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Vehicle-to-Grid Optimisation in Buildings

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Executive Summary

Vehicle-to-grid (V2G) technology has the potential to accelerate the mass adoption of electric vehicles (EVs) by significantly reducing their total operating costs. Leveraging the value of EVs as grid resources, V2G creates value by modulating the rate of charge and discharge of car batteries while they are not being driven. Early market commercialization by Nuvve has demonstrated significant revenue potential from V2G frequency regulation markets [1]. However, a significant source of V2G value creation in certain jurisdictions is from behind-the-meter energy bill savings. This article is based on Nuvve's international experience with behind-the-meter energy optimisation in California, the UK, and Sweden. The article presents an optimal dispatch strategy for V2G-capable vehicles, subject to constraints based on real-world data on daily vehicle usage patterns, peak demand and time-of-use (TOU) tariffs, local building load patterns, and fleet characteristics, to more accurately characterise the range of V2G value.

The scenario results show that the potential bill savings that V2G can offer in different countries range from 32 € (Sweden, spot price arbitrage, residential EV) to 1,244 € (UK, TOU and demand response, high EV availibility) per car per year. In four scenarios, behind-the-meter values were greater than 1,000€/EV/year. Considered over 5 year V2G contracts, these savings are equivalent to 17-20% of the price of a new 30,000€ EV. Behind-the-meter value of V2G can therefore materially improve the economics of EVs relative to uncontrolled and to smart charged EVs.

1 Background

The impacts of mass penetration of EVs on energy systems have been widely studied as EVs are increasingly expected to form a significant part of decarbonized transportation systems in the coming decades [2, 3]. The risks of overload on local distribution networks are drawing particular attention from network operators and policy makers, with smart charging solutions being seen as necessary to smooth peak loads and manage these risks [4]. Vehicle-to-grid (V2G) technology extends smart charging capabilities by transforming EVs from passive, controllable loads into bidirectional storage resources capable of discharging energy back to the grid or a local building. V2G-enabled EVs can participate in remunerated grid services such as frequency regulation via aggregation software platforms such as Nuvve's.

Much research has been conducted on the potential of using EV batteries and V2G to generate revenues in ancillary service markets such as frequency regulation [5] [6] [7] [8], and Nuvve's commercial experience showed market revenues on the order of 1,500€ per car per year [1] [8]. However, the potential value for building energy management using V2G, i.e. vehicle to building, has not been as thoroughly researched.

Nuvve has been deploying V2G globally in different electricity pricing systems and regulatory environments. Based on the insights and real-world data collected from Nuvve's customers and markets, this article explores the business case of local energy management in buildings with V2G under a variety of local market conditions. We provide a range of V2G value under time-of-use (TOU) and grid tariff regulations which, in California, the UK and Sweden, directly reward peak load reduction; under different vehicle driving patterns and use cases; and different profiles of building energy demand. We develop an optimization strategy for V2G dispatch and present results for different scenarios.

The relative benefits of doing V2G versus smart charging are often questioned. A study comparing the value of unidirectional (V1G or "smart charging") versus bi-directional ("V2G") management of EVs has shown that V2G earns 7 to 13 times more than smart charging [9]. A recent study estimates that V2G can mitigate renewables' intermittency 5 times more than smart charged EVs alone, providing capability equivalent to $12.8-$15.4 billion of investments in stationary storage and thus supporting California's renewable integration targets [10]. V2G is therefore receiving significant attention from governments [11] and businesses [12, 13]. A second objective of this article is to compare the value that V1G vs V2G could deliver in each scenario. We also discuss the practical barriers to implementing behind-the-meter business models, implications for energy policy.

2 Data and Methods

2.1 Scenarios

Nine scenarios were defined (Table 1), to consider:

- Vehicle use cases over the day: low availability (commercial fleet), medium availability (residential) and high availability (car pool vehicle);
- Building load profiles with concentrated evening peak (industrial/commercial and residential) versus diffuse daytime peak (office/commercial);
- Grid tariffs in California (demand charge, time-of-use retail prices) versus in the UK ("Triads", DUoS, time-of-use retail prices), and Sweden (demand charge).

The data inputs for the analysis are collected from the following sources. Vehicle use patterns are adapted from fleets Nuvve works with on research & demonstration projects. The commercial fleet has a utilisation pattern with 87% of the fleet having left by 8 am and 93% of the vehicles being back by 5pm during the week, with 100% plug-in time during weekends. The car-pool fleet has a stochastic utilisation pattern, ranging from short trips of 1 mile to overnight bookings with 80 miles driven. The residential vehicle is assumed to be plugged in between 5pm and 8:30am on average weekdays, and 21 hours per day on weekends.

Building hourly energy demand is adapted from a mix of public sources and Nuvve market research: UK generic data [14] for the UK, Nuvve market research in Sweden, a university campus in San Diego and Open EI data for California [15].

The energy price inputs are mostly publicly available data, see sources in Table 1. For detailed methodology on how the UK Triad charges are calculated, see [16]. In Sweden and California, demand charges are typically assessed based on a customer's maximum demand during the given month and a €/kW monthly tariff. For the Swedish residential case, a variable retail tariff was not found, so historical spot energy prices were applied in the optimisation.

The V2G impacts are compared in each scenario to a reference case of uncontrolled EV charging and to an optimisation with V1G/smart charging only, i.e. no possibility to discharge. Uncontrolled charging is assumed to happen as soon as the vehicles are plugged in after returning from a trip at full power.

Roundtrip efficiency losses from the charger and energy conversion are assumed to be 19%. The maximum charger power level is 9.25 kW. Vehicles are assumed to be 24 kWh bi-directional capable vehicles. All optimisations were run over an average month.

Table 1. Scenario definition for V2G & buildings savings analysis

	Scenario	**Vehicle use pattern**	**Building load**	**Electricity prices**
UK	UK 1	Commercial fleet historical data	Hourly historical demand data from a commercial fleet depot	Published Industrial and Commercial 2019 tariffs for Triads [17] and DUoS [18] (London)
	UK 2	Car-pool fleet historical data	Generic hourly demand profile for a medium commercial building	Same as above
	UK 3	Residential simulated profile	Generic hourly demand profile for a detached home residential	Octopus EV Agile time-of-use retail tariff (London) [19]
Sweden	SE 1	Commercial fleet (same as UK1)	Hourly historical office building demand and solar generation data from a municipality	Wholesale energy prices from NordPool 2017-2018 and distribution network grid tariff for peak demand for 2019 published in [20]
	SE 2	Car-pool fleet (same as UK2)	Example hourly demand profile for a medium commercial building (taken from UK)	Same as above
	SE 3	Residential simulated (same as UK3)	Example hourly demand profile for a detached home residential (taken from UK)	Wholesale energy prices from NordPool 2017-2018
California	CA 1	Commercial fleet (same as UK1)	University campus building in California	UCSD Demand charge scheme @ 13.24$/kW + 2.54/0.54 $/kW (summer/winter)
	CA 2	Car-pool fleet (same as UK2)	University campus in California	Same as above
	CA 3	Residential simulated (same as UK3)	Example hourly demand profile for mid-rise appartment [15]	Retail “TOU 2 tariff” San Diego Gas & Electric

2.2 Methods

The Pyomo optimization toolbox is used to solve for minimum cost of energy for vehicles based on a set of constraints on charger power limits and efficiency, vehicle battery size and SOC conservation, vehicle hourly availability, vehicle trip requirements, and building hourly demand. The hourly optimal charge and discharge rate of the V2G-capable EVs are solved for. General disjunctive programming, namely the Big M method, was used to include energy losses in the optimization model, which are dependent on the direction of the power flow.

3 Results

The results in terms of kW of peak load reduction and equivalent bill savings are presented for each of the scenarios in *Table* 2 and *Table 3*.

Table 2. Energy costs and value of V2G optimised charge/discharge cycles versus uncontrolled EV charging. In Euros per car per year

€/EV/year	UK1	UK2	UK3	SE1	SE2	SE3	CA1	CA2	CA3
V2G service description	TOU & Demand response	TOU & Demand response	TOU	Demand charge & energy arbitrage	Demand charge & energy arbitrage	Energy arbitrage (excl. taxes and tariffs)	Demand charge	Demand charge	TOU
EV plug-in profile	Commercial	Car pool	Residential	Commercial	Car pool	Residential	Commercial	Car pool	Residential
Cost of uncontrolled EV charging	292	102	630	1,521	1,339	192	1,518	39,087	1,247
Cost of Smart Charging	167	51	306	1,433	1,268	169	860	39,087	891
Cost of V2G optimised	(820)	(1,142)	187	978	838	160	515	37,915	720
Value of V2G	1,112	1,244	442	543	501	32	1,003	1,172	527
Value of V1G	125	52	323	89	71	23	658	-	356

The results show that relative to uncontrolled charging where a vehicle charges at maximum power upon arrival from a trip, V2G generates savings on energy bills of c. 442-1,244 € per EV per year in the UK, 32-543 €/EV/year in Sweden and 527-1,172 €/EV/year in California.

Higher vehicle availability (car pool vs. commercial fleet) is associated with higher V2G value, as seen by comparing UK1 vs. UK2, SE1 vs SE2, and CA1/CA2 results (Table 2).

For residential use cases (UK3/SE3/CA3), where arbitrage of time-of-use tariffs and energy prices are the main sources of value behind the meter, the value created by V2G ranged from 32 €/EV/year in Sweden to 527 €/EV/year in California. The main interesting finding in the residential cases is that smart charging alone offers c. 68-73% of the benefits of V2G, suggesting that residential EV owners may be better off with smart charging solutions than V2G.

In the commercial fleet/car-sharing cases, this analysis suggests that V1G/smart charging generates significantly less benefit than V2G in each case. In the case of CA2, EV charging was not coincidental with the building peak demand, so smart charging/V1G delivers no benefits at all – see CA2 results. The definition of the reference case or baseline has a greater influence on estimations of smart charging benefits than V2G.

In 3 scenarios (UK1, SE1 and SE2) , V2G offered c. 6.0 to 8.9 times the value of smart charging. In California, for demand charge management with a commercial fleet and a university building (CA1), V2G offered 1.5 times the value of V1G.

In Sweden and California where the main benefits of V2G is in reducing a building's demand charge, the shape of the building peak – concentrated versus diffuse over the day – has an impact on value. In CA1 and SE1 scenarios (Figures 1 and 2), the building "peak" load was diffuse, i.e. it occurred over c. 9 hours of the day, whereas in CA2 and SE2, the peak period was concentrated over c. 6 hours. In a diffuse peak situation, the battery capacity is discharged over more hours. In addition, if the peak to offpeak average load ratio is low, as in CA1, much of the benefits can be achieved by smart charging or V1G (658€/EV/year for V1G, 1,003 €/EV/year for V2G), because there is limited potential to add additional vehicle charging towards a later discharge.

CA2 which is a university campus building, had a maximum peak at a specific occasion: the maximum in the month was 3,336 MW at 11pm whereas the average daily peak (4pm - 9pm) is 2,116 MW. If combined with the ability to forecast such exceptional peaks, V2G can deliver maximum power and benefits during those events, whereas smart charging would not help.

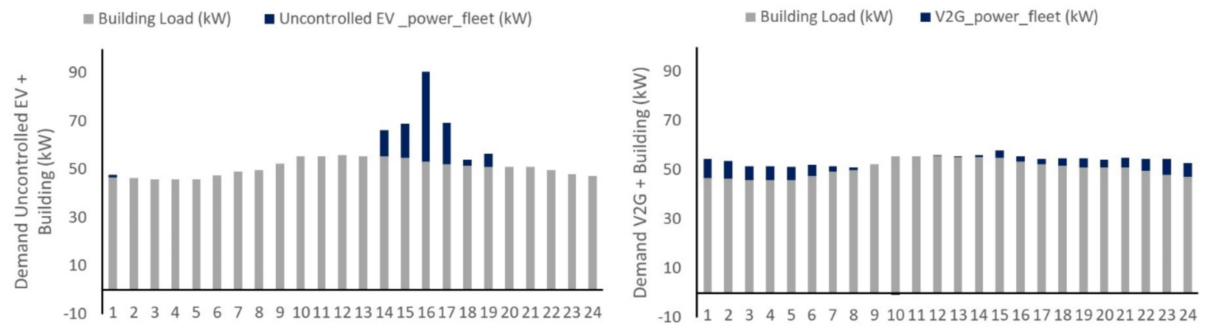

Figure 1. Demand charge optimisation in California with a commercial fleet (CA1) – average day

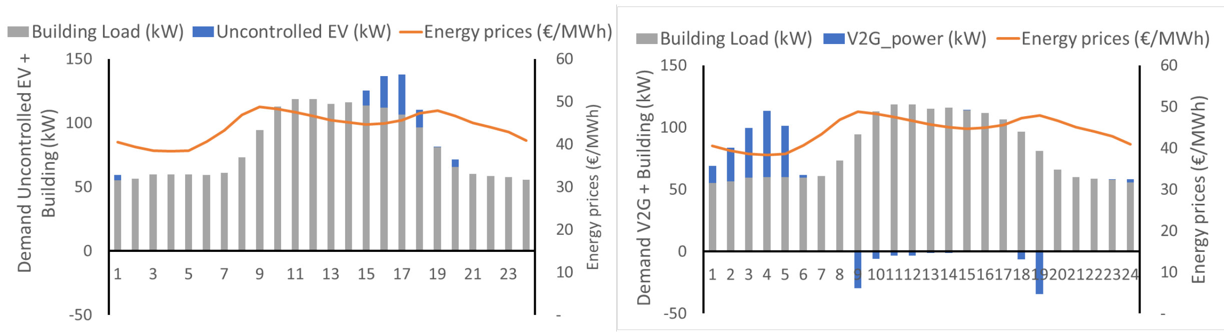

Figure 2. Demand charge and energy price optimisation in Sweden with a commercial fleet (SE1) – average day

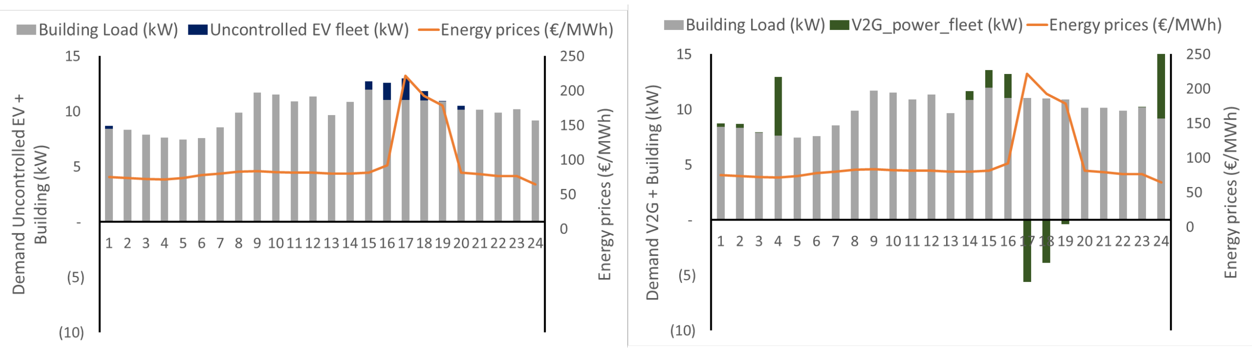

Figure 3. Energy prices incl. DUOS charges and Triads in the UK with a commercial fleet (UK1) – average day

Table 3. Peak demand reduction V2G with demand charges, in kW

kW	**Commercial fleet SE1, CA1**			**Car-pool fleet SE2, CA2**		
	Building + uncontrolled EV fleet	Building + V1G fleet	Building + V2G fleet	Building + uncontrolled EV fleet	Building + V1G fleet	Building + V2G fleet
Sweden	181	127	115	119	118	80
California	99	73	60	3336	3336	3236

4 Discussion

The analysis shows that V2G on sites connected to buildings can earn or save significant value and in some cases be one of the main drivers of the V2G business propositions outside of ancillary market revenues. The range of savings values presented suggest that over a 5 year V2G contract, a commercial fleet or a car sharing operator can save the equivalent of 17-20% of the price of a new 30,000€ Nissan Leaf. These figures are based on battery storage of 24kWh and charger power capacity of 9.25kW. Further savings can be achieved as the EV industry evolves to larger batteries and higher power bi-directional chargers. The analysis also shows that V2G often creates significantly more value than V1G in most of the contexts considered (5 scenarios out of 9) other than residential. This result is particularly important for businesses to justify the additional investment required from V2G charging infrastructure.

4.1 Business model implementation

In practice, there are still barriers for capturing the value of these savings for the aggregator performing them, as the savings will accrue directly to end customers. Different commercial and contractual solutions are required, such as energy savings models with sharing (e.g. 70%/30%). In an early V2G market, different approaches must be trialled and developed based on the feedback of early adopters. Further, the value estimates of behind-the-meter savings such as presented in this paper refer to an energy consumption baseline to compare V2G against. In practice, it may be challenging to establish a baseline when a prospective customer has not yet made the transition to EVs, i.e. no information is available on the reference charging behaviour. Indeed, while V2G can offer substantial benefits by avoiding high potential costs of charging at the wrong times, this may be irrelevant to a customer who cares little about cost avoidance, and more about actual income.

4.2 Implications for policy and tariff design

One interesting insight of this work is for electricity tariff design. Contrasting the cases of the UK (Figure 3) where the time-of-use charges in the evenings lead to "peak avoidance" and a displacement of the peak to the cheapest hour in the night (here, 4am), and of California (Figure 1), where the V2G optimisation of the demand charge results in a much flattened load profile, it is suggested that prices should be designed by policy makers and regulators to avoid creating new peaks with EVs. If such a policy were implemented, this would allow aggregators such as Nuvve to optimize overall EV charging or discharging to lower costs to the grid as a whole. The demand charge applied as a price per kW on a consumer's monthly peak load is more effective than the evening charges and Triads at incentivising load levelling and peak minimisation.

4.3 Limitations

The limitations of the methods are acknowledged. Optimisation strategies relating to energy arbitrage that involve increases in battery cycling may result in accelerated battery degradation. A number of studies have suggested that smart management V2G control strategies are neutral or improve battery health [21] [22], however empirical research to date has led to mixed conclusions on the subject [23]. When real-world trials of V2G produce more specific data on battery degradation, this analysis will be extended to factor battery degradation costs into the optimisation algorithms. In the meantime, it is recommended that V2G aggregators factor in conservative limits on cycling and SoC. A recent study by [24] estimated the impact of additional cycling due to V2G could cost 200-300$/EV/year in battery degradataion.

5 Conclusion

In conclusion, this article suggests that fleets of commercial light duty vehicles or car-pool operators could save 1,100-1,200 €/EV/year in the UK and California given the current structure of energy prices – over a 5 year contract, the savings are equivalent to c. 20% of the price of a new 30,000€ electric vehicle. For residential customers with moderate EV plug-in times and strong time-of-use incentivising tariffs such as the Octopus EV agile tariff in the UK or SDG&E's retail TOU 2 tariff in California, V2G could reduce their home energy bills c. 442 to 527 €/EV/year.

In the cases involving commercial and car pool vehicles in the UK and California, behind-the-meter values were greater than 1,000€/EV/year. These results suggest that behind-the-meter services are viable complementary or alternative value streams for V2G in markets where frequency regulation prices are falling under intense competitive pressure.

The article also presents a comparison of the value of V1G and V2G in each scenario, suggesting that V2G can offer significantly higher financial benefits in a number of circumstances. The analysis also identified cases where the benefits of V2G versus smart charging were marginal: in residential contexts, and where the building peak demand is diffuse, i.e. occurs over many hours and/or there is a low peak to offpeak load ratio.

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