Bi-Directional Power Architectures for Electric Vehicles

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Abstract- **Although electric vehicles (EVs) and plug in hybrid electric vehicles (PHEVs) yield significant gains in driving efficiency and C0$_2$ reduction, the value of these systems are diminished by the cost of the battery subsystem. To offset the cost of electric vehicles, this paper presents two bi-directional charging architectures that use the batteries from electric vehicles for grid ancillary and facility level services. Grid-scale frequency regulation with Vehicle to Grid (V2G) technology and facility peak demand reduction with Vehicle to Base technology (V2B) for military bases, commonly known as Vehicle to Building for commercial applications, are shown as promising potential avenues to make the economics of electric vehicles viable. To effectively analyze the benefit of either technology, the cost of battery cycle life lost and bi-directional inverter purchase are quantified as the main costs of the services. The revenues or savings from using the battery in either scenario are calculated using real utility usage data and rates for three utilities and typical military installations. The optimum V2B vehicle fleet sizes for cars and trucks are derived from these models. V2B operations are sized to offset the transient peak demands in facility electrical loads, while V2G operations make use of contracted frequency regulation with the local grid. The results show that both V2B and V2G can offset a large part of the cost premium of electric vehicles. These services, combined with the enhanced driving efficiency of electricity over liquid fuel, make the life cycle cost of the electric vehicles attractive compared to conventional ones. V2B and V2G can be implemented separately or in combination to greatly improve the economics of electric vehicles in the near future. The magnitude of benefits of either make electric vehicles more attractive to early buyers, and present an opportunity to push the technology into production quantities sufficient to drive the price of electric vehicles down to a level that is economically feasible for the general population.**

Key Words – Electric Vehicle, PHEV, V2B, V2G

I. THE IMPORTANCE OF PHEVS

The United States of America is operating on an unsustainable model of petroleum consumption. The economic future and national security of the US is at risk with a finite supply of oil, and the majority of that supply represents a costly dependency on other countries. The US now accounts for 25% of the worlds C02 production, where 33% of that comes from oil. Transportation now represents 28% of US energy use, and 70% of petroleum use [1].

Efforts to reduce the energy footprint of the United States have economic, environmental, and national security benefits. In the transportation sector, electric vehicles (EVs) and hybrid electric vehicles (HEVs/PHEVs) seek to alleviate the use of petroleum by utilizing a more diverse set of power sources from centralized electric power plants. Additionally, it has long been shown that the driving economy of EVs is far superior to gasoline based cars, and is projected to further strengthen with the increasing price of petroleum. If half the passenger vehicle fleet of the US was replaced by 100 mile per gallon (mpg) PHEVs, the petroleum use of the US would be reduced by approximately the amount now imported from the Mideast [2].

Batteries present the largest increase in cost of ownership for electric vehicles. This cost currently overshadows gains from reduced operation and maintenance and driving efficiency over traditional vehicles. Typical estimates of battery system costs range from $1000/kWh to an aggressive $500/kWh. Across these rates, a 24kWh battery pack would cost between $12000 and $24000. In an attempt to offset the cost of electric vehicles, many studies are being done on potential benefits of using the batteries from electric vehicles for grid and facility level services.

Grid-scale frequency regulation with V2G technology, facility peak demand shaving with V2B, and re-use of partially worn out batteries known as battery second life have been shown as promising potential avenues to make the economics of electric vehicles viable [2,4]. In the following sections, the analysis of case studies of V2B and V2G will support these conclusions and indicate a direction for economically viable deployment of plug-in vehicles. Results of V2B from empirical data acquired from MIT Lincoln Laboratory (MITLL, a 10MW facility) in 2010, Air Force Base Los Angeles 2009-2010 (AFBLA, a 2.5mW facility), and Naval Base San Diego March 2010-April 2011 (NBSD, a 40MW facility) will demonstrate performance in a range of sites. In addition, a general method to optimize fleet size considering the cost of the battery and bi-directional charger will be introduced. The performance of V2B and V2G will be discussed and caveats explored.

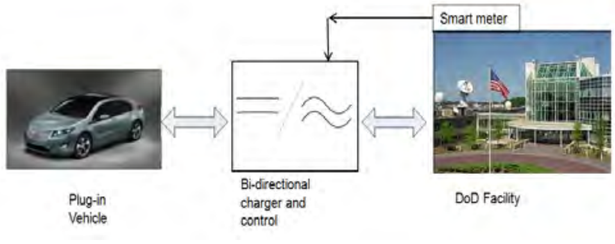

Fig. 1, Illustration of the Vehicle To Base (V2B) Concept

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II. VEHICLE TO BASE (V2B) TECHNOLOGY

V2B attempts to alleviate the power demand charges, charges per peak kilowatt, from utilities for large facilities. Transient peaks that may last only tens of minutes a few times a month can end up costing thousands of dollars in the utility bill. V2B uses information from a smart meter to determine when a peak is beginning to occur in real time, and then controls a bi-directional charger to tap into the energy stored in a plug-in vehicle's battery subsystem. The car, or fleet of cars, will discharge their battery at a determined rate for the duration of the peak event, and offset the peak demand as seen by the utility. Afterwards, the control system allows the plug-in vehicles to recharge at a rate that will not introduce additional peak demand to the facility.

A. *Utility Billing Structure and Peak Shaving*

Large scale electric power customers often pay for consumption of electricity ($/kWh) as well as a demand charge associated with maximum power drawn in that month ($/kW). The rate-structure of the demand charge is set by the utility provider, and is different from one utility to another, but some form of demand charge is common for customers large enough to require 3 phase service. The peak demand at any given time is assessed by average consumption over 5-30 minute intervals [2]. For MIT Lincoln Laboratory, demand charges of $20/kW in summer and $14/kW in the winter offer significant opportunity for reduction in the monthly bill using V2B.

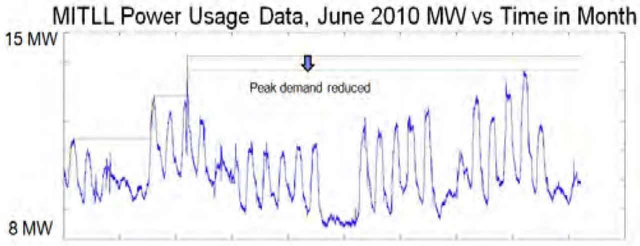

Figure 2, Peak Electrical Demand Characteristics and Opportunities for Peak Reduction

Power meters taking real time measurements at the facility level can be monitored to attempt to predict when a significant transient peak is imminent. Using the slope of the sampled power, current power magnitude, and current maximum daily and monthly demand, an algorithm can determine when a peak is expected to exceed the current monthly maximum. The algorithm will then activate the interface, discharging the batteries for a specified length of time. Recharging is performed such that the demand of the batteries will not increase the current monthly demand maximum. Analysis of V2B for MIT Lincoln Lab shows that many peaks are 15 to 30 minutes in duration. Demand data taken every 15 minutes allows calculation of possible savings, but data sampled at least every 5 minutes is needed for real time control to realize those savings.

B. *Performance of Peak Shaving*

Since the returns of peak shaving are limited by the size of the peaks and utility cost ($/kW), the scale of the fleet energy storage system in terms of the capacity and number of vehicles employed can be chosen to optimize return generated by V2B . The primary site capacity parameters include: Number of vehicles, depth of discharge of battery, capacity of vehicles, and discharge time.

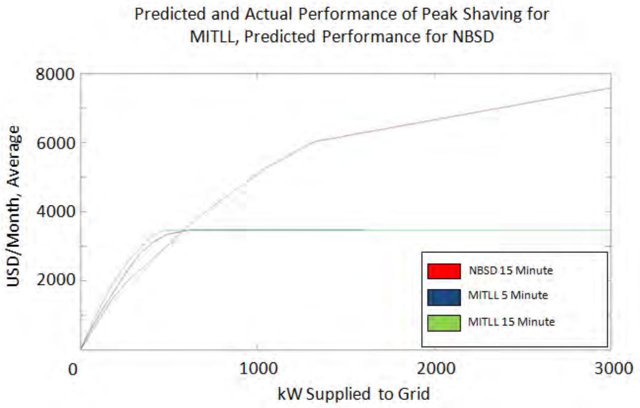

Figure 3, a return on investment by kW supplied curve for nominal NBSD and MITLL.

Figure 3 represents the average earnings of a facility for peak shaving by power supplied. There are diminishing returns by shaving more, where by shaving 10 kW you are addressing 8 months of peak demand reduction, and, at 450 kW, the last 50 kW or so will only be addressing one peak per year. There is no point in shaving beyond the saturation point, which is the largest peak a facility is expected to have. With predicted average performance by power supplied, we can determine the optimum number of vehicles to use for V2B considering the costs of inverter and battery at any depth of discharge and capacity.

C. *Cost of Battery*

Millner addresses the need for a model giving the non-linear relationship of depth of discharge as well as temperature for modeling battery cell damage [3]. This model captures the two mechanisms affecting lithium ion battery lifetime: deposition of insoluble lithium precipitates on surfaces in the carbon electrode, and the separation of anode or cathode material from the electrical collector metal at either electrode. The damage effectively reduces the charge capacity and increases resistance. These effects are modeled as a Life parameter, 1 being a new battery and 0 having no life left at all. By convention, the end of life is defined as 80% of the original capacity remaining. Using the model, a cycle cost vs. depth of discharge curve is generated (Figure 4) for a hot and cold region (Dallas and Boston).

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Due to practical capacity considerations as well as the characteristics of degradation, a broad optimum of 60% depth of discharge is used for the rest of the analysis.

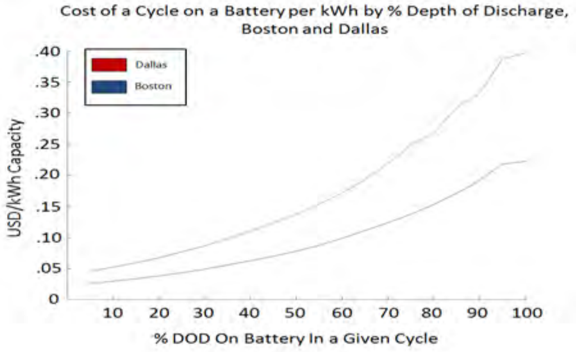

Figure 4, The normalized cost of cycling a battery to a given depth of discharge with a 750/kWh capital cost

D. Cost Of Inverter

V2B technology requires a bi-directional charger so that the battery can act as a source and a sink as necessary. This addition of equipment represents a cost over a baseline one way charger. The system could be implemented on the drive train of the vehicle, reducing the amount of redundant electronics and cutting the cost by up to 80%. AC Propulsion already has such a system that utilizes the electric drive train, but due to the limited production quantity and research costs these enhanced economics are not yet realized [13]. One challenge is that bidirectional chargers appropriate for a 3 phase power interface at the desired rating do not presently exist as commercial products [2]. To estimate the cost, a survey of existing sine wave inverter weights and prices was done to create a power/production quantity scaling law.

We also find that distribution generally marks up by 2x, while manufacturers normally have a 40% gross margin so the costs increase by a factor of 1/.6 and 1/.5 respectively depending on what point in the chain the product is acquired.

For purposes of the analysis, we follow the scaling law with an additional 1.5 cost factor for installation, and a 40% gross margin for ex-factory price at an assumed production quantity of 2000 units / yr. Figure 5 shows the characteristics of the cost model. For purposes of the analysis, an inverter lifetime of 10 years is assumed at an interest rate of 5%.

A. Combined Economic Performance

Now optimum fleet sizes can be determined with the cost of inverters, cost of degradation of the battery subsystem, and the benefits from peak shaving quantified. By considering costs minus benefits, we find trends across three independent variables (capacity, depth of discharge, discharge time). Considering varying depth of discharge, we find that higher depths of discharge are more desirable as you need fewer V2B equipped vehicles, until the effect of very high depth of discharge increases the rate of battery degradation. This splits the net earnings amongst a smaller pool of equipment costs, and also takes advantage of the reduced $/kW for inverters as dictated by the inverter scaling law. As shown in Figure 6, the point of saturation or diminishing returns in benefits will dictate an optimum in net gains per month realized by a the facility.

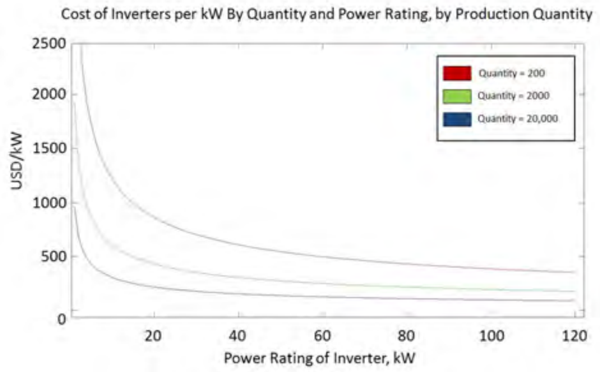

Figure 5, Results of inverter scaling law by production quantity and power rating, normalized cost

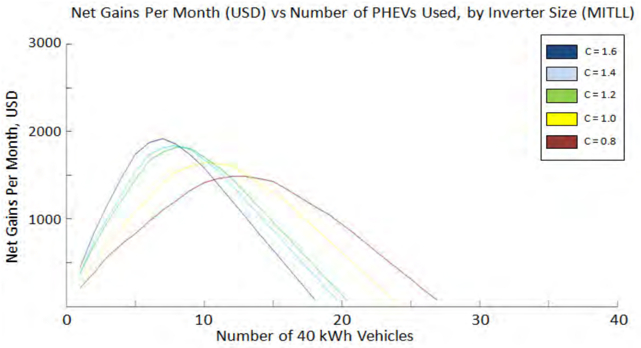

Figure 6, Net gains by discharge shows an optimum value at some point near peak saturation when the costs equal the benefits to add additional peak shaving capability. Higher discharge rates tend to be more optimal.

This method can be applied across all bases and all independent variables to determine optimum discharge times for different bases given a car capacity. The magnitude of the peaks, number of peaks, and cost of peaks from utility all determine the value of peak shaving with V2B.

From the data, we learn that Naval Base San Diego does in fact suffer from large transient peak maxima. All analyzed displayed relevant peak durations within the 15 – 90 minute range. These months are ideal candidates for the finite charge systems such as the electric vehicles. However, since the utility charges less per month for demand charges ($12.79/kW) in NBSD than at MITLL, the overall value of V2B is reduced.

Los Angeles Air Force Base, though smaller than MITLL and NBSD, also shows great promise for a V2B equipped fleet. Every month through 2009-2010 showed transient peaks in 15 minute sampling data. The relevant peak durations were from 15-90 minutes. Winter demand charges were $11.84/kW and an effective summer rate (average of on-peak and mid-peak demand charges) $24.31/kW was used.

With this information, optimum discharge times can be determined for different vehicle sizes. Total net earnings include the cost of battery degradation, but not the cost of purchasing the vehicle battery since it is used for transportation purposes. By comparison, if the cost of the battery is charged against the V2B service, we are analyzing the case of purchasing a trailer load of batteries for just this purpose without buying or using transport vehicles. The analysis shows that buying and using the vehicles will make more money, since the savings of electricity as fuel are added to the ancillary services. If the batteries are stationary and not used for transport, the optimum normalized earnings will give you the most money for a given amount of energy supplied ($/kW). The normalized optimum is used here for apples to apples comparison in Architecture Comparison, while the total optimum return from vehicle fleets is explored here.

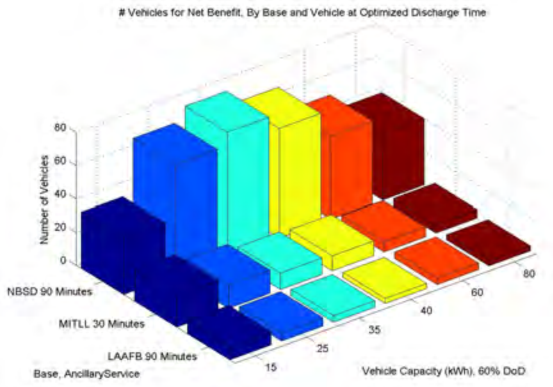

Figure 7, Optimum number of vehicles by vehicle capacity and base

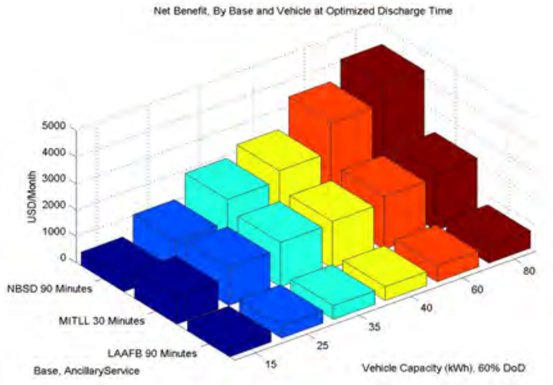

Figure 8, Net benefit at optimized discharge time by base and vehicle capacity

Figures (7,8) show the average monthly optimum net benefits and optimum fleet size. Since optimum fleet size is defined as the point when the costs begin to exceed the benefits, the normalized V2B earnings per car become much more desirable if the fleet is reduced in size from this point. A single car will always yield the highest return per car. To provide a sense of the scale of this return, the net V2B earnings can be compared to the cost of the batteries in the vehicles. The results, Figure 11, indicate that V2B can pay for half to all the cost of the battery subsystem over the life of a battery.

III. VEHICLE TO GRID (V2G) TECHNOLOGY

V2G technology utilizes similar hardware as V2B, but operates under contract with the utility service provider. Instead of an algorithm based on site meter readings, the system responds to the utility regulation demand signal. Tomić identifies frequency regulation ancillary services to be the most lucrative for the V2G paradigm [4]. Regulation seeks to maintain grid frequency and voltage by balancing power flow and match slowly varying generation to rapidly varying load within the control area [9]. Traditional regulation service is provided by generators that ramp up and down to match the needs of the grid. Electric vehicle fleets match well to frequency regulation, as the rapid response time of batteries match requirements for the service and the up and down demand (Figure 9) leaves the batteries at their original state of charge upon completion.

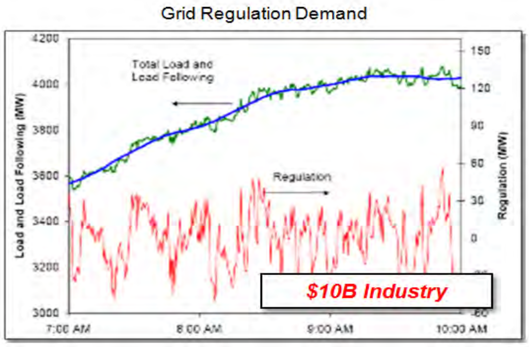

Figure 9, Frequency demand characteristics

The compensation for these services comes by supplied capacity and energy. Capacity is the price paid to have a unit available for a time while energy price is the compensation for when a unit is supplying, or selling back, energy to the grid.

A. System Architecture

Figure 9 depicts an ideal V2G architecture. Centralized and decentralized power sources feed the grid, and are distributed by the ISO to the facilities and homeowners. The utility provider maintains communication with aggregated fleets of electric vehicles, and schedules them for some amount of regulation in what is called a Day-Ahead market.

Aggregated fleets will sign up a day ahead to provide blocks of frequency regulation as needed for some amount of time. Availability of the fleet can often be adjusted up to an hour in advance without impinging the contract and drawing a penalty [10]. If up or down regulation is needed,

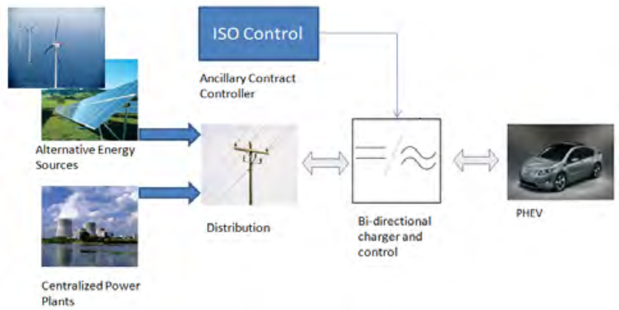

Figure 10, System Architecture of V2G.

the utility service provider will signal the vehicles to charge or discharge accordingly.The fleet will be compensated for the contracted time to be available to provide frequency regulation. Utility ISO's such as PJM, CAISO, NYISO, and ERCOT show real value in the regulation market (Table 1). These clearing prices can be used along with a presumed time of service and time of service dispatched to generate expected revenues for providing V2G service with a fleet.

	Up Regulation	Down Regulation
CAISO, 2000-03	37.35	22.30
ERCOT, 2001-03	12.10	6.73
PJM, 2000-03	35.03	0
NYISO, 2000-03	19.75	0

Table 1, Average Market Clearing Prices Regulation in several A/S markets ($/MWh). Derived from [4].

Most utility companies require a minimum of 1MW blocks of power to consider ancillary services, but some utilities are moving towards more distributed models. PJM is expected to accept 100kW blocks as soon as 2012 [10]. The capacity potential of V2G as a service is determined by the % of the aggregate scheduled demand. California requires between 5 and 10% of the scheduled load [11]. Providers in different areas have varying requirements for this service. Some providers, such as Duke Energy actually do not have a frequency regulation market due to the large presence of hydroelectricity in their area [10].

B. Calculation of Benefits and Costs

The costs of implementing V2G are similar to V2B in the need for a bi-directional charging infrastructure and control system. The degradation of the battery, assuming the system is cycle limited, must also be accounted for. Further details of calculation of costs include cost of energy, availability of cars, and other factors. Details of these calculations can be found in [4].

Compensation from the service comes from capacity provided and time dispatched on contract. The calculation of benefits for V2G can be realized for up and down regulation by equations 1, 2, and 3.

$$r_{reg-up} = (p_{cap} P t_{plug}) + (p_{el} P t_{plug} R_{d-c})$$

Equation 1, the revenue from providing up-regulation services. [4]

$$R_{d-c} = \frac{E_{disp}}{P_{contr} t_{contr}} = \frac{E_{disp}}{P t_{plug}}$$

Equation 2, the ratio of contracted time to total time plugged in, used as 0.1 for purposes of the analysis. [4]

$$r_{reg-down} = (p_{cap} P t_{plug})$$

Equation 3, the revenue from providing down regulation services. [5]

P_{cap} is defined here as the price of capacity, P is the capacity supplied, t_{plug} is the time contacted, P_{el} is the selling price of electricity at that moment, and R_{d-c} is the dispatch to contract ratio that is described further in Equation 2. The costs of up regulation include the loss of electricity due to the efficiency of the battery, while the cost of down regulation is 0 since down regulation is charging.

The cost of battery and amortized cost of equipment along with other costs, such as electricity, can be subtracted from this revenue to realize a net benefit for V2G as a service. For many areas, V2G offers significant gains. Table 2 shows the net profit by $/yr/vehicle for different sized vehicles and inverters. The Th!nk City NY and Toyota RAV4 fleets are evaluated with level 1 and 2 bi-directional chargers (3-15 kW). The class 6 EV trucks are evaluated with 60 kW bi-directional chargers. A charger efficiency of 93% is assumed, with a 10% dispatch ratio and service time of 21.6 hours a day, 7 days a week, and 52 weeks a year. It can be seen that variation in regulation compensation rates dominates the different cases shown.

	ISO	$/vehicle/yr
Th!nk City NY, Lvl 1 Charger	NYISO	192
Th!nk City NY, Lvl 2 Charger	NYISO	410
Toyota Rav4, Lvl 1 Charger	CAISO	2,721
Toyota Rav4, Lvl 2 Charger	CAISO	6,183
Class 6 EV Truck	CAISO	28,442
Class 6 EV Truck	NYISO	4,687
Class 6 EV Truck	PJM	4,305

Table 2, Calculated profits/vehicle/year by ISO, vehicle, and charger.

IV. ARCHITECTURE COMPARISON

Having explored the costs and benefits of V2G and V2B, the normalized net benefit can be analyzed to see the relative impact on the economics of the vehicle. Table 3 shows the normalized annual earnings of V2B and V2G in different bases and regions respectively, along with an example calculation of the expected normalized saving from the driving economy of an electric vehicle. The gains from the driving economy of an electric vehicle can be calculated by Equation 4.

$$r_{DrivingEconomy} = Miles(\frac{Cost_{Gas}}{MPG} - \frac{Cost_{Electricity}}{MPkWh})$$

Equation 4, Calculation of revenue from increased driving economy of electric vehicle

A general fuel and electric economy was derived from [12], and an assumed 1100 miles per month is used. With a 25 kWh battery car, a consumption of 2.94 kWh/mile and cost of \$0.15/kWh is assumed. A baseline gas vehicle of 30 mpg vehicle at \$4/gal assumed. For comparison with Figure 9, the monthly amortized cost of the vehicle battery with a 10 year life can be taken as \$4 to \$8/kWh. From Figure 9 we see that V2G and V2B offer benefits that are comparable to, and often exceed, that of the traditional primary gain from electric driving economy. The combined benefits of driving economy, V2B, and V2G can not only offset the cost of the battery, but pay for a significant amount of the entire vehicle itself.

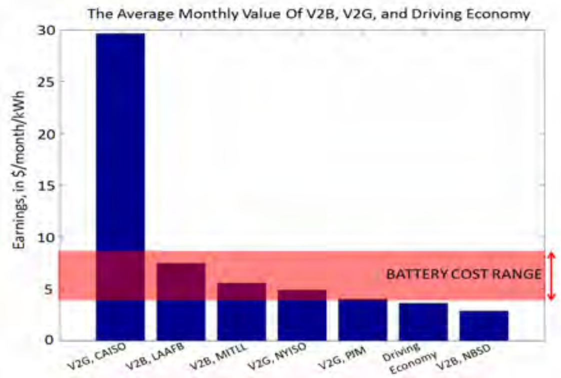

Figure 11, Value Per Month of V2G and V2B in different regions per kWh. Vehicle size of 60 kWh used for V2B.

Having seen the performance of V2B and V2G, it is important to note the fundamental differences between the two systems, explore how these systems can potentially both be used, and denote under what conditions the systems are appropriate to use:

1. V2G's value is from persistent service (number of hours supplied), while V2B's value is from opportunistic service (having the capacity at the right short period of time, and sensing the need for the capacity).
2. The size and applicability of a V2B fleet is limited by the peaks of the facility, requiring a utility demand charge and saturating by the size of the transient demands. V2G is limited by grid regulation demand, and must be of sufficient fleet size to qualify for a contract.
3. V2B operates without a contract while V2G operates on a real time contract agreement with a utility.
4. V2B and V2G are not mutually exclusive. With a flexible V2G contract, the benefits from V2B and V2G could be realized together.

V. REALIZING THE FUTURE

Empirical data from MITLL, NBSD, and LAAFB show high net value in providing V2B services, with the capability to nearly offset the cost of the battery subsystem. V2B provides high returns for fleets of limited size without need for a contract, while V2G shows high net value for larger fleets, and demonstrates the scalability of the concept in several ISO areas.

Bi-directional charging technology, aggregation services, and the hardware and software for control systems will need to be developed to begin widespread deployment of these systems. Investigation of the impact of using one service with the other will need to be explored. Regions and bases that provide desirable returns must be identified. With the right mix of technology and bases, V2B and V2G, coupled with driving economy and reduced operations and maintenance cost, provide a positive argument for purchasing fleet electric vehicles at today's prices.

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