Assessing the Potential of Vehicle-to-Grid Technology for London Bus Fleets

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ABSTRACT

Growing concerns over climate change have accelerated transport electrification. Transport for London (TfL) commits to fully electrifying its bus fleet by 2034. While this transition brings challenges to grid infrastructures, simultaneously, it provides opportunities to integrate Vehicle-to-Grid (V2G) to reduce operational costs and enhance grid stability. This study develops a modelling framework using London bus open data to assess the potential of V2G under different charging and discharging cycles, state-of-charge (SoC) range, battery degradation, passenger load, and tariffs. Results show that maintaining SoC between 40–88% provides a balance between cost savings and V2G capacity. Wider SoC ranges reduce costs but accelerate battery ageing, limiting long-term benefits. Passenger load had little effect on V2G capacity (<5%) but significantly influenced operating costs. Fluctuating tariffs predictably affected costs but not V2G potential. Overall, transitioning from petrol to electric buses with V2G integration could deliver up to 98% cost savings over 14 years.

Keywords: Vehicle-to-Grid, Bus fleet, battery degradation, grid stability

1. INTRODUCTION

Growing concerns over climate change have accelerated the electrification of the transport system, raising the need to design and develop urban transport systems in a resilient and sustainable way. Transport for London(TfL) has recognised the need to transition public transport from fossil-fuel-powered to electric or hybrid alternatives, and has set a target to complete the transition to a fully electric bus fleet by 2034 (Transport for London, 2023). This transition brings challenges to grid infrastructures, but simultaneously, provides opportunities to integrate Vehicle-to-Grid (V2G) to reduce operational costs and enhance grid stability. The main objective of this research is to assess the potential of V2G technology under different scenarios and explore the feasibility of integrating V2G technology for London buses with the current operation patterns.

Fleet electrification is expected to increase electricity demand and may impact grid stability (Tavakoli et al., 2020). However, coordinated charging strategies can mitigate these effects by optimising predictable demand patterns (Kuruvilla and Venkatesh Kumar, 2024). This makes public transport a very strong candidate for V2G integration, as journey lengths are known, and bus movements are pre-determined. Moreover, the centralised ownership and operations of these fleets also mean that there are fewer barriers to overcome compared to private vehicles(Elliott and Kittner, 2022). This also results in another benefit of not requiring aggregators as servant energy accumulators, which are used for private vehicles(Bibak and Tekiner-Moğulkoç, 2021).

Despite these advantages, a research gap remains regarding the feasibility and benefits of transitioning both EV and non-EV fleets to V2G-integrated fleets, particularly in relation to battery degradation and the provision of ancillary services. This study addresses this gap by using London buses as a case study. The main contributions of this research are threefold.

- Firstly, the key operational and technical factors influencing both costs and V2G capacity are identified, highlighting that bus occupancy drives operating cost while state-of-charge ranges and battery capacity shape the balance between grid support and expenses.
- Secondly, it demonstrates the long-term economic viability of V2G fleets, showing that even under conservative battery degradation assumptions, they achieve over 98% cost savings compared with petrol fleets across 14 years.

- Thirdly, it shows that while daily V2G revenues cannot offset operating costs alone, the integration of V2G technology significantly enhances the overall cost-effectiveness and resilience of electric bus fleets under real-world tariff and price variations.

2. METHODOLOGY

In this paper, the methodology employed aims to create a comprehensive framework facilitating the integration of Vehicle-to-Grid (V2G) technology with existing public transport bus fleets and their corresponding timetables.

2.1. Study Context

London bus Route 93 was selected as a representative case. The route is run by Sutton Garage, and has a peak vehicle requirement(PVR) of 26 in the daytime, and PVR of 3 during the nighttime service[1]. It is served by the Alexander Dennis Enviro400 City EV bus model, which serves 44 other bus routes in London, and has the following specifications[2]:

- 0.67 kWh/km energy efficiency in UK Bus Cycle, with 260-mile range on a single charge at the beginning of life
- 472kWh lithium-ion battery
- CCS2 DC plug charging, with a maximum of 150kW nominal power

Using this specification provided by the manufacturer, the minimum time required for the bus to reach full charge from zero at the beginning of the vehicle's life can be calculated (Pilotti et al., 2023)

$$\frac{battery\ size[Kwh]}{charging\ power[Kw]} = \frac{472}{150} = 3.15\ hours \quad (1)$$

2.2. Bus timetable data

The initial input into the framework is timetable data, which is accessible from the Transport for London website and provides both live and historical data[3]. An example of the initial input data is shown in Table 1 below:

Table 1: First rows of timetable data for a fleet serving route 93 on 18/04/24

Vehicle	Trip ID & time		To
Ee168 - LG23 EZN	691999	00:00	Putney Bridge
Ee119 - LG23 FGC	691623	00:00	North Cheam
Ee143 - LG23 FBK	692087	00:05	Putney Bridge
Ee133 - LG23 FAM	691595	00:07	North Cheam
Ee168 - LG23 EZN	692000	00:10	North Cheam
Ee133 - LG23 FAM	691596	00:15	Putney Bridge
Ee116 - LG23 FFY	692030	00:09	Putney Bridge
Ee116 - LG23 FFY	692031	00:20	North Cheam
Ee138 - LG23 FBC	692059	00:18	Putney Bridge
Ee149 - LD72 UHX	691756	00:23	Sutton
Ee138 - LG23 FBC	692060	00:30	North Cheam

The distance travelled for each journey is calculated using longitude and latitude data of the route, also provided by TfL. As shown in Table 2, the journeys where the 'To' and 'From' are the same location. This data frame is then used as the initial input for the created function that calculates the State of Charge (SoC) throughout the day and outputs the time available for charging and discharging.

[1] http://www.londonbusroutes.net/times/093.htm
[2] https://www.alexander-dennis.com/buses-coaches/enviro400/
[3] https://tfl.gov.uk/travel-information/timetables/

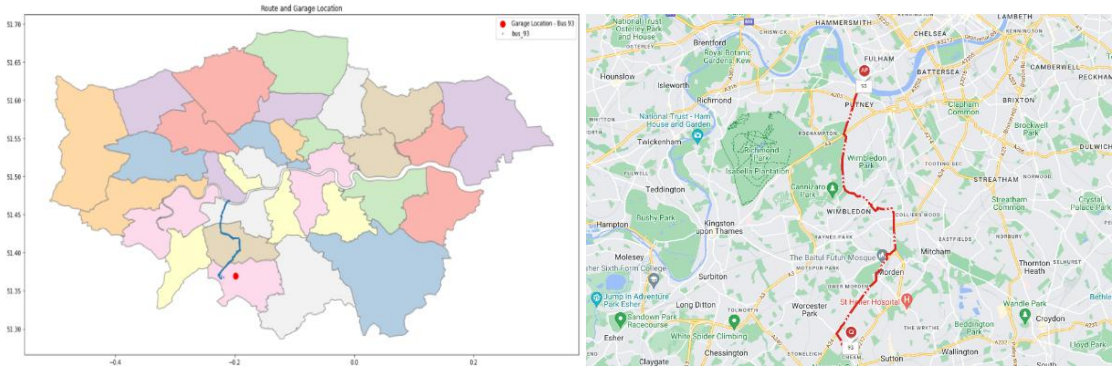


Figure 1: Bus 93 route and garage location plot using longitude and latitude points provided by TfL (left) and Bus 93 route plotted on Google maps by TfL(right)

Table 2: First few rows of data for bus 'Ee177 - LG23 EUU' on 18/04/24

Trip	Time	To	From	Journey (km)
691756	00:23:00	Sutton	Putney Bridge	17.22
691822	06:35:00	North Cheam	Sutton	2.38
691823	06:44:00	Putney Bridge	North Cheam	14.84
691824	08:06:00	Putney Bridge	Putney Bridge	0.00
691825	08:15:00	North Cheam	Putney Bridge	14.84
691826	09:21:00	North Cheam	North Cheam	0.00
691827	09:35:00	Putney Bridge	North Cheam	14.84
691828	10:44:00	Putney Bridge	Putney Bridge	0.00
691829	10:56:00	North Cheam	Putney Bridge	14.84
691830	12:03:00	North Cheam	North Cheam	0.00

2.3. Assumptions and parameters

The function illustrated in Figure 2 requires a set of input parameters, which may be adjusted during the sensitivity analysis stage. The battery capacity and charging power values are given by the manufacturer's specification.

Table 3: Inputs Parameters for the function

Input	Initial value
Battery capacity [kWh]	472[6]
Charging Power [kW]	150
Consumption [kWh/km]	Battery Capacity / Distance travelled
$SoC_{max\ night}$ [%]	80
$SoC_{max\ day}$ [%]	70
$SoC_{safe\ night}$ [%]	40
$SoC_{safe\ day}$ [%]	40

There are many varying off-peak hours, which is largely dependent on suppliers. In this paper, off-peak hours will be defined as midnight to 8am, which follows the British Gas tariff (British Gas, 2024). For the charging rate, the average 2024 rates from four electricity providers[4] is shown in Table 4 and the discharging rates used as input were the typical UK Economy 7 tariffs[5], shown in Table 5.

Table 4: Average 2024 tariffs from different electricity providers

Company	Off peak rate [p/kWh]	On peak rate [p/kWh]
British Gas	14.64	29.38
Eon	10.95	32.06
OVO	17.10	27.60
Utility warehouse	8.43	33.88

[4] https://www.moneysavingexpert.com/utilities/economy-7/

[5] https://www.cenex.co.uk/app/uploads/2019/10/True-Value-of-V2G-Report.pdf

Table 5: Economy 7 discharging tariff

	Economy 7 rate
Off peak discharge rate [p/kWh]	10
On peak discharge rate [p/kWh]	17

2.4. Calculating Framework

The input data frame is in the format shown in Table 2, and each row is set the appropriate conditions corresponding to the time of day. Details of these assumptions are discussed in Section 3.3. The Calculating Framework is shown below in Figure 2 in the format of a flowchart.

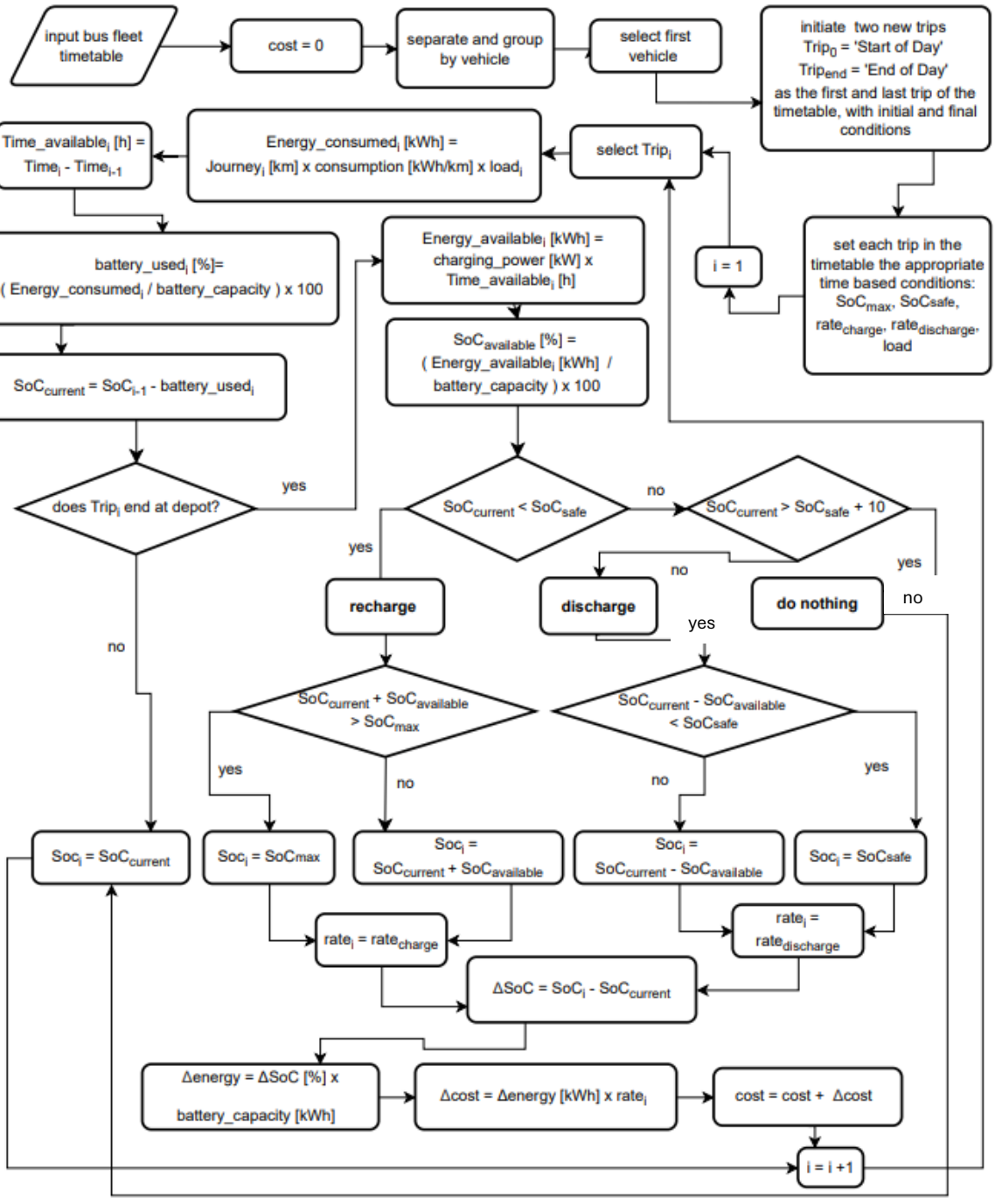


Figure 2: Logic of function

3. RESULTS AND SENSITIVITY ANALYSIS

The sensitivity analysis is conducted to evaluate the influence of several critical factors on V2G capacity and total cost. The four key factors considered are battery degradation, depth of charge and discharge, vehicle weight, and tariff fluctuations.

3.1. Battery degradation and different energy providers

Battery degradation is directly correlated with the longevity and performance of any electric vehicle (EV). In this study, degradation is modelled as a 3.09% annual reduction in battery capacity, consistent with reported averages(Gong et al., 2024). For an initial capacity of 472 kWh, this degradation rate results in a decline to 307.69 kWh over 14 years, aligning with the typical lifecycle of an electric bus(Hill, 2018). Battery replacement is generally recommended once capacity falls below 70%, which occurs after approximately 12 years at 3% degradation and 7 years at 6%. Manufacturers of the Enviro400EV claim battery lifespans of up to two consecutive seven-year contracts without replacement. The laboratory conditions the manufacturers used were likely more conservative, or the battery degradation has less than 3% per year (Alexander Dennis, 2024).

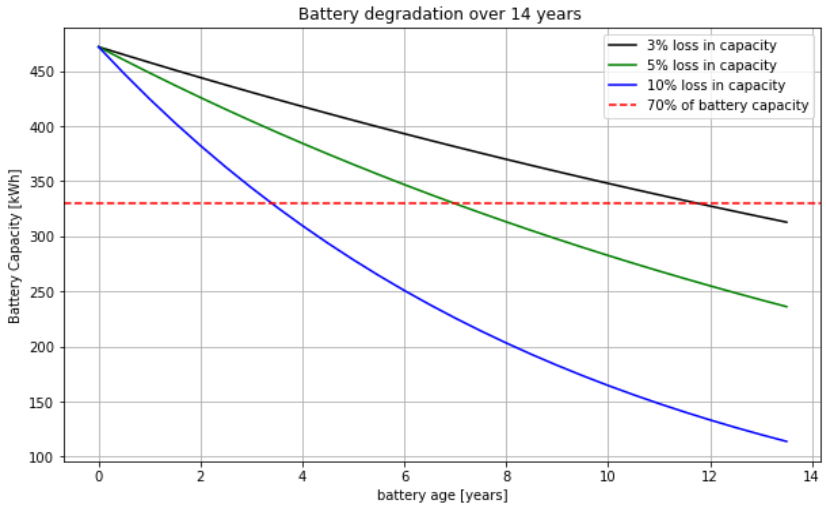


Figure 3: Change in battery capacity under different degradation conditions

Table 6: Calculating cost of petrol equivalent fleet

Total distance travelled by fleet per day [km]	4717.99
Petrol cost[6] [p/L]	145.98
Petrol consumption[7] [km/L]	2.98
Cost of petrol over 14 years (£)	**11,810,139**

Table 7: Calculating cost of energy over 14 years

Supplier	Cost of electricity in first year (£)	Cost of electricity in fourteenth year (£)	Difference between first and fourteenth year (%)	Cost of electricity over 14 years (£)	Difference between petrol fleet and electric V2G fleet (%)
OVO	183,675	195,027	6.18	**2,698,220**	77.15
British Gas	147,048	172,397	17.24	**2,292,621**	80.59
Eon	92,115	138,488	50.34	**1,684,509**	85.74
Utility warehouse	54,582	115,304	111.25	**1,268,962**	89.26

[6] https://www.statista.com/statistics/1293135/uk-weekly-average-gas-prices/
[7] https://www.pfleet.com/blog/comparing-types-of-buses-and-their-mpg

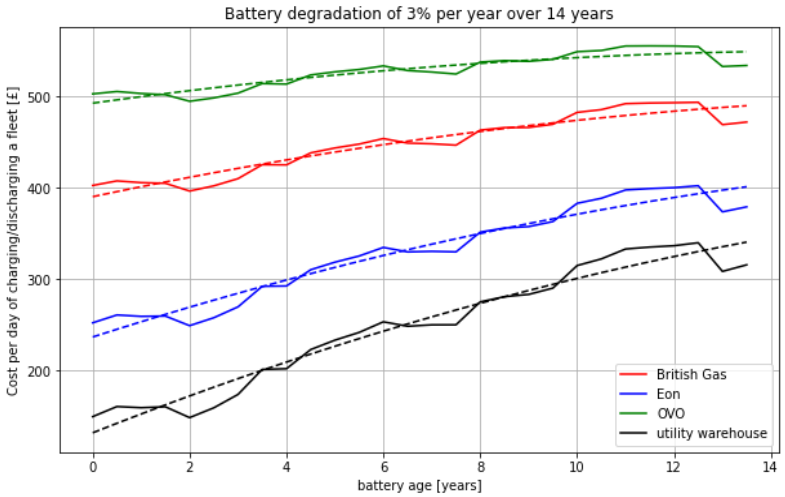


Figure 4: battery degradation and daily costs of charging/discharging fleet for different 2024 tariffs

To contextualise costs, results are compared with a petrol-equivalent fleet operating under identical conditions. Using a petrol price of 145.98 p/L and a consumption rate of 2.98 km/L, the total fuel cost over 14 years is estimated at £11.81 million.

Regarding how cost is affected by battery degradation, the daily cost of charging and discharging the fleet under a fixed timetable and occupancy was analysed. As shown in Figure 4, daily costs increase over time. Utility Warehouse, despite having the lowest tariff, shows the greatest variability (111%), while OVO remains relatively stable (<7%).

To calculate the cost of operating over a 14-year lifespan of the bus fleet, it is assumed the same timetable is used for 365 days of the year for 14 years, and there is no change in bus occupancy during this time. Even with the most expensive supplier (OVO), electricity costs are less than a quarter of petrol. Utility Warehouse results in approximately 10% of the petrol cost, while OVO corresponds to 22.85%.

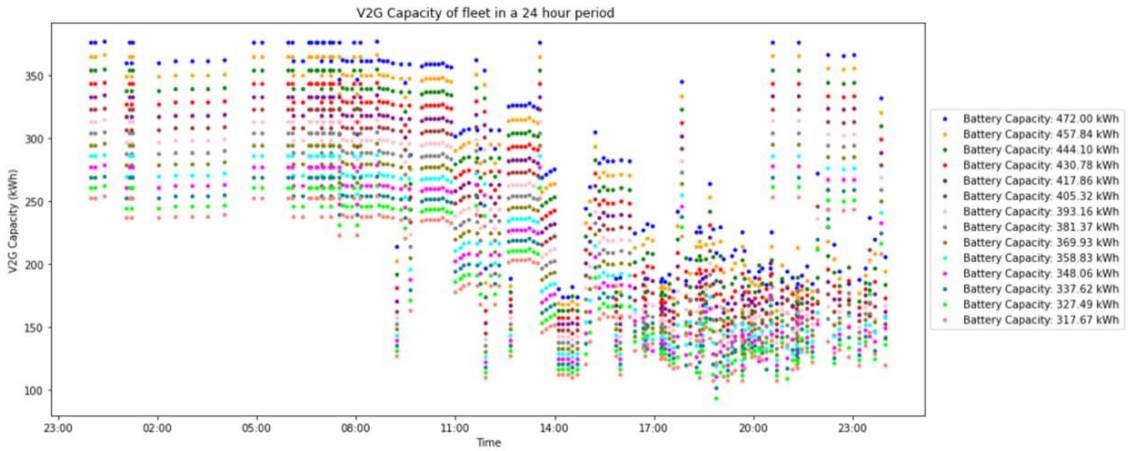


Figure 5: daily V2G capacity at different stages of battery degradation

As battery capacity declines with age, the available Vehicle-to-Grid (V2G) capacity decreases, contributing to higher charging and discharging costs. Figure 5 illustrates how daily V2G capacity varies with battery condition. Despite different capacities, the overall trend remains consistent: V2G capacity is highest overnight, decreases between 08:00 and 14:00, and becomes more variable in the late afternoon. Availability is largely determined by the fleet timetable, meaning the data is not continuous. Each point represents a bus arriving at the depot, with available capacity based on its remaining State of Charge (SoC).

3.2. Allowable SoC range to maintain battery health

To find how the Depth of Discharge(DoD) affects the cost of charging and discharging the fleet per day, the framework was run with varying upper and lower bounds of SoC. The results are presented in the Figure 6.

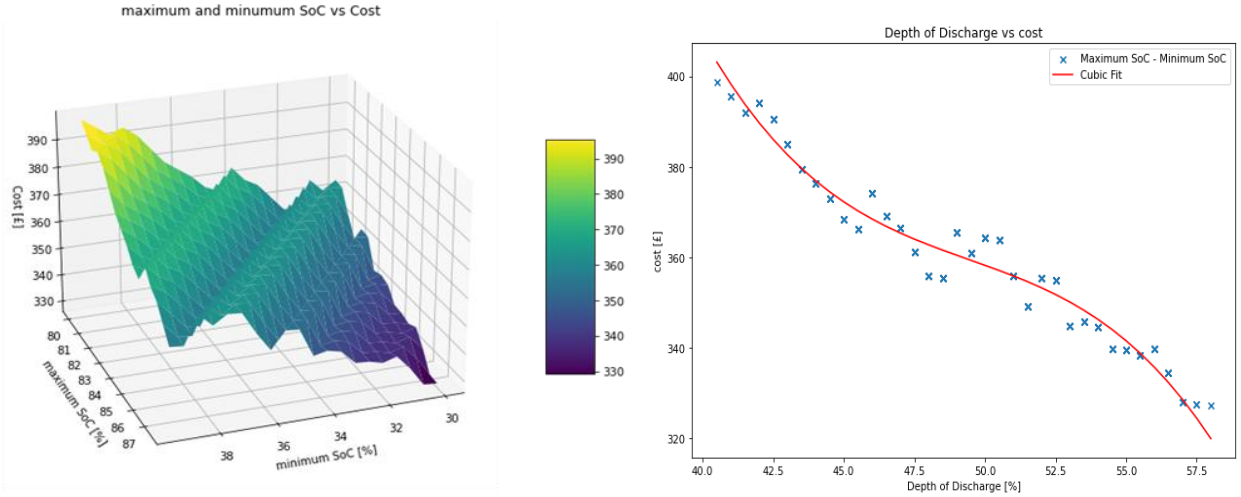


Figure 6 minimum and maximum SoC vs cost(left) and SoC range vs Cost(right)

The highest cost (£398.78) occurs with a restricted SoC range of 40–80%, while the lowest (£327.45) is achieved with a wider range of 30–88%. The £71 difference reflects reduced charging and discharging flexibility at higher minimum SoC thresholds, limiting V2G participation.

However, a low minimum SoC (30%) introduces operational risk, particularly under high-demand conditions when energy consumption increases. To evaluate the impact on V2G performance, four SoC ranges were analysed (Figure 7), where each data point represents a bus arriving at the depot and its available energy for V2G services.

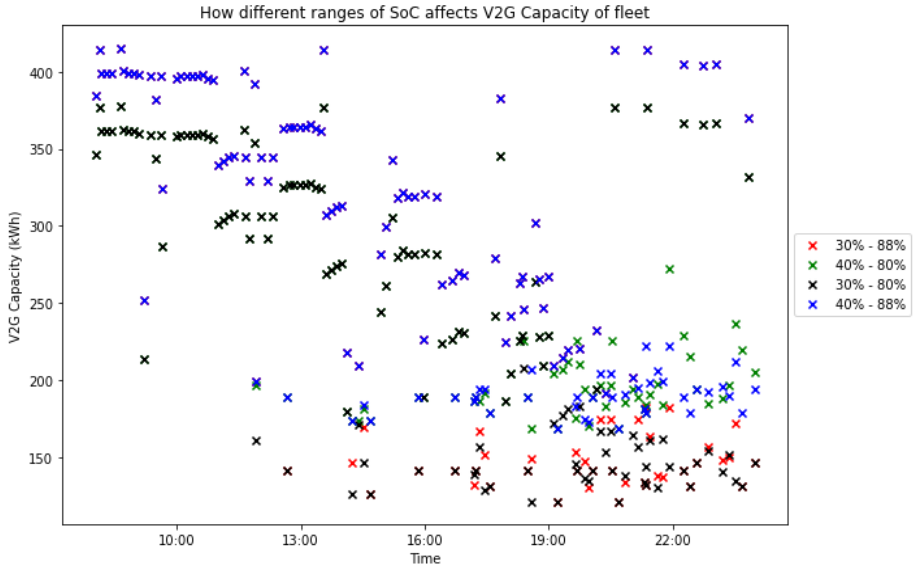


Figure 7: V2G capacity throughout a day with different SoC ranges

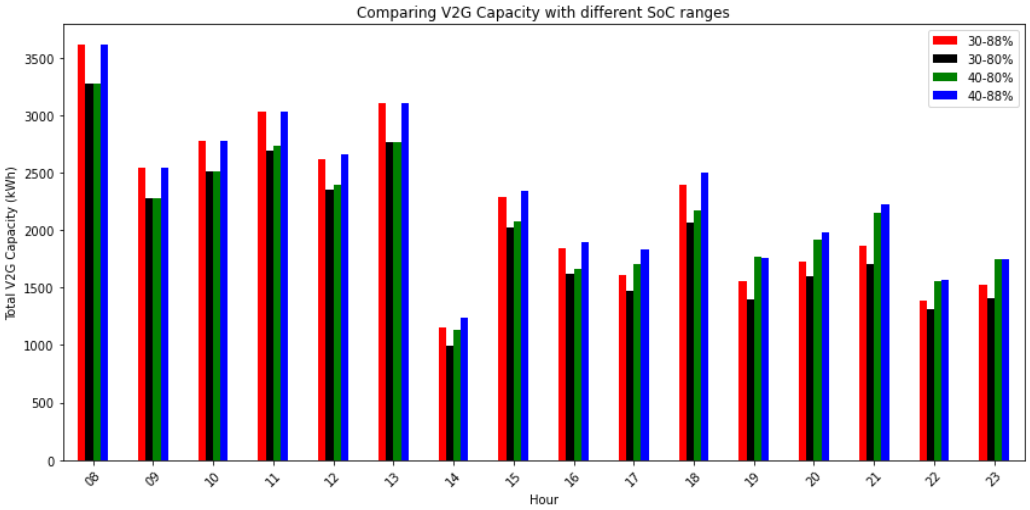


Figure 8: Total V2G capacity of each fleet per hour

Hourly aggregation (Figure 8) shows that although the 30–88% range minimises cost, it provides less V2G capacity after 14:00, despite similar availability earlier in the day. The 30–80% range consistently yields the lowest V2G capacity.

Overall, the optimal balance is achieved with a 40–88% SoC range, delivering the highest V2G capacity at approximately £362/day, only slightly higher than the 30–80% case (£358/day). This marginal cost increase is outweighed by greater V2G revenue potential and improved battery longevity due to a moderated DoD.

3.3 Bus occupancy and loading conditions

The bus occupancy plays a pivotal role in determining the operational costs of a V2G fleet. It directly influences the vehicle's weight, thereby impacting its energy consumption. This is represented in the model through a load factor, with full capacity during peak hours (07:30–10:00 and 16:00–19:30), and reduced levels (0.25) overnight. Results are shown in Figure 9.

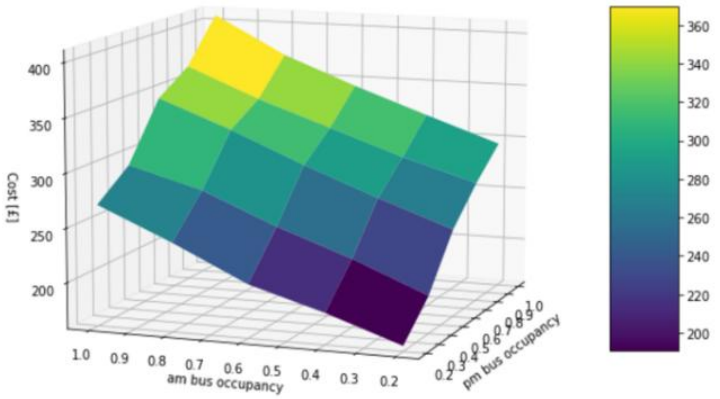


Figure 9: off-peak bus occupancy vs cost

The highest cost (£406/day) occurs under continuous full loading, while the lowest (£163/day) corresponds to reduced off-peak occupancy, a difference of approximately 150%. This highlights the strong sensitivity of operating costs to load conditions.

Analysis of hourly aggregated V2G capacity (Figure 10) shows that loading has minimal impact on total V2G energy. A fully loaded fleet provides 60.52 MWh, compared to 63.51 MWh at lower occupancy—a difference of less than 5%. Although higher loads slightly reduce available V2G energy, the effect is minor compared to the substantial increase in operating costs.

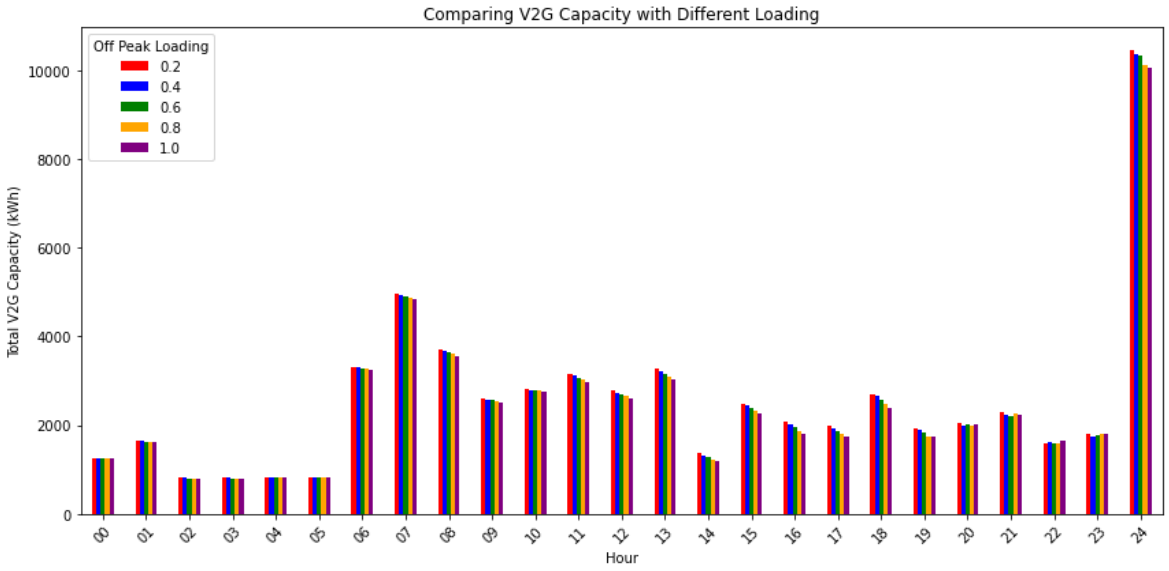


Figure 10: Hourly V2G capacity with different loadings

3.4. Fluctuations in electricity tariffs for charging and discharging

In section 4.1. varying tariffs occur due to different electricity providers. However, there is another type of variability regarding tariffs. Within the last 3 years, the price of electricity in the UK has fluctuated greatly, with the lowest price at 57 £/MWh, which was in March 2021, and spiked in August 2022 at 363 £/MWh, before coming down to 64 £/kWh in early 2024, and expected to reduce a further 12%(Ofgem, 2024).

This variability has significant implications for long-term fleet economics. To assess this, a sensitivity analysis was conducted by varying tariffs by ±20% while holding all other parameters constant. Using 2024 British Gas tariffs for charging and Economy 7 tariffs for discharging, total costs range from £267.57 to £401.30, representing exactly ±20% of the baseline (£334.43), reflecting the linear relationship between tariff and cost (Figure 11).

These results indicate that accurate forecasting of electricity prices is critical, as changes in tariffs translate directly into proportional changes in V2G operating cost

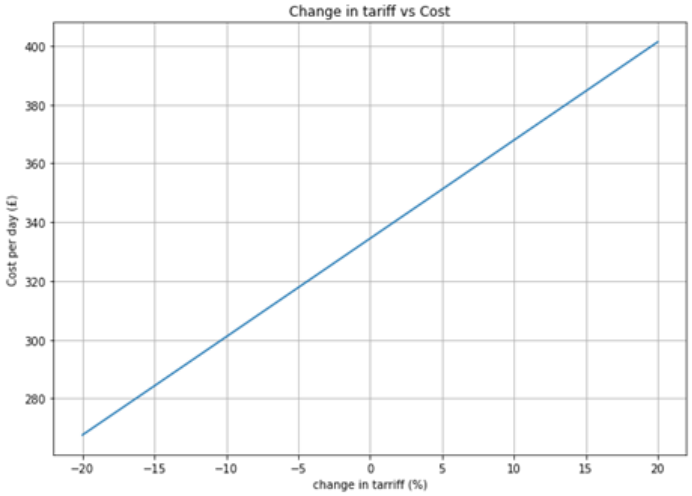


Figure 11: Change in tariff vs cost

3.5. Best' and 'Worst' case scenarios

Given that the ideal state of charge is between 40 – 88%, and the battery performs the worst at the end of the 14 year battery life, with 3% battery degradation, a 'best' and 'worst' case scenario for a fleet can be found and compared.

Table 8: Conditions for two scenarios

	Best case (start of life)	Worst case (after 14 years)
Off peak loading	0.5	1
Battery capacity [kWh]	472	308.14
Cost [£/day]	266.98	546.41

A 51% increase in daily cost is observed from best to worst case, driven by reduced battery capacity. However, even in the worst case, V2G fleet costs remain less than a quarter of the equivalent petrol cost (£2311/day), highlighting strong economic advantages.

V2G availability varies throughout the day shown in Figure 12. In the best case, capacity is highest overnight and after 20:00, but limited between 17:00–20:00 due to recharging needs. The worst case follows a similar pattern but is delayed by approximately three hours and shows minimal availability after 20:00.

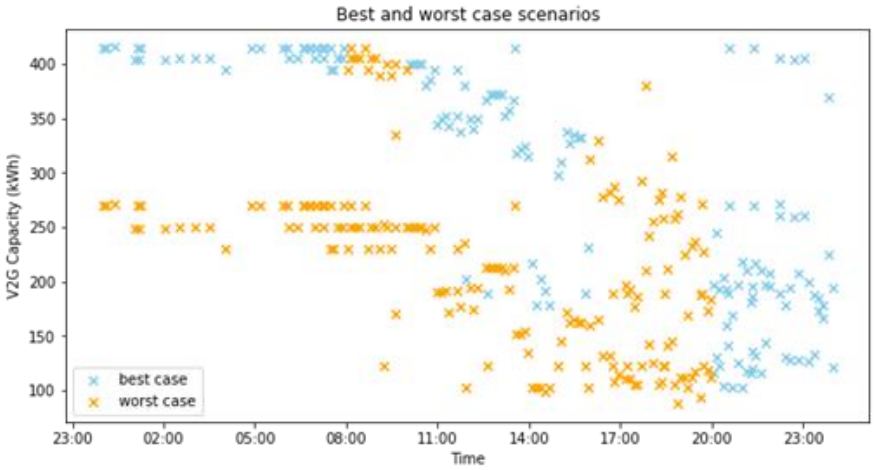


Figure 12: V2G capacity of individual vehicles throughout the day under best and worst conditions

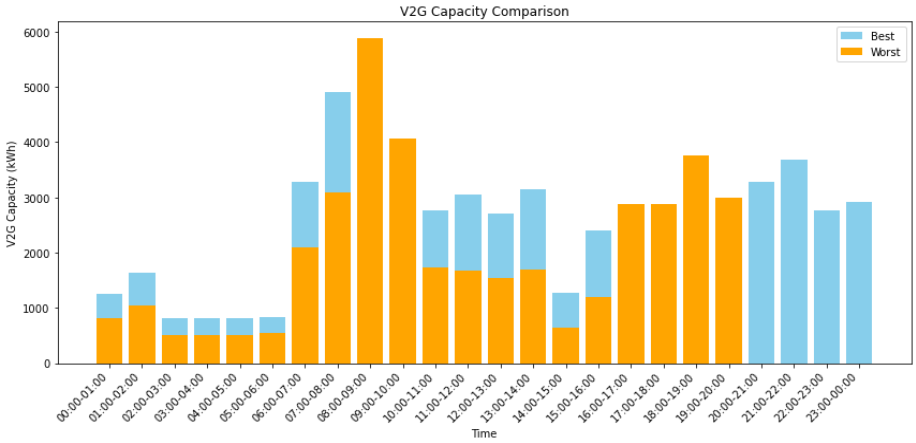


Figure 13: V2G capacity of individual vehicles throughout the day under best and worst conditions

Hourly aggregation shown in Figure 13 indicates that total V2G capacity decreases from 58.68 MWh (best case) to 40.02 MWh (worst case), a reduction of 31.8%. Despite lower overall capacity, the worst case provides higher peak availability around 08:00–09:00.

During critical demand periods (06:00–08:00 and 16:00–18:00), both scenarios contribute to grid support: the best case is more effective in the morning, while the worst case provides greater evening capacity. This demonstrates that, across the vehicle lifecycle, V2G fleets can consistently deliver ancillary services despite performance degradation.

3.6. Comparing with non-V2G fleet

This study evaluates V2G performance using real bus fleet data, comparing operational costs and capacity against a petrol-equivalent fleet. V2G charger costs are estimated at £700–£1000, giving £5600–£8000 for eight chargers required for a 26-bus fleet. Based on a 40–88% SoC range, maximum charging time is ~83–90 minutes, and eight chargers are sufficient for overnight demand.

$$48\% * \frac{battery\ capacity\ [kWh]}{charging\ power\ [kW]} \approx 91\ mins \tag{2}$$

Figure 14 shows that in the first year, the V2G fleet costs £71,950 (including £8000 infrastructure), compared to £421,791 for petrol, achieving payback within one year. Cost parity is reached within three months (Figure 15). Over 14 years, total energy costs are £1.14M for V2G and £88.6M for petrol, a 98.7% reduction. These estimates exclude additional V2G revenue, meaning actual savings may be higher.

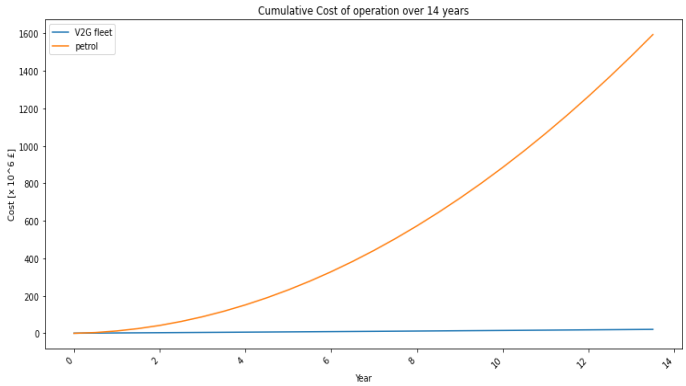


Figure 14: Cumulative cost of energy for V2G fleet and petrol fleet

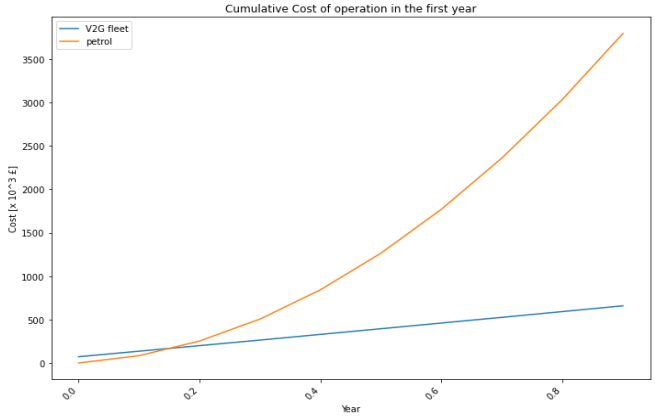


Figure 15: Cumulative cost of energy for V2G fleet and petrol fleet in the first year

4. Conclusion

This study evaluates key factors affecting V2G cost and capacity. Bus occupancy has the greatest impact on operating cost but minimal effect on V2G energy. Increasing occupancy from low (off-peak) to full capacity raises costs by ~150%, while V2G capacity varies by less than 5%.

Optimal performance is achieved with an SoC range of 40–88%, balancing cost and V2G availability. Wider SoC ranges reduce cost but can limit usable V2G capacity, with a nonlinear relationship observed between SoC range and cost.

Under a conservative 3% annual battery degradation, V2G remains more cost-effective than petrol over 14 years, even at the highest tariffs. Higher initial tariffs also result in smaller long-term cost variation. Battery aging reduces both V2G capacity and consistency of availability, particularly in the late afternoon when recharging occurs.

Electricity price uncertainty remains a key risk, but cost changes scale proportionally with tariff variation. Although V2G alone does not generate net profit (excluding fares), it delivers substantial cost savings compared to petrol fleets—exceeding 98% over 14 years.

Future work should assess grid-level impacts, including large-scale charging behaviour and variable charging rates, as well as alternative lifecycle strategies such as battery replacement to extend vehicle lifespan.

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