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Using EV Battery Packs for Vehicle-to-Grid Applications: An Economic Analysis

Lav Agarwal
School of EEE, NTU, Singapore
lav001@ntu.edu.sg

Wang Peng
School of EEE, NTU, Singapore
epwang@ntu.edu.sg

Lalit Goel
School of EEE, NTU, Singapore
elkgoel@ntu.edu.sg

***Abstract*—Electrification of the transportation segment has long been seen as a promising solution to reduce oil dependency and its environmental impacts. Electric Vehicles (EVs) can also be used as distributed energy resources providing ancillary services to the grid through Vehicle-to-grid (V2G). Incentives through V2G can lead to reduced EV ownership cost, thus increasing their acceptance and overall penetration. However, with high current battery prices and increased battery wear due to more frequent charging and discharging during V2G operations, it becomes economically challenging in realizing a profitable business model. This paper presents an economic analysis of various V2G offerings in consideration of market prices and battery wear cost. Aggregate Power Capacity, from a fleet of EVs is realized by modeling their driving pattern using trip chaining based on data from survey conducted, employment pattern and vehicular statistics. Battery life cycle is analyzed, for achievable cycle counts and net energy transferrable, operating to various depths of discharge (DoD) values. Economic analysis is performed using Singapore data.**

***Index Terms*-- Electric Vehicle (EV), Vehicle-to-Grid (V2G), Driving pattern, Battery wear, ancillary services.**

I. INTRODUCTION

Depleting fossil fuels and increased environmental concerns have accelerated the electrification of the transportation segment which covers hybrid (HEV), plug-in hybrid (PHEV) and battery electric vehicles (BEV). The plug-in electric vehicles, when connected to grid, can interact intelligently with the existing power systems providing ancillary services, referred to as Vehicle-to-grid (V2G) [1] and is seen as one of the key elements of the future smart grids. The underlying assumption of the V2G concept is that EV batteries will be underutilized, as vehicles are used only 4% of the time for transportation purposes [2]. V2G proposes significant solutions for power markets in the form of load smoothing (peak shaving, valley filling, etc.) and ancillary services like frequency regulation and reserves. Additional opportunities lie as the storage infrastructure for the emerging renewable energy markets especially after the recent energy storage mandate act (AB2514) by the California Public Utilities Commission (CPUC), which establishes a target of 1,325MW of energy storage to be procured by three of the state's major power companies by 2020 [3].

An intermediate body called Aggregator will be required, since a single EV capacity is too small on the large grid scale. This also achieves the reliability and availability needed, as concluded by the authors in [4], after a comparison made between direct deterministic (non-aggregated) and aggregated architectures. An Aggregator is supposed to enter into contracts with different car parks and individual EV owners to build up its capacity. The main sources of revenues for an Aggregator will be from the markup of the electricity sold during EV charging and the percentage from the profit generated by providing V2G services to the ancillary service markets [2, 5].

Design of a profitable business model stands a crucial step in the framework implementation under the presence of multiple agents like the Aggregator, EV owner, charging point manager or the contracted car park owner, Distribution Company and the Independent system operator (ISO). Reference [5] proposes a long term contract in the form of incentive scheme which provides the EV owner preferential rates for battery acquisition and lower maintenance, charging and parking tariffs. A long term contract like lifetime battery warranty from the Aggregator is a must for freely utilizing EV batteries for V2G purposes, as it contractually binds both the parties and is also reasonable from EV owner's perspective, as they no longer need to be concerned about battery degradation, due to the operations of the Aggregator.

Additional battery wear, due to more frequent charge and discharge cycles during V2G operations, is proportional to the amount of energy transferred, in different state of charge (SOC) ranges, as Achievable cycle count (ACC) varies with respect to Depth of discharge (DoD) [6]. Reference [2] analyzes the economics of V2G for different power market operations, finding it suitable only for ancillary services. However, this analysis did not consider the battery degradation and thus the revenues reported do not account for the wear costs. Reference [7] presents an economic analysis for energy arbitrage considering battery degradation and reports an annual profit ranging from \$140 to \$250 without battery wear cost and only \$10 to \$120 accounting for battery wear costs. These profits alone, however, do not provide sufficient incentives to attract large number of EV owners.

Reference [6] models the battery life based on ambient temperature and DoD mathematically, for lead-acid, lithium-ion and NiMH battery types. The economic analysis conducted for supplying peak load through energy arbitrage in U.K. and China, found only lithium-ion batteries being cost effective in U.K. due to the high peak electricity tariffs in U.K. and longer

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cycle life of lithium-ion batteries. Reference [8] analyzes the economic feasibility of V2G performing frequency regulation considering battery wear under USABC requirements [9] and reports V2G regulation profitable enough to provide sufficient incentives overcoming battery wear costs.

In this paper, we present an economic analysis of the various V2G offerings, in consideration of market prices and battery degradation, to determine the most profitable operation in current scenarios. Section II estimates the aggregate power capacity available from a fleet of 10,000 EVs by modeling their driving patterns. Section III describes the battery wear model considered in the work. We consider only lithium-ion battery and BEVs in our current study. Section IV presents a cost-benefit analysis assessing battery wear cost in different V2G operations and the profitability under current Singapore power market prices. Section V analyzes a 10 year EV life cycle to determine the offset possible in EV ownership costs under normal daily usage and performing V2G services. The conclusions of the research are drawn in Section VI.

II. AGGREGATE POWER CAPACITY

Aggregate Power Capacity (APC) estimation is the first step in determining the capacity for V2G operations. The main challenges in determining the APC lies in the prediction of the vehicle availability and the plug-in probability. While the vehicle availability solely depends on the driving pattern of the EV owner, the plug-in probability depends on the availability of plugs at car park and plug-in human behavior. We do not use trip datasets to determine driving patterns, as they do not trace a car for trip chains over a longer period of time. Instead we model driving patterns based on needs and preferences of the EV driver. Reference [10] presents a realistic mobility model, describing different trip chain possibilities by classifying drivers as per their employment pattern etc., to evaluate parking and charging behavior.

The concept of trip chain has been utilized to model the driving pattern of each EV. A trip is characterized by purpose, source, destination, arrival and departure times and trip duration [11]. We have classified the possible parking locations as *Home (H)*, *Office (O)*, *Lunching outside office (L)*, *Recreation (R)* or *Grocery shopping (G)* related. The plug-in probabilities have been assumed around 1 for home, 0.7 for offices, 0.5 for lunching car parks and 0.3 for recreational and grocery car parks.

The estimated average daily mileage for private cars in Singapore was 52 km in 2010 [12]. Under the assumption that 10,000 of these private cars were EV, the EV drivers were profiled by categorizing them into 3 groups depending on the employment pattern in [13] and the survey conducted, representing around 2% EV penetration in Singapore. 92% of the employees work full-time for 9 hours daily, either from 8 am to 5 pm, 8.30 am to 5.30 pm or 9 am to 6 pm, including 1 hour lunch break which falls in the respective middle hour. 4% of the employees work part time with an average of 5 hours per day. The remaining 4% work either from home or are on leave on any given day. Full working days and holidays are analyzed because full-time employees follow the pattern of part-time employees on half shift days working in morning or afternoon shifts.

A survey was conducted to determine travel preferences [14]. Only responses of employed and unemployed respondents owning a vehicle were used. An average of 50% replied that they take lunch outside office. The average distance to the grocery store from home was around 3 km. Individuals go home directly from work almost 80% of the time while for the remaining 20% of the time, take recreational trips and then drive back home. More than 80% of people had their most visited recreational place between 5 and 25 km. Travel preferences on weekends were 20% between 8 am-12 pm, 25% between 12 pm-4 pm, 40% between 4 pm-8 pm and 15% for 8 pm-midnight and later.

TABLE I. TRIP CHAIN POSSIBILITIES

Employment Status	Day type	Trip Chain
Full time	Working Day	HO-OH HO-OR-RH HO-OL-LO-OH HO-OR-RG-GH HO-OH-HG-GH HO-OL-LO-OR-RH
Part time	Working Day	HO-OH HR-RO-OH HO-OR-RH HO-OH-HG-GH
Working from Home/ On leave	Working Day	HR-RH HG-GH HR-RG-GH
Any	Holiday	HR-RH HG-GH HR-RG-GH HR-RR-RH HR-RH-HG-GH

Table I shows some of the trip chain possibilities for different employment status and day types. However, the average number of trips in Singapore in 2010 was around 3 per day. Hence in the simulation model, lower probabilities have been assigned to trip chains with number of trips other than 3. The average driving speeds in Singapore are estimated around 30 km/h on arterial roads and 60 km/h on Expressways [12]. Any trip was assumed to contain a minimum of 10 km of arterial roads. Thus the travel time, in minutes, was determined by (1).

$$T(x)=\begin{cases}(10+2x)(1+\frac{\alpha_t}{100});x\leq 10\\(20+x)(1+\frac{\alpha_t}{100});x>10\end{cases}\tag{1}$$

x being the distance in km, 10 min considered as buffer to park and plug-in and α_t the traffic congestion index. The congestion index compares travel time during non-congested periods (free flow) with travel times in peak hours. The difference is expressed as a percentage increase in travel time, representing the congestion level [15]. Congestion level varies with day of week, time of day, weather condition, special events etc. 6 AM to 11AM and 4 PM to 9 PM are considered as peak hours with average congestion index of 20% for weekdays and 10% for holidays and travel times are computed accordingly. Distances between home, office and recreational places were assumed to be normally distributed with a mean distance of 15 km and standard deviation of 10 km. Distances for lunching outside office and buying groceries were assumed to be normally distributed with a mean distance of 3 km and standard deviation of 1 km. The arrival and departure time, trip durations were computed accordingly.

The EV fleet comprises Nissan Leaf (2013 model), with a battery capacity of 24 kWh and driving range of 135 km on EPA cycle (vehicle efficiency η_{veh}=5.3645 km/kWh) [16]. In spite of the varying battery capacities, the power transfer capacities are actually limited by the rating of the onboard chargers or inverters (3.3/6.6 kW for Nissan Leaf 2013, 6.6kW assumed in present work) and the voltage and the rated current capacity of the power line at the contracted infrastructure. A uniform Level 2 charging infrastructure consisting of 240V, 20A was considered, limiting the power transfer to approximately 5kW. Thus the APC, at any time t, can be computed using (2) as follows.

$$APC_t = \sum_{i=1}^{N}[P_{i,t}.\rho_p + (1-P_{i,t}).\rho_{p'}].P_l \qquad (2)$$

where, $P_{i,t}$ is the probability of occurrence of trip at time t for i_{th} EV and ρ_p represents the plug-in probability at the corresponding parking location. For instance, for a shopping trip from home to a grocery store, with a probability of occurrence of trip $P_{i,t}$=0.5, the possible parking locations in the given time are either home or the grocery store. Hence ρ_p and $\rho_{p'}$ represent the plug-in probabilities of grocery store and home respectively. Similarly for a trip to office on a working day, $P_{i,t}$=1 ruling out any other case. P_l is the power limit set to 5kW.

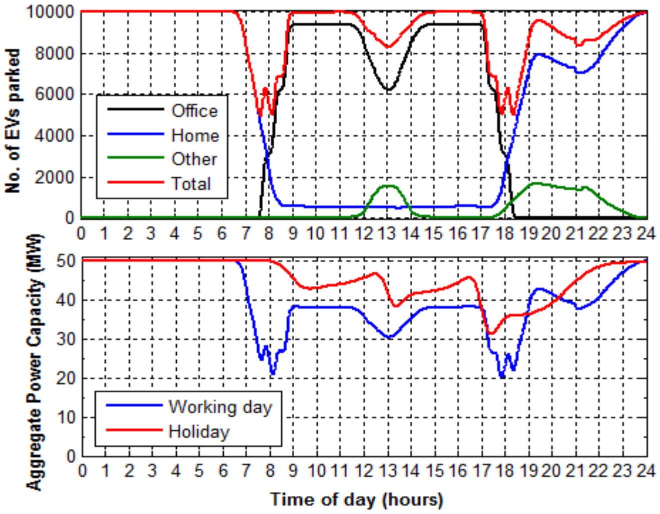

Figure 1. EV Availability on working day & APC for different day types

The model was simulated with a time resolution of 1 minute for EV availability and APC for working day and holiday scenarios. The upper plot in Fig.1 shows the number of EVs parked at different types of parking locations on a working day. It can be observed that the number of cars parked in offices gradually increases as the drivers start reaching offices in the morning. The afternoon dip occurs as the EV drivers take a trip of lunching outside office which results in a corresponding peak in the 'other' curve. The second peak in 'other' reflects the recreational and grocery shopping trips post office hours. It can be concluded that more than 50% of the EVs are parked at any given time and particularly the daytime period of 9 am to 5 pm and nighttime period of midnight to 6 am offer maximum availability. The bottom plot shows the APC on different day types. It can be observed that more than 20MW capacity is available at any given time. Also much higher APC values throughout the day can be realized in a fully developed infrastructure, if a plug-in probability of 1.0 can be achieved.

III. BATTERY DEGRADATION

Several factors including DoD, cell/ambient temperature, charge/discharge rate affect the cycle life and calendar life of the battery. Battery cycle life corresponds to the number of charge-discharge cycles that the battery can perform before its nominal capacity falls below 80% of its initial rated capacity. The effect of ambient temperature has been explained in [6], by a direct correlation with battery chemical reaction rate. Increased ambient temperatures lead to cell oxidation which increase the internal resistance. High charging rates increase the cell temperature. However, the C rates considered in the present work are low (5kW power limit, i.e., around 0.2C), thus the temperature variations can be neglected. Also present day Battery Management Systems (BMS) monitor and control the temperature of the battery pack by performing thermal management operations using passive heaters, fans, etc. It should be noted that the average ambient temperatures in Singapore are moderate (25ºC ±5ºC).

Many studies have modeled battery degradation using experimental data or battery chemistry, and presented different numbers of achievable life cycle such as 3000-cycle at 100% DoD for a Saft lithium ion battery in [17], 5300 cycle to 95% DoD in [18], around 829 cycles to 80% DoD in [6]. In order to analyze this quantitively, the number of battery life cycles *L(D)* was derived from the plot in [6] and is given by (3) where D is the DoD in percentage.

$$L(D) = 694.D^{-0.795} \qquad (3)$$

The maximum utilization of any battery lies in cycling maximum possible energy during its lifetime. The Lifetime Energy throughput (E) can be calculated by (4) where, B_{cap} denotes the battery capacity in kWh (=24kWh, for Nissan Leaf 2013).

$$E(D) = L(D) \times 2 \times D \times B_{cap} \qquad (4)$$

The upper plot in Fig.2 shows the Cycle life and lifetime Energy achievable at different DoD values. It should be noted that though shallow cycles offer more number of life cycles, net energy transferable increases with deeper DoDs. For instance, though life cycle count at 20% DoD is around 2500, energy transferred per cycle is only 9.6 kWh, whereas at 100% DoD life cycle is 694 but the energy transferred per cycle is 48 kWh, hence lifetime cycled energy at 100% DoD is still higher.

The unit degradation cost (UDC) is given by (5) where C_b is the battery cost per kWh. We assume C_b=375 S$ (wholesale/OEM cost of 300 US$ [17], also confirmed by other EV manufacturers and current conversion rate of 1 US\$=1.25S\$). The bottom plot in Fig. 2 shows the variation of UDC with respect to DoD.

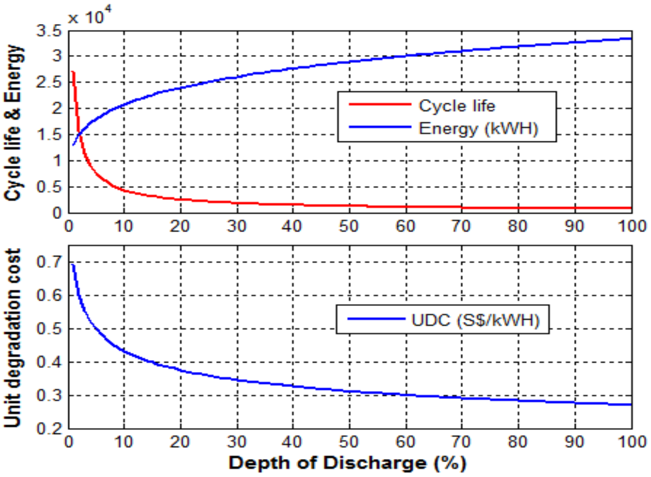

Figure 2. Cycle life, lifetime energy and UDC at various DoD values

$$UDC(S\$/kWh) = \frac{B_{cap}.C_b}{E} \qquad (5)$$

For our present analysis, we assumed that the batteries follow the goal of EV battery cycle life (1000 cycles to 80% DoD) made by USABC [9] and are typically operated to 80% DoD called as "long life mode" by the EV manufacturers, because lithium ion batteries suffer high stress at both ends of the SOC. This gives a more realistic evaluation, as USABC, being the consortium of three major U.S. Automakers and the Department of Energy (DoE) sets these requirement goals, which are perceived as targets during development and testing by the battery manufacturers. This gives us a UDC of S\$0.234/kWh, compared to the UDC of S\$0.283/kWh given by (5) in Fig.2.

IV. V2G APPLICATIONS

In this section we present economic analysis of various V2G offerings using data from Singapore Power market known as the National Electricity Market of Singapore (NEMS). NEMS is a robust deregulated power market consisting of wholesale and retail markets. The wholesale spot market determining the dispatch of electricity (energy, reserve and regulation) is run every half an hour [19]. Buyers in the wholesale energy market pay Uniform Singapore Energy Price (USEP) for energy, which is the weighted average of the nodal prices at all of the off-take nodes in each half-hour.

A. Ancillary Services

TABLE II. ANCILLARY SERVICE TYPES AND AVERAGE MARKET PRICES 2012

Ancillary Service Category	**Response time**	**Average prices'12 (S\$/MWh)**
Frequency regulation	second to second	91.53
Primary reserve	8 sec	0.46
Secondary reserve	30 sec	1.91
Contingency reserve	10 min	15.89

Ancillary service markets, consisting of reserve and regulation markets, are classified based on their response times, with following average clearing prices in 2012 [20], as shown in Table II.

Frequency Regulation or load following is used to mitigate the real time difference between load and generation which causes the frequency to drop/rise thus calling for "regulation up" or "regulation down". Reserves are the capacity procured to substitute the unexpected outage of a scheduled plant. Reserves like primary and secondary, which have a fast response time, are spinning reserves which are already synchronized to the grid. Reserve and regulation are paid for the capacity, i.e., the amount of energy kept ready and available for the time they are procured for, even though there is no energy or much lesser energy actually being transferred. Reserve contracts have limited number and duration of calls, with 20 calls per year, 1 h per call typical maxima and typical calls of 10 min [2].

The overall energy dispatched for regulation is only a fraction of the capacity procured and is usually balanced between regulation up and regulation down such that it sums to zero. In order to obtain this dispatch to contract ratio (R_{dc}), regulation signal from PJM Interconnection as shown in Fig.3 was analyzed, similar to the approach in [8]. The signal is found fairly distributed, with positive x-axis representing regulation up and negative x-axis representing regulation down. The average R_{dc} is around 20% in both directions. Thus the net energy transferred per hour will be only 20% of the contracted capacity and the battery wear will be proportional to it.

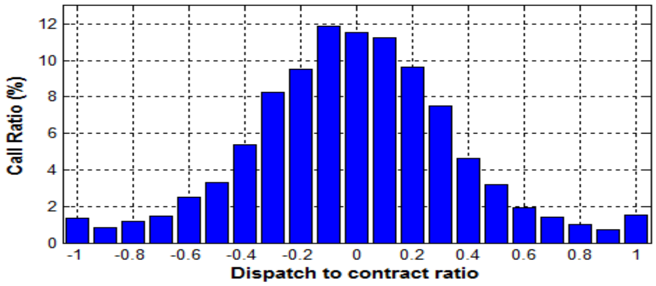

Figure 3. Regulation signal of PJM Interconnection during Jan, 2013

Thus for every kWh of contracted capacity, the battery wear cost will be proportional to 0.2kWh (0.2UDC=S\$0.047). The net profit per kWh capacity, P_i=S\$0.0445. The total profit P from a battery providing frequency regulation throughout its life time is given by (6). So for R_{dc} of 0.2, 1000 cycles to 80% DoD, battery cost of S\$9000 ($B_{cap} \times C_b$), the total profit earned is S\$8544.

$$P = \frac{1}{R_{dc}} \times E(D) \times P_i \qquad (6)$$

The market prices for reserves per kWh are much lower than P_i, which accounts for the battery wear costs also. So reserves are not as profitable as frequency regulation. But still reserves make a reasonable business case, as there are only few calls per year (assume 20 calls, 1 h per call typical maxima as specified earlier) and so the battery degradation incurred is much lower. A 1MWh capacity contracted for contingency reserve for a 1-year period will earn revenue of S$139,196 (S$15.89×8760h) against battery degradation costs of S$9360 (S$234/MWh×20 calls×2 due to charging-discharging). Thus the profit for supplying 1MWh capacity, which may be aggregated from 200 EVs, per year is S$129,836. Similarly, profits for secondary reserve are S$7371.6 and primary reserve is uneconomical. The revenue from supplied V2G energy is assumed to nullify the cost incurred during charging.

B. *Peak load*

V2G can address load smoothing (peak shaving, valley filling, etc.) through energy arbitrage, i.e., charging in low price periods and discharging in peak periods, if it overcomes the battery wear costs during charging and discharging (hence 2 times UDC) in addition to the cost of the purchased energy (C_p) as given by (7). In 2012, USEP rose above S$500/MWh for a total of 95 periods and above S$3000/MWh for 9 periods [20]. With an average USEP of S$222.49/MWh and UDC of 0.234 S$/kWh, it is uneconomical using V2G as peak power sources for USEP around S$500/MWh. However, supplying V2G power to USEP above S$3000/MWh can earn huge profits, though the time window is very small.

$$C_{Pk} = 2.UDC + C_p \tag{7}$$

C. *Renewable Energy Integration*

V2G can also assist the renewable energy integration into the power grid. Renewable energy sources being intermittent need storage or a regulation medium, to be identified as a firm capacity. We analyze only PV in the present work. A minimum buffer storage requirement (MBSR) of 0.75-1.0 h is required to qualify PV as a firm capacity, i.e., in order to qualify 1MW PV as firm capacity, it would require 750 kWh to 1 MWh of V2G [21]. Solar radiation measured at several stations in schools across Singapore is available in [22]. The data measured at NTU Intelligent Systems Centre for June'13 was analyzed.

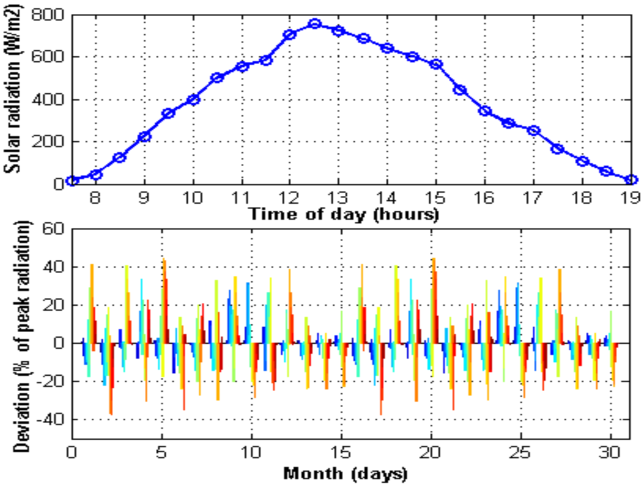

Figure 4. Average solar radiation at NTU and devaition from peak radiation in June'13.

The upper plot in Fig. 4 shows the average solar radiation for the month of June’13. It is assumed that the PV output power is linearly related to solar radiation. The deviation of the real PV power output can be balanced by V2G regulation. The bottom plot in Fig. 4 shows the deviation of real PV output from the average as a percentage of the peak output (or radiation) and is found to be lower than 40%. The APC of up to 50MW from the fleet of 10,000 EVs, as obtained in Section II, can provide regulation to up to 125MW of installed PV capacity. Owing to the high Feed-in-tariff (FIT) prices offered, V2G providing regulation services to renewables can earn high revenues.

V. EV LIFE CYCLE ANALYSIS

This section presents a ten-year life cycle analysis of an EV participating in V2G services and being used for commuting in daily usage by EV owners. A period of 10 years was chosen, owing to the fact that the Certificate of Entitlement (COE) in Singapore grants a vehicle owner to register, own and use a vehicle for a period of 10 years. The capital costs involved in developing and maintaining the V2G infrastructure, such as bidirectional converters, plug-in points at contracted car parks, communication infrastructure, etc., are assumed to be borne by the Aggregator and a percentage of the profits earned from V2G services are passed to the EV owners. The EV owner will have the sole capital investment of purchasing an EV.

We assume a fully developed V2G infrastructure, i.e., a plug-in probability of 1.0, which ensures that the EV will be always ready for V2G, when parked. From the EV Availability analysis in Section II, the average availability of an EV for V2G is around 22 hours (daily average commute of 52 km takes around 2 hours). It is assumed that the Aggregator maintains the EVs at favorable SOC, after determining their default usage profiles, to avoid encountering situations of fully charged batteries or not enough charge to undertake the next trip. Frequency Regulation, being most profitable, is considered as the V2G operation and revenues (R), total degradation cost (D_T) and profit (P) are calculated using (8), (9) and (10) respectively.

$$R = P_l . t_{plug-in} \cdot \mathrm{p}_{fr} \tag{8}$$

$$D_T = UDC\left(2.\frac{d}{\eta_{veh}} + R_{dc} \cdot \mathrm{P}_l . t_{plug-in}\right) = D_d + D_{V2G} \tag{9}$$

$$P = T.\left(R - D_{V2G}\right) \tag{10}$$

Using (8), for an average plugged-in status of 22 hours per day ($t_{plug-in}$), regulation price of S$91.53/MWh ($\mathrm{p}_{\mathrm{fr}}$) and power limit ($P_l$) of 5kW, the total revenue earned is S$10.068/day. Total battery degradation cost (D_T) due to daily driving of 52 km (d) and V2G is S$9.6845/day. The ratio of battery wear due to driving to V2G (D_d:D_{V2G}) is approx. 1:1.135. Thus for a 10-year span (T=3650), the total profit generated is S$17958, which involves battery replacement multiple times.

Federal and state government incentives are available all over the world for purchase of EVs [23] – such as, the American Recovery and Reinvestment Act (or the Stimulus Bill) in the U.S., that allows buyers to get a tax credit ranging from US$2,500-US$7,500, depending on the size of the vehicle's battery. Electric Vehicles currently costs more than their ICE counterparts, owing to high battery prices, but have much lower operation and maintenance costs. However, battery prices have been falling consistently and are expected to drop below US$200/kWH by 2020 [24], in line with the long term USABC goal of US$100/kWH [9], owing to the increased scale of manufacturing and reducing components costs.

Additionally, EV batteries can have a secondary usage as stationary energy storage; once their primary automotive use is over and they no longer meet the requirements as EV storage. These used batteries will have low efficiency due to the existing capacity loss but can be refabricated to create new packages for storage purposes which will have good resale value [25], resulting in reduced life cycle cost of EV batteries. As the battery prices go down and market prices of conventional generation providing ancillary services keeps rising, V2G will become a more viable economic option in the future.

VI. CONCLUSION

This paper has presented an overall economic analysis of V2G offerings under battery degradation cost. It should be noted that though in our present study, we used UDC corresponding to uniform DoD of 80%, which is unrealistic in real world scenario as the batteries will discharge to different DODs, it is still higher compared to the UDC obtained from the Nissan offering of 100,000 miles warranty, confirming that the profits reported are realistic. Future studies will present a more detailed battery wear model and realistic driving cycle considering additional cycles due to regenerative braking etc.

The results can be summarized as follows:

a) EV fleets can offer vast storage infrastructure to the grid. A mere 2% EV penetration in Singapore can offer storage capacity up to 50MW and even more if higher power limits can be availed. Detailed driving patterns play a key role in determining the available capacity which largely depends on personal travel needs and preferences.

b) Even under current battery prices, economical V2G operations are feasible. Profits from V2G together with incentives can result in huge offset in ownership costs making Electric vehicles more cost competitive to ICE based vehicles.

c) More profitable business model can be realized with the Aggregator participating in multiple markets, i.e., whichever offers the most profit for the available capacity in the given hour, such as supplying peak load at prices over S$3000/MWh can earn profits over S$2300/MWh, though only for the short term.

d) However, other grid level energy storage technologies such as redox flow batteries, flywheel, compressed air energy storage, thermal storage, etc., are also getting adopted amidst their pros and cons and may offer competition to V2G in the near future.

The results provide valuable information for a profitable Aggregator design, which is a crucial step in realizing V2G business model. The intelligent integration of vehicles and electric power systems can potentially limit the use of fossil fuels, leading to sustainable transportation and generation systems.

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