V2G-capable shared autonomous electric vehicles fleet: Economic viability and environmental co-benefits

by

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Abstract:

The pursuit of energy efficiency, increasing consumption of non-renewable energy related to fossil fuels, and concerns about the impact of climate change are some of the primary motivators for the introduction of electric vehicles. Battery electric vehicles (BEV) may be used in potential commercial autonomous taxi fleets; in addition to saving energy and maintenance costs, the introduction of these electric vehicles will also provide fleet operators with possible vehicle-to-grid (V2G) service opportunities. This study investigates the life-cycle total cost, greenhouse gas emissions, and energy consumption of automated shared vehicle fleets consisted of internal combustion engine vehicles and electric vehicles with 100-mile short-range and 250-mile long-range capable of achieving the same level of service. The results show that the 250-mile long-range electric vehicle fleet with V2G service has significant advantages in cost, emissions, and energy consumption.

Keywords: autonomous vehicles, vehicle-to-grid, SAEV, shared mobility, electric vehicles

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Nomenclature

Variable	Variable definition	Value used
Inflation rate		2%
Discount rate		5%
$RP_{vehicle}$	The average retail price of the vehicle	25000, 35000, 44000 [1]
Vehicle depreciate rate	The annual rate at which the value of vehicle depreciates	17.5% [2]
Charging Infrastructure	Total cost for building charging infrastructure	58,000 $/plug [3]
V2G equipment cost	Cost for upgrading EVs with V2G equipment	2,000 $/vehicle [4]
R	V2G service revenue	
$P_{capacity}$	Capacity price	$257.53/MW-day [5]
$P_{regulation}$	Average electricity price to all users	30.25-53.79 $/MMBtu [6]
R_{d-c}	The ratio of actual exchange energy to exchange capacity	10% [7]
L_{et}	Battery lifetime	$1000 \times$ battery capacity [7]
$Emi_{bat,LCA}$	Life-cycle GHG emission factor for battery	112kg/kWh [8]
$Energy_{bat,LCA}$	Life-cycle energy use factor for battery	350-650 MJ/kWh [9]

1. Introduction

Transportation is currently the primary contributor to greenhouse gas (GHG) emissions among the US economy and the fastest-growing source of GHG emissions and energy consumption [10,11]. Progressing the energy efficiency of transportation and reducing the related GHG emissions are critical to achieving the 2°C Paris Agreement goal. Emerging mobility technologies and systems including automation, electrification, and shared mobility are poised to reshape the transportation sector and are expected to reduce the negative energy and environmental externalities, once deployed at scale [12–16]. These technologies and systems entail natural synergies, enhance widespread adoption of each individual technology or system, create new business models for mobility as a service, and lead to a more sustainable transportation system [17].

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 more efficient and effective emission control and, most importantly, help increase renewable energy integration. Renewable-based electrification is considered an viable strategy for decarbonizing future mobility without suppressing the demand [18,19]. On the other hand, the current high price, limited charging infrastructure, arguably short driving ranges, and lengthy charging times of EVs prevent the expansion of the their market [20]. 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 [21], centralized operation leading to optimized charging time and driving range issues [22], as well as enhancing profitability and cost-effectiveness due to improved fleet operation [23].

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 [24]. 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 [25]. V2G services are exciting replacements for traditional peaker-plant generators, which are relatively inefficient and have higher environmental impacts. This reduces the system-level environmental footprint of the power grid and transportation sector as a whole [4]. However, the implementation of V2G services is hindered by concerns about battery degradation, inconvenience, mistrust, and long-distance endurance anxiety, making private mainstream EV owners reluctant to participate in V2G program offered by utilities [26–28].

Despite the reluctance of private EV owners, V2G can offer significant additional revenue to fleets of shared autonomous electric vehicles (SAEVs) that can alleviate the aforementioned concerns [4,29]. 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, low operating cost of EVs in high-vehicle-use scenarios, and revenue generation of V2G services when vehicles are not unoccupied. Indeed, a growing number of companies such as Zoox and Tesla have announced their plans to roll out shared EV services (electric robotaxi) with widespread operation between 2022-2030 [30,31]. 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 [32,33], despite a significantly higher utilization rate compared to household vehicles. Among those, Lu et al. 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 hours per day, traveling 109 miles [34]. 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, I build on the results of Lu et al., 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. I 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. I show that from an economic point of view, the operating cost of the SAEV fleet is 3.4%-8.4% higher than SAV fleet, that is, if there is no incentive like that for private electric vehicles, SAV is a better choice for fleet operators. 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 SAV fleet. Besides, from the perspective of energy-saving and GHG emission reduction, V2G can further leverage the environmental benefits of SAEV compared to SAV. Compared with the SAV fleet, the provision of V2G services can enable the SAEV250 fleet to save 7.1 times of GHG emissions and 29% of energy consumption, instead of emitting 64.1% of the GHG and consuming 58.6% of the energy.

I 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, I provide the details on the methodology. Section 4 presents the results, accompanied by a sensitivity analysis of key variables to check the robustness of the findings. Finally, I discuss the conclusions and acknowledge the limitations of the modeling approach in Section 5.

2. Literature Review

2.1. SAV

Although the large-scale deployment of SAV has not yet been available, many studies are investigating the impact of the combination of SAV and SAEV on fleet costs, mobility, and the environment. Martinez et al. claimed that SAV could reduce energy consumption by up to a 45% [35]. At the vehicle level, automatic vehicles (AVs) can achieve energy saving by 2% to 25% and up to 40% in extreme cases. However, the long-term net benefits of AV technology for energy consumption and GHG emissions are not clear when considering the interaction of vehicle fleet, transportation system, and urban system [12]. Lu et al. argued that the increase in total VMT driven by SAVs may increase GHG emissions due to high grid carbon intensity [34].

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% [36]. Bauer et al. estimated that a SAEV fleet powered by the existing power grid in Manhattan, New York City would minimize GHG emissions by 73% and energy consumption by 58% as opposed to an automated fleet of ICEVs. The cost of services will be $0.29-$0.61 per revenue mile, which is $0.05–$0.08 less than the cost of an automated fleet of hybrid or ICEVs [37]. Compostella et al. also reported the cost advantages of battery electric vehicle (BEV) over ICEV in the short and long term, especially in high mileage scenarios [38].

2.2. V2G service

Various studies have proposed that individuals or fleets providing V2G services generate net revenue (Table 2). For instance, Noori et al. explored light-duty EVs with V2G services in five different regions reporting a dramatic reduction in ownership cost and considerable GHG emission savings at the regional level [4]. 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 [39]. In addition, because the GHG emission factors of electric energy production vary greatly across states in the US over the next 30 years [40], 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 local situation.

Table 1 Recent literature

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	[41]
SAEV+V2G		√	Optimization of charge scheduling	Charging	V2G increased the saving from 28% to 43%	[42]
Private EV+V2G	√	√	Optimization of V2G scheduling with wind	Charging	128.9$/day benefit for the EV owner	[43]
Private EV+V2G	√	√	Optimization of V2G	Charging	V2G decrease life-cycle	[44]

		scheduling with renewable energy		charging cost by 14.7% with renewable energy	
Electric delivery truck+V2G	√		Total cost; LCA of fuel for GHG analysis	V2G can yield up to 60000 $ and save approximately 300 tons of GHG emissions in 15 years	[29]
BEV+V2G	√	Agent-Based Modeling	Operation; LCA of fuel for GHG analysis	V2G can yield up to 62000 $ in 16 years；saving 0.5 million tons of CO2 emissions in 15 years if 1% of EV provide V2G services	[4]

2.3. Research Need

As discussed above, a SAEV fleet may not have an advantage over an automated fleet of ICEVs in terms of total cost due to the need to build new charging facilities; but the provision of V2G service can provide the SAEV fleet with better economic and environmental performance. Also, the large-scale deployment of SAV fleets that provide V2G services has many other important side benefits, such as the integration of renewable energy and enhance urban mobility (Table 2). Therefore, it is important to study the overall economic and environmental impacts of a large fleet that can meet the travel needs of a city's residents. However, existing research rarely quantified the environmental impacts at the fleet level.

Table 2 Main benefits of V2G and SAV

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 [45–47].
	Controlled charging	Be able to decide when to recharge EV. Chargings that are highly concentrated and uncoordinated will significantly increase peak demand, and raise the demands on electricity infrastructure [48].
	Help grid system	Provide load balancing and reduce peak loads [49], and make better use of existing power generation and power distribution facilities [50,51].
	Emergency backup power	As a backup power supply in case of sudden power outages such as earthquakes [52].
SAV	Make automobile travel safer	Avoid or even put an end to traffic accidents [53,54].
	Enhance urban mobility	Improve the utilization rate of vehicles, and greatly increasing the speed of vehicle circulation while ensuring safety [55–57].
	Reduce energy consumption	Reduce energy consumption while reducing total travel time by optimizing routes [58,59].
	Free the driver	Allow driving time to be used for work or entertainment [60].
	Reduce land use	Significantly reduce parking and facility land [61,62].

3. Methods and Materials

In this study, I aim to meet the travel needs of 20,000 people who drive to work in Ann Arbor, MI with fleet size and waiting time constraints based on Lu et al. [34]. A 30-year timeframe, including multiple fleet turnover, was chosen to analyze trends in the performance of fleet operations through 2050. The system boundary includes the entire life-cycle of the fleet and fuel. Consistent with Lu et al. [34], I assume that travel demand and traffic conditions will remain same for the next 30 years. To explore the economic feasibility of replacing SAV fleets with SAEV fleets, I convert all future costs into present values in 2020 (in Million $) with a discount rate of 5% [63]. To investigate the environmental advantages of the SAEV fleet, I also estimate total energy consumption (in MJ) and GHG emissions (in ton CO2-eq) over the next 30 years.

I consider both ICEVs and BEVs in this study. The BEV models are available in 100-mile short-range and 250-mile long-range configurations, both 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 [64].

Table 3 Characteristics of all included vehicles

	ICEV (SAV)	BEV100 (SAEV100)	BEV250 (SAEV250)
Fuel economy (Energy efficiency)	55MPG	131MPGe (26 kWh/100 mile)	123MPGe (27 kWh/100 mile)
Purchase price ($)	25000	35000	44000
Battery capacity (kWh)	—	28	75
GHG direct emission (grams/km)	101.3	—	—

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. The aggregate data are extracted from Lu et al. [34]. Due to the different cruising mileage and charging requirements, the size of the SAEV fleet that meets the same transportation services is larger than the SAV fleet.

Table 4 Results of the one-week simulation for SAV and SAEV operation

	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	160k miles / average annual VMT	200k miles / average annual VMT	200k 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. Fleet Operation

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

- The first batch of vehicles will be purchased in 2020. Since then, all vehicles will be 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) [6].

- With the renewal of vehicles, the fuel/energy efficiency increases correspondingly, which is consistent with the average improvement of similar vehicles as suggested in [6].
- The implement of SAEV fleet requires the rebuilding of new charging stations, while the existing gas stations can meet the needs of SAVs.
- The SAEV can provide V2G services for half of the parking time.
- Gradual grid decarbonization and Michigan's high carbon intensity are considered when calculating GHG emissions of SAEVs consistent with [40].

I also consider the cost by cash flow analysis except for the revenue from the provision of travel services. I compare the net present value (NPV) of the total annual cost of three different vehicle models from 2020 to 2050 with and without V2G-capability. Table 5 shows the fixed and variable costs.

Table 5 Fleet Operation Costs

	Fixed	Variable
Vehicle purchase		√
Fuel cost (Gasoline & Electricity)		√
Insurance, Tax Fee	√	
Fleet Maintenance	√	
Vehicle cleaning	√	
Charging Infrastructure Construction & Maintenance	√	
V2G Infrastructure Construction & Maintenance	√	

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: I assume that the new vehicle will be purchased at the average retail price. Starting from the second car purchase, fleet operators can reduce the cost of vehicle purchase 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. I assume the vehicle value depreciates at an annual rate of 17.5% [2].

Fuel (F) cost: EIA predicts the changes in the average energy efficiency of various vehicle categories in the next 30 years [6]. I 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 [6], and the price fluctuation is considered in the sensitivity analysis.

Vehicle maintenance (VM) cost: Maintenance cost comes from [65].

Other fixed vehicle ownership costs: Vehicle insurance, taxes, and cleaning (VITC) costs are based on [38]. For autonomous vehicles that provide travel services, I 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 [66]. In this study, I chose a median estimate for 50kW of $58,000 per DCFC station and the annual maintenance cost is set to 5% of the original price [3].

V2G infrastructure (V2GI) cost: EVs need to upgrade their equipment to provide V2G services, and I assume $2,000 for each EV and only add it in the first year [4].

3.2.2. Net Revenue of V2G Services

The net revenue of V2G service (NR_{V2G}) is calculated as total revenues minus total costs [25]:

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

which expressed as the capacity service revenue plus the energy service revenue minus the cost. 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 I adopt the value from Michigan [5]. P is the lower value of $P_{vehicle}$ and P_{line}. Considering the limitation of the vehicle charging time and the number of devices, I 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 I adopt the predict electricity price from EIA [6]. 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, I introduce a "dispatch to capability" ratio similar to [25]:

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

I use logistic regression and data from Bloomberg New Energy Finance to predict the battery price ($P_{battery}$) in $/kWh (Figure 1) and the prediction is similar to the International Council on Clean Transportation (ICCT) [67,68]. I predict that the cost of the battery rapidly reduces over time, which is even considered to be linearly reduced [69]. As a conservative estimate, I 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 energy (kWh), and DoD stands for 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

[7]. V2G regulation is closer to the *DoD* of 10% and I consider 10,000 times the battery capacity as the battery lifetime.

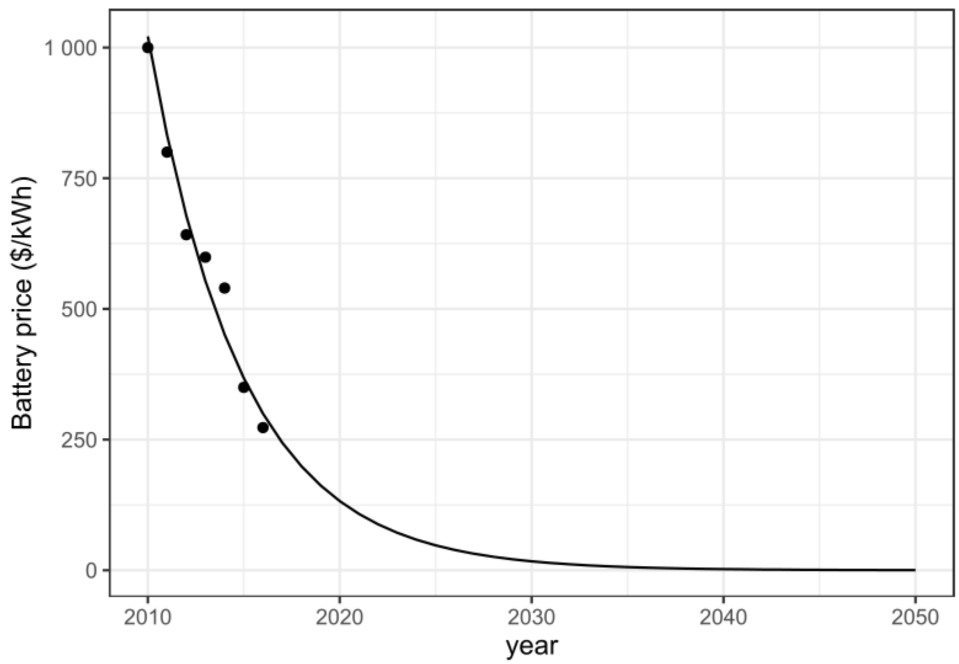

Figure 1 Electric vehicle battery pack price forecast from 2020 to 2050 [67,68]

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:

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

* only added for SAEV fleets

^ only added when providing 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. [70,71]. In the base case from Gawron et al., the power consumption of AV subsystems is about 2,000W in 2020 [70]. Gawron et al. suggested that energy consumption of computation is halved in 2.7 years [72]. With the improvement of the level of autonomous driving and safety considerations, the demand for subsystems may increase in the future. To be conservative, I 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 291W in 2035.

Energy production and use: I estimate the GHG emissions and energy consumption during the energy production and vehicle driving in the Ann Arbor region using data from [1,6,40] 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 112kg/kWh ($Emi_{bat,LCA}$) [8], while Romare et al. estimated battery life-cycle energy use is 350-650 MJ/kWh ($Energy_{bat,LCA}$) [9].

Due to the random fluctuation of power demand, the traditional use of gas turbine generators for regulation service is very inefficient. Makarov et al. argued that the efficiency of gas turbine generators may be only one-third of that of energy storage [73]. I multiplied the emission factor and energy use of gas turbines by three times:

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

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

where E_{disp} is the actual electricity dispatched in energy (kWh), $Emi_{traditonal}$ is the emission factor of the gas turbine generator, Emi_{grid} is the emission rate of the mixed grid, and $Energy_{traditonal}$ 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. Cumulative cost of ownership of fleets and V2G service

Vehicle purchase and maintenance account for the largest proportion in cost. 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's energy efficiency slightly lower than the BEV100's. However, a larger battery means a longer cruising range and stronger passenger carrying capacity, making the fleet size greatly reduced. 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 tram capacity. The larger the battery capacity, the higher the revenue. For SAEV250, the revenue from V2G services could cover approximately 30% of the total cost. If V2G services are provided, the cumulative cost of the SAEV250 fleet is lower than SAV fleet, indicating that SAEV fleets with large battery capacity may be economically feasible to replace SAV fleets.

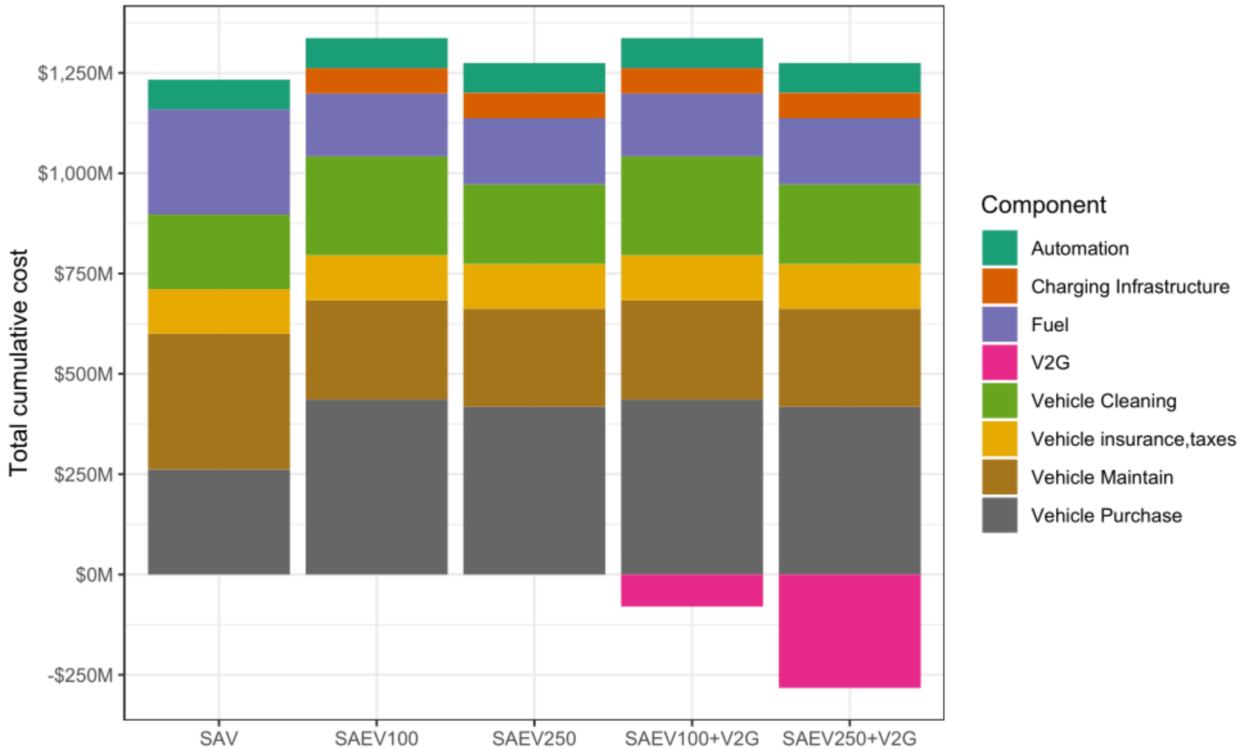

Figure 2 Cumulative cost component of fleets

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

Figure 3 depicts the yearly total cumulative and annual cost of SAV and SAEV fleets with different battery capacities. I 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 SA-EV fleets to replace SAV fleets.

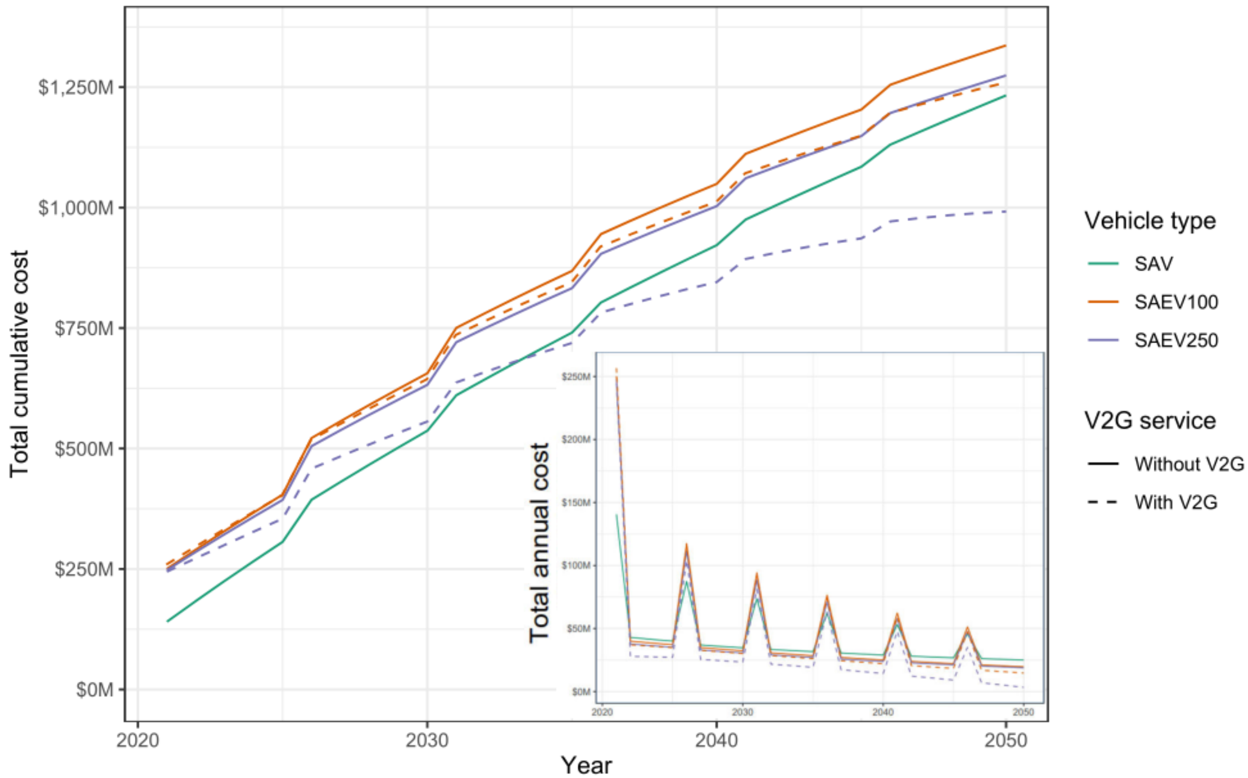

Figure 3 Total cumulative and the annual cost of fleets

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 SAEV250 fleet is 3.4% higher than SAV fleet. It is worth noting that although SAEV250 is more expensive and less fuel-efficient than SAEV100, the total cumulative cost of SAEV250 fleet is actually lower. The longer cruising range enables SAEV250 fleet to meet the requirements of transportation 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 SAEV100 will be about the same as SAV in 2050, and the total cost of SAEV250 will be lower than SAV 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. A SAEV250 fleet can save almost 20% of the cost compared to SAV fleet in a 30-year investment period.

4.1.3. Energy consumption and GHG emissions reduction

Both the energy consumption and GHG emissions in the operation stage are dominant in the whole life-cycle of the fleet, accounting for more than 68% of total GHG emission and 59% of energy consumption. SAEV fleets can save up to 35.8% in GHG emissions and 41.4% in energy consumption in the whole life-cycle compared to 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 a SAV. Coupled with the larger fleet size, the energy consumption and GHG emissions are at least 39.2% and 38.8% higher for the manufacture of SAEV fleet than 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 of the fuel and the pipe emissions. Although the GHG emission coefficient of the power grid in Michigan is higher than the average of the US, the advantages of zero-emission and higher efficiency of EVs are significant. SAEV fleet in Michigan can save 46.3% of GHG emissions compared to SAV fleet. SAEV's GHG reduction effect in other states of the US will be more obvious. Also, high 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 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 influence 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, high 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 the best choice. If V2G service is provided, the advantages of SAEVs with large battery capacity will be more significant. SAEV250 fleet can save.

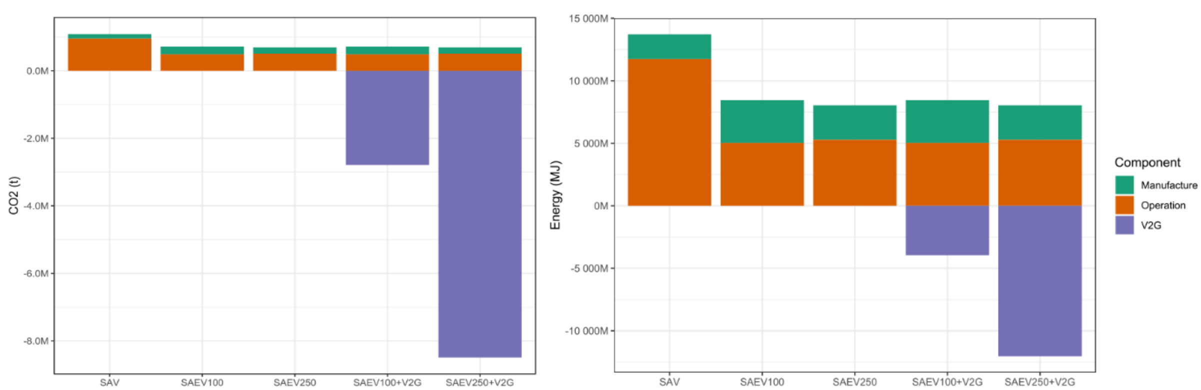

Figure 4 GHG emission and energy consumption component of fleets

4.2. Sensitivity analysis

I 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 EV250 fleet relative to ICV fleet (Table 6).

Table 6 30-year cost, GHG emissions, and energy saving, of SAEV250 relative to SAV

Variable	Cost		GHG emissions		Energy	
(-10%, +10%)	-10%	+10%	-10%	+10%	-10%	+10%
Electricity price (Charging)	28.10 %	11.00 %	819.21 %	819.21 %	129.2 %	129.2 %
Regulation price	12.42 %	26.69 %	819.21 %	819.21 %	129.2 %	129.2 %
Battery capacity	16.64 %	22.46 %	724.39 %	914.04 %	118.6 %	139.8 %
Capacity price	16.75 %	22.36 %	819.21 %	819.21 %	129.2 %	129.2 %
Energy efficiency of SAV	21.91 %	17.62 %	828.96 %	811.24 %	138.6 %	121.5 %
Gasoline price	17.42 %	21.68 %	819.21 %	819.21 %	129.2 %	129.2 %
EV price	20.82 %	18.28 %	819.21 %	819.21 %	129.2 %	129.2 %
Energy efficiency of SAEV	18.06 %	20.77 %	814.01 %	823.47 %	124.9 %	132.7 %
R_{d-c}	19.95 %	19.15 %	740.88 %	897.55 %	120.4 %	138.0 %
Battery price	19.88 %	19.22 %	819.21 %	819.21 %	129.2 %	129.2 %
Vehicle cleaning fee	19.65 %	19.45 %	819.21 %	819.21 %	129.2 %	129.2 %
Insurance fee	19.55 %	19.55 %	819.21 %	819.21 %	129.2 %	129.2 %
Grid emission factor	19.55 %	19.55 %	843.31 %	795.11 %	129.2 %	129.2 %

Gasoline emission	19.55 %	19.55 %	810.45 %	827.98 %	129.2 %	129.2 %
Turbine generator emission factor	19.55 %	19.55 %	721.47 %	916.96 %	129.2 %	129.2 %

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, 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%.

Battery capacity has the greatest impact on GHG emissions, followed by turbine generator emissions 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 effect on GHG emissions (less than 1%).

Battery capacity also has the greatest impact on energy savings, followed by energy efficiency of SAV, 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 will 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. On top of that, the high price of EVs also greatly affects the total cost of ownership; subsidies are helpful to further promote the SAEV fleet. Larger battery capacity can not only greatly reduce the total cost, but also have better performance in reducing GHG emissions and energy use. 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; therefore wide-scale SAEV fleet implementation will also need to consider the actual regulation needs of the local grid. The regulatory capacity far greater than the regulatory requirements will no longer have an impact on energy conservation and emission reduction. In addition, the achievement of emission reduction targets can be considered from the improvement of traditional generators.

5. Conclusions

I analyze the economic and environmental benefits of the commercial SAV and SAEV fleet and further with the provision of V2G services over the next 30 years. The important conclusions of this study are summarized as follows.

1 For the operator of a fleet, the SAEV fleet does not show a cost advantage over the SAV fleet. The provision of V2G services can enable the SAEV250 fleet to save 19.6% of the cost compared to SAV fleet in a 30-year investment period. It is lower than the 40% saving estimated in [41]. This makes sense because I in this study take into account the cost of additional charging infrastructure for SAEV fleets.

2 V2G service revenue can reach $2,272 per vehicle per year. It is similar to the result in [29] after excluding the difference in parking time and power.

3 From the perspective of environmental benefit, the SAEV fleet has absolute advantages 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 75kWh battery can save an average of 66.5 tons of GHG emissions per vehicle per year. It's almost three

times the GHG emission savings shown in [29]. The main reason may be that I expect Michigan's grid emission factor to decline 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 a 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, larger battery capacity has advantages in both economic and environmental aspects.

Due to the lack of data on actual 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, etc. brought by changes in battery capacity. Changes in battery capacity may have greater impacts on economic and environmental factors. Also, bidirectional wireless charging technology can provide more opportunities for V2G services [17]. Quantitative research on cost and environmental impacts that combines these two can be future work.

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