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***Abstract*--It is generally believed that plug-in electric vehicles (PEVs) offer environmental and energy security advantages compared to conventional vehicles. Policies are stimulating electric transportation deployment, and PEV adoption may grow significantly. New technology and business models are being developed to organize the PEV interface and their interaction with the wider grid. This paper analyzes the PEVs' integration into a building's Energy Management System (EMS), differentiating between vehicle to macrogrid (V2M) and vehicle to microgrid (V2m) applications. This relationship is modeled by the Distributed Energy Resources Customer Adoption Model (DER-CAM), which finds optimal equipment combinations to meet microgrid requirements at minimum cost, carbon footprint, or other criteria. Results derive battery value to the building and the possibility of a contractual affiliation sharing the benefit. Under simple annual fixed payments and energy exchange agreements, vehicles are primarily used to avoid peak demand charges supplying cheaper off-peak electricity to the building during workdays.**

***Index Terms*-- battery storage, building management systems, dispersed storage and generation, electric vehicles, load management, microgrid, optimization methods, power system economics, road vehicle electric propulsion**

I. INTRODUCTION

THIS paper analyzes the integration of plug-in electric vehicles (PEVs) into a single office building energy management system (EMS), which serves as a first step towards understanding their potential role in local semiautonomous groupings of energy sources and sinks, or *microgrids*.

In prior research, many authors have described the emerging technologies arising from the power electronics that accompany different distributed energy resources (DER), particularly DC and variable frequency AC power sources, e.g. photovoltaic (PV) systems, batteries, and asynchronous generators such as microturbines[1]. Together with high-speed switches permitting seamless grid disconnect and reconnect, these power electronic devices will enable formation of microgrids that operate semi-autonomously from the traditional centralized power system, or *macrogrid*. 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. At the same time, it is generally believed that PEVs offer environmental and energy security advantages compared to conventional gasoline vehicles. Policies in the U.S. and other countries are stimulating electric transportation, and the number of PEVs will likely grow significantly.

PEVs are unusual additional devices that will be attached to buildings. They would appear as loads during charging, and a significant body of research has explored their potential added burden to the macrogrid [1,2,3] as well as their potential to improve capacity utilization by off-peak charging [4]. PEVs are also potential suppliers of energy at other times [5]. Moreover, they may facilitate the deployment of geographically dispersed renewable energy sources (RES) [6], provide ancillary services to maintain the balance between electricity load and generation, either locally in the microgrid [7,8], in the local distribution segment, or in the wider macrogrid [9,10,11]. New technology and business models will be developed to organize the interface between PEVs and the buildings where they are connected, as well as their interaction with the wider grid. Controlling and benefitting from these

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[1] For background on microgrids, please see the presentations from the five Symposiums on Microgrids held at Berkeley, CA, USA in June 2005; Mont-Tremblant near Montréal, Canada in June 2006; at Nagoya, Japan, in April 2007; on Kythnos Is., Greece, in June 2008; and in La Jolla CA, USA in September 2009, (available at http://der.lbl.gov).

interactions are key challenges to both the microgrid and the macrogrid [12,13].

Only the ability of PEVs to deliver electricity purchased elsewhere, e.g. at home, to the office building and to store energy over a few hours during the workday are considered in this work. Employee PEVs are connected to the building EMS during working hours. A disconnect time state of charge (SOC) requirement lower than the typical SOC at arrival gives the microgrid access to relatively low cost energy purchased by employees at home. While connected, the EMS has full use of the PEVs' batteries within the constraints specified, for example to use the batteries for arbitrage on the prevailing tariff. The benefits of these services to the building are split between the building owner and PEV owners according to an annual contract that provides an upfront connection payment to the employees, as compensation to the owner of the battery for the investment and specifies the terms of energy exchanges.

II. PEVs and Microgrids

PEVs have the potential to allow their owners to participate as demand response resources [14]. Drivers with flexible charging patterns may use smart controls to charge their vehicles when energy prices are low. Furthermore, similar to the existing practice of utilities being able to control end-use devices, PEVs could potentially be a large interruptible load in times of grid emergency or high prices.

The scenario above considers PEVs only as loads and with one-way charging patterns, however, their potential for affecting overall energy use increases dramatically with the adoption of vehicle to macrogrid (V2M) technologies. Bidirectional power flow to and from the vehicles would allow them to participate in a much wider range of roles, e.g. providing ancillary services such as spinning reserve and regulation to respective markets. This requires that system operators have some means of sending accurate and reliable signals to the vehicles to which these can respond appropriately. Effective response, of course, also assumes predictable availability, i.e. vehicle connection.

A potentially additional benefit might accrue when PEVs are recognized and valued for their distributed energy storage capabilities and ability to provide V2M services. The significant capital costs of vehicle batteries may not be justified for mobility reasons alone, but the potential extra income stream through V2M tariff arbitrage and ancillary services provision might tip the economic balance.

High value services, preferably with little energy usage, are most promising, as the high ramping rates of batteries make them superior to other sources of regulation service [9,10]. Thus, one may envision that with future V2M technology it would be possible for PEVs connected at any given time to balance macrogrid load to generation, provided there are sufficient vehicles connected; however, such large-scale efforts require development and deployment of adequately standardized system level interoperable infrastructures for power flow control, monitoring, metering and settlement with numerous mobile sources/load devices.

On the other hand, the same desirable services of PEVs might be utilized in conjunction with the building EMS at their interconnection location, enabling them to prove vehicle to microgrid (V2m) services with relatively minimal additional infrastructure. In this scenario, PEVs are plugged in on the customer side of the meter, along with other electrical loads, other electrical power generation, electrical storage, alternative fuel systems, thermal storage, and heat loads. Such an interconnection of loads and sources configured as a microgrid, which operates in a semi-autonomous manner, has been shown to be an attractive means for optimizing energy use at the local level. From this perspective, PEVs represent natural participants in the microgrid in two aspects. First, they enable the transportation energy use component to become an integral player in the local energy network. Second, their inherent energy storage capacity provides a mechanism for them to play a power-balancing role.

This paper explores the economics of such an operating scenario where PEVs convey V2m storage using the established model for distributed energy resources described in the following section.

III. Distributed Energy Resources Customer Adoption Model (DER-CAM)

DER-CAM solves a commercial building's microgrid problem of investment and operation optimization given its end-use energy loads, energy tariff structures and fuel prices, as well as an arbitrary list of equipment investment options [15]. The Sankey diagram in Fig. 1 shows energy flows in a building scale microgrid and illustrates how DER-CAM operates. DER-CAM solves the system analytically by representing it as a mixed integer linear program written on the GAMS® platform. Regulatory, engineering, and investment constraints are all considered. Energy costs are calculated using a detailed representation of utility tariff structures and fuel prices, operating and maintenance (O&M) expenditures, as well as any amortized DER investment outlays.

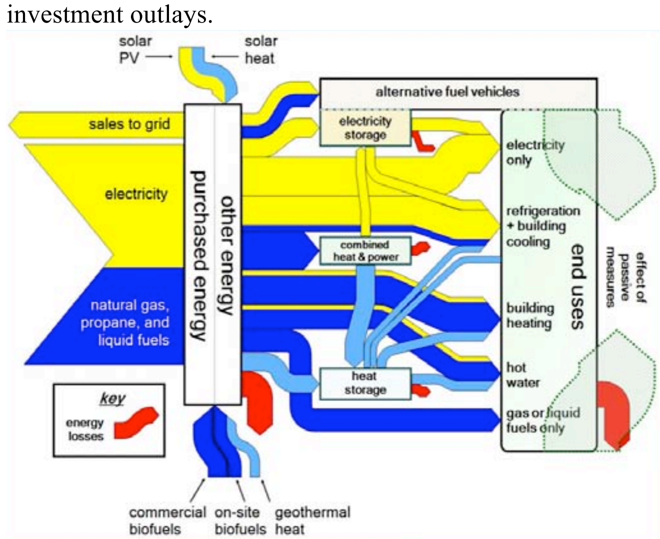

Fig. 1. Sankey diagram – Energy flows in a building scale microgrid.

Optimal combinations of equipment involving PV, thermal generation with thermal energy recovery, heat collection, heat-activated cooling, and both thermal and electrical storage can be identified in a way intractable by simple searching. DER-CAM can report a cost, carbon footprint, or combination minimizing equipment choice and (typically hourly) optimal operating schedule for the microgrid, including CHP and renewable sources. The economics of storage are particularly complex, both because they require optimization across multiple time steps and because of the strong influence of tariff structures. This paper reports on research focused on the upper right part of Fig. 1, where *alternative fuel vehicles* appears.

IV. Integrating PEVs into an Office Building

The optimal integration of PEVs into an office EMS must have an economic justification, e.g. the building benefits by reducing its energy costs and/or carbon footprint while the connected PEV owners receive payments from the building to help finance their vehicle investments.

A. The Economic Model

For illustrative purposes, following is an explanation of the economic rationale behind the formulation of the DER-CAM extension. It is assumed that the office building has a supply contract with a utility. This contract, as in our case study, could be based on a regulated tariff, or be a non-regulated contract negotiated with a supplier. In this type of contract, the reference for the energy price would be the wholesale market price plus a regulated delivery tariff.

The hourly energy price is the economic signal that provides the needed information for the office EMS to make decisions about the operation of the various building DER available. In the case of non-controllable loads or generators, e.g. wind or PV, the amount of energy produced or consumed in each hour is known and cannot be modified. In case of controllable CHP units, they can be dispatched if the energy price times the electricity produced together with the revenues coming from supplying other thermal loads are higher than the variable cost of production (start-up costs can modify this assumption). In the case of electricity storage, depending on storage capacity, energy efficiency, and its maximum output, the optimal strategy would consist of injecting energy into the building during hours of high energy prices and charging the battery in low-price hours.

The value of PEVs for the building can be analyzed as a special case of electricity storage, already included in the analysis and formulation of DER-CAM [16,17]. From a building perspective, stationary storage devices would be in direct competition with storage provided by connected PEVs.

There are differences in the modeling of investment decisions for stationary versus PEV storage since the ownership structures are different. Stationary batteries are most likely owned by an office building owner or manager, while PEVs most likely belong to employees; therefore, it is reasonable to assume that the investment decision will remain with the PEV owner. Additionally, the building may offer just one or multiple options of when to charge the batteries. These issues together make the contractual relationship between the building operator and the car owner a potentially complex and important determinant of PEVs' economic attractiveness.

B. The Business Model

The proposed business model assumes that PEVs parked and connected to the building for a fixed period every workday are managed by the building's EMS, as well as the commercial establishment of an annual contractual relationship between the building operator and each individual PEV owner.

The components of the PEV-building contract are:

1. A *connection payment* to the PEV (***CPT*** in $/kWh of storage capacity per year): the car owner would be compensated by the building just for regularly connecting the car. It gives the building the right to manage the storage but not to consume any net energy from the battery. It is the main mechanism for sharing the benefits between the parties. From the building's point of view, it is like a fixed investment cost in new equipment and can be understood as a contribution to financing initial outlay for batteries.

2. An *energy exchange price* ($\boldsymbol{P_{EX,EV}}$ in $/kWh): in agreement with the PEV owner, the building can take net energy from the battery and pay the PEV owner an approved price.

In addition, the SOC at time of connection ($\mathbf{SOC_{in}}$), the minimum SOC at time of disconnection ($\mathbf{SOC_{out}}$) sufficient for the next trip, and the minimum SOC required at all times $\mathbf{SOC_{min}}$ could all be specified in the contract.

Multiple functions could be considered for the energy exchange price. The simplest one is an equal flat price for charging and discharging, which is described in the test case of Section V. Other price functions, such as linear or stepwise linear are imaginable as represented in Fig. 2. The driver of the vehicle would pay a positive price for receiving energy and pay a negative price (obtain a positive payment) for providing net energy. Therefore, prices for taking net energy from the building are in quadrant I, whereas prices for injecting net energy into the building are in quadrant III. Furthermore, in quadrant I, the PEV owner is the buyer of net energy whereas the building is the seller. In quadrant III the roles are reversed.

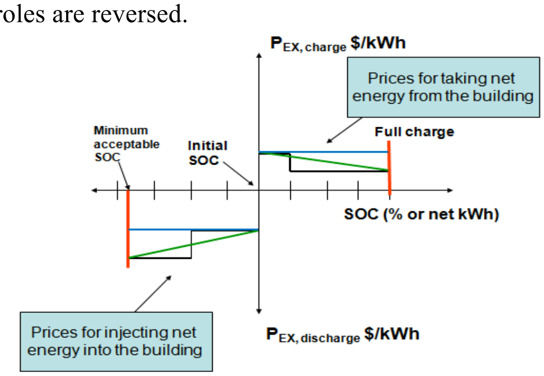

Fig. 2. Possible *energy exchange prices* forming part of the information to be transferred from the PEV energy system to the building EMS.

The objective function specifies the maximization of the storage capacity value to the building. In particular there is a value for the energy charged or discharged from the battery at each hour. The avoided costs for the building are calculated whilst the building takes energy from the battery. Whereas the incurred costs from the energy supplier are determined when the building provides energy to the battery and compared to revenue from the billing of energy exchange with the vehicle. It is clear that the value of the storage is totally dependent on 1) the price spread between maximum and minimum price in all hours over the connection period and 2) the relative price advantage between regulated tariff and energy exchange price.

The constraints that must be met are the SOC_{in} and SOC_{out}. Additionally, in each hour the SOC should be within a minimum and a maximum level according to sustainable capacity usage. A detailed presentation of the DER-CAM formulation concerning V2m appears in the APPENDIX.

The solution optimizes the energy taken from or injected into the battery thereby finding the SOC in each hour as well as the value of that energy for the building. The difference between the value and the energy payments to the PEV owners make up the building's profits. Part of these would be used to pay the connection fee to the PEV owners. Apart from the connection payment, PEV owners could benefit by selling inexpensively bought net energy to the building.

V. DESCRIPTION OF TEST CASE

This example analysis concerns a northern California office building with electricity load profiles based on the California Commercial End-Use Survey (CEUS) [18]. The building has total floor area of approximately 3,000 m^2, a peak electricity demand of 373 kW, and a total yearly consumption of 1.677 GWh. Fig. 3 shows the average *weekday* demand profiles for two representative months. For each month two other day types were created, *weekends*, and *peak days*. The *peak days* are calculated as the average of the three weekdays with highest consumption in each month.

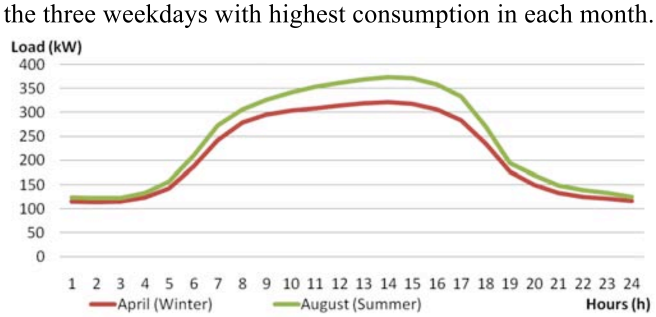

Fig. 3. Representative *weekday* profiles for a summer and a winter month.

A clear difference between summer and winter can be observed, with the highest electricity demand in summer. Over the course of average days, regardless of the month or season, consumption increases sharply in the morning hours to meet a smooth maximum around the early afternoon hours before decreasing in the afternoon.

Table I shows the Pacific Gas and Electric (PG&E) tariff applied to the office building [19]. Two time-of-use (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 the time of occurrence.

TABLE I

PG&E TARIFF FOR SMALL TO MEDIUM COMMERCIAL CUSTOMERS [19]

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

A flat *energy exchange price*, $\mathbf{P_{EX,EV}}$, has been set at 0.115 $/kWh approximating the average residential electricity rate, i.e. the price at which the PEVs are charged at home. Fig. 4 illustrates the relationship between the building tariff and $\mathbf{P_{EX,EV}}$. The exchange price conveniently lies in between the summer and winter rates and will later be shown to be the most powerful determinant of the operating schedule, deciding at what times charging or discharging is economic.

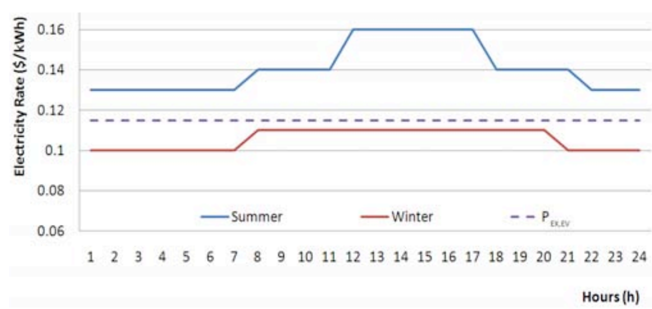

Fig. 4. Building energy rates and energy exchange price [19].

According to the formulation presented in the APPENDIX, the interest rate (*I*) for annuity calculations is 6% real. Investment in charging infrastructure is assumed to be independent of connected battery capacity with a $100 intercept cost (*F*), while the duration of the contract is assumed to be one year, (*T*=1). All payments are settled annually.

By averaging the crucial determinants, such as production volume, chemistry type, type of vehicle and pack size, the industry wide current production cost (*K*) for lithium-ion batteries is assumed to be around $600 per kWh, with the long term goal being around $200 per kWh *(CP)* [20]. A PEV with a battery capacity of 16 kWh currently costing $9,600 will qualify for a full American Reinvestment and Recovery Act 2009 (ARRA) tax credit of $7,500 [21]. This would add up to a government contribution of around $470 per kWh (78% of K for storage capacity). With a projected lifetime of 10 years and the same interest rate as assumed above, for comparison with connection payments (*CPT)*, this equals an annualized payment of around $50 per kWh/a.

The SOC_{in} is assumed to be consistently 73%, and SOC_{out}

is chosen by the building's EMS but must exceed 32%. During the connection time from 9:00 to 18:00, the minimum and maximum SOC can range between 20% and 90%. Battery inefficiencies for charging (1-γ_{eff}) and discharging (1-δ_{eff}) are assumed to be 4.6% each, while round trip efficiency (γ_{eff} * δ_{eff}) is approximately 91%, with losses due to decay from one hour to the next (φ_{decay}) reaching 0.1% of the preceding hour's SOC. A 240 V, single-phase, 30 A circuit infrastructure is assumed to determine the energy exchange constraints at 7.2 $kWh*h^{-1}$.. Therefore the charging rate is limited to 0.45 h^{-1} = 7.2 $kWh*h^{-1}$ / 16 kWh.

VI. Results

The optimization was performed in a two-step planning and operating procedure according to the mathematical formulation in the Appendix. The maximal connection payment or investment contribution in battery technology by the building was derived at a cost of scalable investment *CPT*=$23.361 per kWh/a. At higher connection payments from the building perspective the benefit from avoided peak prices through the PEV connection does not make up for the cost of battery investment. Setting the payment at *CPT*=$5 per kWh/a leads to an optimal number of contracts (or cars connected to the building) of approximately 8, cf. Table II. The payment to all PEV owners is in total $2231, or $263 per car. These can be split into energy payments of $170 and an investment contribution (or connection payment) of $93. Additionally, battery degradation due to cycling the energy amounted at 0.39% of initial capacity and creates a compensation cash flow to the PEV owner of $66, cf. goal function in the Appendix. The building benefit is obtained as the difference in annual energy costs from the reference case with no PEVs, to the comparative energy supply costs with PEVs plus the payments to the PEV owners. Finally, the value created by the connection of PEVs is calculated as the building profit plus the PEVs owners benefit given by the connection payments they receive. It can be observed that, in this example, approximately half of the benefits are for the building and the other half for the PEV owners. *CPT*=0 and *CPT*=10 are optimization runs for comparison.

TABLE II
Summary of Numerical Results

connection payment[$/kWh]	**CPT=5**	CPT=0	CPT=10
Battery Capacity [kWh]	135.86	6415	49
Number of PEV [#]	**~8.5**	~401	~3.1
PEV-Payments [$]	2231	37354	1037
Per 16kWh car [$]	263	93	338
Energy thereof [$]	170	93	145
Connection [$]	93	0	193
Battery Degradation [% capacity]	0.39	0.14	0.56
Battery Degradation [$]	530	8770	277
Per 16kWh car [$]	66	22	90
Building Benefit [$]	704	9475	292
Per 16kWh car [$]	83	24	95
Total Value Created [$]	**1494**	9575	883

The operating schedules for summer and winter rate periods are depicted in Fig. 5. For all months batteries are discharged in the afternoon hours. To increase the amount of energy displaced, the EMS charges in the mornings, but over the day the net energy exchanged is a discharge because energy from PEVs is less expensive than from the utility supply. The result for the winter months is similar but not as extreme. Evidently the building's incentive to avoid demand charges causes the batteries to discharge, despite their higher energy cost compared to utility purchases.

Fig. 5. Operation schedule of PEV batteries for two example months.

In Fig. 6, the building peak is shaved for a typical August week day. The monthly demand charge drops by 5.85% from $3832 to $3607.

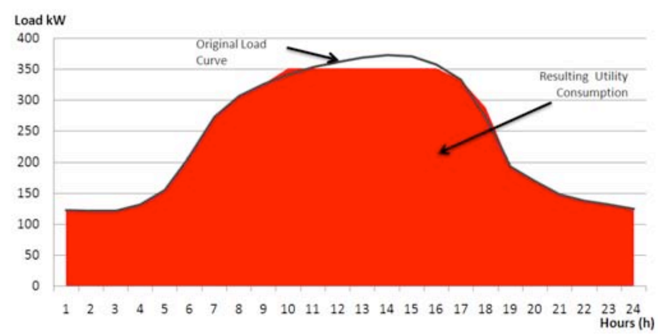

Fig. 6. Original building load and PEV peak shaving effect.

Sensitivity analyses were performed for different round-trip efficiencies and PEV arrivals from 7:00 to 10:00 with corresponding departure times between 16:00 to 19:00, keeping the connection time constant, cf. Fig. 7.

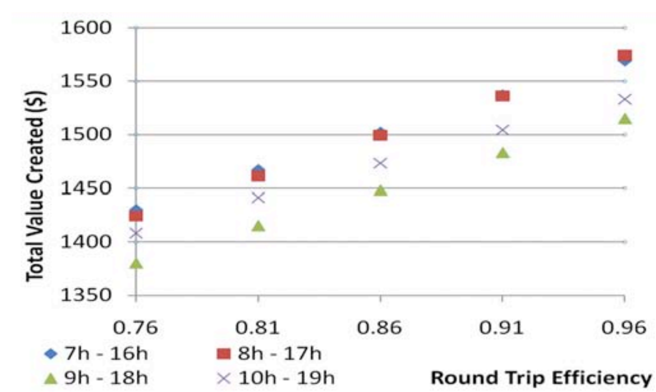

Fig 7. Sensitivity analysis for total value creation as a function of efficiencies and connection intervals.

The price spread between $P_{EX,EV}$ and $P_{EX,supply}$ has to be greater than the charging efficiencies (γ_{eff}) and (δ_{eff}) to yield a gain for the building, as long as demand charges are included. However, the load correlates with business activity and workers present. Efficiencies do impact system behavior and can change the results prominently.

To understand the economic meaning of previous results, boundaries for the objective function are provided with a reference case. For comparison, all electricity was purchased from the utility at an annual cost of $245k, out of which only $32k (13.1%) was due to demand charges, and the TOU energy costs made up $211k (86%) of the bill. The utmost possible benefit from storage (theoretical maximum in reduction of costs) was then calculated with full availabilities, perfect round trip efficiency and zero investment costs for the battery technology. It amounted to $16.8k (6.9%) of the annual bill, with total demand charges over the year still as high as $27k (11.9%). This relativizes the putatively low value creation presented in the results Table II.

VII. Conclusion

Based on the common understanding that PEVs might create economic and environmental benefits for societies, a specific case study has been presented which focuses on the economic impact of PEVs connected to a microgrid. The DER-CAM model, an optimization tool that minimizes the yearly energy costs for microgrids, has been modified to account for PEVs, and first results presented. For a California office building with PEV connection under a business model that distributes value, thresholds for maximum connection payments are derived. It is found that the economic impact is limited, i.e. cost reductions from stationary batteries or PEV connections are modest. Nonetheless, this example shows that some economic benefit is created because of avoided demand charges and TOU rates. The strategy adopted by the office building is to avoid high on-peak costs by using energy from the PEV batteries in the afternoon hours. Results are case dependent. Different end-use requirements, higher differences between TOU energy prices, elevated demand charges, or cost reflective fluctuating real-time energy pricing can all result in more beneficial solutions. CO_2 emission results are not presented here since research is still ongoing.

In future work, the authors intend to extend this work to include the potential of the microgrid to aggregate PEV capacity and sell it into ancillary service markets.

VIII. Appendix Mathematical Formulation

The proposed optimization of PEV storage is embedded within the Distributed Energy Resources - Customer Adoption Model (DER-CAM). It was implemented in GAMS® and computed with the CPLEX solver [22]. To enhance understanding about the modeling of the energy flows, the following graphic is provided.

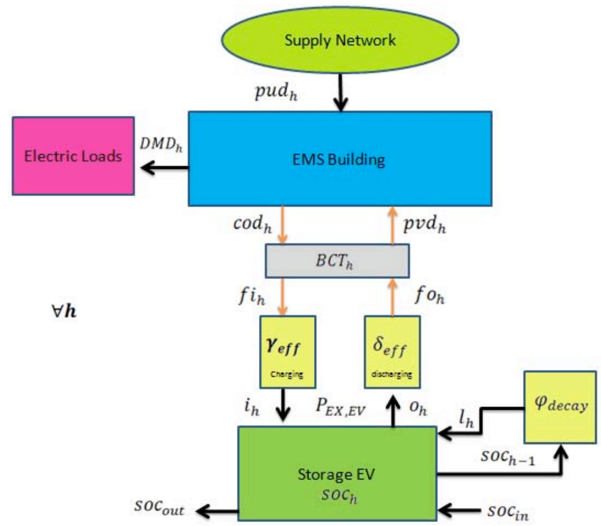

Fig. 8. Energy flows in the model for PEV storage connection.

In the following, an excerpt of the extended mixed integer linear optimization problem (MILP) is presented. It is not exhaustive as it only contains the relevant information concerning PEV and building interactions; it omits the description of all other constraints for generation technologies and reduces the complexity of regulated tariffs. It is formulated for a period of one year and only includes the information concerning the building's contract and payments to PEVs, focusing on the energy balance of the intermittent mobile storage devices. The links to the building model are the vehicle deterministic electricity demand and energy supply prices. The latter is of special importance because in this formulation, prices are simplified to hourly values with more complex tariff components included in this price.

The input parameters in Table III include information about the building input, investment conditions, battery degradation, mobility behaviour, as well as operational input about the PEV connection [23].

The decision variables in Table IV consist of the investment level planning, operation schedule and the energy exchange schedule on the building interface.

The optimization is integrated in the objective function of the EMS for the building, as shown in the algebra below. The goal is to minimize the building electricity costs over the entire year subject to a set of operational constraints, cf. equations (1-10). The first term stands for the investment into the contract, interpretable as a connection fee or a contribution to the purchase cost of the storage. It is separated into a fixed intercept part, e.g. for infrastructure, and another that is variable in the storage capacity, measured in kWh of the connected electric vehicle fleet. This distinction is convenient as it is directly comparable with widely discussed costs for producing batteries. The second term stands for the battery degradation costs that are incurred due to the operation of the vehicles. The costs of degradation are segmented as follows: the replacement cost (*K*) is multiplied by the capacity degradation according to the usage coefficient (energy processed over initial capacity) and the degradation coefficient (*D*) [11,23]; the second to last term bills the net energy exchange with PEVs (here it is net output) according to the agreed *energy exchange price*, $P_{EX,EV;}$ while the last term accounts for the net energy that is procured from the supply network at the applicable tariff.

TABLE III
PARAMETER DESCRIPTION

	Description	Symbol	Unit
Building Input	Electricity Demand By the Building	DMD_h	kWh
	Resolved Hourly Electricity Price	$P_{EX,supply,h}$	\$/kWh
Investment Conditions	Interest Rate	I	%
	Duration of Contract	T	a
	Fixed Cost of Scalable Investment	F	\$
	Variable Cost of Scalable Investment	CPT	\$/kWh
	Hourly Price For Net Energy Exchange	$P_{EX,EV}$	\$/kWh
Battery Degradation	Cost of Production for Li-Ion Batteries	K	\$/kWh
	Capacity Degradation Coefficient	D	%
Mobility Behavior	SOC of PEV batteries at Disconnection	SOC_{in}	%
	SOC of PEV batteries at Connection	SOC_{out}	%
	Connection Array	BCT_h	$\in \{0,1\}$
Operational Battery Input	Maximum Relative Charge Rate	$\overline{CR}$	% * h^{-1}
	Charge Efficiency	γ_{eff}	%
	Maximum Relative Discharge Rate	$\overline{DR}$	% * h^{-1}
	Discharge Efficiency	δ_{eff}	%
	Decay Factor	φ_{decay}	%
	Minimum SOC	$\underline{SOC}_h$	%
	Maximum SOC	$\overline{SOC}_h$	%

TABLE IV
DECISION VARIABLE DESCRIPTION

	Description	Symbol	Unit
Investment Level Planning	Aggregated Capacity of Connected PEVs	c	kWh
Operation Schedule	State of Charge of PEV Batteries	soc_h	kWh
	Energy Output Processed	o_h	kWh
	Efficient Energy Output Processed	fo_h	kWh
	Energy Input Processed	fi_h	kWh
	Efficient Energy Input Processed	i_h	kWh
	Energy Losses Due to Battery Decay	l_h	kWh
Building Interface	Net Energy Flow Batteries To EMS	pvd_h	kWh
	Net Energy Flow EMS To Batteries	cod_h	kWh
	Resulting Load Curve	pud_h	kWh

Objective Function:

$$\min \rightarrow \left(\frac{I}{1-\left(\frac{1}{(1+I)^{T}}\right)}\right)(F + CPT * c) + \frac{(K * c) * D}{1-0.8} * \left(\frac{\sum_h (fo_h + fi_h)}{c}\right) + \left(\sum_h fo_h - fi_h\right) * P_{EX,EV} + \sum_h pud_h * P_{EX,supply,h}$$

Constraints:

$$soc_h = soc_{h-1} + i_h - o_h - l_h < c \quad (1)$$
$$c * \underline{SOC}_h \leq soc_h \leq c * \overline{SOC}_h \quad (2)$$
$$o_h < c * \overline{DR} \quad (3)$$
$$i_h < c * \overline{CR} \quad (4)$$
$$l_h = soc_{h-1} * \varphi_{decay} \quad (5)$$
$$fo_h = o_h * \delta_{eff} \quad (6)$$
$$i_h = fi_h * \gamma_{eff} \quad (7)$$
$$pvd_h = fo_h * BCT_h \quad (8)$$
$$cod_h = fi_h * BCT_h \quad (9)$$
$$pud_h = DMD_h + cod_h - pvd_h \quad (10)$$

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XI. Biographies

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Giri Venkataramanan (M'92-, SM'06) received a B.E. in electrical engineering from the Government College of Technology, Coimbatore, India, an M.S. from the California Institute of Technology, Pasadena, and a Ph.D. from the University of Wisconsin. After teaching at Montana State University, Bozeman, he returned to Madison as a faculty member in 1999. He serves as Associate Director of the Wisconsin Electric Machines and Power Electronics Consortium (WEMPEC).

Michael Stadler is a Research Scientist at Berkeley Lab, He studied at the Vienna University of Technology, from which he holds a Masters degree in electrical engineering and a Ph.D. *summa cum laude* in energy economics. His fields of research are distributed energy, electricity markets, and demand response. He has been involved in the development of DER-CAM for six years.

Sebastian Beer is a visiting research student in the TEMA group writing his master's thesis at KIT in Industrial Engineering and Business on renewable energy and storage adoption in buildings. He has also studied at the Pontifica Universidad Catòlica Argentina and worked at RWE Supply & Trading in London as an intern focusing on energy storage valuation.

Judy Lai is a Senior Research Associate at Berkeley Lab. She has worked with commercial building lighting simulation and analysis, providing documentation and customer support for Lab developed rendering software, and has also studied distributed energy resources, assisting with data gathering, analysis, publishing, graphics, and conference management. Judy has a B.A. in Architecture from U.C. Berkeley.

Chris Marnay (M'90) is a Staff Scientist at Berkeley Lab, and leads the Technology Evaluation, Modeling, and Assessment Group (TEMA). He specializes in likely future adoption patterns of small scale DER, especially those involving commercial building use of heat activated cooling, renewables, and microgrids. He holds an A.B. in Development Studies, an M.S. in Agricultural and Resource Economics, and a Ph.D. in Energy and Resources, all from the University of California, Berkeley.

Vince Battaglia is a Program Manager at Berkeley Lab, and leads the Battery Cell Analysis Group in the Advanced Energy Technology Department. He is a participant on the United States Advanced Battery Consortium Technical Advisory Committee where he assists in the development of battery targets and testing for vehicle applications. He specializes in the design, testing, evaluation, and life prediction of Li-ion batteries. He has an M.S. and a Ph.D in Chemical Engineering from the University of California, Berkeley, and a B.S. in the same area from the Johns Hopkins University.