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Shared autonomous electric vehicle fleets with vehicle-to-grid capability: Economic viability and environmental co-benefits

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HIGHLIGHTS

- Life-cycle impacts of SAV and SAEV fleets are examined.
- SAEV fleets have higher VMT and require additional infrastructure compared to SAVs.
- V2G services can reduce the operating cost of SAEV fleets by up to 19.6% over 30 years.
- V2G can further leverage the environmental benefits of SAEVs.

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ABSTRACT

Vehicle-to-Grid (V2G) services utilize idle electric vehicle (EV) batteries as distributed energy storage units for the power grid to stabilize the fluctuating demand. The commercial implementation and deployment of V2G services are hindered by concerns about battery degradation, inconvenience, distrust, and further range anxiety, making private mainstream EV owners reluctant to participate in V2G program offered by utilities. The centralized operation and fleet-level ownership of shared autonomous electric vehicles (SAEV) can alleviate these barriers. This paper examines the economic and environmental co-benefits of V2G services in SAEV fleets, using results from operational simulations in a mid-size city (Ann Arbor, MI). We present a life-cycle assessment framework by considering SAEV fleets with 100-mile short-range (SAEV100) and 250-mile long-range (SAEV250) powertrain vehicles and compare the trade-offs of higher vehicle-mile-traveled (VMT) and additional infrastructure requiem nets in the electrified fleet with SAV counterpart. Incorporating a 30-year time-frame, we show that from an economic point of view, the operating cost of the SAEV fleet is 3.4%-8.4% higher than SAV fleet. However, providing V2G service can reduce the cost of SAEV250 fleet by 19.6% compared to SAV fleet by generating revenue, thus making it economically feasible to replace the SAV fleet. We find that on average, V2G service yields a revenue of $2,272 per vehicle annually while saving 66.5 tons of GHG emissions per vehicle per year. We also conduct a thorough sensitivity analysis to quantify the uncertainty of results from key parameters. Finally, we highlight the major opportunities for maximizing the environmental and economic performance of SAEV fleets under the provision of V2G services over the long term.

1. Introduction

Transportation is currently the largest contributor to greenhouse gas (GHG) emissions among the US economic sectors and the fastest-growing source of GHG emissions and energy consumption [1,2]. Improving the energy efficiency of transportation and reducing the associated GHG emissions are crucially needed to meet the 2°C Paris Agreement goal. Emerging mobility technologies including automation, electrification, and shared mobility are poised to reshape the transportation sector and are expected to reduce the energy and environmental externalities, once deployed at scale [3–7]. These technologies have natural synergies, enhance widespread adoption of each individual technology, create new Mobility-as-a-Service business models, and lead to a more sustainable transportation system [8].

Electric vehicles (EVs) not only entail higher energy efficiency compared to internal combustion engine vehicles (ICEVs), but also can concentrate emissions from point sources of tailpipes to power plants for

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Nomenclature

Inflation Rate 2%
Discount Rate 5%
$RP_{vehicle}$ The average retail price of the vehicle [$25K, $35K, $44K]
Vehicle Depreciate rate The annual rate at which the value of a vehicle depreciates [17.5%]
Charging Infrastructure Total cost for building charging infrastructure [58,000 $/plug]
V2G Equipment Cost Cost for upgrading EVs with V2G equipment [2,000 $/vehicle]
R V2G service revenue
$P_{capacity}$ Capacity price [$257.53/MW-day]
$P_{regulation}$ Average electricity price to all users [0.10–0.18 $/kWh]
$P_{transport}$ Average electricity price for transportation [0.10–0.12 $/kWh]
$P_{battery}$ Battery prices [$/kWh]
T_{plug} The time when electric vehicles can provide V2G services [h]
$P_{vehicle}$ Maximum output power of electric vehicles in ten minutes [kW]
P_{line} Maximum power of the discharging line. [50 kW]
E_{disp} Actual electricity dispatched [kWh]
R_{d-c} The ratio of actual exchange energy to exchange capacity [10%]
DoD Depth of discharge [10%]
L_{et} Battery lifetime [$L_c \times B \times DoD$]
$Emi_{traditonal}$ GHG emission factor of the gas turbine generator
Emi_{grid} GHG emission factor of the mixed grid
$Emi_{battery}$ Life-cycle GHG emission factor for battery [112 kg/kWh]
$Energy_{battery}$ Life-cycle energy use factor for battery [350–650 MJ/kWh]

more efficient and effective emission control and, most importantly, help increase renewable energy integration. Renewable-based electrification is considered an effective strategy towards decarbonizing future mobility without suppressing the demand [9,10]. On the other hand, the market penetration of EVs is currently hindered by their high cost, arguably short driving ranges, long charging times, and limited charging infrastructure [11]. Shared mobility services enabled by vehicle automation can reduce the economic and technical barriers to EV adoption. This includes a higher utilization rate leading to the shorter payback time of higher upfront vehicle cost for fleet vehicles [12,13], centralized operation leading to optimized charging time and driving range concerns [14], as well as enhancing profitability and cost-effectiveness due to increased fleet utilization [15].

Vehicle-to-Grid (V2G) is another emerging technology that can improve the economic and environmental benefits of electrified fleets while helping make the power grid system more resilient. V2G refers to the use of on-board batteries of EVs as distributed energy storage units to discharge to the grid to stabilize the fluctuating power demand [16]. V2G can provide revenue by both trading electricity and providing capacity to the grid, which can significantly reduce the life-cycle cost of EV ownership and make up for the construction of public EV facilities [17]. V2G services are promising substitutes for traditional peaker-plant generators, which are relatively inefficient and have high environmental impacts. This reduces the system-level environmental footprint of the power grid and transportation sector as a whole [18]. However, the implementation of V2G services is hindered by concerns about battery degradation, inconvenience, distrust, and further range anxiety, making private mainstream EV owners reluctant to participate in the V2G program offered by utilities [19–22].

Despite the reluctance of private EV owners, V2G can offer significant additional revenue to a fleet of shared autonomous electric vehicles (SAEVs) while avioding the aforementioned concerns [8]. Therefore, commercial taxi fleets may be early adopters of V2G-enabled SAEVs, taking advantage of mutual complementary attributes including the optimized and centralized operation of shared autonomous vehicle (SAV) technology, the low operating cost of EVs in high-vehicle-utilization scenarios, and the revenue generation from power exchange when vehicles are not unoccupied. A growing number of companies such as Zoox and Tesla have announced their plans to roll out shared autonomous electrified services (electric robotaxi) with widespread operation between 2022 and 2030 [23,24]. Several studies on the operation of SAV and SAEV fleets have shown that an average vehicle is unoccupied or idling 8–16 hours a day [25,26], despite a significantly higher utilization rate compared to household vehicles (less than 1 hour on average). Among those, Lu et al. (2018) showed that in a fleet of 4,000 SAVs in Ann Arbor, Michigan (MI) in the US, an average vehicle is in service only 7.4 h per day, traveling 109 miles [27]. This creates an excellent opportunity for the fleet to provide V2G services, harnessing the mutual benefits of grid stabilization, revenue generation, and reducing life-cycle environmental impacts.

In this study, we build on the results of Lu et al. (2018), by modeling the economic and environmental impacts of commercial SAV and SAEV fleets composed of ICEV and EV, respectively, and investigate the provision of V2G services on the latter. We consider SAEV fleets with 100-mile short-range (SAEV100) and 250-mile long-range (SAEV250) powertrain options and compare the trade-offs of higher vehicle-mile-traveled (VMT) in the electrified fleet with SAV counterpart. We show that the operating cost of SAEV fleet is 3.4%-8.4% higher than SAV fleet. Providing V2G services can reduce the cost of SAEV250 fleet by 19.6% compared to the SAV fleet by generating revenue, thus making it economically feasible to replace SAV fleet. From the energy-saving and GHG emission reduction perpectives, V2G can further leverage the environmental benefits of SAEV compared to SAV.

We begin the article with a comprehensive literature review on SAV and SAEV operation, state-of-the-art on V2G services, and the mutual benefit when SAEVs are V2G-enabled. In Section 3, we provide details on the methodology. The results are presented in Section 4 followed by a sensitivity analysis of key variables to check the robustness of our findings. Finally, we discuss our conclusions and acknowledge the limitations of the modeling approach in Section 5.

2. Literature review

2.1. SAV and SAEV

Although large-scale SAV and SAEV deployment has not yet been achieved, many studies have investigated the impact of the combination of SAV and SAEV on fleet costs, mobility, and the environment. SAV, especially the SAEV fleet, has significant advantages in reducing energy consumption and GHG emissions [28]. Wadud et al. claimed that SAV could result in up to a 45% reduction in energy consumption if different numbers of passengers can use vehicles of corresponding sizes [5]. At the vehicle level, automation can increase fuel efficiency by 2% to 25% and up to 40% in extreme cases. Martinez et al. ran an agent-based model and found full adoption of SAV can save 38.2% of GHG emission [29]. However, the long-term net benefits of automated vehicle (AV) technology for energy consumption and GHG emissions are not clear when considering the interaction of vehicle fleet, transportation system, and urban system [3]. Lu et al. argued that the increase in total VMT by SAEVs may increase GHG emissions due to deadheading VMT and high grid carbon intensity [27].

Compared with ordinary vehicles, AVs tend to have higher operating costs, including equipment upgrades, additional energy consumption, etc. The electrification of SAVs can not only further reduce energy consumption and GHG emissions but also help reduce the operating costs of AVs. Gawron et al. showed that electrified SAVs in Austin, Texas can reduce GHG emissions by 60–87% [30]. Bauer et al. estimated that a SAEV fleet in Manhattan, New York City drawing power from the current power grid would reduce GHG emissions by 73% and energy consumption by 58% compared to the SAV fleet. The cost of of SAEV service is estimated to be $0.29-$0.61 per revenue mile, which is $0.05–$0.08 lower than that of SAV service [31].

2.2. V2G service

Various studies have proposed that individuals or fleets providing V2G services generate net revenue and environmental benefits (Table 1). For instance, Sufyan et al. simulated the charging and discharging process for private EV with renewable energy, and found that a price-based optimization of charging scheduling can reduce charging cost by 14.7% [32]. Noori et al. explored light-duty EVs with V2G services in five different regions reporting a significant reduction in ownership cost and GHG emission savings at regional level. They assume that the time that the vehicle is connected to the grid, the duration and the power of the grid's regulation demand are randomly and uniformly distributed [18]. Iacobucci et al. used a price-based strategy for exchanging electricity with the grid in simulating SAEV fleet operations, resulting in a 40% drop in break-even prices [33]. Li et al. found that, in Shanghai, it is only when the peak price of electricity sent back to the grid is more than three times the price of electricity in the valley that private users of BEV can profit from V2G peak shaving [34]. However, for large-scale commercial fleets, providing stable capacity may generate greater profits than performing V2G services based on price. Capacity payment revenue accounts for a significant portion of the net revenue from V2G services [22]. Also, the charging and discharging strategy based on the electricity price will affect the maximum utilization of the SAEV fleet for mobility services, thereby increasing the required fleet size, resulting in an increase in costs. Hence, we assume that the SAEV participates in the regulation service at any idle time, regardless of the electricity price at that time. In addition, because the GHG emission factors of electricity vary greatly across states in the US over the next 30 years [35], if the entire life-cycle is considered, the emission reduction effects of V2G service will also be quite different. Therefore, the economic and environmental benefits of V2G need to be carefully evaluated according to the regional situation.

2.3. Research needs

A SAEV fleet may not have an advantage over a SAV fleet in terms of total cost due to new charging infrastructure requirements and higher capital cost of EVs; but the provision of V2G service can provide the SAEV fleet with better economic and environmental performance. Also, a large-scale deployment of SAEV fleets that provides V2G services has many other important side benefits, such as the integration of renewable energy and enhanced urban mobility (Table 2). Boewing et al. suggested that V2G operation can enable a 100% renewable energy source without affecting high-quality mobility services [38]. However, the usual V2G service assumptions are based on 90% parking time and free scheduled charging and discharging for private EVs. This may not apply to the situation where the SAEV fleet replaces private vehicles on a large scale and becomes the mainstream mode of transportation [39].

Table 2
Main benefits of V2G and SAEV.

Emerging technology	Benefits	Description
V2G	Integrate local renewable energy	Help solve the fluctuations caused by the connection of renewable energy to local microgrids or large power grids [40–42]
	Controlled charging	Ability to decide when to recharge EV. highly concentrated and uncoordinated charging can significantly increase peak demand, and raise the demands on electricity infrastructure [43]
	Increase power grid reliability	Provide load balancing and reduce peak loads [44], and make better use of existing power generation and power distribution facilities [45,46]
	Emergency backup power	As a backup power supply in case of sudden power outages such as earthquakes [47]
SAEV	Increase safety	Avoid or even put an end to traffic accidents [48,49]
	Enhance urban mobility	Improve the utilization rate of vehicles, and increase the speed of vehicle circulation while ensuring safety [50–52]
	Reduce energy consumption	Reduce energy consumption while reducing total travel time by optimizing routes [53]
	In-vehicle time productivity	Allow driving time to be used for work or entertainment [54]
	Reduce land use	Significantly reduce parking and facility land [55,56]

Table 1
Recent literature on private and fleet-level V2G services.

Technology	Renewable Energy	Battery Degradation	Approach	Scope	Impact	Source
SAEV + V2G		√	Optimization of transport model and trip request model	Operation	40% drop in break-even prices	[33]
SAEV + V2G		√	Optimization of charge scheduling	Charging	V2G increased the charge saving from 28% to 43%	[36]
Private EV + V2G	√	√	Optimization of V2G scheduling with wind	Charging	128.9$/day benefit for the EV owner	[37]
Private EV + V2G	√	√	Optimization of V2G scheduling with renewable energy	Charging	V2G decrease life-cycle charging cost by 14.7% with renewable energy	[32]
Electric delivery truck + V2G		√		Total cost; LCA of fuel for GHG analysis	V2G can yield up to 60,000 $ and save approximately 300 tons of GHG emissions in 15 years	[22]
BEV + V2G		√	Agent-Based Modeling	Operation; LCA of fuel for GHG analysis	V2G can yield up to 62,000 $ in 16 years; saving 500,000 tons of CO2 emissions reductions by the end of 2030 if 1% of EV provide V2G services	[18]

3. Methods and materials

In this study, we aim to meet the travel needs of 20,000 people who drive to work in Ann Arbor, MI with the fleet size and waiting time constraints based on Lu et al. [27]. A 30-year timeframe, including multiple fleet turnovers, was chosen to analyze the fleet operations through 2050. The system boundary includes the entire life-cycle of the fleet and fuel. Consistent with Lu et al. [27], we assume that travel demand and traffic conditions will remain the same for the next 30 years. To explore the economic feasibility of replacing SAV fleets with SAEV fleets, we convert all future costs into present values in 2020 (in Million $) with a discount rate of 5% [57]. To investigate the environmental advantages of the SAEV fleet, we also estimate total energy consumption (in MJ) and GHG emissions (in ton CO2-eq) over the next 30 years.

We consider both ICEVs and BEVs in this study. The BEV models consist of both 100-mile short-range and 250-mile long-range options with and without V2G capabilities. The long-range BEV has a lower efficiency than the short-range BEV due to the extra weight from the larger battery. Relevant parameters are shown in Table 3 [58].

3.1. SAV service simulation

The main characteristics of the shared autonomous fleet scenarios that can meet the travel demand are shown in Table 4. Based on the model made by Lu et al., we added a simulation of SAEV fleets with different battery capacities [27]. Due to the different cruising mileage and charging requirements, the size of the SAEV fleet that meets the same mobility services is larger than the SAV fleet.

3.2. Fleet operation

The following assumptions are made regarding the operation of the shared autonomous fleet:

- The first batch of vehicles are purchased in 2020. Since then, all vehicles are replaced with new vehicle models every five years. The purchase price of new vehicles will increase in line with the average increase projected by the US Energy Information Administration (EIA) [59].
- With the renewal of vehicles, the fuel/energy efficiency increases correspondingly, which is consistent with the average improvement of similar vehicles as suggested in [59].
- The implement of SAEV fleet requires building charging stations, while the existing gas stations can meet the needs of SAVs.
- The SAEVs can provide V2G services for half of the parking time as a baseline. Noel et al. assumed all parking times for school buses are available for V2G service. We believe 50% of parking time is a more reasonable baseline for the availability of V2G services and tested this hypothesis in the sensitivity analysis section [60].
- Gradual grid decarbonization and Michigan's high carbon intensity grid are considered when calculating GHG emissions of SAEVs consistent with [35].

We also consider the cost by cash flow analysis except for the revenue from the provision of mobility services. We compare the net present value of the total annual costs of three different vehicle options from 2020 to 2050 with and without V2G capability.

Table 3
Assumed characteristics of vehicles in the fleet operation simulations [27].

	ICEV (SAV)	BEV100 (SAEV100)	BEV250 (SAEV250)
Fuel economy (Energy efficiency)	55MPG	131MPGe (26 kWh/100 mile)	123MPGe (27 kWh/100 mile)
Purchase price ($)	25,000	35,000	44,000
Battery capacity (kWh)	—	28	75
GHG direct emission (grams/km)	101.3	—	—

Table 4
Results of the one-week simulation for SAV and SAEV operations [27].

	SAV	SAEV100	SAEV250
Fleet Size	4000	5290	4256
Number of DCFC chargers	0	650	650
Average Revenue Generating VMT per Vehicle per Week[1]	764.75	575.22	719.75
Average unoccupied VMT per Vehicle per Week	149.39	126.45	143.11
Average Park Time per Vehicle per Week (hr)	116.17	129.40	118.22
Fleet Total VMT per Week[2]	3,656,563	3,711,834	3,672,332
Average vehicle lifetime	160 k miles/ average annual VMT	200 k miles/ average annual VMT	200 k miles/ average annual VMT

[1] Revenue generating miles are occupied miles.
[2] 2–4% of trips were unserved when the 10-minute wait time threshold is not met.

3.2.1. Modeling of fleet operation costs

While the vehicle purchase cost is only added in the year of purchase, the fuel cost, maintenance, insurance, tax fee, and vehicle cleaning are averaged over a year.

Vehicle purchase (VP) cost: We assume that the new vehicle will be purchased at the average retail price, with data collected from the US Department of Energy [61]. Starting from the second car purchase, fleet operators can reduce the cost of vehicle purchases by selling the old ones. For the replaced vehicles, it is assumed that they have a residual value and can be recovered by vehicle selling at the net present value. We assume the vehicle value depreciates at an annual rate of 17.5% [62].

Fuel (F) cost: EIA predicts the changes in the average energy efficiency of various vehicle categories in the next 30 years [59]. We assume that the energy efficiency of selected models will increase in the next 30 years and apply the new energy efficiency after replacing the vehicles. The energy price adopts the predicted value from EIA [59], and the price fluctuation is considered in the sensitivity analysis.

Vehicle maintenance (VM) cost: Maintenance cost estimates are adopted from [63].

Other fixed vehicle ownership costs: Vehicle insurance, taxes, and cleaning (VITC) costs are based on [64]. For autonomous vehicles that provide travel services, we expect that safer driving and management in the future can greatly reduce insurance fees, which will be discussed in the sensitivity analysis.

Charging infrastructure (CI) Cost: Unlike SAVs, SAEVs need to build new charging stations to meet the demand for frequent charging. The total price (including equipment and installation) of DC fast charger (DCFC) is between $14,000 and $91,000 [65]. In this study, we chose a median estimate for 50 kW of $58,000 per DCFC station and the annual maintenance cost is set to 5% of the original price [66].

V2G infrastructure (V2GI) cost: EVs need to upgrade their equipment to provide V2G services, and we assume $2,000 for each EV and only add it in the first year [18].

3.2.2. Net revenue of V2G services

The net revenue of V2G service (NR_{V2G}) is calculated as total revenues minus total costs [17]:

$$\mathrm{NR}_{V2G} = P_{capacity} \times P \times T_{plug} + P_{regulation} \times E_{disp} - P_{transport} \times E_{disp} - \frac{E_{disp}}{L_{et}} \times P_{battery} \quad (1)$$

where the first term is the capacity service revenue and the second term is the energy service revenue. The cost refers to the cost due to V2G services, including purchasing energy and battery degradation due to V2G. The capacity revenue is for the maximum capacity specified in the contract for that duration. $P_{capacity}$ is the capacity price in \$/kWh and we adopt the value from Michigan [67]. P is the lower value of $P_{vehicle}$ and P_{line}. Considering the limitation of the vehicle charging time and the number of devices, we assume that the vehicle can provide V2G services for half of the parking time (T_{plug}). $P_{regulation}$ is the average electricity price to all users and we adopt the predict electricity price from EIA [59]. We updated the original unit \$/MMBtu to \$/kWh to be consistent in our units.E_{disp} is the actual electricity dispatched in kWh. Due to the uncertainty of adjustment, P and T can vary greatly. Therefore, to estimate the cost and benefit of V2G, we introduce a "dispatch to capability" ratio similar to [17]:

$$R_{d-c} = \frac{E_{disp}}{P \times T_{plug}} \quad (2)$$

We use logistic regression and data from Bloomberg New Energy Finance to predict the battery price ($P_{battery}$) in \$/kWh (Fig. 1) and the prediction is similar to the International Council on Clean Transportation (ICCT) [68,69]. We predict that the cost of the battery rapidly reduces over time, which is even considered to be linearly reduced [70]. As a conservative estimate, we assume 107.9 \$/kWh in the first year as a base scenario and it will remain unchanged after that. The impact of battery cost is further discussed in the sensitivity analysis. L_{et} is the lifetime of battery in energy (kWh):

$$L_{et} = L_c \times B \times DoD \quad (3)$$

where L_c is the lifetime in cycles, B is the battery capacity in kWh, and DoD is the depth of discharge corresponding to L_c. Peterson et al. suggested that DoD of 100% corresponds to about 3000 cycles, and DoD of 10% corresponds to 100,000 cycles [71]. V2G regulation is closer to the DoD of 10% and we consider 10,000 times the battery capacity as the battery lifetime.

3.2.3. Total annual cost

From the perspective of a fleet operator, the total annual cost (TAC) of fleet operation includes vehicle purchases (VP), fuel (F), vehicle maintenance (VM), vehicle insurance, taxes and cleaning (VITC), charging infrastructure (CI), V2G infrastructure (V2GI), and possible costs and revenues generated by V2G services.

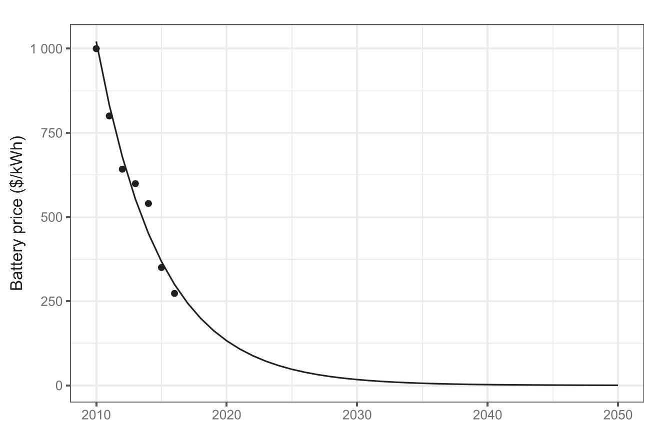

Fig. 1. Electric vehicle battery pack price forecast from 2020 to 2050 [68,69].

$$TAC = VP + F + VM + VITC + [CI + (\mathrm{V2GI} - \mathrm{NR}_{V2G})] \quad (4)$$

where the items in parentheses are only added for SAEV fleets and the items in brackets are only added to the V2G service.

3.3. GHG emissions and energy use

The system boundary of environmental impact analysis includes the process from cradle to grave including energy production, energy use, battery degradation, and V2G service.

Fleet and AV sub-system manufacturing: GHG emissions and energy use data for the production of fleet vehicles are obtained from the GREET Model and data for sub-system is gathered from Gawron et al. [72,73]. In the base case from Gawron et al., the power consumption of AV subsystems is about 2,000 W in 2020 [72]. Gawron et al. suggested that energy consumption of computation is halved in 2.7 years [74]. With the improvement of the level of autonomous driving and safety considerations, the demand for subsystems may increase in the future. As a conservative estimate, we assume that the energy consumption is halved in 5.4 years. The power consumption will be 2,000 W in 2020 and decreases to around 291 W in 2035.

Energy production and use: We estimate the GHG emissions and energy use during the energy production and vehicle driving in the Ann Arbor region using data from [35,59,61] and found that they were higher than the national average.

V2G service emissions and energy reduction: Providing V2G services will accelerate the degradation of batteries, which in turn leads to an increase in GHG emissions and energy consumption from the production and disposal of batteries. The US Environmental Protection Agency estimated battery life-cycle emissions as 112 kg/kWh ($Emi_{battery}$) [75], while Romare et al. estimated battery life-cycle energy use is 350–650 MJ/kWh ($Energy_{battery}$) [76].

Due to the random fluctuation of power demand, the traditional use of gas turbine generators for regulation service is very inefficient. Lin et al. argued that the efficiency of gas turbine generators may be only one-third of that of energy storage [77]. We multiplied the emission factor and energy use of gas turbines by three times:

$$\mathrm{Emi}_{reduction} = E_{disp} \times \left(Emi_{traditional} \times 3 - Emi_{grid}\right) - \mathrm{Emi}_{battery} \quad (5)$$

$$\mathrm{Energy}_{reduction} = \left(Energy_{traditional} \times 3 - Energy_{grid}\right) - \mathrm{Energy}_{battery} \quad (6)$$

where E_{disp} is the actual electricity dispatched in kWh, $Emi_{traditional}$ is the emission rate of the gas turbine generator, Emi_{grid} is the emission rate of the mixed grid, and $Energy_{traditional}$ and $Energy_{grid}$ are the energy use for generating electricity from gas turbine generators and the average energy use for generating grid electricity, respectively.

4. Results and discussion

4.1. Baseline scenario

4.1.1. 30-Year cost of ownership of SAV fleets, SAEV fleets with and without V2G service

Vehicle purchase and maintenance account for the largest proportion of 30-year cumulative cost. Even if the intial costs of SAEV fleets (including the purchase of vehicles and the construction of charging facilities) were spread over a 30-year operating cycle, it would still be an economic disincentive to use a fleet of SAEVs instead of a fleet of SAVs. The advantages of EVs in terms of higher energy efficiency and lower maintenance costs are not enough to offset the high car purchase costs, not to mention the additional vehicle cleaning costs brought by the larger fleet size and the cost of building new charging facilities. Without providing V2G services, the cumulative cost of SAEV fleets is higher than that of SAV fleet.

The extra weight of the larger battery makes the BEV250 energy efficiency slightly lower than the BEV100. However, a larger battery means a longer cruising range, higher passenger capacity, and reduced fleet size. As a result, vehicle purchase, maintenance, and cleaning cost are reduced, making the overall cost of SAEV250 lower than SAEV100.

V2G services can bring considerable benefits, especially for the SAEV250 fleet with a larger battery capacity. The increase in battery capacity can significantly increase the benefits of V2G services. For SAEV250, the revenue from V2G services can cover approximately 30% of the total cost. If V2G services are provided, the cumulative cost of the SAEV250 fleet is lower than the SAV fleet, indicating that SAEV fleets with large battery capacity may be economically feasible to replace SAV fleets (Fig. 2).

4.1.2. TAC of ownership of commercial SAV fleets and V2G service

Fig. 3 depicts the yearly total cumulative and annual cost of SAV and SAEV fleets with different battery capacities. We find that although the cost of replacing vehicles in the fleet is slowly decreasing, the TAC of the vehicle replacement year is much higher than that of ordinary operating years. Especially for SAEV fleet, a large amount of start-up capital is required in the first year due to the high vehicle price and the construction of new charging facilities. The construction of new charging facilities accounts for about 14.5% of the initial cost. Higher initial costs may become one of the economic constraints for SAEV fleets to replace SAV fleets.

For a 30-year long-term shared autonomous fleet investment, the cumulative cost is the primary consideration for fleet owners. Although the cost of the SAEV fleet operation is lower than that of the SAV fleet, the much higher vehicle replacement cost makes the SAEV fleet not dominant in the total cumulative cost even in the long-term investment. The 30-year cumulative cost of the SAEV250 fleet is 3.4% higher than the SAV fleet. It is worth noting that although SAEV250 is more expensive and less fuel-efficient than SAEV100, the total cumulative cost of the SAEV250 fleet is actually lower. The longer cruising range enables SAEV250 fleet to meet the requirements of mobility services with a smaller fleet size, thus significantly reducing the total cost.

With the provision of V2G services, the total cost of the SAEV fleet drops significantly, and the reduction is largely related to the battery capacity. The total cost of the SAEV100 fleet will be about the same as the SAV fleet in 2050, and the total cost of the SAEV250 fleet will be lower than the SAV fleet after 2032. In other words, for medium and long-term investments over 15 years, if V2G services are provided, it is economically feasible to replace the SAV fleet with SAEV250 fleet or a longer-range SAEV fleet. A SAEV250 fleet can save almost 20% of the cost compared to SAV fleet in a 30-year investment period.

4.1.3. Energy and GHG emission saving

The energy consumption and GHG emissions in the use phase account for more than 68% of total GHG emission and 59% of energy consumption in the whole life-cycle of the fleet. SAEV fleets can save up to 35.8% in GHG emissions and 41.4% in energy consumption in the whole life-cycle compared to the SAV fleet.

From the perspective of vehicle production and assembly, the energy consumption and GHG emissions of a single SAEV are 30.8% and 30.4% higher than those of SAV. Coupled with the larger fleet size, the energy consumption and GHG emissions are at least 39.2% and 38.8% higher for the production phase of the SAEV fleet than the SAV fleet. It is worth noting that the energy consumption and GHG emissions of SAEV250 fleet are 19.5% lower than that of SAEV100 fleet, due to the smaller fleet size.

In the operation, the main emissions come from the upstream fuel and the tailpipe emissions. Although the carbon intensity of the power grid in Michigan is higher than the US average, the advantages of zero-emission and higher efficiency of EVs are still significant. SAEV fleet in Michigan can save 46.3% of GHG emissions compared to the SAV fleet. GHG reduction effect of SAEVs in other states of the US are more pronounced. Also, higher energy efficiency makes SAEVs consume 40% less energy than SAVs. The larger battery capacity of SAEV250 only increases 5.2% and 5.1% on the total energy consumption and GHG emissions compared to SAEV100. The impact of the lower fuel efficiency is partially offset by the reduction in total fleet VMT due to the longer range.

V2G service can greatly reduce energy consumption and GHG

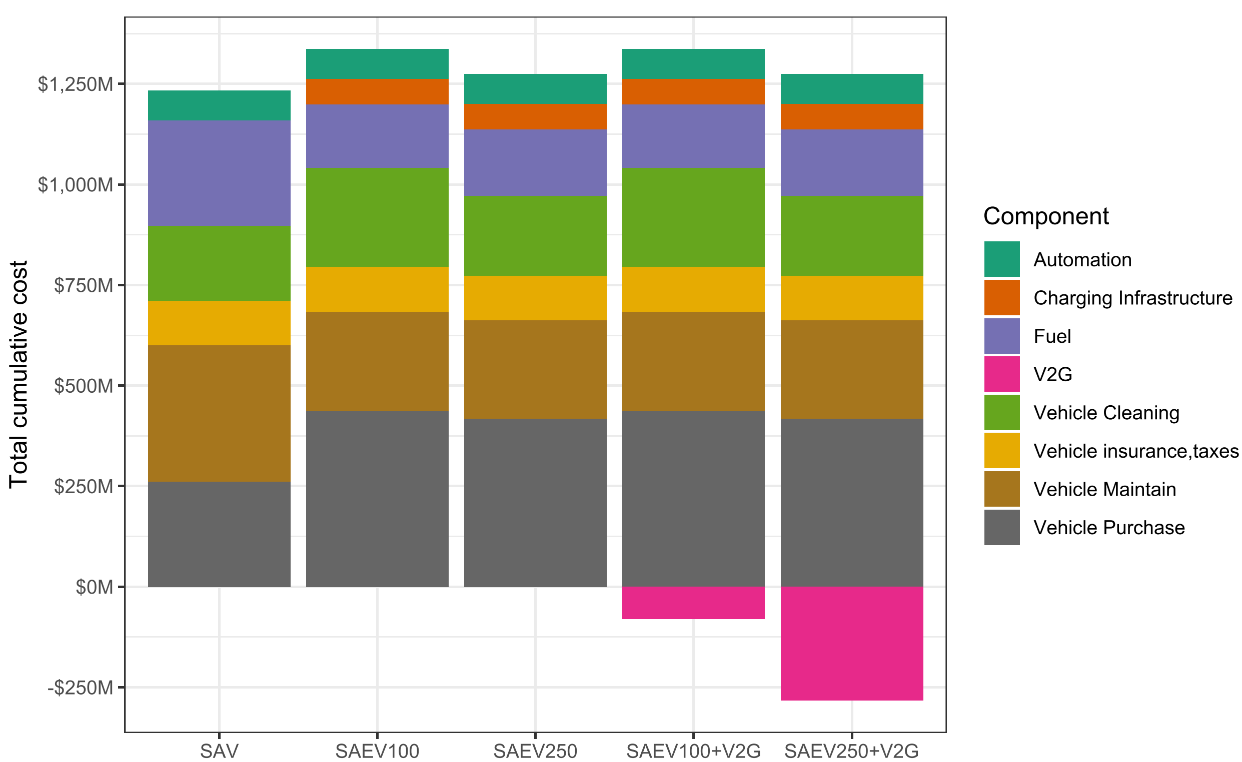

Fig. 2. 30-year cost component of fleets.

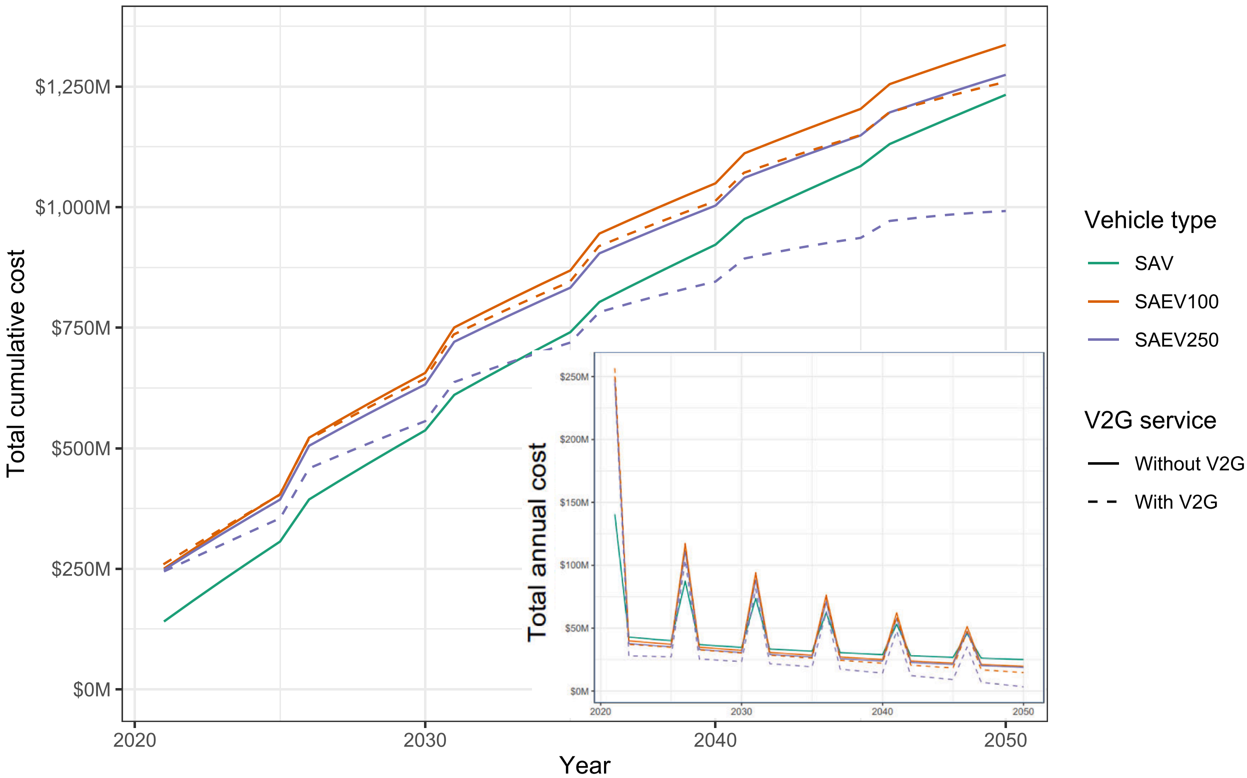

Fig. 3. Total cumulative and the annual cost of fleets.

emissions, which is an excellent choice to achieve complete decarbonization and saving energy. Even with SAEV100 which offers fewer V2G services, V2G services can save 46.8% of total energy consumption and reduce total GHG emissions by 8.7 times. Battery capacity has a significant impact on the effect of V2G services. From 28kWh to 75kWh, the energy consumption saving and GHG emission reduction from V2G services increase more than three times.

Obviously, higher energy efficiency makes SAEV the best choice for environmental benefits. Although the energy efficiency of SAEV250 is slightly lower than that of SAEV100, the smaller fleet size makes SAEV250 a better choice. If V2G service is provided, the advantages of SAEVs with larger battery capacity will be more significant. SAEV250 fleet can save 8 times of GHG emissions and 1.3 times of energy consumption from SAV fleet operation (Fig. 4).

4.2. Sensitivity analysis

We conduct sensitivity analysis to understand the impacts of various parameters on the modeling results including the 30-year cost, GHG emissions, and energy savings of the SAEV250 fleet relative to SAV fleet (Table 5).

In a small range of fluctuations (±10%), electricity price (charging) has the greatest impact on cost savings, followed by regulation price, battery capacity, capacity price, V2G availability, energy efficiency of SAV, gasoline price, EV price, and energy efficiency of SAEV. Note that the change of total cost saving caused by R_{d-c}, battery price, vehicle cleaning fee, and insurance fee are less than 1%. In contrast, a 10% reduction in electricity price increases total cost savings to 28.1%.

Turbine generator emission factor has the greatest impact on GHG emissions, followed by battery capacity, V2G availability, and R_{d-c}. A 10% increase in battery capacity increases total GHG emission savings to 31 times of SAV GHG emissions. The changes of other variables, such as grid emission factor, energy efficiency of SAV, energy efficiency of SAEV, and gasoline emission factor, has marginal effects on GHG emissions (less than 1%).

Battery capacity also has the greatest impact on energy savings,

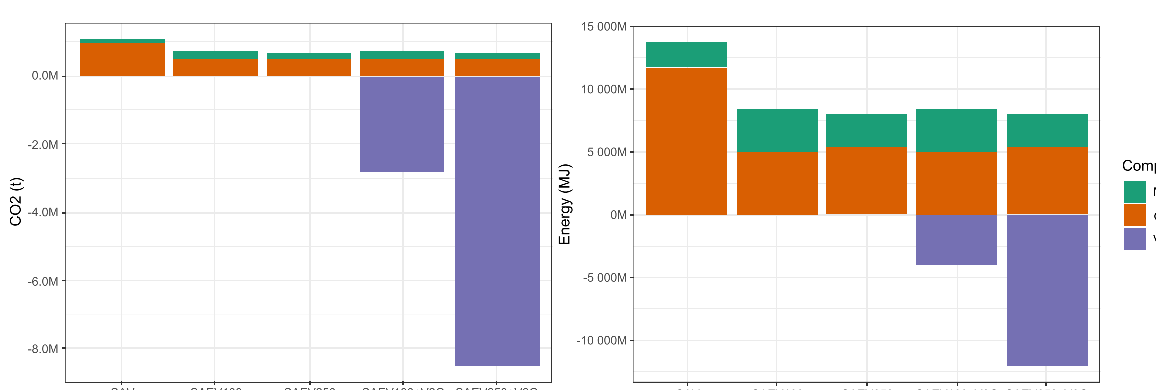

Fig. 4. GHG emission and energy consumption component of fleets.

Table 5
Sensitivity analysis of 30-year cost, GHG emissions, and energy saving of SAEV250 compared to the baseline.

Variable	Cost		GHG emissions		Energy	
(−10%, +10%)	−10%	+10%	−10%	+10%	−10%	+10%
Electricity price (Charging)	43.71%	−43.71%	0.00%	0.00%	0.00%	0.00%
Regulation price	−36.49%	36.49%	0.00%	0.00%	0.00%	0.00%
Battery capacity	−14.90%	14.90%	−11.58%	11.58%	−8.23%	8.23%
Capacity price	−14.35%	14.35%	0.00%	0.00%	0.00%	0.00%
V2G availability (50% parking time)	−12.31%	12.31%	−9.56%	9.56%	−6.80%	6.80%
Energy efficiency of SAV	12.09%	−9.89%	1.19%	−0.97%	7.30%	−5.97%
Gasoline price	−10.88%	10.88%	0.00%	0.00%	0.00%	0.00%
EV price	6.50%	−6.50%	0.00%	0.00%	0.00%	0.00%
Energy efficiency of SAEV	−7.63%	6.24%	−0.64%	0.52%	−3.29%	2.69%
R_{d-c}	2.04%	−2.04%	−9.56%	9.56%	−6.80%	6.80%
Battery price	1.68%	−1.68%	0.00%	0.00%	0.00%	0.00%
Vehicle cleaning fee	0.49%	−0.49%	0.00%	0.00%	0.00%	0.00%
Insurance fee	−0.02%	−0.02%	0.00%	0.00%	0.00%	0.00%
Grid emission factor	0.00%	0.00%	2.94%	−2.94%	0.00%	0.00%
Gasoline emission	0.00%	0.00%	−1.07%	1.07%	0.00%	0.00%
Turbine generator emission factor	0.00%	0.00%	−11.93%	11.93%	0.00%	0.00%

followed by energy efficiency of SAV, V2G availability, R_{d-c}, and energy efficiency of SAEV. A 10% increase in battery capacity increases total energy consumption savings to 139.8%.

In summary, the future fluctuations of electricity price (charging) and regulation price have a great impact on the total cost; and the availability of cheap electricity determines the cost advantage of the SAEV fleet with V2G service. Furthermore, the higher initial price of SAEVs also greatly affects the total cost of ownership; subsidies could further promote the SAEV fleet. Larger battery capacity can not only reduce the total cost, but GHG emissions and energy use due to smaller fleet size. Therefore, the SAEV fleet with a longer cruising distance is a better choice overall. R_{d-c} has a large impact on energy saving and emission reduction. The regulatory capacity far greater than the regulatory requirements will no longer have an impact on energy saving and emission reduction. In addition, reaching emission reduction targets can be considered from the improvement of traditional generators.

5. Conclusions

In this study, we analyze the economic and environmental benefits of the commercial SAV and SAEV fleets with and without the provision of V2G services over the next 30 years. The important conclusions of this study are summarized as follows.

1. A minimized fleet that can meet the travel demand has an average 120 hours of parking time a week. Even if V2G services are available only half of the parking time, the impact can be considerable. V2G revenue can reach $2,272 per vehicle per year. It is similar to the result in [22] after excluding the differences in parking time and power transferred. It is worth noting that V2G services are greatly dependent on the grid's demand for regulation services. Greater fluctuations in the grid often mean greater revenues.
2. For the operator of a fleet, the SAEV fleet does not have a cost advantage over the SAV fleet even in the 30-year investment period. The provision of V2G services can enable the SAEV250 fleet to save 19.6% of the cost compared to the SAV fleet in a 30-year investment period. It is lower than the 40% savings estimated in [33], taking into account the cost of additional charging infrastructure for SAEV fleets.
3. From the perspective of environmental benefits, the SAEV fleet has an absolute advantage in reducing GHG emissions and saving energy, regardless of the battery capacity and length of the operation. V2G service plays a role in further increasing this advantage. Providing V2G service with a 75-kWh battery can save an average of 66.5 tons of GHG emissions per vehicle per year. It is almost three times the GHG emission savings shown in [22]. The main reason may be that we expect Michigan's grid emission factor to declining rapidly over the next 30 years. Providing V2G service can help save 46.8% of energy use even with only a 25-kWh battery.
4. From the policy perspective, subsidizing the purchase of commercial EVs and the construction of charging facilities can reduce the high start-up costs of SAEV fleets. This will help attract short-term investment in the SAEV fleet.
5. For commercial SAEV fleets with or without V2G services, larger battery capacity has advantages in both economic and environmental aspects.

Due to the lack of data on grid regulation demands, the actual regulation services provided may be greater or less. The sensitivity analysis partly ignores the changes in fleet size, fleet behavior, fuel efficiency, brought by changes in battery capacity. Changes in battery capacity may have greater impacts on economic and environmental factors.

It is worth noting that range anxiety still prevents a large number of private EV owners from opting for battery electric vehicles [78,79]. Lack of understanding of V2G further prevents private EV owners from participating in V2G services [80]. At the same time, private EV owners may not trust their electricity company or third party running V2G services, and concerns about privacy are also one of the obstacles [21]. Hence, commercial SAEV fleets may be more likely to apply V2G services than private electric vehicles, and more research effort will be required on how to improve the performance of V2G services in commercial SAEV fleets.

CRediT authorship contribution statement

Zitong Liao: Data curation, Formal analysis, Visualization, Writing - original draft. **Morteza Taiebat:** Conceptualization, Formal analysis, Methodology, Project administration, Validation, Writing - review & editing. **Ming Xu:** Conceptualization, Methodology, Supervision, Validation, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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