*, vol. 4, no. 1, 2022.
18. Yang Y, Yang N, Li H. Cost-benefit study of dispersed battery storage to increase penetration of photovoltaic systems on distribution feeders. In: Proceedings of the PES general meeting| conference & exposition, IEEE; 2014. p. 1-5.
19. Pollitt MG, Davies S, Price CW, Haucap J, Mulder M, Shestalova V, et al. Vertical unbundling in the EU electricity sector. Inter economics 2007; 42:292–310.
20. C. Lu, H. Xu, X. Pan, J. Song, Optimal sizing and control of battery energy storage system for peak load shaving, Energies 7 (2014) 8396–8410.
21. E. Kabir, P. Kumar, S. Kumar, A.A. Adelodun, K.-H. Kim, Solar energy: potential and future prospects, Renew. Sustain. Energy Rev. 82 (2018) 894–900.
22. Thompson CC, Oikonomou PK, Etemadi AH, Sorger VJ. Optimization of data center battery storage investments for microgrid cost savings, emissions reduction, and reliability enhancement. IEEE Trans Ind Appl 2016; 52:2053–60.
23. Mehta RM VK. Principles of Power System. 4th ed. New Delhi: S. Chand; 2005.
24. Vaiju Kalkhambkar, Rajesh Kumar, Rohit Bhakar, Energy loss minimization through peak shaving using energy storage, Perspectives in Science, Volume 8, 2016, Pages 162-165.
25. Xing Luo, Jihong Wang, Mark Dooner, Jonathan Clarke, Overview of current development in electrical energy storage technologies and the application potential in power system operation, Applied Energy, Volume 137, 2015, Pages 511-536.
26. Shaker H, Zareipour H, Wood D. Impacts of large-scale wind and solar power integration on California ′ s net electrical load. Renew Sustain Energy Rev 2016;58: 761–74.
27. Wang Z, Wang S. Grid power peak shaving and valley filling using vehicle-to-grid systems. IEEE Trans Power Deliv 2013; 28:1822–9.
28. Zheng M, Meinrenken CJ, Lackner KS. Smart households: dispatch strategies and economic analysis of distributed energy storage for residential peak shaving. Appl Energy 2015; 147:246–57.
29. Koh SL, Lim YS. Evaluating the economic benefits of peak load shifting for building owners and grid operator. In: Proceedings of the international conference on smart grid and clean energy technologies, IEEE; 2015. p.30-4.
30. S. M. Shakil and M. H. Rashid, "The potential impacts of wireless power transfer on the global economy, society, and environment," presented at the 14th Power Electronics, Drive Systems, and Technology Conference, Babol, Iran, January 2023.
31. Solar Energy production, https://www.eia.gov/todayinenergy