Modelling the Feasibility and Benefits of Vehicle-to-Grid Technology for Urban Bus Fleets: the Case Study of London

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SHORT SUMMARY

Bus operators are increasingly seeking ways of electrifying their fleets, which is motivated by a combination of policy (decarbonization, emission standards) and economic (operational efficiency) factors. For example, in London there is now an explicit objective set by the Mayor of London to transition to a fully electric bus fleet by 2034. At the same time, the dynamic, spatially disperse but predictable nature of bus services (routes, timetables) suggests their applicability as a potential source of flexible electricity storage and supply for the grid, via adjustable charging as well as discharging (vehicle-to-grid, V2G) capabilities. To-date, simulation-based analyses have demonstrated the potential for bus fleets to support electricity grid operations, for instance by enabling more volatile renewable energy generation into the grid. The current paper advances the modelling of such benefits, by presenting a modelling framework developed using Transport for London (TfL) working timetables to map vehicle duty cycles at a 15-minute resolution. The approach defines bus archetypes using battery capacity and energy consumption, with load factors applied to account for passenger occupancy, auxiliary loads and time-of-day variations. State-of-charge dynamics were simulated for bus archetypes operating according to a real-world working timetable, with rules to safeguarded service reliability through departure floors, safety margins and export scheduling windows aligned with UK energy demand peaks. The empirical case study, based on Edgware Depot in London, indicated that fleet operating from that bus depot could shift up to 6,455 kWh in a single day, equivalent to the daily consumption of 650 UK households. Exports were concentrated in the evening super-peak, though some capacity was available during the day due to school services and certain buses dwelling in the depot during the interpeak period. Route and vehicle level analysis revealed substantial heterogeneity, with some buses unable to participate due to continuous duties, while others offered disproportionate contributions.

Keywords: Bus, Electric Vehicles, Fleets, V2G, Urban Transport

1. INTRODUCTION

The electrification of the bus network creates both opportunities and challenges. While battery electric buses eliminate tailpipe emissions and improve air quality, they also impose substantial new demands on urban electricity networks. Large depots may host hundreds of buses, each with battery capacities of 300-500 kWh, resulting in gigawatt-scale demand in charging is unmanaged. Meeting this demand requires not only investment in charging infrastructure but also integration with electricity systems to ensure reliability and cost-effectiveness (IEA, 2023).

Vehicle-to-Grid (V2G) technology has emerged as a potential solution. V2G enables bidirectional energy flows between electric vehicles (EVs) and the grid, allowing buses to discharge energy when idle. Thus, fleets can act as distributed energy storage, providing ancillary services such as peak shaving, demand response and frequency regulation. This dual role of buses as both transport providers and grid resources has the potential to add revenue streams for operators, reduce reliance on fossil-fuel based peaking plants and accelerate renewable integration.

Public bus fleets are particularly well suited for V2G applications. Unlike private cars, buses follow predictable duty cycles, return to centralised depots and use high-capacity batteries. This predictability reduces the uncertainty that complicates V2G in passenger car contexts (Lund & Kempton, 2008). Despite their promise, the integration of V2G into public bus operations remains in its infancy, with limited empirical evidence. Incorporating V2G capable buses into the grid can enhance overall energy system resilience and efficiency. By discharging stored energy at times of peak demand, electric buses can help shave peak loads and can defer the need for additional power generation or network upgrades. V2G also increases the utilisation of variable renewables by soaking up surplus wind and solar that would otherwise be curtailed, which speeds the transition away from thermal generation (Kumar et al., 2024; Wohlschlarger et al., 2024).

From the bus operator's perspective, V2G offers the prospect of new revenue streams and cost offsets. Rather than buses sitting idle, the operator can earn money by selling energy back to the grid or providing services such as frequency control and reserve capacity. One simulation study showed that participating in V2G with an optimised strategy could extend an EV battery's lifetime compared to not doing V2G (Sagria et al., 2024, Tan et al., 2015). Over a three- month test scenario, capacity fade was reduced by ~6% thanks to careful control of charge levels (Uddin, Jackson et al., 2017). This counterintuitive result (using the battery more but in a gentler way) indicates that V2G need not always accelerate degradation if managed properly.

Although the technical feasibility of V2G has been demonstrated in pilot projects such as the Bus2Grid trial in London, significant barriers remain to scaling up. The operational priority of public bus fleets is service reliability, which means energy discharge to the grid must never compromise availability for scheduled routes. This creates tension between transport operations and grid services, requiring intelligent scheduling approaches that optimise across both objectives. Research gaps also persist in understanding how passenger occupancy, auxiliary loads (such as heating and air conditioning), and seasonal variations influence energy availability for V2G. These factors introduce variability in state-of-charge profiles, which in turn affects the reliability of grid services. Existing studies often simply make assumptions around load profiles, neglecting the dynamic interaction between operational energy use and V2G capacity.

This paper aims to investigate the potential of V2G systems in public bus fleets to support urban grids, balancing transport operations and energy market participation. It extends earlier feasibility

research based on route-level data into depot-level analysis (Chan et al., 2025). The case study is Edgware Bus Garage in London, UK, operated by Metroline, which runs five daily service routes (113, 142, 204, 240, 251) and two school services (605, 606). The proposed approach ensures that energy can be exported without jeopardising scheduled passenger services.

2. METHODOLOGY

The fleet at Edgware comprised of three main battery-electric bus types, modelled as archetypes (Table 1). The modelling was built around the working timetables of each route, which specify exactly when each vehicle departs, returns and dwells in the depot. These schedules were mapped onto a 15- minute resolution timeline, producing a series of "in-depot" and "out-of-depot" intervals for every bus. A depot interval was only considered valid if the entire 15-minute block was spent stationary at the garage. If any portion of the step overlapped with a trip, the whole interval was treated as "out of depot." This rule prevented the model from double-counting short overlaps at the edges of trips.

The operational day was defined from 03:00 to 03:00 the next day. This convention avoided splitting duties that straddle midnight, which is common in London bus operations, and kept depot dwell periods intact. By treating each 24-hour period this way, late-night returns and early-morning runouts were handled consistently, avoiding bleeds across days.

At each step, the model decided whether the bus was:

- Driving – energy consumption applied.
- In depot – eligible to either charge or discharge to the grid, subject to scheduling rules.

The controller only permitted export if three conditions were met:

1. The bus was physically present in the depot.
2. The next departure could still be achieved with a safe level of battery charge.
3. Export was taking place within a defined demand window if it would benefit the grid.

The outputs were a time series of SoC, charging, and discharging for each bus, which were then aggregated to route-level and depot-level export profiles.

Inputs and assumptions

The backbone of the model was TfL's official working timetables. These provide precise duty schedules, including dead runs (out-of-service movements to and from the depot). They were then consolidated to form a table of runs completed by each running number. This is called a "working." Table 2 (see next page) is the working for running number 121. It details what the trip number is, where it starts and finishes and the times it completes it. It also indicates that a bus is in the depot between a trip that ends in EW GR, and one that starts it. Once the working is complete it is assumed that it loops back to the beginning of the day and the cycle restarts. Trips highlighted in yellow are classed as outbound, blue inbound, and grey trips are DEAD.

Trip lengths were estimated using Google Maps. These included both in-service mileage and dead-running mileage, as both draw on the battery. This allows the energy consumption to be computed accurately for each working.

Table 1: Specifications of Each Bus Archetype

(Source: Volvo 2021; BYD, 2019; Wrightbus, 2025)

Archetype	Abbreviation	Base traction consumption [kWh/km]	Battery Capacity [kWh]

Wrightbus Electroliner	WDE	0.79	454
BYD ADL E400 City EV	BDE	0.75	382
Volvo BZL Single Decker	VMSL	0.70	470

Table 2: Run 121 Working

Run No	Trip	Start	End	From	To
121	DEAD	04:53	04:54	EW GR	EW SN BS
121	5	04:54	05:45	EW SN BS	MARB CG
121	6	05:57	06:46	MARB CG	EW SN BS
121	35	06:56	08:10	EW SN BS	MARB CG
121	40	08:17	09:26	MARB CG	EW SN BS
121	DEAD	09:26	09:27	EW SN BS	EW GR
121	DEAD	12:37	12:38	EW GR	EW SN BS
121	117	12:38	13:54	EW SN BS	MARB CG
121	122	14:05	15:26	MARB CG	EW SN BS
121	159	15:36	16:55	EW SN BS	MARB CG
121	164	17:03	18:27	MARB CG	EW SN BS
121	201	18:37	19:49	EW SN BS	MARB CG
121	204	19:56	20:55	MARB CG	EW SN BS
121	227	21:12	22:08	EW SN BS	MARB CG
121	228	22:20	23:13	MARB CG	EW SN BS
121	249	23:24	00:10	EW SN BS	MARB CG
121	250	00:32	01:18	MARB CG	EW SN BS
121	DEAD	01:18	01:19	EW SN BS	EW GR

Table 3: Summary of Trip Lengths for Route 113

Route	Trip	Start	End	Length (km)
113	DEAD	EW Depot	Edgware	0.13
	Outbound	Edgware	Marble Arch	18.13
	Inbound	Marble Arch	Edgware	17.69
	DEAD	Edgware	EW Depot	0.31
	DEAD	Marble Arch	EW Depot	17.54

Table 3 is a summary of the length of various trips buses on Route 113 undertake over the course of their working. These include “DEAD” trips from the depot to either end of the route, plus the length of the route in either direction which has small variations due to factors such as the geometry of the road, one-way systems, or different pick up and drop of locations at the termini.

Each vehicle was assumed to have access to a 150-kW bi-directional DC charger when in the depot. SoC was constrained between 20% (lower bound) and 90% (upper bound). The lower bound protected against deep cycling, while the upper bound was set to ensure buses weren't continually charged to full as this can be damaging to battery health. To ensure service reliability, the controller always reserved a +10% margin above the energy required for the next scheduled duty. This prevented situations where a vehicle might technically make its next trip but with no operational buffer.

Energy consumption per trip was calculated as a product of distance, base consump-tion and load factor (Table 4), which accounted for passenger occupancy, stop-start driving intensity, and auxiliary loads like heating and air-conditioning.

Table 3: Load factors

Local time band	Load factor (dimensionless)	Rationale
23:00-06:59	0.85	Nighttime low demand
07:00-09:29	1.15	Morning commuter peak
09:30-15:59	0.95	Inter-peak shoulder
16:00-19:29	1.20	Evening commuter peak
19:30-22:59	1.05	Late-evening shoulder

To guarantee service integrity, two floors anchored the model:

- Departure floor: the minimum SoC required before a bus could leave the depot for its next block of service, including a 10% margin.
- Overnight floor: the SoC required for any buses departing the depot at 07:00, ensuring the bus could both export an AM discharge and still complete its first block of service.

The departure floor represented the minimum SoC that bus needed the moment it left the depot for its next scheduled block of service. This floor ensured that vehicles always had sufficient energy to complete their upcoming duty without risk of underperformance. To calculate the departure floor at any depot step t, the model constructed a "need series," This was formed by summing driving energy required for the entire upcoming in-service block, then stamping this requirement backwards across the preceding depot dwell. The model tracked battery energy directly, by updating it at each time step depending on the state and conditions. Any step that contained non-zero driving energy was treated strictly as "out of depot" for energy exchange, preventing the overlap between driving and V2G.

Two design decisions shaped how discharges were scheduled so that results were both interpretable and battery friendly. First, the controller enforced constant-rate discharges inside the AM export window (07:00 to first departure), the evening super-peak (16:00-21:00), and the later-evening tail (21:00-23:00). Flattening export into constant blocks avoided rapid toggling and produced smooth profiles that could realistically be contracted as firm grid services. Second, the controller required a minimum event length of at least two consecutive steps (30 minutes) for any off-peak export block. This removed isolated one-step blips and reduced harmful micro-cycling.

The constant export power within a given window was determined algebraically, by selecting either a maximum of the admissible battery-side energy discharge (driven by the departure floor, i.e. SoC required at departure from the depot). If no capacity was available, no discharge could occur during the window. Converting to the grid side (by multiplying it by the efficiency factor) and dividing by the available dwell time gave the provisional export power.

Window-Specific Behaviour

In general, V2G actions were aligned with the shape of the UK energy demand curve (Table 4). During the super-peak, the controller exported whenever feasible. If a bus remained in the depot for the entire interval and had no departure within it, the target was set to leave enough energy to continue discharging into the late-evening tail. If a departure occurred at a time within the supe-peak, the constant-rate segment was shaped to land precisely on the departure floor at that time. When a bus arrived partway through the super-peak, the same logic applied,

Table 4: V2G actions aligned to UK energy demand curve (NESO, 2024)

Period	Time	Explanation
Super-peak	16:00-21:00	The main export window. Whenever buses were in the depot, the controller aimed for steady discharges across this period.
Peak tail	21:00-23:00	Continued export at constant rates, tapering down to reach the SoC floor by 23:00.
AM export	07:00-first departure	Small discharges when buses dwelled in the depot before morning service.
Off-peak night	23:00-07:00	Charging was prioritised, with export strictly prohibited before 06:00. This "no export before dawn" rule was imposed as a policy choice, recognising that overnight demand is relatively low and pre-dawn micro-cycling would offer little value to the grid.

beginning from the actual arrival timestamp rather than the start of the window. In the peak tail, the controller extended the constant-rate discharge towards the 20% SOC if depot dwell permitted. If a departure occurred during this period, the target again reverted to the relevant departure floor. Where a bus exhausted its admissible energy before 23:00, the discharge flattened earlier. This tail mattered in practice because it allowed the depot to contribute beyond the strict definition of peak hours, while the overnight floor later absorbed the effect of the tail when computing the subsequent charging plan.

In the AM export window, the controller discharged whenever the bus was in the depot and had sufficient headroom. As in the evening, the export rate was determined by a difference-over-time calculation, bringing the SoC precisely to the departure floor at departure unless clipping occurred at the 150-kW charger limit.

During the off-peak, the default behaviour was to charge rather than export, ensuring that energy was banked for the high-value windows. Exceptions were permitted only when the run had no remaining super-peak or AM-export opportunities before its next departure, and two additional conditions held: (i) the available off-peak dwell lasted at least 30 minutes, and (ii) the vehicle could still reach its departure floor using the remaining non-super-peak charging time. Even in these cases, the policy rule against export before 06:00 overrode the logic, recognising that pre-dawn export cycles delivered little system value. In practice, a stable daily pattern emerged within three iterations for Edgware, after which results were taken as representative.

3. RESULTS AND DISCUSSION

Overall, Edgware Depot was able to export a total of 6,455 kWh over the course of a day. Figure 4 illustrates how the model has restricted all V2G events to occur between 06:00 and 23:00. Much of the energy is exported after 18:00 (Figure 1), which coincides with the evening run-in, but there is still significant V2G activity happening between 08:30 and 15:00, reaching a peak instantaneous export of 257 kW at 11:00. Peak periods are shaded as blue (06:00-23:00) and the super-peak is shaded in orange (16:00 to 21:00).

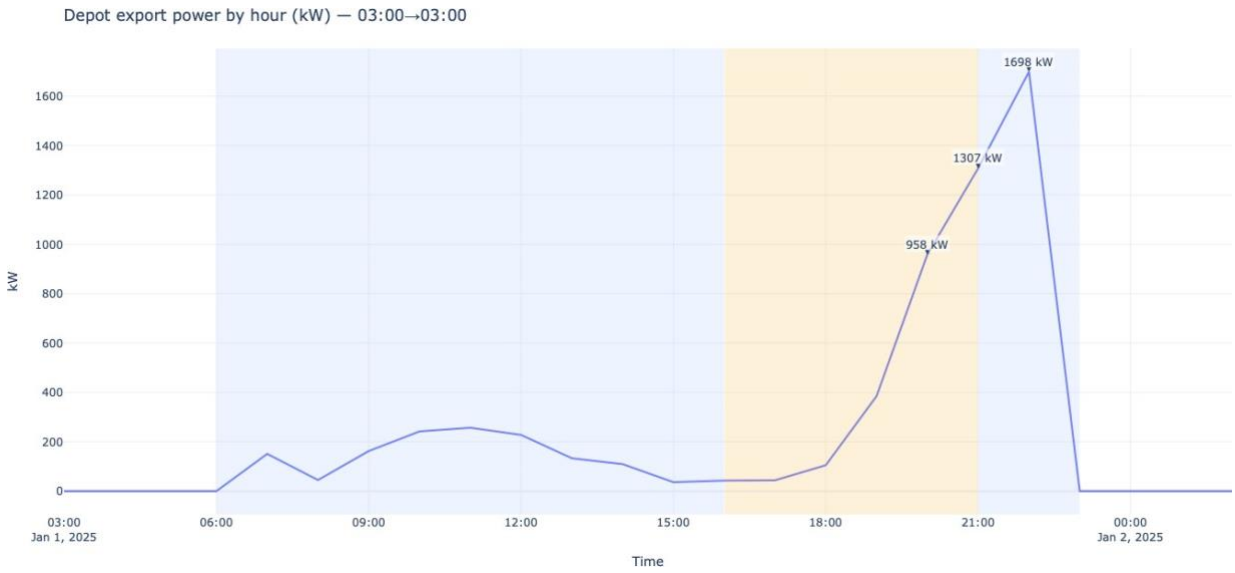


Figure 1: Depot export power by hour (kW)

There was substantial heterogeneity when comparing how much each route contributed to the amount of energy exported. Figure 3 depicts the total kWh per route. Route 113 exported the most energy at 1460 kWh, route 251 closely followed, contributing 1397 kWh over the course of a day. The 204 exported 1222 kWh. The 142 and 240 had a rather low export of 898 kWh and 724 kWh respectively, while the 605 and 605 had impressive contributions totalling 759 kWh despite only having three vehicles allocated to them.

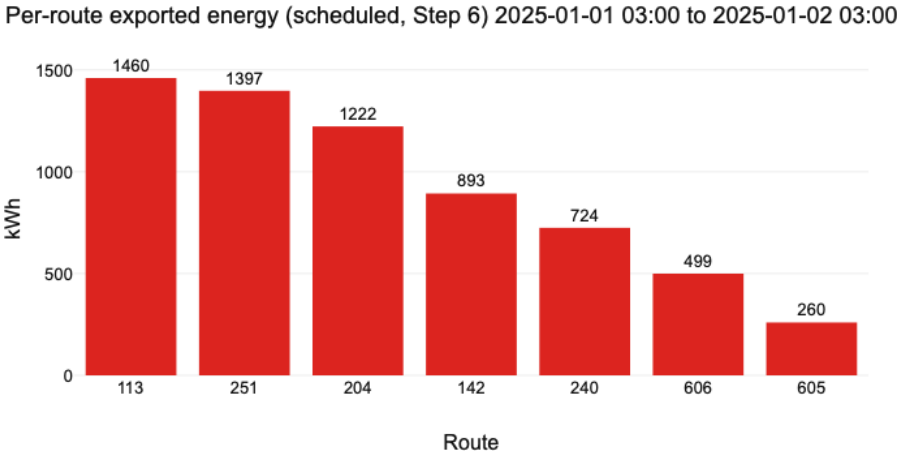


Figure 2: Per-route exported energy

Figure 3 is a comparison of the SoC of three typical running number workings on route 113. Running number 107 departs the depot at 05:14 with a SoC of 90%, the upper limit permitted by the simulation. It then begins discharging energy, by driving, as represented by the blue line. The steepness of the line is affected by the relevant load factor being applied at different points in the day. It then returns to the depot at 18:51 with 50.8% of its battery capacity remaining. It is then connected to the grid via a 150-kW terminal and discharges its remaining available energy until it reaches a SoC of 22%. At 00:30, it is then charged up back to 90% until 02:45, ready for the next day's service.



Figure 3: SoC Comparison of Run 107, 114 and 121

4. CONCLUSIONS

This study aimed to investigate the potential of Vehicle-to-Grid (V2G) technology at Edgware bus depot, assessing both depot-wide and route-level contributions, and evaluating how vehicle-level duty cycles affect the capacity of export energy back to the grid. The results demonstrated that the depot could export a total of 6,455 kWh in a single day under the simulation rules, with the bulk of exports concentrated in the evening super-peak period. At a more granular level, the analysis highlighted substantial heterogeneity between routes and individual running numbers, with some buses consistently positioned to contribute to grid support, while others were unable to participate due to duty structure or timing mismatches with export windows.

Depot-Level Findings

At the aggregate level, Edgware depot was able to export 6,455 kWh over the modelled day, a non- trivial amount of energy equivalent to the daily consumption of approximately 650 average UK households. The temporal distribution of exports, however, was highly uneven. The simulation restricted V2G operations between 06:00 to 23:00, but exports were disproportionately concentrated after 18:00, coinciding with the evening peak in residential electricity demand. This outcome demonstrates the alignment between bus depot availability and system needs. Vehicles that complete their run in the evening and return to the depot can contribute meaningfully to demand-supply balancing during the critical evening peak. This suggests that depot-wide export is shaped less by fleet size than by the duty structures governing vehicle availability for connection.

Route-Level Patterns

The disaggregation by route revealed clear contrasts. Route 113 emerged as the largest contributor, exporting 1,460 kWh, closely followed by route 251 (1,397 kWh) and route 204 (1,222 kWh). Routes 142 and 240 exported considerably less (898 kWh and 724 kWh respectively), while the school routes 605 and 606 provided disproportionately high contributions, combined more than route 240 (759 kwh), given their small fleet size.

These differences can be explained by duty cycle structure, route peak vehicle requirements (PVR) and vehicle type. Route 113 benefits from having a high PVR of 21, short dead runs – with many buses only having to run not in service from Edgware Depot to Edgware Bus Station – and WDE vehicles with a relatively high battery capacity, at least compared to the BDE. Route 251 also benefits from high capacity VMSL vehicles but also benefits from a large number of buses returning to the depot between morning and afternoon peaks, enabling inter-peak discharges as well as evening exports.

By contrast, route 142 has both a longer routing when in service (over 20 km) and longer dead runs to either Watford or Brent Cross from the depot. This results in more mileage being driven therefore a higher energy consumption. It also uses BDE vehicles that have a lower battery capacity of 382 kWh. These two factors in combination mean less energy is left over to be exported to the grid. Both the 142 and 240 also maintain a more continuous in-service operation, limiting the windows for V2G connection.

The school routes at Edgware Depot represent a particularly promising case. These buses only operate short AM and PM runs and remain idle in the depot for much of the day. Therefore, they can provide long, sustained discharges at times that align with grid needs.This heterogeneity highlights that V2G potential is not uniform across a depot's fleet. Instead, it is contingent on the choice of vehicle and the service characteristics. Certain routes that have shorter duties, inter-peak breaks or school buses are far more valuable when looking to implement a V2G system at a bus depot with a more well-rounded export capacity. This finding has important implications for prioritising which vehicles to equip with V2G technology such as bi-directional chargers, suggesting that a targeted rather than blanket approach may maximise returns.

Vehicle-Level Dynamics

At the level of individual running numbers, the results showed striking variability in the State of Charge (SoC) trajectories and the ability to participate in V2G. Some buses, such as running number 107 of route 113, followed a conventional pattern where the bus discharged through the service, returned to the depot with residual capacity, then exported to the grid before recharging overnight. Others such as running number 114 were unable to contribute at all, as their schedules kept them out the depot during export windows.

These results reveal the promise and the constraint of depot-based V2G. On one hand, vehicles like running number 121, which return mid-morning, demonstrate how inter-peak opportunities can be leveraged to smooth exports across the day. On the other hand, the fact that five buses on route 113 were unable to export at all during the useful periods illustrates the limitations imposed by the duty cycles.

Another interesting feature was the prioritisation embedded in the simulation, which often held back vehicles from discharging small amounts in the morning, instead reserving capacity for the evening tail. This reflects the optimisation strategy, where the key driver for the simulation was the discharge during the evening as energy is more valuable and demand is higher, however, it also reduces the extent to which buses contribute to daytime flexibility. From an operational perspective, this points to a trade-off between maximising the evening peak-participation and providing more continuous grid services such as frequency regulation throughout the day.

Operational and Policy Implications

The results carry significant implications for both transport and energy stakeholders. For Transport for London (TfL) and Metroline, the study suggests that V2G could provide a supplementary revenue stream while enhancing the sustainability credentials of bus

electrification. However, the variability in route-level contributions indicates that not all buses should necessarily be equipped with V2G technology. Instead, prioritisation of school services and inter-peak duties may deliver the highest cost-benefit ratio.

From the grid perspective, the depot's export profile is particularly well suited to supporting the evening peak. However, the lack of sustained daytime exports may limit the role of bus depots in providing continuous ancillary services. Coordination between TfL, operators and the grid could explore hybrid strategies, whereby schedules that allow for more garage dwell time (using extra resources) during the day could be implemented to balance revenue-maximising evening discharges with more distributed contributions across the day.

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