2021 International Conference on Smart Energy Systems and Technologies (SEST) | 978-1-7281-7660-4/21/$31.00 ©2021 IEEE | DOI: 10.1109/SEST50973.2021.9543188

A Comprehensive Building Load Optimization Method from Utility Rate Structure Perspective with Renewables and Energy Storage

A S M Jahid Hasan, Luis Fernando Enriquez-Contreras, Jubair Yusuf, Sadrul Ula
College of Engineering - Center for Environmental Research and Technology
University of California Riverside
CA, USA
ahasa006@ucr.edu, lenri001@ucr.edu, jyusu001@ucr.edu, sula@cert.ucr.edu

***Abstract*—To accommodate the changes in the nature and pattern of electricity consumption with the available resources, utility companies have introduced a variety of rate structures over the years. This paper develops a comprehensive optimization method that addresses the diversity of utility rate structures of buildings principally commercial buildings. It includes a general set of constraints that can be used for any system with a building load, a renewable source, and a battery energy storage system (BESS). A cost function is formulated for each type of rate structure that can be exercised by a utility on a commercial building. A novel algorithm is developed to apply the optimization model and generate the desired optimal outputs by using the appropriate cost function. The results for several building loads and rate structure types were obtained and compared. The results exhibit that adding BESS is more effective for buildings with lower load factor and Critical Peak Pricing (CPP) rate structures in comparison to the buildings with flat energy rates. These results can help a customer with deciding on the different rate structure options and resource planning of their renewable generation and energy storage.**

Keywords—building load, optimization, utility rate structure, energy storage, renewable generation

NOMENCLATURE

Parameters

t=Timestep
Δt= Duration of each timestep
T'= Total number of timesteps
E^{Bmin}/ E^{Bmax} =BESS minimum/maximum stored energy limit
P^{B+max}/P^{B-max}=BESS maximum charge/discharge power
E^{B}_{init}=Initial stored energy of the BESS
P^{S}_{t}= Solar generation t
P^{L}_{t}= Load at t
α_t = Energy charge at t
β=Monthly peak demand charge
$\beta^{On}_t / \beta^{Mid}_t / \beta^{Off}_t$ = On/Mid/Off-Peak demand charges at t
η^{+}/η^{-}=Charging/discharging efficiency of BESS

Variables

E^{B}_{t}= Energy stored at t in BESS
P^{B}_{t}= BESS power at t
P^{B+}_{t}/P^{B-}_{t} = BESS charging/discharging power at t
P^{G}_{t}= Power drawn from the grid at t
P^{SB}_{t}= Solar power fed to BESS at t
P^{SL}_{t}= Solar power fed to load at t
P^{BL}_{t}= BESS power fed to load at t

I. INTRODUCTION

A. Background and Motivation

The nature and pattern of electrical loads have changed significantly over the years. The recent adoption of high renewable penetration has made the change even more severe and rapid. The utilities have developed numerous types of electrical rate structures accordingly that would facilitate their operation with the existing generation, transmission, and distribution resources. Concepts such as Time of Use (TOU) and different types of energy and demand charges have been introduced to remedy the limitations of these resources. Additionally, highly distinctive load patterns and consumption amounts have urged the utilities to include separate rate structures for residential and industrial/commercial sectors. Commercial buildings are one of the largest electricity users in the U.S. as they consume about 35% of the total electricity consumption [1]. As a result, their users are immediately affected by any change in the electrical rate structure. As one of the largest electricity users in the U.S., these building loads offer great potential for optimization with the help of renewables and energy storage that would largely benefit both the customers behind the meter and utility operators. But these extremely diverse and highly complex rate structures as well as the pattern of the loads with building size and types create a major challenge for formulating an appropriate optimization strategy. Therefore, in order to design an optimal strategy for reducing building loads with renewable generation and energy storage, the rate structure is an important component that needs to be considered.

B. Relevant Literature

Many research works have been done on the optimization of the building loads using distributed energy resources (DERs). Minimizing the energy cost of the building-integrated microgrid is the main objective in most literature. Thermal modeling of a building and interactive load management [2] and building to the grid scheme are shown in [3], to minimize TOU energy cost. The compromise between user comfort and energy optimization is executed in terms of energy prices to provide a universal model-based anticipative building energy management system [4-5]. Electric vehicle's (EV) activity with grid for two types of rates is used to provide the optimal strategies [6-7]. Mixed Integer Linear Programming (MILP) approaches are taken to optimize energy through demand response with different electricity prices [8-10]. Though their economic cost function includes complex costs such as fuel cost, generator start-up cost, operation and maintenance cost, etc., the utility cost considered is only TOU energy cost. While commercial buildings almost always include a demand cost charged for the peak demand occurring within the billing month, it is mostly neglected. Demand charges are analyzed in some works. Effects of the tariffs on the optimal BESS sizing and cycle scheduling are also shown for a residential load coupled with a solar generation [11-12]. Their optimization is done incorporating the demand charge through residential loads, but the residential loads usually don't have it. All these works while adding the effect of demand charge show the analysis only for a single demand charge. Whereas time-related demand charges are not uncommon in industrial rates that charge for the highest demand based on different periods of the day. Critical Peak Pricing (CPP) has been introduced by the utilities to provide monetary rewards to the consumers for reducing their usage during grid congestion. The impacts of Vehicle to Grid (V2G) on commercial buildings are investigated during CPP events [13]. Only the effect of a high CPP energy rate is presented in the paper during the CPP event hours while the benefits derived from lower demand charge at non-CPP event hours are not shown.

C. Contribution and Organization

From the discussions above we can see that while there are ample works on the electricity cost optimization of building loads with renewable and BESS, they have overlooked to address the fact that there are numerous and diverse types of utility electricity rates that require distinct optimization strategy. Much attention is needed on this topic since an optimization strategy for one type of rate structure will not be suitable for the other type and may end up incurring a non-optimal higher cost. Though there are works done on different rate structure-based optimizations, to the best of the authors' knowledge no work has been done yet on a comprehensive optimization model that addresses the issue of this complexity and diversity of these utility rates and aims to solve it. The objective of this work is to bridge the abovementioned gap that persists in the existing literature.

The main contributions of this paper can be summarized as follows: proposing a comprehensive framework for building load optimization using renewables and energy storage, ubiquitous to any type of rate structure; detailed modeling of solar fed BESS and system power balance in compliance with system constraints and configuration; formulating a novel algorithm to carry out the optimization; investigating effects of these various rate structures applied to different building load types and sizes and to decide the best rate structure for a building user. These are discussed in detail in subsequent sections.

II. System Configuration and Modeling

A. Overview of the System

The system we are considering here is a building equipped with a renewable generation such as solar and battery energy storage system (BESS). All the buildings considered here are commercial buildings and have electrical load sizes equivalent to industrial size loads and fall under industrial rate structure.

Figure 1 shows the block diagram of the system configuration. The building load receives some of the power from the utility grid. The power generated from the solar inverter branches out to two portions: one delivers power directly to the building load while the other delivers the power into the BESS. Then the BESS delivers power to the building load as required. This configuration ensures both reduction of inverter associated losses and a higher percentage of renewable generation within the power mix.

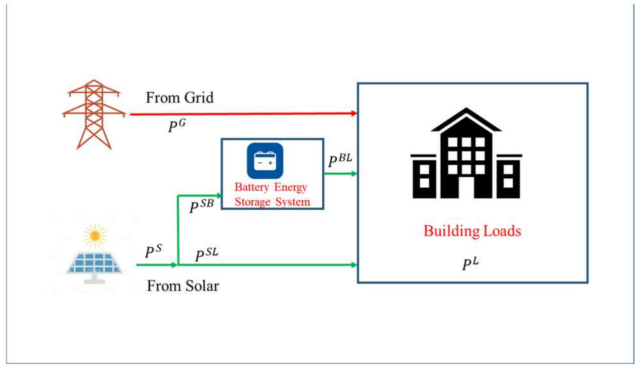

Fig. 1. System Configuration Block Diagram

B. Battery Energy Storage System (BESS) Modeling

The BESS is modeled by taking many real-world operational constraints into consideration. The stored energy at each time step can be calculated with the following equation:

$$E_{t+1}^B = E_t^B + P_t^B.\Delta t \quad (1)$$

The constraints that the BESS must maintain are: stored energy must be within some limits for battery longevity, charging and discharging cannot happen simultaneously, and charging and discharging power must be within some limit imposed by BESS inverter size and specification. These constraints can be modeled with the following equations and inequalities:

$$E^{Bmin} \leq E_t^B \leq E^{Bmax} \quad (2)$$
$$P_t^B = P_t^{B+} - P_t^{B-} \quad (3)$$
$$0 \leq P_t^{B+} \leq P^{B+max} \quad (4)$$
$$0 \leq P_t^{B-} \leq P^{B-max} \quad (5)$$
$$P_t^{B+} P_t^{B-} = 0 \quad (6)$$

C. Power Balance Equations

Complying with the configuration in subsection A, the system should obey the following power balance equations:

$$P_t^{B+} = \eta^+ P_t^{SB} \quad (7)$$
$$P_t^S = P_t^{SB} + P_t^{SL} \quad (8)$$
$$P_t^L = P_t^{SL} + P_t^{BL} + P_t^G \quad (9)$$
$$P_t^{BL} = \eta^- P_t^{B-} \quad (10)$$

III. Formulation of the Cost Functions

In this section, the cost functions or the objective functions of the optimization problems are formulated for different utility rates. The following subsections show detailed formulations for five types of rate structures. Though the utility rates can be versatile, we can cover almost all industrial utility rates with these five types. This paper uses the traditional technical terms such as On-Peak, Mid-Peak, and Off-Peak, etc. which may vary by utility company and location. While formulating the cost functions, careful attention is paid to derive them in a way so they become convex for solving them conveniently and efficiently with the available optimization tools.

A. Time of Use Energy (TOU) Rate with a Monthly Peak Demand Charge

In this utility rate, the energy charge is decided based on how much the grid is stressed at some period of the day. Typically, they are separated into three periods: On, Mid, and Off-Peak where the value of the energy charge is from highest to lowest, respectively. Customer is billed based on total energy consumed at each period over the billing cycle. For the demand charge part, a high value is charged for the maximum 15-minute moving average demand occurring in the billing cycle. Then both are added to get the total charge for monthly usage.

α_t is equal to the On-Peak, Mid-Peak, or Off-Peak energy charge depending on when t is within the corresponding time period. Then we can write the cost function or the objective function as:

$$f(P_t^G) = \Delta t \sum_{t=0}^{T'-1} \alpha_t P_t^G + \beta max(P_t^G) \quad (11)$$

We can write the set of all α_t and P_t^G as vectors $\boldsymbol{\alpha}$ and $\boldsymbol{P^G}$as:

$$\boldsymbol{\alpha} = [\alpha_0\ \alpha_1 \ldots .\alpha_{T'-1}]^{\boldsymbol{T}} \quad (12)$$

$$\boldsymbol{P^G} = [P_0^G\ P_1^G \ldots \ldots P_{T'-1}^G]^{\boldsymbol{T}} \quad (13)$$

Then we can write the cost function as:

$$f(\boldsymbol{P^G}) = \Delta t\ \boldsymbol{\alpha^T P^G} + \beta \max(\boldsymbol{P^G}) \quad (14)$$

B. TOU Energy Rate with TOU or Time Related (TR) Demand Charge

For this rate structure demand charge, β is time-dependent similar to the energy charge mentioned in subsection A. For each of the peak period within the whole billing cycle, the maximum 15-minute demand is multiplied with their respective demand charges. The main complexity here is that the largest power value from the vector $\boldsymbol{P^G}$ from each of the time periods must be picked and try to minimize each of them in a way that achieves total minimum cost. To resolve it, this paper proposes to introduce three diagonal matrices $\boldsymbol{\beta^{On}}$, $\boldsymbol{\beta^{Mid}}$, and $\boldsymbol{\beta^{Off}}$ to represent the demand charge of each of the periods.

$$\boldsymbol{\beta^{On}} = \begin{bmatrix} \beta_0^{On} & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \beta_{T'-1}^{On} \end{bmatrix}, \boldsymbol{\beta^{Mid}} = \begin{bmatrix} \beta_0^{Mid} & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \beta_{T'-1}^{Mid} \end{bmatrix} \ and\ \boldsymbol{\beta^{Off}} = \begin{bmatrix} \beta_0^{Off} & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \beta_{T'-1}^{Off} \end{bmatrix} \quad (15)$$

Where the diagonal elements β_t^{On}= On-Peak demand charge for t=On-Peak times and 0 for t=other times. All the off-diagonal elements in the matrix $\boldsymbol{\beta^{On}}$ are zero. Similarly, $\boldsymbol{\beta^{Mid}}$ and $\boldsymbol{\beta^{Off}}$ can be formed. Now, we can write the cost function as:

$$f(\boldsymbol{P^G}) = \Delta t\ \boldsymbol{\alpha^T P^G} + \max(\boldsymbol{\beta^{On} P^G}) + \max\left(\boldsymbol{\beta^{Mid} P^G}\right) + \max(\boldsymbol{\beta^{Off} P^G}) \quad (16)$$

Depending on the season and utility company there may be no On-Peak demand charge or lower Super Off-Peak period charge. In those cases, we can similarly formulate the cost function, by making adjustments to $\boldsymbol{\alpha}$ and $\boldsymbol{\beta}$ as required.

C. TOU Energy Rate with both Monthly Peak Demand and TR Demand Charge

This rate is a combination of the rates described in the previous two subsections. It has both a TR demand charge and a monthly peak demand charge. We can write the cost function for this rate as:

$$f(\boldsymbol{P^G}) = \Delta t\ \boldsymbol{\alpha^T P^G} + \max(\boldsymbol{\beta^{On} P^G}) + \max\left(\boldsymbol{\beta^{Mid} P^G}\right) + \max\left(\boldsymbol{\beta^{Off} P^G}\right) + \beta \max(\boldsymbol{P^G}) \quad (17)$$

Though for most utilities the Off-Peak demand charge is absent and we just need to simply remove that part from equation 17 in those cases.

D. Critical Peak Pricing (CPP) Rate

Critical Peak Pricing or CPP rates offer lower demand rates in non-CPP event days in exchange for very high energy rates in CPP event days. CPP events are usually called when electricity demand peaks due to extreme conditions. They are usually the 12 hottest days occurring within the summer season rates. The CPP event hours comprise the evening hours and early part of the night namely 4 PM to 9 PM. The customers are generally notified a day before the CPP event. A non-CPP day will have the energy charge vector $\boldsymbol{\alpha_{non-CPP}} = \boldsymbol{\alpha}$ just like the rates mentioned before. For a CPP day, we modify it as $\boldsymbol{\alpha_{CPP}}$ where α_t is equal to the CPP energy charge when t falls within the CPP event hours. The demand charge matrices for the non-CPP days $\boldsymbol{\beta^{On}_{non-CPP}}, \boldsymbol{\beta^{Mid}_{non-CPP}}$, and $\boldsymbol{\beta^{Off}_{non-CPP}}$ need to be modified by replacing the t-th diagonal element in the matrix with the regular demand charge minus the discount charge offered by the utility company when t falls under the CPP event hours. The same matrices for CPP days $\boldsymbol{\beta^{On}_{CPP}}, \boldsymbol{\beta^{Mid}_{CPP}}$, and $\boldsymbol{\beta^{Off}_{CPP}}$ are similar to the other TR demand matrices shown in the previous subsections. So, we get two cost functions:

$$f(\boldsymbol{P^G}) = \Delta t\ \boldsymbol{\alpha_{non-CPP}}^{\boldsymbol{T}} \boldsymbol{P^G} + \max\left(\boldsymbol{\beta^{On}_{non-CPP} P^G}\right) + \max\left(\boldsymbol{\beta^{Mid}_{non-CPP} P^G}\right) + \max\left(\boldsymbol{\beta^{Off}_{non-CPP} P^G}\right) + \beta \max(\boldsymbol{P^G}) \quad (18)$$

and

$$f(\boldsymbol{P^G}) = \Delta t\ \boldsymbol{\alpha_{CPP}}^{\boldsymbol{T}} \boldsymbol{P^G} + \max\left(\boldsymbol{\beta^{On}_{CPP} P^G}\right) + \max\left(\boldsymbol{\beta^{Mid}_{CPP} P^G}\right) + \max\left(\boldsymbol{\beta^{Off}_{CPP} P^G}\right) + \beta \max(\boldsymbol{P^G}) \quad (19)$$

Where equations 18 and 19 represent the cost functions for non-CPP days and CPP days respectively. Note that, the discounted demand charge rates on non-CPP days are also provided during the same hours as the CPP event hours on CPP days.

E. Flat Energy (TOU) Rate with a Monthly Peak Demand Charge

For a flat energy rate with a monthly peak demand charge, the variable α_t becomes a constant independent of time and we can replace the energy charge vector $\boldsymbol{\alpha}$ with a single scalar value α. The cost function then becomes:

$$f(\boldsymbol{P^G}) = \Delta t. \alpha\ .\boldsymbol{1^T P^G} + \beta \max(\boldsymbol{P^G}) \quad (20)$$

Where $\mathbf{1}$ denotes a vector of size T with all elements as 1.

IV. Optimization Problem Formulation

Using the cost functions formulated in section III as the objective function and the BESS modeling equations from subsection B of section II as constraints, we can now derive the optimization problem for each of the rate structures. But equation 6 in the model is a nonlinear equality condition which makes the problem nonconvex and consequently computationally difficult to solve. We can resolve it by introducing a binary variable $\delta_t \in \{0,1\}$ to the power limit inequality constraints and perform a convex relaxation on δ_t. So, we reformulate them as:

$$0 \le P_t^{B+} \le \delta_t \, P^{B+max} \tag{21}$$
$$0 \le P_t^{B-} \le (1-\delta_t) \, P^{B-max} \tag{22}$$
$$0 \le \delta_t \le 1 \tag{23}$$

We can now write the optimization problem as:

$$\min_{\boldsymbol{P^G}} f(\boldsymbol{P^G})$$

subject to:

$$E_{t+1}^B = E_t^B + P_t^B . \Delta t \tag{1}$$
$$E^{Bmin} \le E_t^B \le E^{Bmax} \tag{2}$$
$$P_t^B = P_t^{B+} - P_t^{B-} \tag{3}$$
$$P_t^{B+} = \eta^+ P_t^{SB} \tag{7}$$
$$P_t^S = P_t^{SB} + P_t^{SL} \tag{8}$$
$$P_t^L = P_t^{SL} + P_t^{BL} + P_t^G \tag{9}$$
$$P_t^{BL} = \eta^- P_t^{B-} \tag{10}$$
$$0 \le P_t^{B+} \le \delta_t \, P^{B+max} \tag{21}$$
$$0 \le P_t^{B-} \le (1-\delta_t) \, P^{B-max} \tag{22}$$
$$0 \le \delta_t \le 1 \tag{23}$$

By applying the appropriate cost function and parameter values, we can use this optimization model to obtain the optimal operation of any BESS, for any rate structure shown, given a building load and a renewable generation profile.

V. Algorithm

For our proposed method we do the optimization on a day-by-day basis instead of doing a monthly optimization for a couple of reasons. Firstly, the day ahead prediction of load and solar can be produced more accurately and easily for a shorter time resolution such as 15 minutes. Secondly, doing a monthly optimization with this 15-minute data resolution would be computationally exhaustive. The total number of timesteps T' in daily optimization will be 96 for 15-minute resolution. We can write the daily building load profile and solar generation profile in vectorized form as:

$$\boldsymbol{P^L} = [P_0^L \; P_1^L \dots\dots P_{T'-1}^L]^{\boldsymbol{T}} \tag{24}$$
$$\boldsymbol{P^S} = [P_0^S \; P_1^S \dots\dots P_{T'-1}^S]^{\boldsymbol{T}} \tag{25}$$

In this section, we will refer to the daily energy charge and demand charges as $\boldsymbol{\alpha}$ and $\boldsymbol{\beta}$ in general. To calculate the monthly usage bill, we need modified vectors and matrices to accommodate the monthly calculation. If the number of total days in the monthly billing cycle is D, then we can create the new matrices and vectors of size $D \times T'$ for the monthly bill calculation. The energy charge vector for the month $\boldsymbol{\alpha_{month}}$ will then becomes:

$$\boldsymbol{\alpha_{month}} = [\, \boldsymbol{\alpha^T} \; \boldsymbol{\alpha^T} \dots\dots \boldsymbol{\alpha^T}]^{\boldsymbol{T}} \tag{26}$$

Where $\boldsymbol{\alpha}$ is repeated D times. We can get the On-Peak TR demand charge matrix for the month $\boldsymbol{\beta^{On}_{month}}$ by:

$$\boldsymbol{\beta^{On}_{month}} = \begin{bmatrix} \boldsymbol{\beta^{On}} & \cdots & \boldsymbol{0} \\ \vdots & \ddots & \vdots \\ \boldsymbol{0} & \cdots & \boldsymbol{\beta^{On}} \end{bmatrix} \tag{27}$$

Where $\boldsymbol{\beta^{On}}$ matrix is repeated on the diagonal position D times and $\boldsymbol{0}$ is a square matrix of size T' with all elements as zeros. Similarly, we can find $\boldsymbol{\beta^{Mid}_{month}}$ and $\boldsymbol{\beta^{Off}_{month}}$, which represent the Mid-Peak and Off-Peak TR demand charge matrices for the month respectively.

If we are dealing with a CPP rate structure in the summer season, then equations 26 and 27 will be a little different. All the alphas in $\boldsymbol{\alpha_{month}}$ will be replaced by $\boldsymbol{\alpha_{non-CPP}}$ except d-th position will be replaced by $\boldsymbol{\alpha_{CPP}}$ when day number d is the CPP event day. Similarly, all the betas will be replaced by $\boldsymbol{\beta^{On}_{non-CPP}}, \boldsymbol{\beta^{Mid}_{non-CPP}}$, and $\boldsymbol{\beta^{Off}_{non-CPP}}$ as in their respective monthly matrices except for d-th position where they will be replaced by $\boldsymbol{\beta^{On}_{CPP}}, \boldsymbol{\beta^{Mid}_{CPP}}$, and $\boldsymbol{\beta^{Off}_{CPP}}$, respectively.

We can then calculate the monthly usage bills by using the applicable cost function in equation 28 just by using the appropriate power vector of the right size and parameters $\boldsymbol{\alpha_{month}}$ and $\boldsymbol{\beta_{month}}$.

$$Monthly\ Usage\ Bill = f(\boldsymbol{X}; \boldsymbol{\alpha_{month}}, \boldsymbol{\beta_{month}}) \tag{28}$$

Where **X** is the appropriate power vector of size $D \times T'$. To better understand the effects of the optimization, we define two types of savings, Savings 1 and Savings 2. Savings 1 shows the savings if only the solar is added. Savings 2 shows the effect of BESS optimization that is the additional savings we achieve through BESS optimization when solar is already present in the system. We can write them as:

$$Savings\ 1 = f\big(\boldsymbol{P^L_{month}}; \boldsymbol{\alpha_{month}}, \boldsymbol{\beta_{month}}\big) - f\big(\boldsymbol{P^L_{month}} - \boldsymbol{P^S_{month}}; \boldsymbol{\alpha_{month}}, \boldsymbol{\beta_{month}}\big) \tag{29}$$
$$Savings\ 2 = f\big(\boldsymbol{P^L_{month}} - \boldsymbol{P^S_{month}}; \boldsymbol{\alpha_{month}}, \boldsymbol{\beta_{month}}\big) - f\big(\boldsymbol{P^G_{month}}; \boldsymbol{\alpha_{month}}, \boldsymbol{\beta_{month}}\big) \tag{30}$$

To run the optimization, we would need E^B_{init} of the BESS. Variables $\boldsymbol{P^{SL}}$, $\boldsymbol{P^{SB}}$, $\boldsymbol{P^{B+}}$, and $\boldsymbol{P^{B-}}$ need to be declared similar to vectors shown in equations 24 and 25. Now the algorithm for the optimization can be written as:

Algorithm

Select the type of Rate Structure
Select Season
Get parameters E^{Bmax}, E^{Bmin}, E^B_{init}, P^{B+max}, P^{B-max}, η^+ and η^-.
if (Rate type=CPP rate) **and** (Season=Summer) then:
    Get $\boldsymbol{\alpha_{CPP}}$, $\boldsymbol{\beta_{CPP}}$, $\boldsymbol{\alpha_{non-CPP}}$, and $\boldsymbol{\beta_{non-CPP}}$ and the CPP cost function $f(.)$
else
    Get $\boldsymbol{\alpha}$, $\boldsymbol{\beta}$ and the appropriate cost function $f(.)$
endif
Declare empty vectors $\boldsymbol{P^G_{month}} = [\ ]$, $\boldsymbol{P^L_{month}} = [\ ]$, $\boldsymbol{P^S_{month}} = [\ ]$
for each day d=0,1, ……., D-1 **do**:
    Get $\boldsymbol{P^L}$, $\boldsymbol{P^S}$ for day d
    Declare the variables $\boldsymbol{P^{SL}}$, $\boldsymbol{P^{SB}}$, $\boldsymbol{P^{B+}}$ and $\boldsymbol{P^{B-}}$
    Initialize E^B_0=E^B_{init}
    Run Optimization
    Run the optimum BESS operation according to $\boldsymbol{P^{B+}}$ and $\boldsymbol{P^{B-}}$
    Update $\boldsymbol{P^G_{month}} = \begin{bmatrix} \boldsymbol{P^G_{month}} \\ \boldsymbol{P^G} \end{bmatrix}$
    Update $\boldsymbol{P^L_{month}} = \begin{bmatrix} \boldsymbol{P^L_{month}} \\ \boldsymbol{P^L} \end{bmatrix}$ and $\boldsymbol{P^S_{month}} = \begin{bmatrix} \boldsymbol{P^S_{month}} \\ \boldsymbol{P^S} \end{bmatrix}$
    Update E^B_{init}=$E^B_{T'-1}$
endfor
Calculate the unoptimized monthly cost $f(\boldsymbol{P^L_{month}}; \boldsymbol{\alpha_{month}}, \boldsymbol{\beta_{month}})$
Calculate the unoptimized monthly cost if solar is added $f(\boldsymbol{P^L_{month}} - \boldsymbol{P^S_{month}}; \boldsymbol{\alpha_{month}}, \boldsymbol{\beta_{month}})$
Calculate the optimized monthly cost with solar and BESS $f(\boldsymbol{P^G_{month}}; \boldsymbol{\alpha_{month}}, \boldsymbol{\beta_{month}})$
Calculate Savings 1 and Savings 2

VI. Results and Discussions

Data for four commercial building loads with separate industrial rates are collected for simulation of the optimization model. These buildings differ in electrical usage and functionality. Among them, three of the buildings have actual onsite solar generation and two of them have actual BESS integrated. Except for CPP, the rates that are used are actual utility rates these buildings are billed for. For the buildings which did not have solar or BESS, National Renewable Energy Laboratory or NREL's REopt Lite [14] and System Advisor Model (SAM) [15] were used to find the ideal solar or BESS size and generate the solar profile for the corresponding building. Table I summarizes the characteristics of the buildings that were used for the optimization: average daily energy usage, load factor (average load divided by maximum load in a period), rate structure, solar and BESS size. The rate structure types mentioned in the table refer to the subsections in section III.

TABLE I. Characteristics of the Buildings Used in Optimization

Characteristics	Building 1	Building 2	Building 3	Building 4
Average Daily Usage (kWh)	11,223	1,660	13,451	805
Load Factor	0.283	0.341	0.811	0.411
Solar Size (Real)	800 kW	220 kW	-	180 kW
BESS Size (Real)	-	100 kW/ 500 kWh	-	100 kW/ 500 kWh
Solar Size (Simulated)	-	-	650 kW	-
BESS Size (Simulated)	150 kW/ 500 kWh	-	120 kW/ 320 kWh	-
Rate Structure	Type A	Type B	Type C	Type E

Using the data and parameters collected and simulated the optimization for these four buildings were done for their corresponding rate structures. All the data were from the summer months and the rates used were summer season rates. For all these rates the daily On-Peak hours were from 12 to 6 PM, Mid-Peak hours were from 8 AM to 12 PM and from 6 to 11 PM and the remaining hours are all Off-Peak Hours. At the start of each simulation, it is assumed that all the BESS have their initially stored energy E_{init}^{B}, limits for maximum and minimum stored energy E^{Bmax} and E^{Bmin} are 50%, 90%, and 20% of the total capacity, respectively. Figure 2 shows the results of the optimization. For each of the simulations, the building load without optimization and the load optimized with solar and BESS for a month are shown. The figures show what should be the optimal net load profile to achieve the minimal cost compared to the actual. For simulations, Matlab-based convex optimization toolbox CVX has been used [16].

For rate type D or CPP, the utilities normally give customers an option that they can either move to CPP or can stay under the existing rate structure. The customers decide what option they want. In this paper, Building 1 is chosen for CPP rate simulation and the rates for the CPP option for that rate structure are applied here. This rate has four months in the summer season (June to September) and 12 CPP event days in the summer season in total. So, on average each month will have three CPP days. The three highest demand days (day numbers 9, 12, and 20) are selected as CPP event days in this simulation. The CPP event hours take place from 4 PM to 9 PM. Figure 3 shows simulation results similar to figure 2 presenting the Building 1 load with and without optimization for rate structure type D.

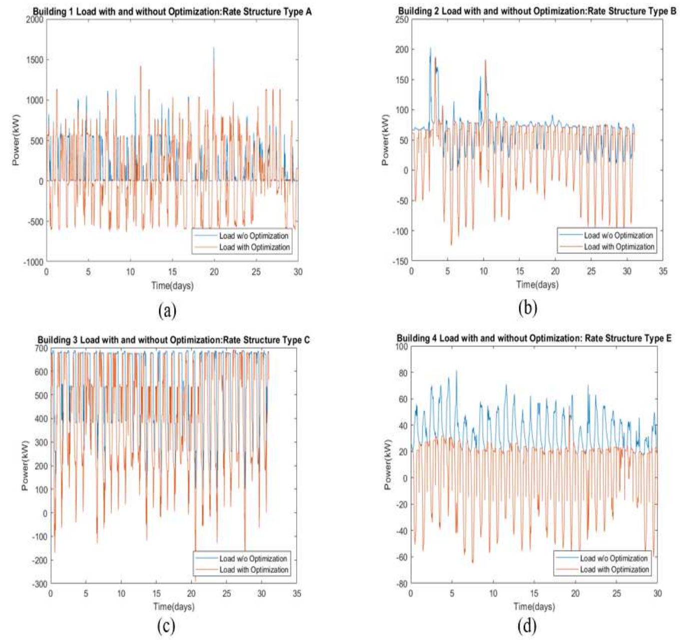

Fig. 2. Results from Optimization of (a) Building 1 with Rate Structure Type A, (b) Building 2 with Rate Structure Type B, (c) Building 3 with Rate Structure Type C, (d) Building 4 with Rate Structure Type E

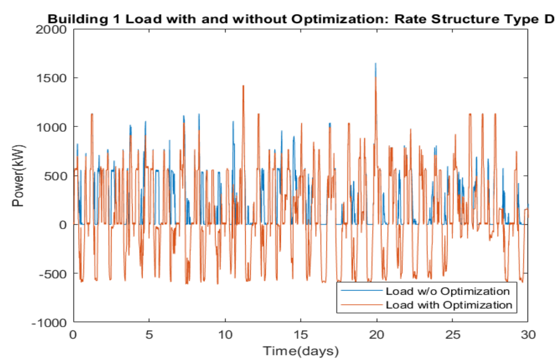

Fig. 3. Results from Optimization of Building 1 with Rate Structure Type D

Table II summarizes the optimization results from all the simulations. By comparing the results, we can see that TR demands and CPP charges cause higher unoptimized costs. If we compare the buildings of similar energy usage size 1 and 3, we can infer two insights: a combination of both TR and monthly peak demand charges reduce the savings than a single monthly peak demand charge; buildings with lower load factor offers more potential for optimization using BESS. In the case of CPP while only solar may not result in being more beneficial, adding BESS with optimization will provide increased benefits. Adding BESS would provide much lower savings in case of flat energy rate than TOU energy rates.

TABLE II. SUMMARY OF OPTIMIZATION RESULTS

Optimization Parameters and Results	**Type A**	**Type B**	**Type C**	**Type D**	**Type E**
Building	Building 1	Building 2	Building 3	Building 1	Building 4
Energy Charge ($/kWh)	On-Peak: 0.3397 Mid-Peak: 0.13837 Off-Peak: 0.07637	On-Peak: 0.35987 Mid-Peak: 0.1007 Off-Peak: 0.03545	On-Peak: 0.10258 Mid-Peak: 0.07566 Off-Peak: 0.05727	On-Peak: 0.07817 Mid-Peak: 0.07422 Off-Peak: 0.0724 CPP: 0.4	Flat rate: 0.0139
Demand Charge ($/kW)	Monthly Peak: 11.87	On-Peak: 7.06 Mid-Peak: 3.13 Off-Peak: 1.53	On-Peak: 21.73 Mid-Peak: 4.17 Monthly Peak: 19.02	On-Peak: 16 Mid-Peak: 5.16 Monthly Peak: 17.52 CPP discount: 4.11	Monthly Peak: 10.58
Unoptimized Cost ($)	48,825	9,278	61,704	79,714	4,218
Unoptimized Cost with Solar ($)	14,849	1,911	50,766	68,778	1,122
Optimized Cost with Solar and BESS ($)	12,483	1,270	49,250	63,067	1,064
Savings 1 ($)	33,976	7,368	10,938	10,936	3,096
Savings 2 ($)	2,366	641	1,516	5,711	58

VII. CONCLUSION AND FUTURE WORK

In this paper, a comprehensive optimization method was developed for commercial buildings equipped with renewable generation and BESS to capture the diversity in utility rate structure types. The utility rate structures were categorized into five universal rate structure types that cover almost all the industrial rate structures. Then for each of the types, a cost function was formulated. Formulated optimization problem, using the cost functions and the BESS model was applied to four buildings using all the rate structures. Results presented that buildings with lower load factors can benefit more from BESS optimization than buildings with higher load factors. Buildings with CPP rates can save more by adding BESS with solar. The savings from flat energy rates are not as attractive as the savings from the TOU energy rates. Another thing to consider, the energy and demand charges of utility rates change each year. The authors would like to make a projection of the rate change based on the historical values of the charges and see how these rate changes affect the optimization and the savings attained from it. Future works will also include forecasting day-ahead load and solar and use them in the optimization to see how much the results vary from the ones presented here. Additional investigations can be done to enhance this work such as the effect of load deferral, EV charging and V2G optimization, the prospect of providing grid ancillary services, etc.

REFERENCES

[1] L. Schwartz, M. Wei, W. Morrow, J. Deason, S. R. Schiller, G. Leventis, S. Smith, W. L. Leow, T. Levin, S. Plotkin, and Y. Zhou, “Electricity End Uses, Energy Efficiency, and Distributed Energy Resources Baseline,” 2017.

[2] X. Xue and W. Shengwei, "Interactive building load management for smart grid," 2012 Power Engineering and Automation Conference, Wuhan, China, 2012, pp. 1-5.

[3] M. Razmara, G. R. Bharati, M. Shahbakhti, S. Paudyal and R. D. Robinett, "Bidirectional optimal operation of smart building-to-grid systems," 2015 American Control Conference (ACC), Chicago, IL, USA, 2015, pp. 288-293.

[4] R. Missaoui, H. Joumaa, S. Ploix, and S. Bacha, “Managing energy Smart Homes according to energy prices: Analysis of a Building Energy Management System,” *Energy Build.*, vol. 71, no. 2014, pp. 155–167, 2014.

[5] F. Wang et al., "Multi-Objective Optimization Model of Source–Load–Storage Synergetic Dispatch for a Building Energy Management System Based on TOU Price Demand Response," in IEEE Transactions on Industry Applications, vol. 54, no. 2, pp. 1017-1028, March-April 2018.

[6] J. Yusuf and S. Ula, "Impact of Building Loads on Cost Optimization Strategy for a Plug-in Electric Vehicle Operation," 2019 IEEE Transportation Electrification Conference and Expo (ITEC), Detroit, MI, USA, 2019.

[7] J. Yusuf and S. Ula, "A Comprehensive Optimization Solution for Buildings with Distributed Energy Resources and V2G Operation in Smart Grid Applications," 2020 IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT), Washington, DC, USA, 2020, pp. 1-5.

[8] H. T. Dinh and D. Kim, “An Optimal Energy-Saving Home Energy Management Supporting User Comfort and Electricity Selling with Different Prices,” *IEEE Access*, vol. 9, pp. 9235–9249, 2021.

[9] A. Amer, K. Shaban, A. Gaouda, and A. Massoud, “Home Energy Management System Embedded with a Multi-Objective Demand Response Optimization Model to Benefit Customers and Operators,” *Energies*, vol. 14, no. 2, p. 257, 2021.

[10] M. Samadi, J. Fattahi, H. Schriemer, and M. Erol-Kantarci, “Demand management for optimized energy usage and consumer comfort using sequential optimization,” *Sensors (Switzerland)*, vol. 21, no. 1, pp. 1–18, 2021.

[11] M. Gitizadeh and H. Fakharzadegan, "Effects of electricity tariffs on optimal battery energy storage sizing in residential PV/storage systems," 2013 International Conference on Energy Efficient Technologies for Sustainability, Nagercoil, India, 2013.

[12] D. H. Tang and D. Eghbal, "Cost optimization of battery energy storage system size and cycling with residential solar photovoltaic," 2017 Australasian Universities Power Engineering Conference (AUPEC), Melbourne, VIC, Australia, 2017, pp. 1-6.

[13] J. Yusuf, A. Hasan and S. Ula, “Impacts Analysis & Field Implementation of Plug-in Electric Vehicles Participation in Demand Response and Critical Peak Pricing for Commercial Buildings”, 2021 IEEE Texas Power and Energy Conference, Austin, Texas, USA, 2021, in press.

[14] “REopt Lite: REopt Energy Integration & Optimization,” *NREL*. [Online]. Available: https://reopt.nrel.gov/tool. [Accessed: 16-Mar-2021].

[15] System Advisor Model Version 2020.11.29 (SAM 2020.11.29). National Renewable Energy Laboratory. Golden, CO. Accessed December 27, 2020. https://sam.nrel.gov.

[16] M. Grant and S. Boyd. CVX: Matlab software for disciplined convex programming, version 2.0 beta. http://cvxr.com/cvx, [Accessed: 16-Mar-2021].