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An Economic Analysis of Used Electric Vehicle Batteries Integrated Into Commercial Building Microgrids — Source link

Sebastian Beer, Tomás Gómez, D. Dallinger, Ilan Momber ...+3 more authors

Institutions: Complutense University of Madrid, Fraunhofer Society, Lawrence Berkeley National Laboratory

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Beer, Sebastian; Gómez, Tomás; Dallinger, David; Momber, Ilan; Marnay, Chris

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Working Paper Sustainability and Innovation
No. S 10/2011

Sebastian Beer
Tomás Gómez
David Dallinger
Ilan Momber,
Chris Marnay
Michael Stadler
Judy Lai

An economic analysis of used electric vehicle batteries integrated into commercial building microgrids

Fraunhofer
ISI

Abstract

Current policies in the U.S. and other countries are trying to stimulate electric transportation deployment. Consequently, plug-in electric vehicle (PEV) adoption will presumably spread among vehicle users. With the increased diffusion of PEVs, lithium-ion batteries will also enter the market on a broad scale. However, their costs are still high and ways are needed to optimally deploy vehicle batteries in order to account for the higher initial outlay. This study analyzed the possibility of extending the lifecycle of PEV batteries to a secondary, stationary application. Battery usage can be optimized by installing used battery packs in buildings' microgrids. Employed as decentralized storage, batteries can be used for a microgrid's power supply and provide ancillary services (A/S).

This scenario has been modeled with the Distributed Energy Resources Customer Adoption Model (DER-CAM), which identifies optimal equipment combinations to meet microgrid requirements at minimum cost, carbon footprint, or other criteria. Results show that used PEV batteries can create significant monetary value if subsequently used for stationary applications.

Key words

Battery storage, building management systems, dispersed storage and generation, electric vehicles, load management, microgrid, optimization methods, power system economics, road vehicle electric propulsion

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1 Introduction

This paper analyzes the integration of used plug-in electric vehicle (PEV) battery packs into the energy management system (EMS) of a Californian office building. It aims to be a first step towards understanding the combined economic value that can be created with such batteries for the vehicle owner and a so-called local microgrid. This microgrid is capable of seamlessly separating from normal utility service at a single point of common coupling during a disruption and can continue to serve its critical internal loads until acceptable utility service is restored [1].

In prior research, different authors have described the emerging technologies arising from the power electronics that accompany distributed energy resources (DER), particularly DC and variable frequency AC power sources, e.g. photovoltaic (PV) systems, batteries, and asynchronous generators such as microturbines. In commercial building applications, local control of microgrids might be achieved with specific controls, or, potentially more economically, by extending the functionality of a legacy EMS.

So far, battery technology has proven to be uneconomic for employment in microgrids [2]. This picture might change, however, as the supply of Li-ion batteries increases in line with a presumably widespread deployment of PEVs in the medium term [3]. Used battery packs will need to be recycled and then can be used to provide services in a “secondary life” to micro- and macrogrids.

Combining PEV battery employment in vehicles with a consecutive stationary application may yield economic benefits for car owners and building operators [4]. The overall economic value of batteries can be maximized and the risk of uncertain lifetime expectancy is reduced. Batteries are subject to fast charging and discharging cycles in the vehicle, high operating temperatures as well as deep cycles, which lead to stressful low state of charge (SOC) operations. If PEV batteries are replaced prior to their actual end-of-life (EOL), the vehicle owner stands to benefit from fast developing and improved state-of-the-art technology.

Microgrids, on the other hand, seem perfectly suited for the embedment of large volumes of energy storage. The battery capacity can be used to level intermittent power supply on a local level, and to flatten the building electricity demand during peak hours. Consequently, microgrids can participate in high-value demand-response programs [5]. Furthermore, storage can be used to provide high-value ancillary services (A/S) to the macrogrid, such as regulation energy and spinning reserves, defined by [6]. This might turn out to be especially beneficial, if there is a greater need for regulation capacity due to an increase in intermittent power supply [7]. Such an arrangement makes a legal agreement between the Independent System Operator (ISO) and the microgrid for installing communication equipment necessary. At the same time, a microgrid would favorable to act as an intermediary or aggregation agent between PEV fleets to provide A/S and the ISO. Microgrids could act as a Virtual Power Plant (VPP), combining dispersed generation units to form one large market player [8].

This study examined the value of used PEV storage in three case studies in the balancing area of the California Independent System Operator (CAISO).

2 California's electricity market and the provision of ancillary services by microgrids

To balance electricity generation and demand, the CAISO is in charge of managing California's electricity system. It organizes electricity trading and regulates power generators' participation in the transmission grid in both economic and physical terms. For this purpose, four scheduling mechanisms are run: day-ahead market (DAM), hour-ahead scheduling process (HASP), real-time dispatch (RTD) and automatic generation control (AGC).

Seventy-five percent of the electricity provided to the system is scheduled by the participating units via their scheduling coordinator (SC) in the DAM. Here, bids for each operating hour are accepted until 10:00 h of the day prior to delivery. After the DAM closes, the HASP is operated. Supply and demand are scheduled up to 75 minutes before the hour of delivery. RTD is used to follow the load in 5-minute intervals for economic dispatch. Participating units are committed for 15 minutes and must reach the determined operating target by the middle of the interval [9]. To ensure a fast and adequate response to contingencies, units that can provide A/S are also part of the system and are under AGC. CAISO sends them a signal when needed through a direct communication system, requiring them to increase or decrease power supply.

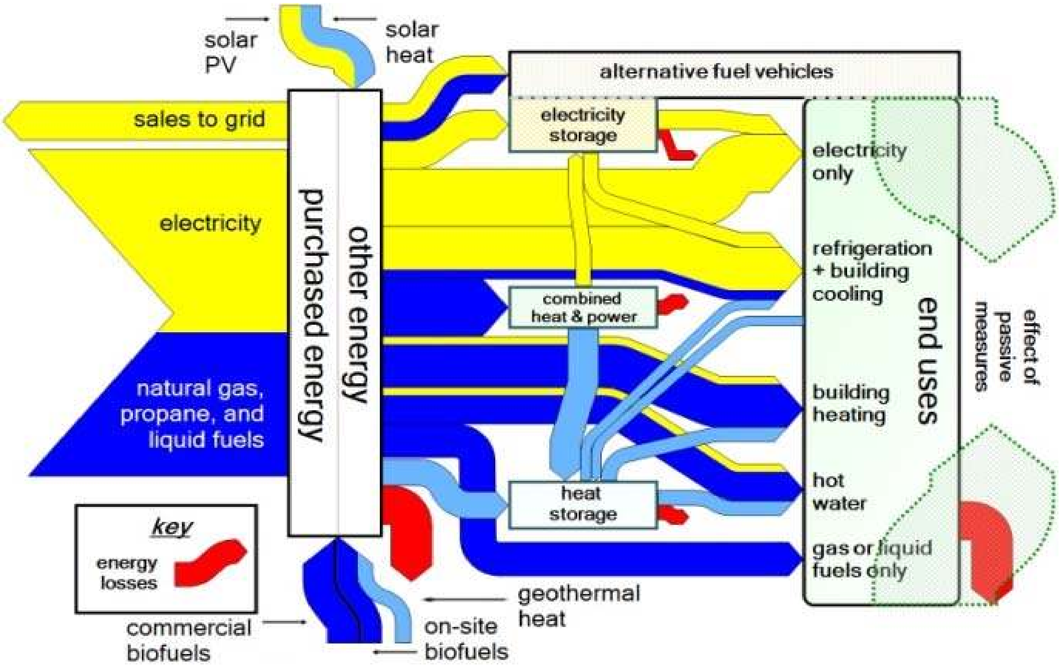
Out of the four types of A/S procured by CAISO, two seem lucrative for batteries: regulation reserves and spinning reserves. Regulation reserves serve the purpose of frequency regulation of the transmission grid. Participating units must be able to ramp up capacity immediately upon receiving a signal from the CAISO. To participate in the market, bids starting at one MW capacity are accepted and must be submitted hourly in MW-h. The bid capacity must be deliverable as equivalent energy for at least one hour. Spinning reserves are the second type of high value A/S. They are kept in the system to preserve frequency stability during emergencies and are called to provide or drop generation as needed. Capacity must be ramped up within ten minutes and be delivered in equivalent energy for at least two hours.

To be under AGC, regulation providers must install a communication system that connects directly to the CAISO. The principal communication system is the Remote Intelligent Gateway (RIG), but alternative systems exist [10]. This study examines the provision of regulation reserve by PEV batteries. However, spinning reserve may also become a worthwhile alternative service to be offered by batteries.

3 Distributed Energy Resources Customer Adoption Model (DER-CAM)

The economic evaluation of PEV storage capability interactions with the building EMS is done using DER-CAM. DER-CAM is a mixed integer linear program written on the GAMS® platform. It optimizes a commercial building's microgrid investment decision and operation problem based on underlying end-use energy loads, energy tariff structures and fuel prices, and an arbitrary list of equipment investment options [11]. The Sankey diagram in Figure 1 depicts possible energy flows in a building-scale microgrid and illustrates how DER-CAM matches energy supply and demand. Regulatory, engineering, and investment constraints are all considered. Energy costs are calculated using a detailed representation of supply tariff structures and fuel prices, operating and maintenance (O&M) expenditures, as well as any amortized DER investment outlays.

Figure 1: Energy flows in a building microgrid



Optimal combinations of technologies including PV, thermal generation with heat recovery, thermal heat collection, heat-activated cooling, as well as both thermal and electrical storage are obtained as results. DER-CAM can report a cost, carbon footprint, or co-optimization, and an optimal operating schedule (typically hourly) for the microgrid including CHP and renewable sources. The economics of storage are particularly complex. This requires optimization across multiple time steps and is subject to the strong influence of tariff structures and A/S prices. The DER-CAM formulation has been extended to deal with storage optimization as presented in section 5.

4 Business models

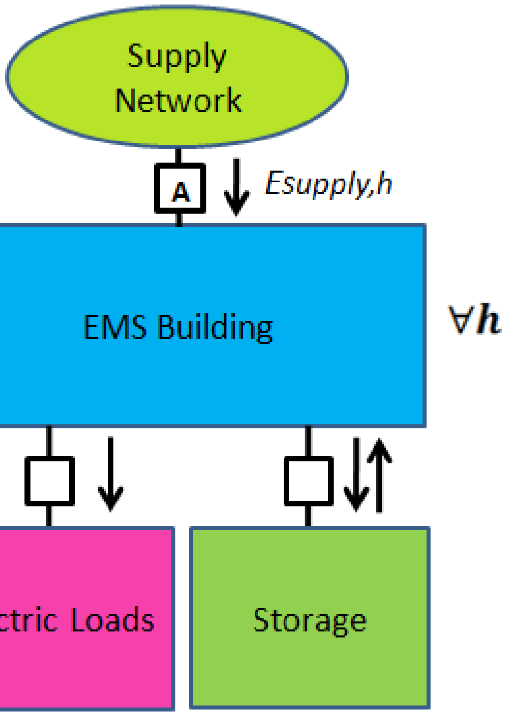
Different business models are proposed to analyze the added value of PEV storage capability for the building EMS. PEV storage is hereby optimally managed at different levels of integration with the building EMS and simultaneously provides frequency regulation to the ISO.

A. Integration of PEV storage in the EMS with no provision of regulation

The building has a contract with a supplier with two terms: i) an energy payment in \$/kWh based on different time of use (TOU) rates, and ii) a demand charge in \$/kW-month applied to the maximum demand in each month.

The PEV storage is integrated with the other electrical loads and on-site local generation and optimally managed by the building EMS in order to minimize the total energy bill. Other objectives can also be included in DER-CAM such as minimizing CO_2 emissions. Figure 2 illustrates this business model, where the commercial relationship between the building and the supplier is based on the meter (A) located at the supply point. This optimization problem is formulated in Section 5.

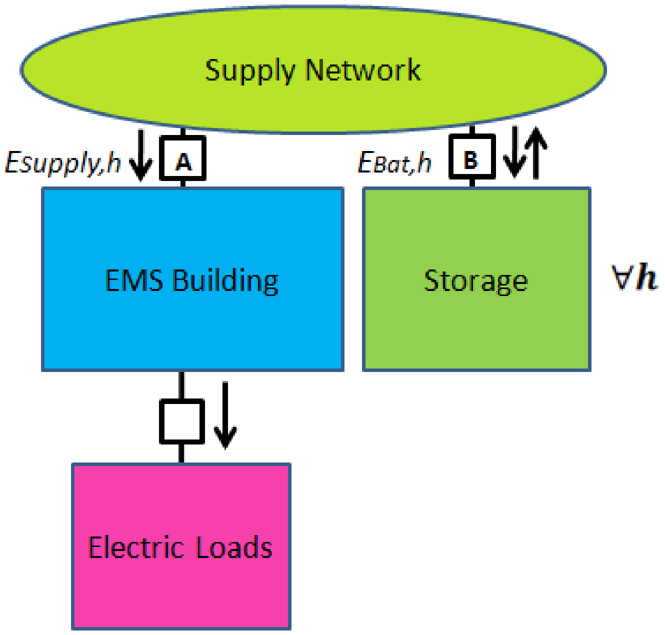
Figure 2: PEV Storage integrated in the building EMS without provision of regulation reserve



B. PEV storage providing frequency regulation to the ISO

The building PEV storage is managed by an aggregator who offers frequency regulation services to the ISO market. The PEV storage is managed independently of the other loads or generators located in the building. Optimal management is based on maximizing the profits, income minus costs, of providing regulation. In addition to the energy supply contract, there is a contract between the building aggregator and the ISO for providing frequency regulation and for selling or buying the required energy on the ISO energy market. Figure 3 shows this business model. The commercial relationship between the building and the supplier is governed by meter (A). The provision of regulation is monitored and controlled by the ISO EMS via specific equipment (RIG) required to participate in the AGC which is represented by (B).

Figure 3: PEV Storage providing regulation reserve to the ISO while not being integrated with other building loads



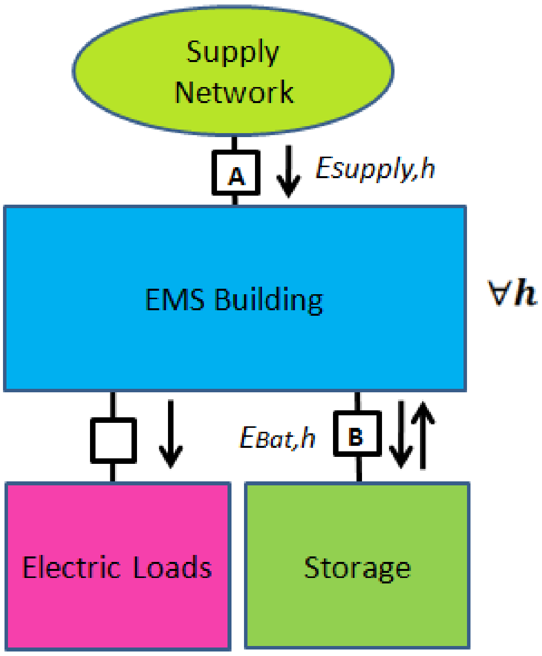
The main limiting factor for generation units providing frequency regulation is their ramp rate measured in (MW/min). However, for energy limited resources such as the considered PEV storage, the limiting factor for providing frequency regulation is the amount of energy that they can supply or store in a predetermined amount of time [13]. CAISO has set this period of time to one hour. Therefore, assuming an initial SOC of 50%, a battery with a storage capacity of E (MWh) can provide regulation-up of 0.3 E (MW-h) if it can be discharged down to a minimum SOC of 20%, and can provide regulation-down of 0.4 E (MW-h) if it can be charged up to a maximum SOC of 90%.

This business model assumes that the expected energy use taken for regulation by the ISO is known. The detailed formulation of this optimization problem is explained in Section 5.

C. Integration of PEV storage in the EMS with provision of regulation

The building has two contracts. One is a supply contract with a supplier like the one described in section IV.A. The other is with the ISO for providing regulation. In this case, the aim is to simultaneously minimize the building's electricity bill while maximizing profits from providing capacity regulation to the ISO. The total energy managed by the storage is optimized within the building, i.e. there are no other agreements with the ISO to buy or sell energy on the ISO market. Figure 4 represents this case. The contract with the supplier is settled according to the energy and demand measurements made at the supply point (A). Capacity regulation offered to the ISO is measured and controlled by the ISO via the specific equipment (RIG) required to participate in the AGC represented by (B). The formulation of the optimal storage management is presented in Section 5.

Figure 4: PEV Storage integrated in the building EMS with provision of regulation reserve



5 Model Extension

A. Nomenclature

The following notation is employed to model the use of PEV battery storage in the building EMS. Where indicated, an hourly resolution, *h*, of price data and energy flows is used.

Parameters:

DMD_h	Electricity demand by the building	[kWh].
$P_{supply,h}$	Resolved electricity price	[$/kWh].
F	Fixed cost of scalable battery inv:	[$].
V	Variable cost of scalable battery inv:	[$/kWh].
I	Interest rate	[% p.a.].
T	Technology lifetime	[a].
$P_{RegEnergy,h}$	Regulation energy price	[$/kWh].
$P_{RegUp,h}$	Regulation capacity-up price	[$/kW-h].
$P_{RegDown,h}$	Regulation capacity-down price	[$/kW-h].
dc	Dispatch-to-contract ratio	[%].
MCR	Maximum ISO charge rate	[%*h^{-1}].
MDR	Maximum ISO discharge rate	[%*h^{-1}].
Tr	Transmittable capacity	[kW].
CP	Replacement cost of Li-ion batteries	[$/kWh].
D	Capacity degradation coefficient	[%].
CR	Maximum battery charge rate	[%*h^{-1}].
DR	Maximum battery discharge rate	[%*h^{-1}].
γ_{eff}	Battery charge efficiency	[%].
δ_{eff}	Battery discharge efficiency	[%].
φ_{decay}	Battery decay factor	[%].
max_{soc}	Maximum battery SOC	[%].
min_{soc}	Minimum battery SOC	[%].

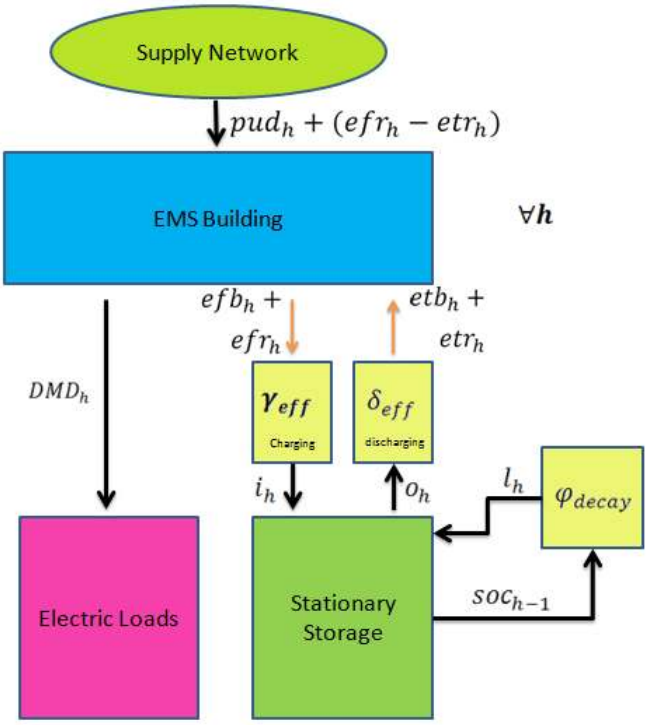
Decision Variables:

c	Installed battery capacity	[kWh].
soc_h	Battery SOC	[kWh].
efb_h	Energy flow from building	[kWh].
etb_h	Energy flow to building	[kWh].
bcd_h	Capacity bid regulation-down	[kW-h].
bcu_h	Capacity bid regulation-up	[kW-h].
efr_h	Energy flow from ISO	[kWh].
etr_h	Energy flow to ISO	[kWh].
o_h	Battery energy output	[kWh].
i_h	Battery energy input	[kWh].
l_h	Energy losses in battery	[kWh].
pud_h	Utility electricity consumption	[kWh].

B. Integration of PEV storage in the building EMS

The energy flows, as modeled in DER-CAM, are illustrated in the following diagram. The optimization has been implemented in GAMS® and computed with the CPLEX solver [12].

Figure 5: Representation of energy flows in the extended model



The optimization of battery storage is integrated in the objective function of the DER-CAM model. The following describes the excerpt of the mixed integer linear optimization problem (MILP) that deals with the storage management and provision of regulation reserve. Electricity costs for the microgrid are minimized on an annual basis. All price data is considered on an hourly basis and represents aggregated values for week, peak and weekend days of each month.

The investment decision for the microgrid is based on the initial outlay for technology acquisition, composed of fixed and variable investment costs and listed in equation (1). It further includes costs for battery degradation as described in equation (2). These costs are discounted with the annuity factor to obtain an annual perspective. The first fraction depicts the costs for battery replacement. It accounts for purchasing costs and a battery EOL at 80% of initial capacity. The second fraction considers battery wear-out as a result of energy processing. The sum of the entire energy exchange with the building's EMS is divided by the installed capacity and multiplied by a technology-specific capacity degradation coefficient, as introduced in equation (22).

In addition to technology costs, the costs for purchasing electricity from the supply network and from the ISO are billed in equations (3) and (7), respectively. Furthermore, revenue streams created by offering regulation reserve to the grid and by providing regulation energy are deducted from the annual invoice in equations (4-6).

The optimization is also subject to operational constraints as listed in equations (8-21) due to energy flows, represented in Figure 5, and other requirements imposed by the regulation procurement.

Objective Function:

$$\min \rightarrow \frac{I}{1-(1/(1+I)^{T})} * \left[\left(F + V * c\right) \right. \qquad (1)$$

$$\left. + \frac{\left(CP * c\right)}{100-80} * \frac{D * \sum_{h}\left(efb_{h} + efr_{h} + etb_{h} + etr_{h}\right)}{c} \right] \qquad (2)$$

$$+\sum_{h} pud_{h} * P_{supply,h} \qquad (3)$$

$$-\sum_{h} bcu_{h} * P_{RegUp,h} \qquad (4)$$

$$-\sum_{h} bcd_{h} * P_{RegDown,h} \qquad (5)$$

$$-\sum_{h} etr_{h} * P_{RegEnergy,h} \qquad (6)$$

$$+\sum_{h} efr_{h} * P_{RegEnergy,h} \qquad (7)$$

Constraints:

$$soc_{h} = soc_{h-1} + i_{h} - o_{h} - l_{h} \qquad (8)$$

$$\min_{soc} * c \leq soc_{h} \leq \max_{soc} * c \qquad (9)$$

$$o_{h} < c * DR \qquad (10)$$

$$i_{h} < c * CR \qquad (11)$$

$$l_{h} = soc_{h-1} * \varphi_{decay} \qquad (12)$$

$$o_{h} = \left(etb_{h} + etr_{h}\right) / \delta_{eff} \qquad (13)$$

$$i_{h} = \left(efb_{h} + efr_{h}\right) * \gamma_{eff} \qquad (14)$$

$$bcu_{h} \leq \left(soc_{h} - \min_{soc} * c\right) * MDR - etb_{h} \qquad (15)$$

$$bcd_h \le (\max_{soc} * c - soc_h) * MCR - efb_h \tag{16}$$

$$bcu_h \le Tr + pud_h \tag{17}$$

$$bcd_h \le Tr - pud_h \tag{18}$$

$$etr_h = bcu_h * cd \tag{19}$$

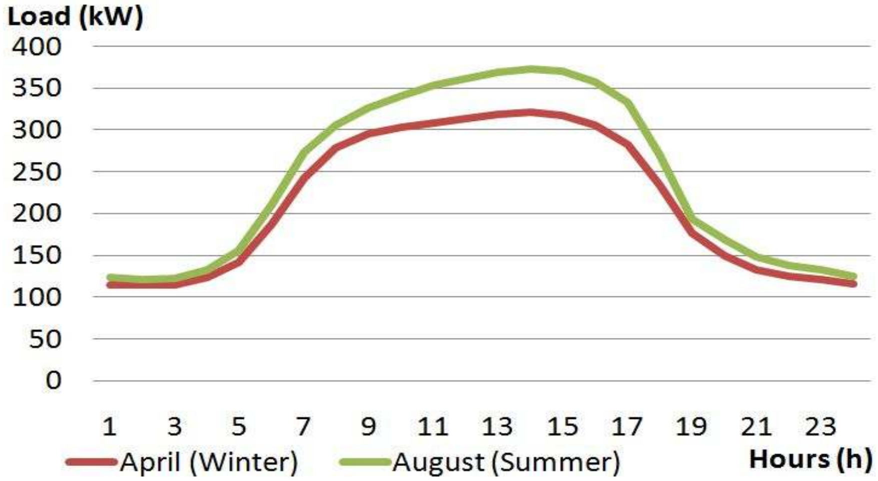
$$efr_h = bcd_h * cd \tag{20}$$

$$DMD_h = pud_h - efb_h + etb_h \tag{21}$$

6 Case Studies

A medium-sized office building in North California was analyzed. The electricity load profile was derived from the California Commercial End-Use Survey (CEUS) [14]. The building has a total floor area of 3,000 m^2, a peak electricity demand of 373 kW, and an annual electricity consumption of 1.7 GWh. Figure 6 depicts the monthly average demand profiles of two *weekdays* in summer and winter [15]. For the model optimization, two other day types were created, *weekends* and *peak days*.

Figure 6: Weekday profiles for two months



The highest electricity demand occurs during the summer. This results from the electricity needed for cooling. Consumption generally rises sharply in the morning to meet a smooth maximum in the early afternoon. This profile applies throughout the entire year, regardless of the month or season, and is typical for office buildings.

Table I shows the Pacific Gas and Electric (PG&E) tariff applied to the office building. Two TOU periods exist in winter (Nov-Apr): mid-peak (08:00-21:00) and off-peak (all other times). In summer (May-Oct.), a third on-peak period (12:00-18:00) is added. The demand charge is per maximum kW monthly load irrespective of when it occurs. A fixed monthly fee is applied.

Table 1: PG&E Tariff for Small to Medium Commercial Customers [16]

	Summer (May – Oct.)		Winter (Nov. – Apr.)	
Electricity	electricity ($/kWh)	demand ($/kW/Mon.)	electricity ($/kWh)	demand ($/kW/Mon.)
non-coincident	-	10.27	-	5.76
on-peak	0.16	-	-	-
mid-peak	0.14	-	0.11	-
off-peak	0.13	-	0.10	-
Monthly fee (US$/month)	118.28			

To apply the concept of a secondary use, cost assumptions are made as listed in Tables II and III. They result from prior battery usage in the vehicle, collecting and uncasing used PEV battery packs, as well as the consequential integration into a microgrid's EMS.

Table 2: Assumptions about Battery Wear-Out in PEVs

Overall battery lifetime [years]	12
Use of batteries in PEV [years]	7
Use of batteries in microgrid [years]	5
Battery wear-out in PEV due to cycling [%]	12
Battery degradation factor driving [%]	-0.006
Battery degradation factor V2G [%]	-0.0027
Energy consumption [kWh/mile]	0.35
Daily distance traveled in CD mode [miles]	25
Number of driving days [p.a.]	330

Battery life expectancy is limited to 12 years due to the calendar life of battery cells. In comparison to research targets for the medium term of around 15 years, this is a moderate postulation [17] that takes into account the less stressful conditions in the battery's secondary life. Of the 12 years, batteries are used in the vehicle for the first seven years. The remaining five years then allow for considerable value creation with the batteries being used in the microgrid.

The consideration of battery wear-out resulting from cycling is based on a physical model that tested high-power $LiFePO_4$ cells, simulating realistic driving conditions and vehicle-to-grid (V2G) use [18]. Based on the observed results, the following equation was derived to describe cell degradation:

$$Battery\ Degradation = \frac{D * E}{c} \tag{22}$$

$D :=$ Battery Degradation Factor [%].
$E :=$ Energy Throughput [kWh].
$c :=$ Battery Capacity [kWh].

The battery degradation factor *D* depends on the battery type and driving habits. The numbers in Table II therefore represent average values. To calculate the battery capacity remaining after seven years of mobile employment, an average energy consumption of 0.35kWh/mile, an average daily distance traveled in charge depleting (CD) mode of 25 miles, and 330 driving days per year have been assumed. The result is that 12% of battery capacity will be degraded after use in the vehicle.

Table 3: Costs for Integrating PEV Batteries into a Microgrid's EMS

Transport [$/battery pack]	10
Module and battery assembly [$/battery pack]	40
Balance of plant [$/kWh]	3.08
Inverter [$/kW]	2
Electric connections [$/kW]	5
Battery replacement costs [$/kWh]	150
Communication gateway [$]	3,000

Costs for collecting and aggregating battery modules as well as for integrating them in a building EMS are listed in Table II. To fit the model needs, these costs are split into fixed costs and variable costs in $/kWh which depend on the installed battery capacity. Where necessary, costs have been weighted for a battery capacity of 567 kWh which was identified as optimal for the studied microgrid.

Transport costs account for collecting the battery modules and shipping the entire pack to the final location. They are valued at $10 per battery pack with 10.2 kWh of initial capacity. The required disassembly and assembly of modules to form the "new" battery costs $40 for the same type of battery pack [19].

Balance of plant (BOP) describes the energy management system of a battery that monitors voltage, temperature, and SOC of battery modules. Furthermore, it includes battery hardware and casing. The variable costs of the required BOP components decrease with an increase in battery size. They have been calculated according to eq. 23 [20].

$$y = 388.94 * x^{-0.605} \tag{23}$$

$y :=$ *BOP Costs [\$].*
$x :=$ *Battery size [kWh].*

The costs used for the inverter are based on price projections for current PV inverters [21]. In the same way, costs for electric connections were derived from current market data. Finally, battery replacement costs represent the price that is paid to the vehicle owner for the PEV battery pack. This price is set at $150/kWh, to make it comparable to current Pb-acid battery prices. Used Li-ion batteries will still have a higher available capacity and higher cycling life expectancy and should not cost less than Pb-acid batteries.

The only fixed costs considered include the costs for installing the RIG to communicate with the ISO. Total costs are then valued based on a depreciated storage capacity after the seven years of mobile usage. Furthermore, where the necessary technical equipment exceeds a life expectancy of five years, annual payment flows are calculated for a five year investment decision. The variable costs thus total $165/kWh and the fixed costs $1,100 for the investment decision of the microgrid.

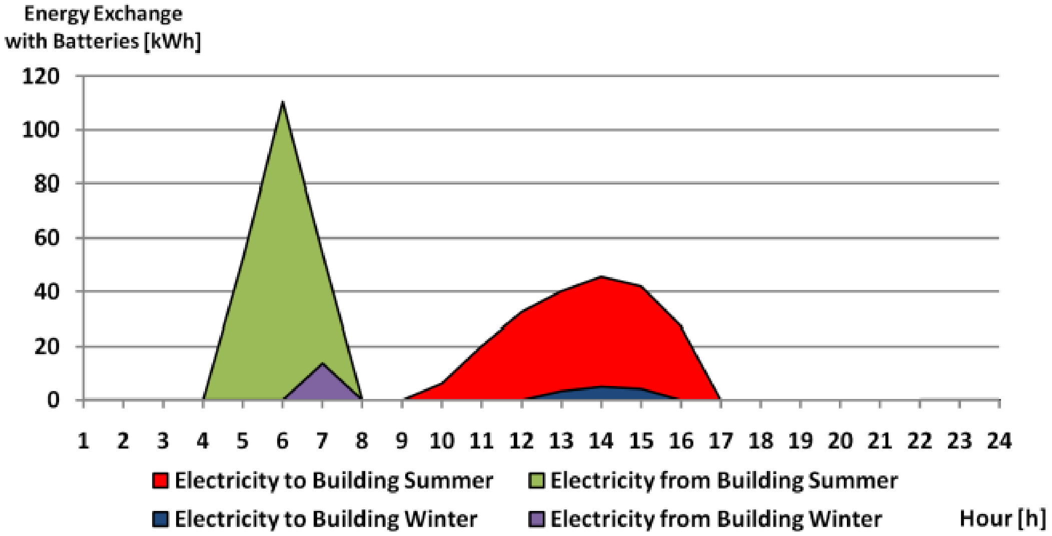
A. Integration of PEV storage in the EMS without provision of regulation reserve

The first case models the situation where battery storage serves the internal EMS of the building. Capacity bids for regulation reserve (bcu_h and bcd_h) are thus set to zero.

Results show that, at current prices, no battery capacity is installed. The break-even point of investment is only reached starting at variable costs of $100/kWh and no fixed costs. This threshold represents the cost barrier for this particular case at which battery use becomes profitable as an investment from the microgrid's perspective. However, even at zero costs, only a capacity of maximal 310 kWh is identified as optimal for the building by the model. This scenario would lead to a reduction of the annual electricity bill by $901, which is equivalent to a modest 0.3% of the annual costs.

The energy exchange between building and batteries is illustrated in Figure 7. As can be seen, energy flows would be used to avoid demand charges during peak hours. Batteries would be charged just prior to consumption during morning hours to minimize energy losses due to battery decay. During winter, energy costs caused by battery inefficiencies offset the gains that could be made by avoiding demand charges and TOU tariffs. The shifted amount of energy is therefore considerably smaller.

Figure 7: Energy exchange with batteries for January and August

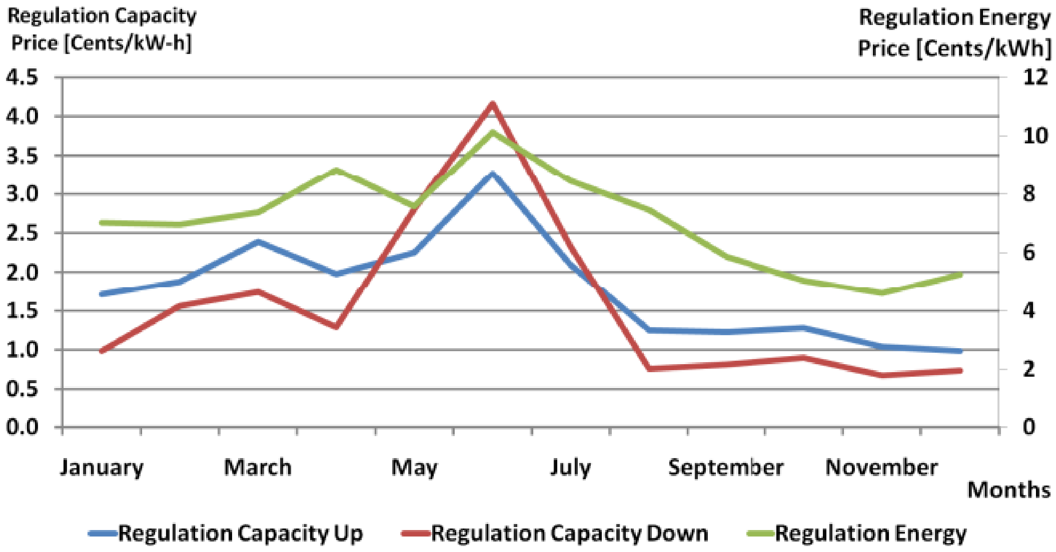


It can therefore be concluded that, lacking other sources of intermittent power supply, the installation of battery storage without the provision of A/S is not an economical option for the studied building.

B. PEV storage providing frequency regulation to the ISO

To examine the economics of providing A/S, CAISO day-ahead market prices of 2008 for regulation capacity have been calculated in cents/kW-h. The dispatched regulation energy is billed with the wholesale electricity price in cents/kWh. Monthly average prices are depicted in Figure 8.

Figure 8: Monthly average regulation capacity and wholesale electricity prices [22]



As can be seen, prices increased during spring and early summer when offers for the provision of regulation reserve declined. Thermal units which otherwise provide regulation reserve were off-line then due to imports of low-cost hydroelectricity. Nevertheless, prices were still in the range of earlier years and thus seem suitable for use.

To represent the case of used PEV batteries providing frequency regulation to the macrogrid, the following adaptations to the model are made: The building energy demand (DMD_h) is deactivated to prevent energy consumption by the building. In addition, prices for the purchase of electricity ($P_{Supply,h}$) and energy sales to the ISO are calculated at the wholesale electricity price. Hence, during each hour, the battery SOC can be changed to optimally provide regulation reserve.

Finally, the dispatch-to-contract (dc) ratio is fixed at 10% in accordance with empirical data on regulation energy in California [23]. It is thereby assumed that the amount of required regulation energy is known and constant for each hour. Under these settings, a battery capacity of 567 kWh is selected manually. This is done for comparison reasons and matches the size selected by the model in section VI.C. The resulting payment streams are listed in Table 4.

Table 4: Annual Payment Streams When Providing Frequency Regulation to ISO

Revenue from regulation reserve [$]	64,088
- Revenue due to capacity payments [$]	64,750
- Revenue due to energy payments [$]	-662
Costs of energy purchase from ISO [$]	-4,409
Revenue in energy sales to ISO [$]	3,384
Battery degradation costs [$]	-993
Annualized upfront costs [$]	-22,470
Total electricity cost reduction [$]	39,600

The revenue from regulation reserve comprises the income in capacity payments and costs due to exchanged regulation energy. Over the year, 1.6 GW-h of regulation capacity-up provided compared to 1.8 GW-h of regulation capacity-down. This, in combination with the fixed dc ratio, gives the net costs for the exchange of regulation energy. In addition, 62.2 MWh of electricity is purchased at an average price of 7 cents/kWh and 32.8 MWh are sold to the ISO at an average price of 10.3 cents/kWh to balance the batteries' SOC. Including costs for battery degradation and the initial outlay yields an annual electricity bill reduction of $39,600 or 14.8%.

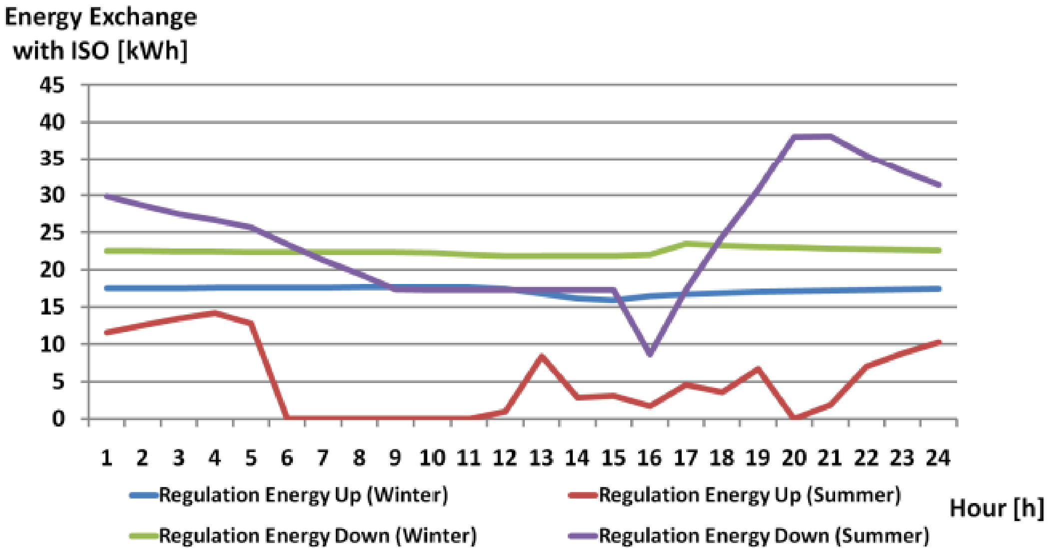
It can be observed that the optimal management of the battery maximizes the revenue obtained from regulation reserve. This can be done by changing the hourly battery SOC by buying or selling energy on the wholesale market at the ISO. However, energy purchases and sales remain at a low level throughout the year. In the majority of cases, equal amounts of regulation capacity are provided to keep the batteries' SOC constant over time.

C. Integration of PEV storage in the EMS with provision of regulation reserve

In the final case, batteries are used to provide frequency control to the macrogrid and to serve the internal EMS of the microgrid. Hence, the optimal management of the storage here is a combination of the previous two cases. The building tries to minimize energy payments under the supply contract and maximize incomes by offering regulation capacity. The energy required to alter the hourly SOC of batteries is either taken from or exported to the building and therefore valued according to the supply contract.

A battery capacity of 567 kWh is chosen by the model. Over the year, accumulated capacities of 840 MW-h are bid for regulation-up and 2.3 GW-h for regulation-down. The excess regulation capacity-down creates an electricity surplus that satisfies the building's demand. More expensive electricity from the utility provider is substituted. Exclusively regulation energy is stored in the batteries throughout the year. Electricity from the utility is used to directly meet the electricity demand of the building. As well as the benefits of providing regulation capacity-down, the possibility to store purchased electricity during off-peak hours is offset by the energy losses during charging. Figure 9 shows the seasonal use of battery capacity: During winter months, the available capacity is predominantly used to provide frequency control. This results in a nearly constant amount of regulation energy up and down being offered.

Figure 9: Electricity provision to the ISO for January and August



The peak electricity load of the microgrid is therefore only shaved during afternoon hours by an average of 6 kW. In contrast, during summer months, the batteries are used to supply energy to the building. During weekdays, peak demand is capped at 333 kW compared to the original 373 kW. This is caused by the high demand charges of $10.42 /kW, which are applied in this service territory for the summer months and can thus be avoided. To store the energy needed during office hours, an excess of regulation capacity-down is offered throughout the day. The resulting payments are listed in Table 5 and can be interpreted in the same way as in the preceding section.

Table 5: Annual Payment Streams for Battery Integration in EMS and Provision of Frequency Regulation to ISO

Revenue in regulation reserve [$]	49,848
- Revenue due to capacity payments [$]	58,351
- Revenue due to energy payments [$]	-8,503
Substituted energy costs [$]	14,655
Battery degradation costs [$]	-1,078
Annualized upfront costs [$]	-22,470
Total electricity cost reduction [$]	40,955

7 Conclusions

The results show, used PEV battery packs can be beneficially employed to serve vehicle owners, microgrid operators and the ISO. Uncasing batteries at an early stage of their lifecycle creates considerable economic value. This also lowers the risk presented by uncertain battery life in a vehicle environment. The optimal time at which to collect PEV batteries is subject to their usage and was not a focus of this study.

Embedded in a microgrid, batteries can serve the internal EMS and provide frequency regulation. However, using them solely for the building EMS was not proven to be economic. Their use to primarily serve the microgrid or the macrogrid was modeled in cases B and C, respectively. Whereas the income obtained from regulation reserve was higher in case B, the overall electricity cost reduction for the microgrid was greater in case C. It can be assumed that, with increasing intermittent power supply, this value will rise still further in the medium term.

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Authors' affiliations

David Dallinger
Sebastian Beer

Fraunhofer Institute for Systems and Innovation Research (Fraunhofer ISI)
Competence Center Energy Policy and Energy Systems

Chris Marnay
Michael Stadler
Judy Lai

Ernest Orlando Lawrence Berkeley National Laboratory (Berkeley Lab),
Berkeley, USA

Tomás Gómez
Ilan Momber

Pontificia Comillas University of Madrid,
Madrid, Spain,

Contact: Brigitte Kallfass

Fraunhofer Institute for Systems
and Innovation Research (Fraunhofer ISI)
Breslauer Strasse 48
76139 Karlsruhe
Germany
Phone: +49 / 721 / 6809-150
Fax: +49 / 721 / 6809-203
E-mail: brigitte.kallfass@isi.fraunhofer.de
URL:www.isi.fraunhofer.de

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