Assessment of Vehicle to Grid Power as Power System Support

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***Abstract* -- Currently large scale electricity energy storage is in the form of pumped hydro-electric storage. By contrast, Electric Vehicles (EVs) with transportation as their primary function, when parked could be connected and aggregated in large numbers and used either as a form of controlled load or generation. EVs customers could be offered cheap tariffs to encourage storage utilization e.g. During a shortage of power, value can be derived through delivery of energy back to the grid in the form of Vehicle to Grid (V2G) power, by participation in the GB electricity market through the provision of balancing services.**

***Index Terms*-- Electric Vehicle, Vehicle to Grid, Pumped hydro electric storage, Grid to Vehicle, Balancing services, Battery storage cost, Electricity cost**

I. INTRODUCTION

Vehicle to Grid (V2G) [1,2,3] is a concept whereby the electrical energy storage onboard Electric Vehicles (EVs), i.e. the vehicle main traction batteries, has the power flow of this element controlled bi-directionally. This means that the vehicle batteries can be recharged with power flow *from the grid to the vehicle*, and power flow can also be reversed to deliver power directly *from the battery back to the grid* if necessary/appropriate.

Current large scale electricity energy storage is in the form of pumped hydro-electric storage which has a generating capacity of 2,728MW in Great Britain and an estimated usable energy storage capacity of 20.5GWh, which is 2.3% of the typical daily electricity grid energy consumption [4]. By contrast, currently there are some 33.3 million vehicles registered within GB, including some 26.5 million cars and 3.1 million light goods vehicles [5]. The current estimated power available in the form of engine power for private cars is 1.98TW, with associated 'energy storage' in the form of on board fuel reserves of 13.2TWh.

Hence, wide scale take up of EVs, and V2G enabled EVs, would be expected to make significant demands on the electricity supply infrastructure, however it could comfortably be predicted to offer at least proportionate grid control, stability and peak lopping functionality compared to current pumped storage hydro electric schemes.

II. PUMPED HYDRO-ELECTRIC STORAGE

Current large scale electricity energy storage is in the form of pumped hydro-electric storage. During low electricity demand, excess generation capacity is used to pump water into the high reservoir, while at the times of higher demand, water is released back through a turbine thereby generating electricity. GB has a pumped storage generating capacity of 2,728MW (3.3% of the total installed generation capacity of 82,591MW) and an estimated usable energy storage capacity of 20.5GWh (2.3% of the typical daily electricity grid energy consumption of 883GWh (based on annual GB consumption of 322,500GWh on an average daily basis)) [5].

For example, First Hydro Company (FHC) operates 10 pumped storage units (4 at Ffestiniog and 6 at Dinorwig) in the GB market. FHC chooses to participate in three main sectors of the market, Trading, Balancing Mechanism and Balancing Services [6]. FHC buy and sell electricity (Trading) in all time scales from an hour ahead of delivery through to several years ahead of delivery on the power exchange and bilaterally with counterparties either directly or through brokers, and submit bids and offers in the Balancing Mechanism. Thus also tender for the dynamics and operating regime of the plant in the Balancing Services (BS) section.

However pumped hydro-electric storage has high initial construction costs and has significant restrictions on plant location. By contrast EVs are likely to be practical, highly distributed and accountable in large numbers and able to provide BS through V2G capability.

III. ELECTRIC VEHICLES

Initially the development and deployment of large numbers of EVs is viewed principally as a means of tackling high levels of road air pollution, particularly in urban areas. However, recently researchers have highlighted the potential of V2G to support the network.

EVs have the potential to become an important power resource for the GB electricity system, improving power system reliability and delivering economic benefits. The concept of dual use energy storage will allow the vehicle batteries to contribute to network services based on the fact that EVs naturally have considerable energy storage capacity. In principal dual use of EVs can permit power flow in both directions: Grid to Vehicle (G2V) (battery charging) and V2G (battery discharging) are commonly used shorthand terms for the different modes of operation.

The EVs plugged into the grid are more likely to assist the adoption of renewable energy sources, such as wind and solar photovoltaics (PV), which are fundamentally variable in nature. Hence wind and PV generated surplus energy can be stored in the batteries of G2V connected EVs during periods of low grid demand.

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Moreover the average car is parked for ~95% of the time in the GB [5], so deployment of V2G is a significant opportunity within the electricity market to provide energy to the grid with high quality electric power from vehicles whilst the vehicles are parked. So V2G power could be sold back to the national grid for profit, hence stimulating the development of the EVs market.

Among the electricity market services, the BS usually requires a quick response time yet relatively low energy delivery, so the BS is better suited for V2G customers with high idle parking times. Usually there are two parts that make up the price of providing services: the capacity price; the energy price. Capacity price is paid for power being available to respond, and the energy price for the actual energy delivered.

IV. Balancing Services

In GB, the BS are procured by the System Operator (SO), the National Grid Company (NGC) and are used to balance the amount of demand and supply on the system in real time, whilst ensuring the security and quality of electricity supply across the whole of the GB transmission system. Services can generally be provided to NGC in one of two ways, either as an increase or reduction in generation/demand by parties interconnected to the GB electricity network. NGC procures useful BS to operate the system in an efficient, economic and co-ordinated manner, either via market trading arrangements or bilateral contracts throughout the year. The BS, for example [7] provides:

- Frequency Response - Mandatory Frequency response, firm frequency response
- Reserve Services - Fast reserve, Short term operating reserve, BM start-up
- Reactive Power
- Fast Start/Black Start capacity
- System to Generator operational intertripping schemes
- Commercial intertrip services

In the following two subsections, mandatory frequency response and short term operating reserve of balancing services are detailed.

A. Mandatory Frequency Response (MFR)

MFR is an automatic change in active power output in response to a frequency change. All generators covered by the requirements of the Grid Code [8] are required to have the capability to provide mandatory frequency response. The capability to provide the service is a condition of connection for generators connecting to the GB system.

If companies deliver this service, they would be paid with two types of payment [7]:

- ***Holding payment (£/h)*** (H_f)***:*** made for the capability of the unit (MW) to provide response when the unit has been instructed into responsive mode. Generators need to submit holding prices on a monthly basis through the NGC frequency response price submission system. For this paper, tendered prices for all units to receive acceptances on any given day are assumed.
- ***Response energy payment (£/MWh)*** (E_f)***:*** remunerates for the amount of energy delivered to and from the system when providing frequency response. The response energy payment for a settlement period is calculated based on the formula:

$$E_f = \text{Market index price} * \text{Response energy MWhrs} * \text{Factor} \quad (1)$$

where, if the response energy is low frequency response energy (additional energy), the factor (f) is 1.25

If the response energy is high frequency response energy (reduced energy), the factor (f) is 0.75

So overall the revenue for mandatory frequency response R_{MFR} is shown as in (2)

$$R_{MFR} = ((H_f) * h) + ((E_f) * MWh) \quad (2)$$

where, h is the hour of the capability of the unit to provide response,

MWh is the amount of energy delivered when providing frequency response

Table I shows the market summary data for MTR in Jan 2009.

TABLE I
Market data for MFR in Jan 2009 [7]

MFR service	
Holding volumes (MWh)	873497.5
Holding payment spend (£m)	5.43
Average holding payment (£/h)	6.22
Response volumes (MWh)	736.27
Total response energy payment spend (£m)	0.15
Average response energy payment (£/MWh)	203.73

B. Short Term Operating Reserve (STOR)

STOR is a service for the provision of either additional active power from generation, or demand reduction. At certain times of the day NGC needs reserve power in the form of either generation increase or demand reduction to be able to deal with actual demand being greater than forecast demand and plant breakdowns. The service is procured by NGC ahead of the day through STOR, where it is economic to do so.

The potential V2G or other power provider will be paid through two forms of payment that NGC will make for provision of this service [7]:

- ***Availability payment (£/MW/h)*** (A_r)***:*** service providers are paid to make their units available for STOR service within an availability window.
- ***Utilisation payment (£/MWh)*** (U_r)***:*** service providers are paid for the energy delivered as instructed by NGC, this includes the energy delivered in ramping up to, and down from, the contracted MW level.

So overall revenue for short term operating reserve R_{STOR} is shown as in (3)

$$R_{STOR} = ((A_r) * MWh) + ((U_r)* MWh) \quad (3)$$

where, MWh is the energy volume delivered when providing STOR service

Table II gives the market summary data for STOR in Jan 2009.

TABLE II
Market data for STOR in Jan 2009 [7]

STOR service	
Total accepted volumes (MWh)	1609
Total spend (£m)	5.19
Average availability payment (£/MW/h)	7.34
Average utilization payment (£/MWh)	288.07

V. Storage Cost

There are two costs to consider for an electricity storage system [9,10]: the Energy Cost (EC) is the cost per unit of stored energy, for example £/MWh. (The energy cost is calculated as the cost to produce each MWh times the number of MWh produced per cycle and times the number of cycles per year e.g. pumped hydro reservoirs or vehicle batteries).

$$EC = Asset*CRF/EnP \quad (£/kWh) \quad (4)$$

where, Asset is the value of storage element,

Capital Recover Factor (CRF) is derived from

$$CRF=\left[\frac{(1+d)^{n_i} * d}{(1+d)^{n_i}-1}\right],$$

EnP is the amount energy delivered by a storage unit

The Power Cost (PC), or fixed cost, is the cost per unit of power, for example, £/kW. For example, this would include the rotating synchronous machines in a pumped hydro unit, or the power electronic rectifier/inverters in a vehicle battery storage system. These two combined costs give the storage cost to provide services.

$$PC= (PE+SU+BP) *CRF \quad (£/kW) \quad (5)$$

where, PE is the power electronics cost,

SU is the storage units,

BP is the balance of plant

In the following case studies, the power cost of vehicle batteries is assumed for their transportation purpose (i.e. it is assumed that operating function for BS does not affect priority for vehicle operation). Hence only the energy cost is attributed to the cost of providing BS. The cost of pumped hydro-electric storage by comparison, is calculated by the two parts cost combination, purely for use as energy storage.

The data inputs required to calculate the storage cost are summarised in Table III. And the resulting cost to store each kilowatt hour of electricity in the Pumped Hydro-electric storage and V2G batteries is calculated in Table IV.

TABLE III
Inputs of the storage cost calculation [9, 11]

Pumped Hydro	*Value*	*Unit*
Rated output	10000	(kW)
Efficiency	75	%
Annual operating days	250	(day/yr)
Unit power cost	0.3	(£/kWh)
Interest rate	7.7	%
Fixed operation and maintenance cost	2.5	(£/kW)
Future amount of replacement cost	0	(£/kWh)
Vehicle Battery	*Value*	*Unit*
Battery Capacity	45	kWh
Vehicle Battery cost	18000	£
Efficiency	83.9	%
Number of charge/discharge cycles per day	2	N
Length of each cycle	1	h
Number of charge/discharge operation cycles in life	1600	n
Interest rate	7.7	%
Future amount of replacement cost	18000	£

From Table IV, the EVs batteries cost per unit of energy delivered is cheaper than the pumped hydro-electric storage, (excluding the power cost of storing electricity in the battery) so V2G use of EVs in the following case studies are considered. The same vehicle batteries (as assumed 120 vehicles using typically 45kWh of battery each) are being controlled in a regional control centre. The storage cost of £0.153/kWh is calculated for EV batteries as shown in Table IV by (4) (£18000*0.513/(45*1600*83.9%)) and is assumed unchanged for each of the 120 EVs in the case studies. In practice, however it is likely that the storage costs would change for different V2G operation cycles.

TABLE IV
Costs to the unit of energy delivered

Items	*Value*	*Unit*
Pumped Hydro-electric Storage	0.347[7]	(£/kWh)
Electric Vehicle Batteries	0.153	(£/kWh)

VI. Economic Value of V2G

V2G power providers will require to tender for services that the dynamics and operating regime of the batteries lend themselves to, and can deliver. The calculation of revenue and storage costs for V2G using the studied electricity buying cost will be used as worked examples in the following case studies. The economic value of V2G is the revenue minus the cost of the storage and of buying the electricity. In order to demonstrate the concept of economic value of V2G easily, the G2V power purchased from the grid to the vehicle is assumed when the price is cheapest, for example overnight. Actually V2G could be discharged during peak price time and then controlled to charge anytime when the electricity price is cheap enough. For this paper, the average electricity buying price is assumed to be £0.034/kWh.

VII. Case Studies

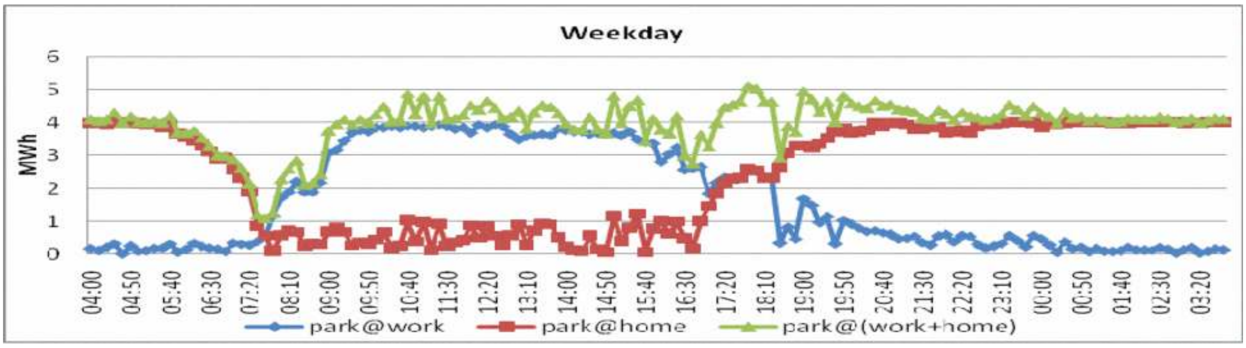

Fig. 1. Available energy for aggregated 120 EVs under three senarios

In the case of the implementation of V2G incorporated into the network, where it is assumed tens of thousands of vehicles would be connected for providing balancing services, it is highly unlikely that NGC will contract with individual vehicle owners. Moreover, services provided to National Grid have a minimum contracted capability of 3MW. Hence it is expected that NGC will want to control the aggregate capacity of the V2G via a regional aggregator. Such a regional aggregator would manage the information flows between the grid operator and the V2G users. To the SO, the aggregators would appear to be many large regional sources of controllable generation or load. The regional control centres would communicate via charging communication infrastructure to the V2G vehicle. Also the control centre will be interfaced to the electricity trading or balancing services markets.

Figure 1 shows the available aggregated energy for the 120 assumed EVs considered in the case studies. Three scenarios are studied (only grid connected EVs at home (4:00-5:00); only grid connected EVs at work (10:20-11:20); and a combination of these (17:40-18:10, 19:00-19:30)): in the following case studies V2G users participated within two BS services separately.

For the same network region as the aggregated EVs are connected to, it is assumed the load demand mirrors the typical scaled GB regional demand (6/7-Jan-2009) as shown in Fig 2.

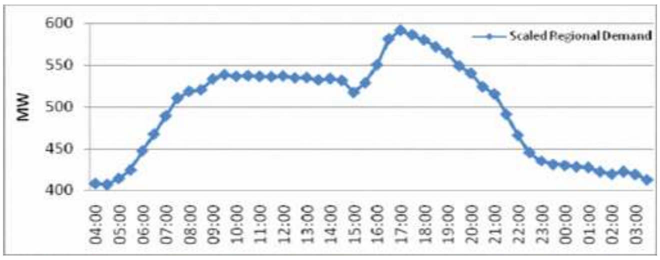

Fig. 2. Total scaled regional demand in the same area as aggregated EVs

A. *EVs participating in MFR service*

When the 120 EVs are involved in the MFR balancing service, it is assumed all the tendered volumes/prices are accepted without competitive providers. Data of available energy for aggregated 120EVs between 4:00~5:00 are extracted and are shown in Table V.

TABLE V
Available energy for aggregated 120EVs between 4:00~5:00

Time	04:00	04:10	04:20	04:30	04:40	04:50
Energy (MWh)	3.96	3.96	3.92	4	4	3.96

The first column in Table VI, states the time of the highest values of available V2G power chosen under each scenario. Assuming in this hour the batteries could be discharged until 20% of its rated capacity, and that they could be recharged at other times.

In the second column, the revenue of providing MFR is derived as in (2) (unit holding payment times all available holding hours plus energy payment times all response amount of energy). Take the vehicles parked at home only case for example, if under this an hour 6 ten minutes slot energy added together, the energy is:

(3.96+3.96+3.92+4+4+3.96)/6*0.8 = 3.17MWh

The energy is held and used for an hour, the price for MFR service is calculated through:

1*£6.22/h*1h+3.17MWh*£203.73/MWh = £652.72

The third column is calculated through (the energy used times per unit cost of storage and electricity buying). For these two case studies the sum of per unit cost of the storage cost and electricity cost are unchanged as:

£153/MWh+£34/MWh = £187/MWh

So for example the sum of the storage cost and electricity cost in the case of vehicles parked at home only is £187/MWh* 3.17MWh = £593.41

The last column states the net profit as the difference between revenues and costs.

TABLE VI
Net profits calculation under MFR service over the typical day

120 V2G highest power period	MFR service (£)	Storage cost+ Electricity cost (£)	Net profits (£)
Parked at home only (4:00-5:00)	**652.72**	**593.41**	59.31
Parked at work only (10:20-11:20)	636.42	578.45	57.97
Combination (17:40-18:10, 19:00-19:30)	788.54	718.08	70.46

B. *EVs participating in STOR service*

Similar to the last subsection, all 120 EVs are now involved in the STOR balancing service, assuming all the tendered volumes/prices are accepted without other competitive providers and the state of charge of the batteries would remain above 20%. The second column shown in Table VII is derived as in (3), where all the available energy would be used to provide these two BS services, so under the same scenarios the storage costs plus the electricity costs are the same in the third columns for both Tables VI and VII.

TABLE VII
Net profits calculation under STOR service over the typical day

120 V2G highest power period	STOR service (£)	Storage cost+ Electricity cost (£)	Net profits (£)
Parked at home only (4:00-5:00)	998.55	593.41	405.14
Parked at work only (10:20-11:20)	982.85	578.45	404.39
Combination (17:40-18:10, 19:00-19:30)	1282.34	718.08	564.27

From the results it is shown that V2G power from aggregated EVs is potentially economically attractive. They are very positive with net profits in all the cases, and provision of the STOR services in particular demonstrates higher net profits for V2G power than provision of MFR services. However a regional control centre to manage multiple vehicles is required as well as transparent pricing signals. Overall these results are very encouraging for the prospects of V2G enabled vehicles to participate in the GB electricity market.

VIII. CONCLUSION

Case studies of 120 V2G vehicles were considered. The case studies were analysed for the provision of balancing services in the GB electricity market. The results show that battery storage vehicles can realise significant potential revenue if aggregated and carefully controlled. The dual use of EVs not only for transportation, but as a source of grid scale energy storage offers benefits for the electricity system as a whole.

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