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Electricity Cost Optimization for Large Loads through Energy Storage and Renewable Energy

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***Abstract*—Demand charge contributes to a significant portion of the electric bill for large electric loads. Shaving peak demand and adopting optimal demand management strategies can reduce this cost significantly. This paper deals with an optimization problem to reduce the electricity cost for a bulk load with the help of energy storage and renewable energy. An optimal demand control strategy is developed based on the formulated problem that aims to minimize the total electricity cost. The optimization problem was solved using the MATLAB based modeling system CVX. The system considered here is a real system that is situated in University of California, Riverside. Available renewable energy (solar) prediction data and lithium iron phosphate battery data has been used for the simulation purpose. Two different strategies, battery only strategy and battery with solar strategy, are tested with the proposed strategy. The results are validated with National Renewable Energy Laboratory (NREL) developed System Advisor Model (SAM). The results show that 14.5-15.4% peak reduction is possible which leads to a monthly savings of *$6,410* to *$38,820*.**

***Keywords*—Demand cost, Optimization, Energy storage, Renewable sources, Bulk loads.**

I. INTRODUCTION

The world's population and economy are experiencing uncontrolled growth, accompanied by rapid urbanization. This trend is expected to lead to a significant surge in energy demand in the coming years. However, conventional energy sources are struggling to keep up with this increasing demand, as many of them are becoming scarce and their availability is diminishing. To address this challenge, renewable energy has emerged as a popular and viable solution to meet the growing energy demand. Renewable energy sources, such as solar, wind, hydro, and geothermal power, offer sustainable alternatives that can help satisfy the increasing energy needs without further depleting finite resources.

Countries around the world have recognized the importance of transitioning to renewable energy sources and have taken initiatives to meet their energy demands through renewable means. For example, California has set a goal to rely entirely on zero-emission energy sources for electricity by the year 2045, demonstrating a commitment to renewable energy adoption [14]. The shift towards renewable energy brings numerous benefits. It helps reduce carbon emissions, mitigating the impact of climate change and improving environmental sustainability. Additionally, renewable energy sources offer long-term energy security, as they are naturally replenished and not subject to the same constraints as fossil fuels.

The most recent works have been done on cost minimization of residential loads and is landed micro-grids. Large building loads have not been analyzed to a great extent because minimizing large building loads can be quite strategic and tricky. While analyzing the large building loads, very high peaks are usually observed. Peak shaving has been considered as a very efficient and cost-effective approach for large consumer groups as peak demand cost occupies a major portion of the electricity bill for the consumers in commercial and industrial sectors. Renewable energy like solar, wind etc can be applied for peak shaving in large building loads for a short period of time.

Peak demand reduction-related research has been done in the area of determining the size and best operation of battery energy storage systems. Large industrial plants are particularly interested in the peak shaving application because their electricity bill includes both energy cost and demand cost. The latter one frequently reaches a level of 50% of the entire cost of the electricity bill and corresponds to the highest value of power demand during a specified time period (usually between 15 minutes and an hour). Battery energy storage systems (BESS) have previously been used to lower peak demand and electricity bills utilizing the tactic of discharging stored energy at peak times for various sorts of tariffs [16], [18]–[20]. Meanwhile, renewable energy can also play a vital role for supplying the additional energy in cases when the BESS is not enough or gets out of order due to any unavoidable occurrence. But the initial installation cost for large solar and wind facility is way too high which makes it an economically inefficient plan both from the utility as well as customers' perspective [2]. Strong public support for renewable energy has prompted academics to look at novel ways to improve renewable energy penetrations, mostly in the form of solar, wind, and wave energy [3].

Traditional approaches, such as on-site diesel generators, generate issues such as cost inefficiency, high fuel consumption, carbon dioxide (CO2) emissions, increased transportation and maintenance costs, and quicker depreciation of equipment [4], [5]. Multiple algorithms such as genetic algorithm, ant colony optimization algorithm have also been applied to reduce the electricity cost and smart energy management for bulk loads [5], [7]- [14]. Previous work has been done in the case of a freestanding hybrid solar-wind system [Hong Kong]. Different storage technologies, such as pumped hydro storage and flywheels, have also been considered in some circumstances [2], [4]. The economics of hybrid photovoltaic-diesel-battery power systems for residential loads have been investigated in [2]. However, no study has been done on the techno-economic analysis of a big load grid-connected system with peak shaving for cost optimization. In [12], authors suggest novel net-zero energy management and optimization methodologies for commercial buildings in metropolitan locations powered by renewable energy sources. The goal of applying these measures is to get buildings to consume as much energy as they create from renewable sources, resulting in a net-zero energy balance. Moreover, Machine learning algorithms have been very useful in processing multi-modal data [13]. Also, Genetic Algorithom has been used in a dynamic system with discrete time and spatial neighborhood structure [17].

This research paper primarily focuses on addressing the classical cost optimization problem in the context of a large load consisting of multiple university building accounts, while also taking into consideration the constraints imposed by batteries. Previous studies conducted in this field have not given sufficient attention to cost optimization and validation across multiple accounts. In this paper, the integration of grid energy, solar energy, and battery energy storage systems (BESS) is explored with the objective of achieving peak shaving and power leveling at any given time. Simulations are performed on two different combinations of these energy sources in order to improve peak shaving capabilities and reduce overall costs. The research problem is formulated as a convex optimization problem, where the objective function is the total cost that combines energy cost and demand cost. The simulated results demonstrate significant cost savings for bulk loads. The System Advisory Model (SAM) is employed to validate the modeled system, and the cost reduction obtained from the formulated MATLAB program closely aligns with the analysis conducted using SAM. Additionally, the paper considers monthly and annual cost savings as crucial aspects of the techno-economic analysis.

The organization of this paper is as follows: Section II states the control strategy and description of the notations. Problem formulation and constraints have been explained in section III. Section IV describes the optimization algorithm whereas simulation results are shown in section V. A few limitations with future directions have been noted in section VI and section VII gives the concluding remarks.

II. System Description

The system consists of a large load with an average of 6682.838 kW daily for any 15-minute period throughout a year. It is a billing account of multiple buildings situated in University of California Riverside campus. Currently the buildings have no solar, wind and battery storage for providing energy during on peak hour. A 100-kW solar panel and 5000 kWh $LiFePO_4$ battery has been assumed to be connected to the buildings for the simulation purpose. Solar and wind data of the location has been predicted for respective weather data with machine learning approaches.

A. Control Strategy

The peak power drawn by the load can be shaved by using energy storage and solar energy individually. Extra power is drawn from the grid during low-demand periods and stored in batteries so that it can be used during peak periods later. Batteries will discharge the energy during peak periods which will eventually reduce the power drawn from the grid and will help reduce the electricity bill. Solar energy has been used as additional source of renewable energy along with the energy storage. Simulation has been done assuming two different combination of the surplus energy such as battery only and battery and solar. Fig. 1 depicts the system diagram and power flow from various energy sources to the building load.

Renewable energy (solar) can be stored in the BESS and be used in the moment of need, which will eventually reduce the amount of required energy to be drawn from the grid. Renewable sources can also provide energy to the load directly. Any surplus energy source can reduce the cost of electricity by using at a proper time schedule. But the drawback of renewable energy sources such as solar and wind generation is their high intermittency and heavy dependency on weather conditions. Solar generation data and corresponding weather data were collected from National Renewable Energy Laboratory's (NREL) National Solar Radiation database

B. Notation

To solve the cost saving problem analytically, we have used some notations for different parameters such as time slot, solar energy, battery storage etc. The notations that have been used throughout our algorithm to implement the strategy are summarized below.

III. Problem Formulation and Constraints

A. Objective Function

The objective of our problem is to minimize the electricity cost. Electricity cost has two parts: Energy charge (kWh) and demand charge (kW). So, in order to reduce the electricity cost we have to minimize the following equation.

$$Minimize \quad a\mu\sum_{i=1}^{n} t_i + b\cdot max(t_i) \tag{1}$$

Where, a denotes the energy price measured in ($/kWh) and b is the peak price measured in ($/kW) and is the power

TABLE I
SUMMARY OF NOTATIONS

Notation	Notation Description
i	index of a slot in the billing period
t_i	total power drawn from grid in slot i
g_i	grid power fed into the load in slot i
$\mathrm{C_i}$	power charged into the battery in slot i
$\mathrm{d_i}$	power discharged from the battery in slot i
l_i	power provided to the load in slot i
s_i	solar generation in slot i
$C_{\max}$	battery's maximum charging rate
$\mathrm{D}_{\max}$	battery's maximum discharging rate
$E_{\max}$	battery's maximum storage capacity
η_c	li-ion battery's conversion efficiency
η_l	li-ion battery's leakage efficiency
a	the energy price measured in (\$/KWH)
b	the peak price measured in (\$/KW)
μ	duration of time slot i
E_{primary}	energy left first slot when billing period starts
e_i	energy left in battery at beginning of slot i

(kW) consumed from the grid in time slot i and μ is the duration of time slot i. μ is 15 minute duration as the peak load has been selected based on the peak of any 15 minutes throughout the monthly billing period. For Riverside Public Utility (RPU) rate schedule (designed for large building load and demand is consistently greater than or equal to 150 kW), the energy price is 0.1033 (\$/kWh) and peak demand price is 6.88 (\$/kW). The rate schedule is not a Time of Use (TOU) schedule and does not vary with the different time periods of the day. So, the first portion of the objective function denotes the energy charge or kWh charge and the second portion of the objective function denotes the demand charge or the kW charge. Together they comprise the total electricity cost that we are trying to minimize.

B. Constraints

We are trying to solve the optimization problem subject to some constraints. These constraints are mentioned below:

i. $t_i = g_i + c_i; \quad 1 \leq \mathrm{i} \leq \mathrm{n}$

ii. $g_i + d_i + s_i = l_i; \quad 1 \leq \mathrm{i} \leq \mathrm{n}$

iii. $\mathrm{e}_i = \begin{cases} E_{\text{primay}} & \mathrm{i}=1 \\ \eta_c c_{i-1}\mu + \eta_l\left(e_{i-1} - d_i\mu\right) & 2 \leq \mathrm{i} \leq \mathrm{n} \end{cases}$

iv. $\mathrm{d}_i\mu \leq e_i; \quad 1 \leq \mathrm{i} \leq \mathrm{n}$

v. $\mathrm{d}_i \leq \mathrm{D}_{\max}; \quad 1 \leq \mathrm{i} \leq \mathrm{n}$

vi. $\mathrm{c}_i \leq \mathrm{C}_{\max}; \quad 1 \leq \mathrm{i} \leq \mathrm{n}$

vii. $\mathrm{e}_i \leq \mathrm{E}_{\max}; \quad 1 \leq \mathrm{i} \leq \mathrm{n}$

viii. $\mathrm{t}_i,\ \mathrm{g}_i, \mathrm{c}_i,\ \mathrm{d}_i, \mathrm{e}_i,\ \mathrm{s}_i \geq 0; \quad 1 \leq \mathrm{i} \leq \mathrm{n}$

The explanations of these constraints are described below: The first constraint stands for the fact that at any time slot i, the total power drawn from the grid must be equal to the power supplied directly to building load plus the power supplied to charge the li-ion battery. The second constraint denotes that at any time slot i, the power supplied directly to the load need to be commensurate with the summation of the solar generation, the power discharged from the battery and power drawn from the grid. The third constraint focuses on the energy calculation of the battery. At any instant the battery storage must be equal to the energy supplied from the grid to charge it from the previous time slot times the conversion efficiency with the remaining battery energy from the previous period minus the discharged energy from the previous time slot times the leakage efficiency. We assume that initially the stored energy in battery is zero. The fourth constraint tells us that at any time slot i the discharged energy from the battery must be less than or equal to the stored energy in battery. The fifth constraint tells us that at any time slot i the power discharged from the battery must be less than or equal to the maximum discharging rate which is 5000 kW. The sixth constraint denotes that at any time slot i the power charged in to the battery must be less than or equal to the maximum charging rate which is 5000 kW. The seventh constraint states that at any time slot i the remaining energy in battery must be less than or equal to maximum storage capacity of battery which is 5000 kWh. The last constraint states that the total power drawn from the grid, the power supplied directly to the building load, the power discharged from the battery, the power charged into the battery, the stored energy in the battery, solar generation at any time instant must be non-negative.

C. Convex Optimization

The formulated problem is a convex optimization problem. Since the energy charge part in the objective function is linear, it can be considered as convex. The demand charge part of the objective function is a function of max function which is a convex function. The energy price measured in (\$/kWh), a, the peak price measured in (\$/kW), b the duration of time slot, μ and the time itself are positive quantities. So, the objective function is a convex function as it will minimize the nonnegative weighted sum of two convex functions. All the constraints are linear and therefore, they can be considered as convex, too. Since the objective function and the constraints are all convex, the stated optimization problem stated in this paper is a convex optimization problem. This problem has been solved with MATLAB CVX [15] tool to find out the cost and compare it with the cost in absence of our algorithm.

IV. Optimization Algorithm

The algorithm implemented for convex optimization problem solving has been stated below:

Algorithm:

Step 1: Solve the optimization problem using the building load data along with the battery specifications. each time slot i.

Step 2: Generate the decision variables t_i, g_i , c_i , d_i for each time slot i.

Step 3: Take the following actions for each time slot i for the intended day:

- Draw $\mathrm{t_i}$ kW from grid.

- Draw s_i kW from solar panels.
- Supply g_i kW directly to building.
- Use c_i kW from grid to charge the battery.
- Discharge d_i kW from the battery to meet the building load demand.

We applied this algorithm continuously for each day of the month and optimized the monthly cost.

V. Simulation Results

The applied algorithm shaves the peak at a certain limit each day and hence the maximum demand has been reduced. Two different strategies have been adopted for the simulation purpose with the proper modification to the algorithm. The first strategy does optimization with battery only and the second strategy includes solar generation alongside battery for optimization purpose. The simulation results produce good outcomes in terms of both peak reduction and cost minimization. Both the strategies reduce the peak load by a significant amount. Consequently, a considerable amount of money is saved as demand charge accounts for the most of the billing amount. The following figures and tables present the findings from the simulation results. Figure 3 shows the actual load without optimization and the load optimized with battery only strategy. Figure 4 shows the actual unoptimized load and the optimized load with battery plus solar strategy. The performance of these strategies are compared in table II and table III which show the cost savings and the peak reduction respectively for these two strategies.

Table II tabulates the actual cost of electricity and the minimized cost after the optimization algorithm and monthly savings both in dollar amount and percentage amount for both of the systems. Battery only strategy holds an unoptimized value of $502,970 and optimized cost of $496,560. As a result of the optimization, $6,410 can be saved on a monthly basis which is 1.27% of the actual cost. On the other hand, the actual electricity cost of combined battery plus solar strategy is $502,970 whereas the optimized cost is 464,150. As a consequence, $38,820 can be saved monthly which represents 7.72% of the actual cost.

Table III demonstrates the peak load before and after optimization has been performed and the total monthly peak reduction both in kW and as percentage. For battery only strategy, the usual peak load is 7,910 kW and the optimized peak load is 6,763 kW which stands for 1,147 kW load reduction (14.5% of the total load). The combined battery and solar strategy reduces 1,217 kW load after the optimization algorithm has been applied on the system which is 15.39% of the total load (7,910kW).

From the SAM analysis report, the yearly electric bill without system is $6,122,238 and yearly electric bill with the optimization algorithm is $5,656,963. Net savings with system is $465,275 and the payback period is 17.1 years. Therefore,

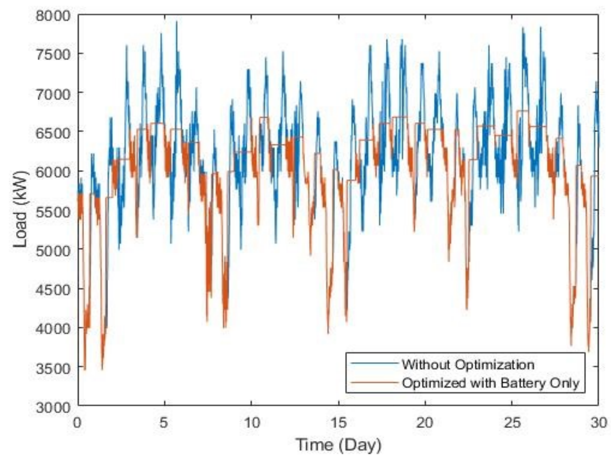

Fig. 1. Load optimization with battery only

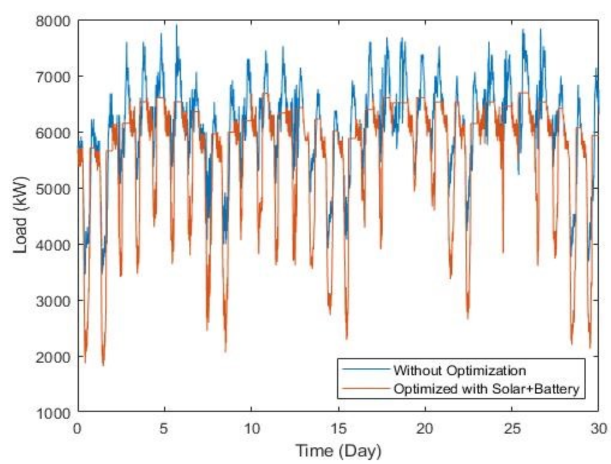

Fig. 2. Load optimization with solar plus battery

TABLE II
COST SAVINGS

Strategy	Actual Cost ($)	Optimal cost ($)	Monthly Savings ($)
Battery	502970	496560	6410
Battery + Solar	502970	464150	38820

TABLE III
PEAK REDUCTION

Strategy	Peak without Optimization (kW)	Peak with Optimization (kW)	Peak Reduction (kW)
Battery	7910	6763	1147
Battery + Solar	7910	6763	1217

from economic point of view, this algorithm can save a huge amount of money for a customer who intend to use the system for a long period of time.

VI. Limitations and Future Consideration

The algorithm used here does not consider the Time of Use (TOU) demand rate which is different based on different time periods like on-peak, mid-peak and off-peak. Mid-peak and off-peak hours usually offer lower rates and incentives are offered usually for shifting energy use away from more expensive peak hours. Undoubtedly, this Time of Use policy can help the users save money and reduce the stress on the electric grid as well as utility companies. Moreover, change of SOC (State of Charge) of batteries has been considered as linear with time. For non-linear characteristics along with other constraints of Li-ion batteries, the algorithm may act differently. So, this algorithm can be applied by considering these limitations to produce better results in future. Moreover, deep learning models can be employed to learn the relationships between input variables, output variables, and the constraints that need to be satisfied. The model can then be used to optimize the output by adjusting the input variables while ensuring that the constraints are met.

VII. Conclusion

This paper presents an algorithm that can help in peak reduction of large electric loads which results in the reduction of cost in electric bill with demand charge. Most of the previous work that dealt with this type of optimization was done only on small to medium residential or commercial loads and on simulated systems. The system considered here is a real system with a large load comparable to industrial loads, which is situated in the University of California, Riverside's campus. Two strategies, one with battery only and the other with solar plus battery are examined here with necessary modifications. Both of the strategies are successfully able to do peak shaving and cost reduction for the given load profile and existing system. As expected, the generated results show that the battery plus solar strategy is superior to battery only strategy, providing a monthly savings of almost six times than the latter. The results are proven acceptable as they are validated with SAM. With proper long-term planning this amount of savings can prove to be profitable for the industrial customer with a similar size load. The utility companies can also be benefitted from such approach as it the optimized load with reduced peak would put less stress on generating units. The future of energy use will be dominated by renewable generation with storage systems and this work can be made impactful and valuable with proper implementation and integration

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