Peak Load Reduction in a Smart Building Integrating Microgrid and V2B-Based Demand Response Scheme

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***Abstract*—In this paper, we study the peak load reduction in a smart building integrating microgrid and present a comprehensive finite-horizon optimization problem formulated as a dual tracking control problem subject to the quadratic cost function. The smart building integrates a microgrid consisting of photovoltaic modules, battery bank, and plug-in electric vehicles (PEVs). The objective of the microgrid is to satisfy the PEVs load as well as to reduce the peak load of the building. The control strategy aims to take advantages of the microgrid to pay the minimum billing demand to the main grid according to the subscribed power rating. These objectives can be reached through exploiting power generated on-site, local energy storage system, and the operational flexibilities of the PEVs via the vehicle-to-building alternative. In this paper, we focus on the fundamental issue of exploring smart charge and discharge scheduling of PEVs to reduce the peak load of the building. The proposed model has been extensively simulated and tested through case studies using measured solar and load data under the Quebec electricity pricing.**

***Index Terms*—Demand response (DR), dual tracking control, energy management system, renewable energy, smart building integrating microgrid.**

NOMENCLATURE

Acronyms

DR	Demand response.
V2B	Vehicle-to-building.
BMS	Building management system.
PV	Photovoltaics.
LESS	Local energy storage system.
PEV	Plug-in electrical vehicles.

Parameters

η_{pv}	Module reference efficiency.
$\xi_{\mathrm{Ch},i}^{\mathrm{pev}}$	Charging efficiency of the *i*th PEV.
$\xi_{\mathrm{Dis},i}^{\mathrm{pev}}$	Discharging efficiency of the *i*th PEV.
β_{Ch}	Charging efficiency.
β_{Dis}	Discharging efficiency.
A_{pv}	Solar cell array area.
η_{pc}	Power conditioning efficiency.
P_f	Packing factor.
P_{bpl}	Bilateral power limit.
$p_{\mathrm{ch,min},i}^{\mathrm{pev}}$	Minimum charging rate of the *i*th PEV.
$p_{\mathrm{ch,max},i}^{\mathrm{pev}}$	Maximum PEV charging rate of the *i*th PEV.
$p_{\mathrm{dis,max},i}^{\mathrm{pev}}$	Maximum PEV discharging rate of the *i*th PEV.
$p_{\mathrm{dis,min},i}^{\mathrm{pev}}$	Minimum PEV discharging rate of the *i*th PEV.
$p_{\mathrm{ch,min}}$	Minimum LESS charging rate.
$p_{\mathrm{ch,max}}$	Maximum LESS charging rate.
$p_{\mathrm{dis,min}}$	Minimum LESS discharging rate.
$p_{\mathrm{dis,max}}$	Maximum LESS discharging rate.
$\mathrm{SOC}_{\mathrm{max},i}$	Maximum state of energy of PEV.
$\mathrm{SOC}_{\mathrm{min},i}$	Minimum state of energy of PEV.

Variables

$p_{\mathrm{pv}}(t)$	Probabilistic output power of the PV.
$G(t)$	Probabilistic solar irradiance.
$p_{\mathrm{Ch}}(t)$	Charged power at time *t* to the LESS.
$p_{\mathrm{Dis}}(t)$	Discharged power at time *t* from LESS.
$p_{\mathrm{Ch}}^{\mathrm{pev}}(t,i)$	Charged power at time *t* from the *i*th PEV.
$p_{\mathrm{Dis}}^{\mathrm{pev}}(t,i)$	Discharged power at time *t* from the *i*th PEV.
$p_{\mathrm{Ch,pv}}^{\mathrm{pev}}(t,i)$	Charged power from PV system to the *i*th PEV.
$p_{\mathrm{Ch,st}}^{\mathrm{pev}}(t,i)$	Power charged to the PEV coming from the LESS.
$p_{\mathrm{pv,load}}(t)$	Power sent from the PV modules to the local electrical grid.
$p_{\mathrm{pv,net}}(t)$	Power sent from the PV modules to the main grid.
$p_{\mathrm{st,load}}(t)$	Power sent from the LESS to satisfy the loads.
$p_{\mathrm{net}}(t)$	Power sent from the main grid to satisfy the loads.
$p_{\mathrm{load}}(t)$	Total power loads.
$\tilde{p}_{\mathrm{load}}(t)$	Total dynamic reference of the loads.
$\mathrm{SOC}_{\mathrm{pev}}(t,i)$	State of charge of the *i*th PEV.
$s(t)$	State of charge of the LESS.
$\tilde{s}(t)$	Dynamic reference state representing the desired stored energy state in the battery.

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I. INTRODUCTION

FOR the past years, buildings have been considered as demand from the perspective of utilities. Under the smart grid paradigm, the role of buildings in the electric grid can be changed to that of an active contributor in managing their local grid and serving as a key player in maintaining grid reliability [1]. Demand response (DR) programs have many potential benefits to smart grids development. It can support power markets set efficient energy prices, mitigate market power, improve economic efficiency, and increase energy security [2]. The idea of DR is that buildings can actively participate in changing their electric use from the normal usual pattern as to reduce their electrical bills. From the main grid viewpoint, this means that with adequate building energy management, the peak load can be avoided or decreased.

In practice, local load management techniques for peak load reduction are important for all actors of the power grid. Specifically, this can avoid grid instability issues and increase the reliability.

The DR adopted by the building energy management system can have many configurations, and it is highly dependent on the pricing scheme established with the main electric grid. For example, in a time-of-use-based DR scheme, the aim is to encourage the building decision maker to adjust their loads through shifting building appliances to off-peak hours [3]. In addition to reducing, shifting, or shaving electricity usage during critical peak periods, another way to implement DR schemes and avoid high peak demands in the building is by exploiting the onsite generated and stored energy. In institutional buildings, such as campuses, peak demand limiting will not only bring significant economic benefits to the building owner but also to the main grid. In addition, onsite power generation can enable DR without limiting the actual usage of energy in the buildings. For instance, energy consumption in the building can be lowered by exploiting the available plug-in electric vehicles (PEVs) as a means to smooth the building energy consumption and shave load peak.

In fact, PEVs have been regarded as a flexible energy option for commercial buildings. In census metropolitan area, such as Montreal city, in average, people make about 40 min commuting to work [4] and for the rest of the day, their cars are mostly parked at parking lots or workplace building garage [5]. Specially, during daytime, aggregating many PEVs in the parking lots can form a single resource from the building management system (BMS) perspective and then can be exploited as a distributed storage to enable serving internal loads in peak periods, which is defined as a "vehicle-to-building" (V2B) operation [6]. The V2B technology is based on the idea of powering buildings by PEVs during peak hours.

Providing the building with a local microgrid can offer more opportunity to the building's manager to improve the efficiency of energy consumption [7] while maintaining the comfort level of occupants. Specially, the microgrid provides another DR scheme that helps building to reduce energy consumption and hedge peak power costs without affecting the comfort of occupants. In fact, the microgrid offers local power generation to building as to maintain buildings comfort level and improve an operational efficiency. Hoff *et al.* [8] proved that coupling energy storage with PV systems for peak load shaving may be beneficial to enhance the economic outlook of both systems beyond a simple sum of benefits that one might expect.

Most recently, increasing attention has been paid on the coordinated charging of PEVs [6], [9]–[12]. In [13], a fuzzy logic control technique is applied to the design of a vehicle-to-grid infrastructure. The objective of a vehicle-to-grid controller is to control the power flow between a particular node and the charging station to meet peak power demand and reduce voltage sag. In [14], a real-time energy management algorithm for a grid-connected charging park in an industrial/commercial workplace is presented. Among the objectives of the developed energy management algorithm are to reduce the overall daily cost of charging the PEVs and contribute to shaving the peak of the load curve. Nguyen and Song [15] presented an optimization based on the game-theoretical framework for a coordinated charging problem for multiple PEVs using demand-side management in V2B operation. The authors also designed a distributed algorithm to encourage electric vehicle owners to participate in the charging and discharging process. Another study in [16] presented a model for optimal strategies of parking lots, as responsive demands, in both price-based and incentive-based DR programs.

To reduce peak demand, some authors focused on the use of DR-based storage systems. In [17], Leadbetter and Swan suggested installing electricity storage devices in residential buildings. Their work aims at finding storage characteristics of capacity, power, and cycle life for peak load shaving. Kumar Nunna and Doolla [18] included DR and distributed storage in an agent-based energy management system to facilitate power trading among microgrids. The idea is to reduce peak demand and to minimize energy costs through the exploitation of the diversity in loads, distributed storage, distributed generations and DR in each microgrid. In [19], the proposed method aggregates battery energy storage system with the PV system to level the load. The paper delivers an insight into how combined storage and generation can be used to level the peak load. While some research works have been recently introduced to investigate the charging and discharging scheduling problem of PEVs and also the impact of energy storage system to level the peak load, no major research has been reported to study the interaction between different DR schemes for peak load reduction. In particular, the emergence of advanced sensing and monitoring technologies will present a new opportunity for BMS to monitor, manage, and control energy use. Specifically, the integration of distributed generation, local energy storage system (LESS) and PEVs at the building level can bring additional flexibility to the BMS for minimizing energy bills and avoiding peak load. However, in the presence of DR programs, the control and optimization of the building' energy usage become a challenging task. In this study, we propose a method to level building' peak load through the conjunction of microgrid composed by PV system, LESS and PEVs through the V2B concept. The main contributions of this paper are as follows.

1) The development of an energy management system based on dual tracking control problem to reduce peak load as seen by the electricity grid in a smart building. A microgrid

is used to balance the demand and the power provided by the main grid. The components of microgrid such as PV, PEVs, and LESS will be used to reduce the peak load, to compensate for the variability of the building's load and minimize its electricity bill. Specifically, when the demand is below an agreed fixed bilateral power limit, the building imports its needs from the main grid based on a flat rate pricing scheme; whereas in the case where the load is over this bilateral power limit, the BMS is in charge of delivering optimal control strategy of power management based DR programs at the microgrid level to supply as much as possible the peak load.

2) The proposed framework is tested through case studies where the influence of the priority on the tracking references is investigated. Numerical studies demonstrate the usefulness and efficiency of the proposed model to deal with peak load uncertainties. Extensive simulation results demonstrate the advantages of integrating PEVs via the V2B alternative. The performance of the proposed scheme is verified under different schemes to evaluate the impacts of different scenarios on the optimal solution.

This paper is organized as follows. The building-based microgrid architecture and modeling are presented in Section II. Then the energy management algorithm based on the tracking control problem is presented in Section III. The simulation results are discussed in Section IV, and conclusions are given in Section V.

II. Building-Based Microgrid Modeling

A. Microgrid Design

The PV system produces power that is basically used to meet variant PEVs loads. Any surplus of power can be potentially stored in the LESS, and/or exchanged with the electric grid to satisfy the building's load in peak periods. The building's load is typically met by the main grid following an established bilateral contract.

However, in case of exceeding the fixed bilateral power limit, the building manager profits of the local microgrid to reduce the peak and minimize the amount of power imported from the main grid. In this case, the microgrid can send power to the building directly from the solar panels, or/and through the V2B concept or/and using the LESS. It is assumed that in order to encourage PEV owners to participate in the V2B program, financial incentives, rewards, and services can be offered. In this paper, it is assumed that the BMS is in charge to control the microgrid as well as the whole building.

B. DR Scheme

The peak shaving measures adopted by the customers can have many configurations, and it is highly dependent on the pricing scheme established. A strategy aiming to optimize the daily cost saving under the electricity price structure of the power utility is proposed. Under the particular pricing scheme, the objective of the BMS is to pay the minimum billing demand, keeping the power demand under the bilateral power limit as possible. This implies that internal DR strategies, including use of local power generation, local storage, and PEVs should be triggered by the BMS when the power appeal tries to exceed the bilateral power limit. From the grid viewpoint, this can be seen as the building has implemented a peak shaving strategy.

C. PV Module Generators

PV modules are assumed to be installed in some of the rooftops of campus buildings. The probabilistic output power of the PV is calculated as follows:

$$p_{\mathrm{pv}}\ (t) = A_{\mathrm{pv}}\eta_{\mathrm{pv}}P_f\eta_{\mathrm{pc}}G\,(t)\,. \tag{1}$$

D. Plug-in Electrical Vehicle Modeling

The state of the charge of the PEVs available in microgrid can be expressed as follows:

$$\mathrm{SOC}_{\mathrm{pev}}\,(t+\Delta t, i) = \mathrm{SOC}_{\mathrm{pev}}\,(t,i) + \xi^{\mathrm{pev}}_{\mathrm{Ch},i}p^{\mathrm{pev}}_{\mathrm{Ch}}\,(t,i)\,\Delta t - \frac{p^{\mathrm{pev}}_{\mathrm{Dis}}\,(t,i)\,\Delta t}{\xi^{\mathrm{pev}}_{\mathrm{Dis},i}} \tag{2}$$

where $t \in [t^{\mathrm{arr}}\, t^{\mathrm{dep}}]$ is the scheduling time horizon, t^{arr} and t^{dep} are, respectively, the arrival and departure time vectors of the PEVs available in the campus, and $p^{\mathrm{pev}}_{\mathrm{Ch}}\,(t,i)$ and $p^{\mathrm{pev}}_{\mathrm{Dis}}\,(t,i)$ are, respectively, the charged and discharged powers.

E. Local Energy Storage System

The energy storage system could be used mainly for charging PEVs and peak load limiting purposes. The evolution of energy stored in the LESS is described by the following equation:

$$s\,(t+\Delta t) = s\,(t) + \beta_{\mathrm{Ch}}p_{\mathrm{Ch}}\,(t)\,\Delta t - \ \beta_{\mathrm{Dis}}p_{\mathrm{Dis}}\,(t)\,\Delta t. \tag{3}$$

III. Energy Management Algorithm: The Tracking Control Problem

The aim of the BMS is to optimize and control the microgrid operation as well as to interface between all the microgrid components. The BMS is in charge of delivering optimal control strategy of power management based DR programs at the microgrid level to supply as much as possible peak load. The BMS will select the adequate and optimal control strategy among the following four scenarios.

1) Dual tracking control strategy without (DTCSW) local DR (contribution of the campus buildings through appliance-based demand responses).
2) Dual tracking control strategy supported (DTCSS) by local DR.
3) Single load tracking (SLT) control strategy.
4) Single battery state tracking (SBT) control strategy.

The choice of the control strategy adopted will consider performance and advantages in term of minimizing power deficit and maximizing costs saving. As well as the impacts of maintaining or not customers comfort level on the control strategies and specifically on providing the peak load.

The BMS decides how much energy should be imported from the electric grid at each time slot and how to schedule the energy usage in the local microgrid. The main objective is to ensure the evolution of dynamic building loads over the time horizon. In order to keep an adequate energy security level for charging PEVs, the objective function also considers keeping the level of energy in LESS as close as possible to the optimal working level. This choice is justified by the fact to keep an adequate energy security for charging PEVs in case of PV energy shortage.

In case of exceeding peak load, the BMS aims to maintain occupants comfort level using the onsite power generated by the microgrid. The BMS can also decrease the comfort level of occupants when the power generated by the microgrid does not cover the exceeding peak load. The objective function minimizes the dual costs of quadratic terms formulated as follows:

$$J(s,p) = \sum_{t=1}^{T} \Delta t(p_{\text{load}}(t) - \tilde{p}_{\text{load}}(t))^T K \Delta t (p_{\text{load}}(t) - \tilde{p}_{\text{load}}(t)) + (s(t) - \tilde{s}(t))^T M (s(t) - \tilde{s}(t)) \tag{4}$$

where M is a weighting factor representing the deviation cost from the reference state, and the weighting factor K describes the deviation cost from the reference power value.

The total load of the building $(\tilde{p}_{\text{load}})$ is assumed to include controllable load $l_c(t)$ and non-controllable load $l_{\text{nc}}(t)$. It is defined by a dynamic reference control $\tilde{p}_{\text{load}}(t) = l_c(t) + l_{\text{nc}}(t)$ that represents the real nominal power consumed by the building. Moreover, in the case of peak load occurrence, the BMS can also respond to the demands by decreasing the comfort level and the consumption to a certain acceptable level. So, in this case, the total load $\tilde{p}_{\text{load}}(t) = (1-\xi)l_c(t) + l_{\text{nc}}(t)$ is reduced by a factor ξ that represents the self-contribution (load shaving) of the building in the time interval $t \in [t^{\text{peak},s}\ t^{\text{peak},f}]$.

A. State Equations and Operation Constraints

The power produced by the PV plant can be dedicated to charge both the LESS $(p_{\text{Ch}}(t))$ and the PEVs $(p^{\text{pev}}_{\text{Ch,pv}}(t,i))$. In addition, a part of PV power $(p_{\text{pv,load}}(t))$ may be sent to the local electric grid to reduce/shave the peak in case of exceeding the minimum billing demand.

In case the LESS is fully charged and/or in case of the absence of PEVs' loads, the produced PV power can be sent to the local grid

$$p_{\text{pv}}(t) = p_{\text{Ch}}(t) + \sum_{i=1}^{I} p^{\text{pev}}_{\text{Ch,pv}}(t,i) + p_{\text{pv,load}}(t) + p_{\text{pv,net}}(t). \tag{5}$$

It is worth to notate that the electric grid completely supplies the building load. However, in case of exceeding the minimum power demand, storage system, and/or PV plant and/or some of the available connected PEVs can be used to overcome this power raising.

The power balance is described by the following equation:

$$p_{\text{load}}(t) = p_{\text{net}}(t) + p_{\text{pv,load}}(t) + p_{\text{load,st}}(t) + \sum_{j=k\geq 1}^{J\leq I} p^{\text{pev}}_{\text{Dis}}(t,j). \tag{6}$$

The power used to charge the PEVs can be supplied directly by the PV plant $(p^{\text{pev}}_{\text{Ch,pv}}(t,i))$ and/or from the energy storage system $(p^{\text{pev}}_{\text{Ch,st}}(t,i))$

$$p^{\text{pev}}_{\text{Ch}}(t,i) = p^{\text{pev}}_{\text{Ch,pv}}(t,i) + p^{\text{pev}}_{\text{Ch,st}}(t,i). \tag{7}$$

The discharged power from the LESS can be used to feed a part of the load and/or charge the PEVs

$$p_{\text{Dis}}(t) = p_{\text{st,load}}(t) + \sum_{i=1}^{I} p^{\text{pev}}_{\text{Ch,st}}(t,i). \tag{8}$$

The power generation is constrained between an upper and lower bounds

$$p_{\text{pv,min}} \leq p_{\text{pv}}(t) \leq p_{\text{pv,max}}. \tag{9}$$

The contribution of the PV plant to supply the load is set equal to zero below the bilateral power limit (P_{bpl})

$$p_{\text{pv,load}}(t) = 0, \text{ if } \tilde{p}_{\text{load}}(t) \leq P_{\text{bpl}}. \tag{10}$$

The stored energy in the LESS is constrained by an upper and lower bounds

$$s_{\min} \leq s(t) \leq s_{\max}. \tag{11}$$

The charging and discharging rates of the LESS have lower and upper bounds to meet physical constraints

$$p_{\text{dis, min}} \leq p_{\text{Dis}}(t) \leq p_{\text{dis,max}} \tag{12}$$

$$p_{\text{ch,min}} \leq p_{\text{Ch}}(t) \leq p_{\text{ch,max}}. \tag{13}$$

Charging and discharging states of the LESS cannot occur simultaneously

$$p_{\text{Dis}}(t) * p_{\text{Ch}}(t) = 0. \tag{14}$$

The contribution of the LESS to supply the load is set equal to zero below the bilateral power limit

$$p_{\text{st,load}}(t) = 0, \text{ if } \tilde{p}_{\text{load}}(t) \leq P_{\text{bpl}}. \tag{15}$$

The energy stored in each PEV's battery at every time slot should satisfy the battery capacity limits

$$\text{SOC}_{\min,i} \leq \text{SOC}_{\text{pev}}(t,i) \leq \text{SOC}_{\max,i}. \tag{16}$$

The charging and discharging rates of the PEVs have upper and lower bounds

$$p^{\text{pev}}_{\text{ch,min},i} \leq p^{\text{pev}}_{\text{Ch}}(t,i) \leq p^{\text{pev}}_{\text{ch,max},i} \tag{17}$$

$$p^{\text{pev}}_{\text{dis,min},i} \leq p^{\text{pev}}_{\text{Dis}}(t,i) \leq p^{\text{pev}}_{\text{dis,max},i}. \tag{18}$$

Charging and discharging states of the PEVs cannot occur simultaneously

$$p^{\text{pev}}_{\text{Dis}}(t,i) * p^{\text{pev}}_{\text{Ch}}(t,i) = 0. \tag{19}$$

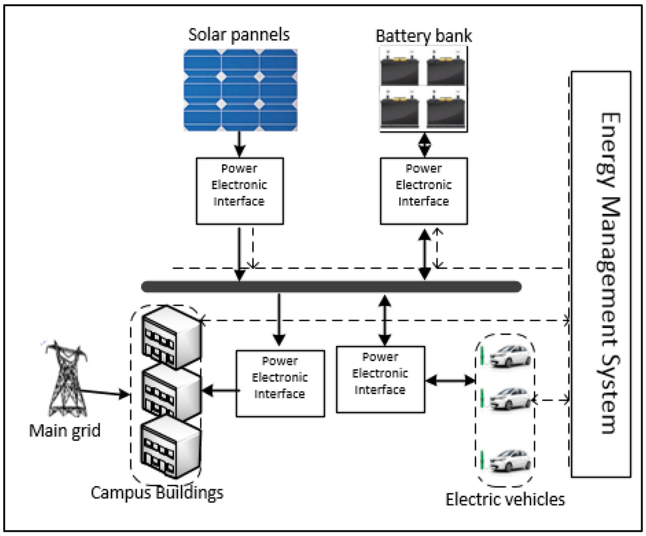

Fig. 1. Proposed architecture.

The PEV does not supply the load if it is below the bilateral power limit

$$p_{\text{Dis}}^{\text{pev}}(t,i) = 0, \text{ if } \tilde{p}_{\text{load}}(t) \le P_{\text{bpl}}. \tag{20}$$

The main electric grid covers the whole load until reaching the fixed bilateral power limit. So any peak load above that limit should be supplied by the campus itself

$$p_{\text{net}}(t) = P_{\text{bpl}}, \text{ if } \tilde{p}_{\text{load}}(t) \ge P_{\text{bpl}}. \tag{21}$$

IV. Application and Numerical Results

A. Simulation Setup

The dual tracking control problem presented in the previous sections is solved and tested through extensive simulations considering buildings of a university campus. Fig. 1 represents the architecture of the proposed microgrid. Numerical analyses are provided to show its concrete practices and to verify its operations and performances. It is worthwhile to mention that the problem is solved by LINGO software. The proposed microgrid consists of 900-kW rated rooftop PV array, a Li-ion-based battery storage system (LESS) of 200 kWh, and a charging facility for PEVs. The PV power generation in a typical day of July is reported in Fig. 2.

Ten PEVs are considered with a maximal capacity of charge equal to 24 kWh. It is assumed that all PEVs can be charged either by the PV power or/and the battery, whereas the PEVs discharge option (V2B) is allowed just to assist the BMS to fulfill the peak load if needed. Furthermore, it is assumed that $t \in$[8 A.M. 5:30 P.M.] is the scheduling time horizon for PEVs, where 8 A.M. and 5:30 P.M. are, respectively, the arrival and departure times for all PEVs. In the proposed approach, the distributed PEVs batteries are considered as a secondary energy storage system, forming an available total maximum capacity of 440 kWh.

The main grid supplies totally the load until a fixed power limit which is equal to 5 MW (bilateral contract). So, in this case, the microgrid does not contribute to supply the loads and hence the power flows coming from PV, battery system, and PEVs should be equal to zero $(p_{\text{pv,load}}(t) = p_{\text{st,load}}(t) = \sum_{j=k\ge 1}^{J\le I} p_{\text{Dis}}^{\text{pev}}(t,j) = 0)$. While in case the campus power exceeds 5 MW, the exceeding powers must be covered mainly by the microgrid. The length of the control horizon is set equal to 24 hours, and the sampling time is 5 min. The optimization problem has been solved for each time step, in order to find the optimal control operation strategy considering real solar data and measured load profile of the campus of a typical day of July. However, the proposed approach is general and is not case dependent.

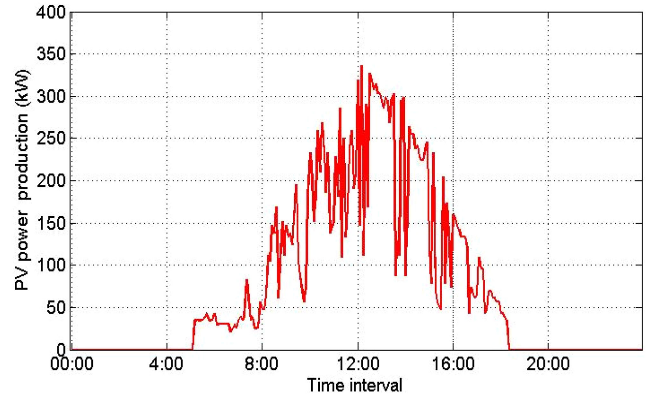

Fig. 2. PV power generation.

B. Pricing Scheme: Quebec

In Quebec, the campus can be subject to a flat price rate structure where an LG rate [20] can be applied to an annual bilateral contract with a fixed power limit of 5 MW. The campus is charged according to the highest power demand at any point during the monthly billing period (power charged 13.05$ per kW, where kW are 15-min averages). Additionally, demand pricing also has a separate, additional charge for energy, charged 3.35¢ per kWh. The billing demand at this rate (contract) can be equal to the maximum power demand during the consumption period but is never less than fixed power limit. For instance, in a given month, even if the maximum power demand is lower than 5 MW (for example, 4 MW) the campus will be charged according to 5 MW. Exceeding this bound can generate cost penalties.

C. Results and Discussion

1) Case Study 1: In this case, the proposed dual tracking control problem has been solved. The optimization problem aims to minimize two conflicting objectives considering equal subjective weighting factors: $K = M = 1$. The optimal tracking of the load reference is shown in Fig. 3. It can be seen that the optimal power output fits in each time interval the dynamic reference power with some minimal errors.

Fig. 4 presents the optimal results of tracking the desired stored energy in the battery. We note that it is assumed that the reference stored energy has a fixed value equal to 100 kWh during the entire horizon; this choice is justified by the fact

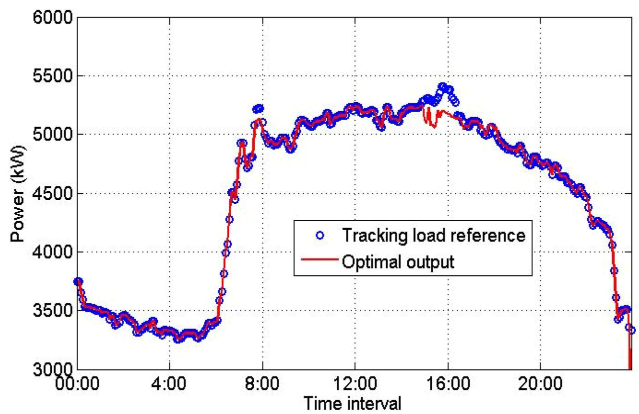

Fig. 3. Optimal tracking of the load reference.

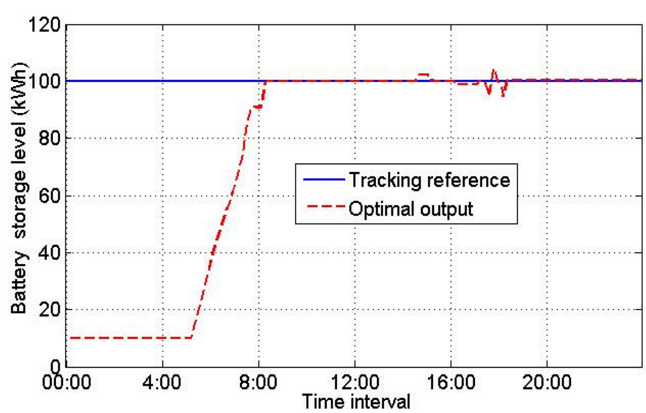

Fig. 4. Optimal tracking of the battery state reference.

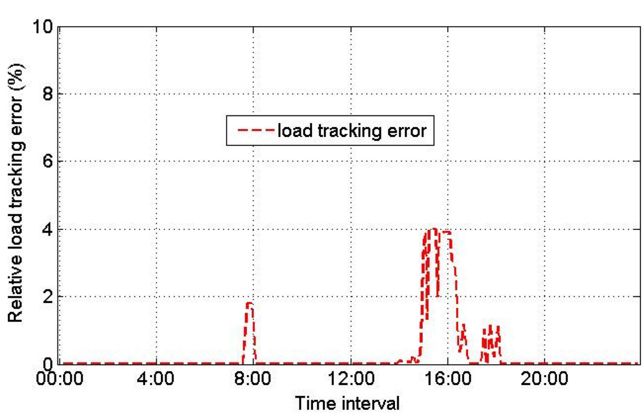

Fig. 5. Relative load tracking error (%).

to keep a security energy level for charging PEVs in case of PV energy shortage.

It can be seen from the figure that the optimal energy storage in the LESS does not track the reference curve from 12:00 A.M. to 8:15 A.M.; this is attributed to the fact that the initial state of the battery system is set to be 10 kWh (battery almost empty) and the PV plant is still not producing power. For the rest of the day, the stored energy follows exactly the reference except some minor errors. The relative load and battery state tracking errors are reported, respectively, in Figs. 5 and 6.

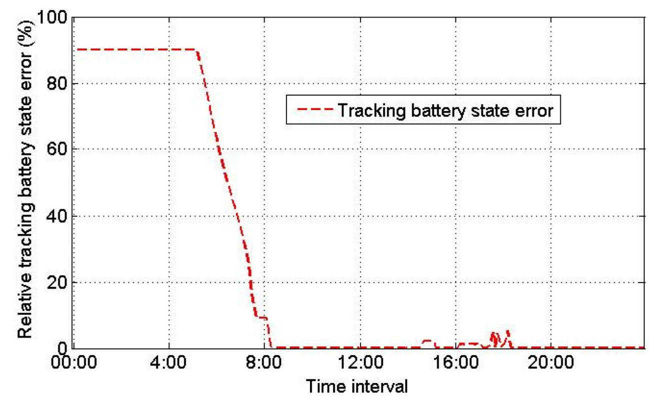

Fig. 6. Relative tracking battery state error (%).

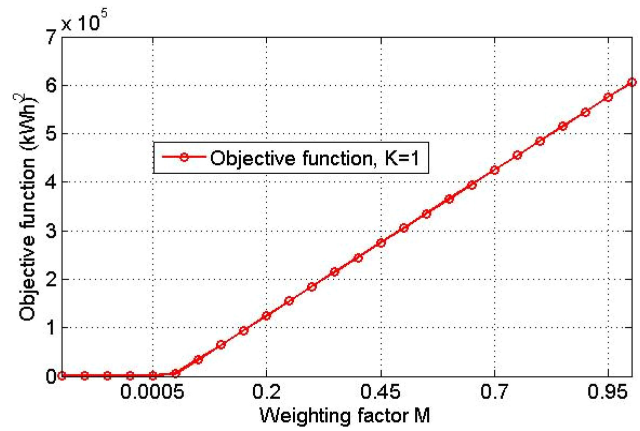

Fig. 7. Objective function performance for $K = 1$.

As it can be illustrated in Fig. 5, the relative load tracking errors can be observed at about 8:15 with a value of 2%; this is mainly due to the shortage in PV power generation. In addition, from 15:00 to 17:00, a maximum of 4% can be observed. This is mainly due to the fact that the PV plant is not producing enough power, in addition to the approaching departure time of PEVs that must have a charging battery level near as possible to the desired value fixed by the owner.

In Fig. 6, the relative battery state tracking errors show the highest values in the early morning when PV plant is not yet generating power, and it is not allowed to charge the battery from the main grid. In general, the relative tracking errors show negligible values specifically for both the load and the battery when the PV starts generating power.

2) Case Study 2: The optimization problem based on the two conflicting objectives has been solved giving the priority to the load tracking. The aim of this case study is to investigate the best combination of the weighting factors that minimize the objective function. It is reasonable to fix $K = 1$ and varying the weighting factor M. The trend of the objective function according to the weighting factor M is reported in Fig. 7. It can be seen that the objective function reaches its minimum between 0 and 0.0005 with a value of about 1070 kWh^2. Although the decrease in the weighting factor M starts from 0.0005, the objective function preserves the same value. So, highest performances can be obtained for values of M less than or equal to 0.0005.

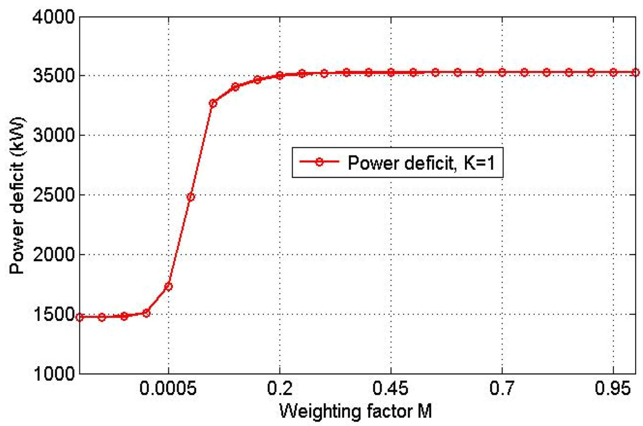

Fig. 8. Power deficit for $K = 1$.

The daily power deficit in covering the peak load according to weighting factor M is shown in Fig. 8. The daily power deficit has a fixed value of about 3500 kW for M higher than 0.2, while it drops according to M until reaching a fixed value of about 1470 kW for M equals or less than 0.00005. This behavior is due to the fact that by decreasing the weighting factor M, high priority is given to the load tracking by discharging the battery. As a result, the tracking load errors are minimized while the tracking battery state errors have higher values.

3) Case Study 3: In this section, the performances of the control strategies are compared relative to the following four objectives.

1) Dual tracking control strategy without local DR (contribution of the campus buildings through appliance-based demand responses) (DTCSW).
2) Dual tracking control strategy supported by local DR (DTCSS).
3) Single load tracking control strategy (SLT).
4) Single battery state tracking control strategy (SBT).

The aim of this case study is to evaluate the impact of the control strategy adopted on the operation, performance, and advantages in term of minimizing power deficit and maximizing saving costs. Also, we investigate the impacts of maintaining the comfort level of the customers on the control strategies and specifically on providing the peak load. We note that in this case it is supposed that the contribution of the local DR (contribution of the campus buildings through appliance-based demand responses) is set to be equal to 10% of the total daily peak load. The detailed results of the impacts of the considered control strategies on the campus operation are reported in Tables I and II.

As defined in Section II-B, the campus is charged according to the highest power demand at any point during the monthly billing period. Assuming that the used load profile contains the maximum power demand in the July month, we can calculate the monthly power saving costs for the campus. According to Fig. 3, the highest power demand reaches a value of 5407 kW. This means that the CBMS objective is to keep the amount imported from the main grid to 5000 kW and supplies the difference (407 kW) internally using the microgrid. Tables I and II also depict the energy and power savings using different control strategies in the campus.

TABLE I
IMPACTS OF CONTROL STRATEGIES DTCSS AND DTCSW ON THE UCIM OPERATION AND BENEFITS

	DTCSS		DTCSW	
	K=M=1	K=1 M=0.01	K=M=1	K=1 M=0.01
Total peak demand (kWh)	1548	1548	1548	1548
Maximum peal load (kW)	407	407	407	407
PV (kWh)	854	935	854	935
Battery (kWh)	69	130	69	130
V2B (kWh)	331	251	331	251
Local DR (kWh)	155	155	0	0
Energy deficit (kWh)	139	77	294	232
Objective function $(\mathrm{kWh})^2$	605358	8865	605358	8865
Daily energy saving costs ($)	47	44	49	44
Power saving costs ($)	3194	4134	2641	3581

TABLE II
IMPACTS OF CONTROL STRATEGIES SLT AND SBT ON THE UCIM OPERATION AND BENEFITS

	SLT	SBT
Total peak demand (kWh)	1548	1548
Maximum peak load (kW)	407	407
PV (kWh)	1067	735
Battery (kWh)	205	88
V2B (kWh)	154	528
Energy deficit (kWh)	123	196
Objective function $(\mathrm{kWh})^2$	1068	600769
Daily energy saving costs ($)	47	45
Power saving costs ($)	3956	2338

Table I shows that for the dual tracking cases, the scenario DTCSS with $K = 1$, and $M = 0.01$ presents the best performances in term of energy deficit minimization (77 kWh) and a monthly power saving costs of 4134$. While in Table II for a single tracking problem, the scenario SLT shows best performances with a power saving costs of 3956$ in July and a daily energy saving costs of 47$.

The time-varying daily peak load satisfactions in case of DTCSW considering two scenarios $K = M = 1$ and $K = 1$, $M = 0.00005$ are reported, respectively, in Figs. 9 and 10. It can be seen from Fig. 9 that the deficit shows high value when the peak load is covered mainly by the PV and V2B; this is due to the fact that both tracking references have the same priority (conflicting objectives). Whereas Fig. 10 shows that the deficit is minimized by also discharging the battery since the peak load tracking has a preponderant priority.

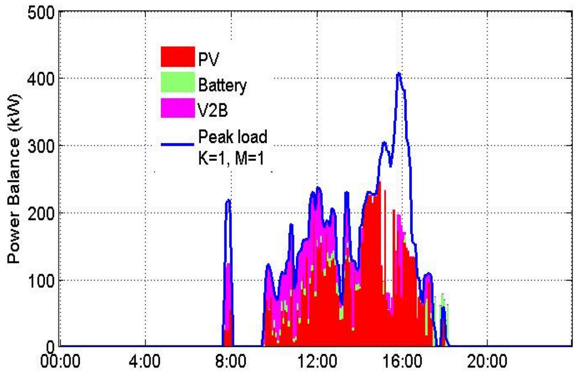

Fig. 9. Peak power dispatch in the campus in the case of DTCSW, $K = M = 1$.

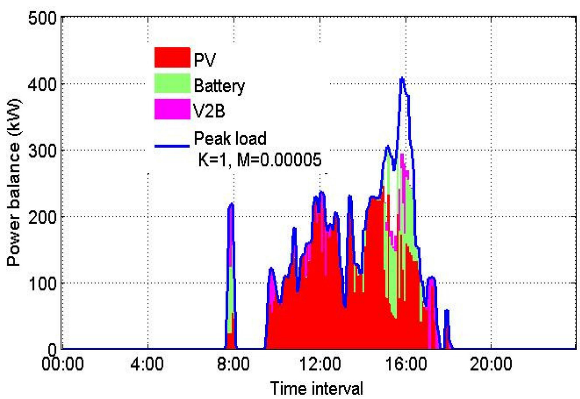

Fig. 10. Peak power dispatch in the campus in the case of DTCSW, $K = 1$, $M = 0.00005$.

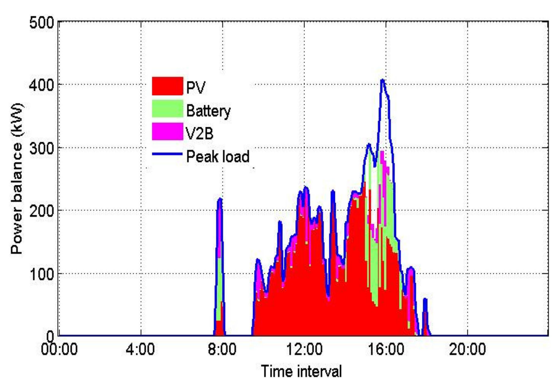

Fig. 11. Peak power dispatch in the campus in the case of SLT.

The time-varying global peak load satisfactions in case SLT is reported in Fig. 11. The figure shows similar behavior to cover the peak load as presented in Fig. 10 where $M = 0.00005$. It can be concluded that by giving high priority to the load tracking and penalizing the battery state tracking (affecting low values to M), the campus has the same optimal operation under both cases SLT and DCTSW.

Under the dual tracking control strategy case, the PEV1 is selected as a representative example to show the optimal control strategy of the state of charge of the PEVs considering two scenarios ($K = M = 1$) and ($K = 1$, $M = 0.00005$) reported in Fig. 12. It can be observed that in the scenario where the peak load tracking has a priority ($K = 1$, $M = 0.00005$), the

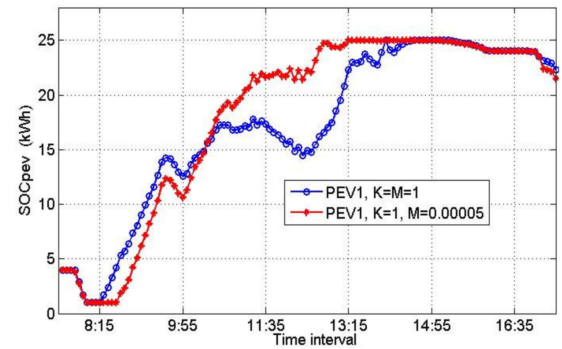

Fig. 12. Optimal control strategy of the state of the charge of the PEVs.

TABLE III
ENERGY BALANCES OF ALL THE PEVs

	Arrival state (kWh)	Desired departure state (kWh)	Optimal departure state (kWh)
PEV1	4	24	22.3
PEV2	5	20	18.3
PEV3	2	18	16.4
PEV4	3	22	20.3
PEV5	1	24	22.3
PEV6	2	20	18.3
PEV7	5	22	20.3
PEV8	4	18	16.4
PEV9	6	22	20.3
PEV10	5	24	22.3

discharging state of the PEV1 is minimized specifically between 10:30 and 12:30. This remark is owing to the fact that the peak load is partially covered by the battery since its constraint on the reference tracking is penalized.

While in the case where both tracking references have equal priority, the discharge of the PEVs is promoted to cover a part of the peak load deficit. The energy balances of all the PEVs are reported in Table III, where the initial arrival state, the desired departure state, and the optimal departure state of the PEVs are reported. It can be observed that mostly the desired departure states of charge of the PEVs are satisfied.

V. CONCLUSION

In this paper, we analyze and evaluate the effectiveness of exploiting onsite generated and stored energy to supply the exceeding peak load of a building integrated microgrid. A dual tracking control problem is proposed that aims to track simultaneously the total load of the campus, including the peak load and the energy storage system reference value. The onsite generation and storage-based DR are investigated through exploiting the flexible charging/discharging behavior of aggregated PEVs and also through the use of the LESS. Results show that by penalizing the battery state tracking, significant benefits could be reached even without implementing further DR strategies.

We have clearly illustrated that using PV, LESSs, and PEVs could be potentially beneficial from both campus buildings decision maker and the main grid. In fact, adopting such an approach by commercial and institutional buildings could decrease significantly the peak load and reduce the pressure on the grid. For this reason, utilities should allow financial benefits to large-scale building owners to encourage adopting peak loads reduction measures.

The results of this paper can be extended in many ways. First, a detailed DR of the campus loads can be implemented in order to quantify the real contribution of the local campus appliances and specifically the HVac system. Second, the discharging process should take into account the impacts on battery life (battery aging). From this perspective, the economic profitability of using PEVs batteries need to be further investigated. Third, this paper could be solved using more intelligent strategy, such as model predictive control, which allows online optimization (real-time optimization) implementing rolling optimization and feedback correction to compensate for prediction error.

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