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Additional emissions of vehicle-to-grid technology considering China's geographical heterogeneity

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Abstract

Vehicle-to-Grid (V2G) technology is regarded as a promising distributed energy storage solution that can help address grid challenges arising from the integration of renewable energy and the large-scale uncoordinated charging of electric vehicles. However, issues such as additional battery degradation and energy efficiency losses induced by V2G may lead to increased greenhouse gas (GHG) emissions in providing energy storage services, thereby reducing its overall potential to contribute to power system decarbonization. Existing studies on the additional GHG emissions of energy storage technologies have largely overlooked V2G technology. To fill this research gap, this study develops a comprehensive life cycle assessment model for V2G technology in China. The model first simulates the charging and discharging processes of EV batteries in V2G applications, as well as the additional battery degradation caused by V2G participation. Building on this technical modeling and incorporating multidimensional geographic heterogeneity data, a high-resolution assessment of V2G's lifecycle additional GHG emissions is conducted across 337 cities in China. The results reveal that V2G's additional GHG emissions for frequency regulation (FR) and peak shaving and valley filling (PSVF) services range from 0.046-0.152 and 0.036-0.148 $kgCO_{2\text{-eq}}$/kWh, respectively. Energy-related GHG emissions constitute the largest proportion, accounting for 59.0% and 66.8% of total emissions for FR and PSVF services, respectively. From a geographic perspective, the additional GHG emissions of V2G are lowest in southwestern China and highest in the northeast. The findings of this study highlight significant regional variations in the environmental impacts of V2G technology in China and underscore the importance of region-specific strategies for the effective and sustainable deployment of V2G technology.

Keywords: Vehicle-to-grid, life cycle assessment, energy storage, lifecycle greenhouse gas emission

INTRODUCTION

The development of electric vehicles (EVs) is widely recognized as one of the effective strategies for achieving decarbonization and sustainable development in the transportation sector, as it eliminates the sector's fundamental dependence on petroleum resources and mitigates the distributed nature of carbon emissions generated from the use of petroleum-based fuels[1-3]. According to the China Automotive Industry Yearbook, annual EV production in China has increased from approximately 0.2 million units in 2013 to 9.5 million units in 2023[4]. The future development of EVs is expected to accelerate.

The rapid growth of EVs is expected to drive an increase in electricity demand and grid load. Such a surge in demand will have considerable long-term implications for the infrastructure construction and development of electricity generation, transmission, and distribution. Furthermore, the widespread uncoordinated charging of EVs contributes to a substantial rise in grid load during peak periods, posing challenges to the stability and reliability of the grid[5]. In scenarios with high EV penetration, uncoordinated charging is projected to increase peak load by over 10%, which will not only place great demands on generation capacity and the transmission network but also threaten the safe operation of local distribution grids[6].

Vehicle-to-Grid (V2G) technology offers a promising solution to the challenges arising from the large-scale deployment of EVs. V2G enables bidirectional electricity flow between EVs and the grid through bidirectional charging equipment, effectively transforming EVs into distributed energy storage systems that provide storage services[7]. When participating in V2G, EVs can both charge from the grid and return stored energy to the grid, generating revenue in the process. V2G technology can support services such as peak shaving and valley filling, as well as frequency regulation[8]. Currently, the development of V2G technology has entered the demonstration stage, with hundreds of demonstration projects underway globally[9,10]. As an emerging low-carbon technology, it is crucial to assess the carbon emission impacts of V2G technology.

For the power system, V2G technology can optimize EV charging and discharging strategies, shifting charging to low-carbon periods when renewable energy generation is higher. It can also feed energy back into the grid during periods of low renewable energy availability, which provides flexibility to the power system, promotes the integration of renewable energy, and subsequently reduces greenhouse gas (GHG) emissions from the power system. Current research on the emission reduction potential of V2G technology primarily focuses on its impact on the overall carbon emissions of the power system. Yao *et al.* analyzed the role of V2G technology in promoting the low-carbon transformation of the power system at different V2G penetration levels, assessing GHG emissions under various scenarios[11]. The results showed that as the proportion of V2G participation increases, GHG emissions in the power system continue to decrease. Wohlschlager *et al.* analyzed the environmental benefits of EVs as distributed storage resources in Germany's power system[12]. The research demonstrated that V2G technology helps accelerate renewable energy integration, thereby reducing overall GHG emissions in the power system; however, as the power system gradually achieves deeper decarbonization, the environmental benefits of V2G technology will weaken. Sioshansi *et al.* analyzed the role of V2G in improving energy efficiency and GHG emission reduction in the electricity sector[13]. The results showed that V2G technology can effectively reduce emissions, including CO_2 and SO_2, from electricity generation. Liang *et al.* explored the impacts of V2G on the environmental benefits of the power system, using both GHG emissions and costs as objectives[14]. The results indicated that, under the peak shaving and valley filling service scenario, V2G technology could significantly reduce GHG emissions in the power system. Ali *et al.* examined the emission reduction benefits of V2G under both non-intermittent and intermittent grid scenarios, finding that integrating V2G into the grid could reduce overall GHG emissions by up to 25%, with further reductions expected as renewable energy penetration increases[15]. Wang *et al.* incorporated EVs with V2G into an energy system model and analyzed its impacts on GHG emissions. The results highlighted that, despite the increased use of EV batteries, V2G still offers a positive impact on overall GHG emissions compared to random and uncoordinated EV charging[16]. Noori *et al.* assessed the GHG emission reduction potential of V2G technology across five U.S. independent system operators, finding that V2G could help specific regions reduce CO_2 emissions by up to 500,000 tons by 2030[17]. Based on existing research, the large-scale application of V2G technology contributes to advancing the low-carbon transformation of the power system and effectively reduces overall GHG emissions in the power system.

While using EVs as distributed energy storage resources facilitates the integration of renewable energy and supports the decarbonization of the power system, it is important to recognize that, from a life cycle assessment (LCA) perspective, providing electricity through energy storage systems inevitably incurs additional GHG emissions compared to directly drawing electricity from the grid, which could reduce the potential of energy storage systems for decarbonizing the power system. Additional GHG emissions from energy storage systems stem from the materials and manufacturing of related equipment, as well as electricity losses due to the round-trip efficiency in charging and discharging processes[18,19]. Existing studies have already assessed the additional GHG emissions of stationary energy storage systems. Fares *et al.* evaluated the additional GHG emissions from home energy storage in residential solar energy systems[19]. The results showed that storage operation could increase household annual emissions by 153-303 kg CO_2, 0.03-0.20 kg SO_2, and 0.04-0.26 kg NO_x, respectively. Schmidt *et al.* quantified the additional lifecycle GHG emissions of various battery storage technologies when providing grid services, highlighting that lithium-ion batteries (LIB) exhibit the best lifecycle emissions (LCE)[20]. Hittinger *et al.* analyzed the additional GHG emissions resulting from the application of bulk energy storage in the United States, estimating that deploying such systems across different regions would lead to additional CO_2 emissions of 104-407 $kgCO_{2\text{-eq}}$/MWh[21]. However, existing studies have not accounted for V2G technology. As a promising energy storage solution, it is crucial to evaluate the additional GHG emissions of V2G technology.

This study focuses on addressing two key gaps in the existing literature. First, in response to the lack of a systematic analysis of the additional GHG emissions associated with V2G technology, we developed an LCA model specifically for V2G technology. We first constructed a V2G technical model to simulate the operation of EVs when participating in V2G. Based on the technical model, we then quantified the additional lifecycle GHG emissions associated with V2G technology. Furthermore, China, with the largest EV market globally, holds significant potential for V2G applications. Due to notable differences in EV market structures, external environments, and electricity market policies across various regions in China, the GHG emissions of V2G technology exhibit substantial geographical heterogeneity. Therefore, this study focuses on the Chinese EV market, analyzing the geographical variation in the additional GHG emissions of V2G technology across 337 cities using high-resolution data on the EV market and driving behaviors. This research contributes to a comprehensive understanding of the carbon emission impacts of V2G deployment and provides a theoretical foundation for the future regional development of V2G technology in China.

METHOD

To evaluate the additional GHG emissions of V2G technology, this study developed an LCA model based on the operational mechanisms of EVs within the V2G framework. The system boundary is shown in Figure 1A, including the materials and manufacturing of related equipment, as well as electricity losses resulting from the round-trip efficiency of battery charging and discharging, while excluding the GHG

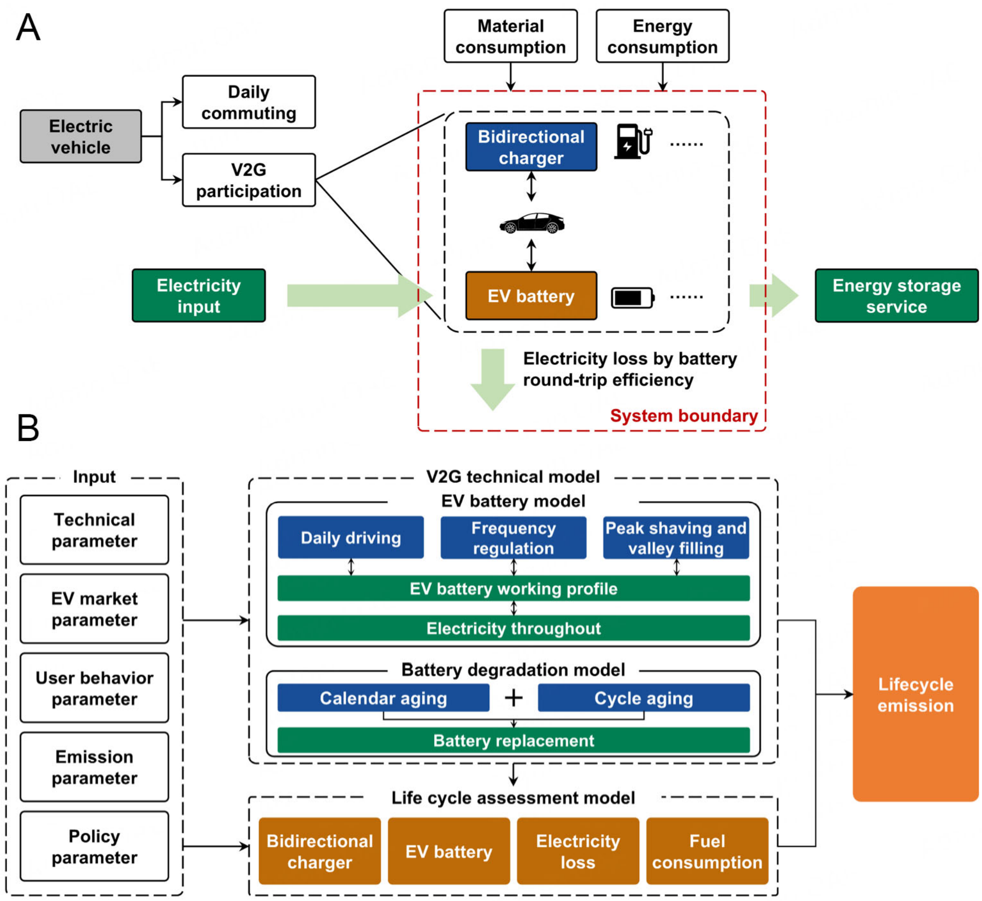

Figure 1. Research framework. (A) Schematic of system boundaries for analyzing V2G's additional GHG emissions. (B) Model framework.

emissions related to the electricity of each unit of energy storage service. Two types of energy storage services were considered, including frequency regulation (FR) and peak shaving and valley filling (PSVF). The charging and discharging profiles of EV batteries in V2G operation were simulated using the V2G technical model. Based on simulation results, a battery degradation model was integrated to evaluate the frequency of battery replacement over the vehicle's entire lifecycle. By combining the outcomes of both models with relevant GHG emission intensities, the study provides a comprehensive evaluation of the additional lifecycle GHG emissions associated with V2G technology. The model framework is shown in Figure 1B, with the subsequent sections offering a detailed explanation of each component of the research framework.

V2G technical model

The V2G technical model consists of three sub-models corresponding to different stages of EV operation: the daily commuting model, the frequency regulation service model, and the peak shaving and valley filling service model. Different operational stages of an EV participating in V2G were simulated, including daily commuting, providing FR and PSVF services, parking, and charging. For the commuting stage, it is assumed that the EV is primarily used for daily commuting between home and workplace on weekdays and for occasional trips on weekends. During the V2G stage, the EV is assumed to be parked near the workplace during working hours and connected to the grid via a public bidirectional charging station to provide energy storage services. The vehicle can also charge at the public station to ensure adequate energy for subsequent trips. Due to the variability of weekend travel and limited parking opportunities, the vehicle's participation in V2G is not considered during weekends. For the charging stage, it is assumed that the vehicle charges through a private charger upon returning home. Based on these assumptions, the battery's operational profile, including output power and changes in the State of Charge (SOC), was modeled over the vehicle's entire lifecycle. This study focuses specifically on commuter vehicles, as they are well-suited to both meet commuting needs and provide energy storage services. The model operated with a one-minute time resolution and was implemented in MATLAB.

For EVs, prioritizing energy for daily commuting is essential, and only the surplus battery capacity beyond this requirement can be utilized for V2G participation. Therefore, it is crucial to first model the vehicle's commuting stage and define the constraints on the available battery capacity. The battery's operational profile during the driving stage is influenced by factors such as commuting duration, daily commuting distance, energy consumption rate, and speed. In this study, it is assumed that the EV operates at a constant speed. Variations in user behavior, particularly changes in daily commuting distance and commuting time, affect the battery's operational profile. To account for these impacts, the study independently modeled the battery's operational profile for different commuting periods and distances, and the results were subsequently weighted according to the probability distributions in the LCA model.

FR services are crucial for maintaining the stability of the grid frequency[22]. Fluctuations in electricity supply and demand during grid operation can lead to frequency deviations, which, if significant, pose risks to the safe and stable functioning of the grid. FR services help stabilize the grid frequency by providing real-time charging and discharging in response to the grid's scheduling. When the grid frequency exceeds the standard value, the EV battery can absorb excess electricity through charging, thereby reducing the frequency. Conversely, when the grid frequency drops below the standard, the EV battery can discharge electricity to supplement the grid, raising the frequency. In this study, the operation of EV batteries providing FR services was modeled using the droop model[23]. According to the droop model, the EV battery is only activated when the frequency deviation exceeds a predefined deadband threshold, and the dispatch capacity is determined by the magnitude of the frequency deviation.

PSVF services are employed to mitigate long-term load fluctuations in the grid, alleviating grid congestion and postponing the need for grid expansion[24]. In this study, the process of EVs providing PSVF services was modeled based on the time-of-use (TOU) tariff policy[25]. EVs charge during valley load periods and discharge electricity back to the grid during peak load periods. Through the differential in TOU tariff, users can earn profits.

By considering the battery's operational profile across different stages, the daily variation in the SOC of EV batteries throughout the vehicle's lifecycle can be calculated, as shown in Equation (1).

$$SOC_{i,t} = SOC_{i,0} + \int_{t=1}^{t=1440} (\Delta SOC_{D,i,t} + \Delta SOC_{FR,i,t} + \Delta SOC_{PSVF,i,t}) \cdot dt \tag{1}$$

where $SOC_{i,t}$ denotes the SOC of EV batteries at time t on day i (%), $SOC_{i,0}$ denotes the initial SOC of EV batteries on day i (%), $\Delta SOC_{D,i,t}$ denotes the SOC change of EV batteries during the daily commuting stage at time t on day i (%), $\Delta SOC_{FR,i,t}$ denotes the SOC change of EV batteries during the FR service stage at time t on day i (%), and $\Delta SOC_{PSVF,i,t}$ denotes the SOC change of EV batteries during the PSVF service stage at time t on day i (%). The detailed calculation process for each sub-model is provided in the Supplementary Material.

Battery degradation model

One of the key factors limiting users' participation in V2G is the additional battery degradation, which results in extra economic costs for the user. From an environmental perspective, the additional battery degradation associated with V2G also leads to increased GHG emissions related to the materials and manufacturing of EV batteries. Therefore, it is crucial to analyze the battery degradation that occurs when EVs participate in V2G. In this study, a data-driven empirical model was developed to quantify the battery degradation throughout the vehicle's lifecycle. The model incorporates both calendar aging and cycle aging, with the calculations outlined in Equation (2)[26].

$$Q_{l,i} = Q_{l,cal,i} + Q_{l,cyc,i} \tag{2}$$

where $Q_{l,i}$ denotes the capacity loss of EV batteries on day i (%), which is measured by State of Health (SOH); $Q_{l,cal,i}$ denotes the capacity loss caused by calendar aging on day i (%); and $Q_{l,cyc,i}$ denotes the capacity loss caused by cycle aging on day i (%).

When the battery's SOH reaches the End-of-Life (EOL) threshold and the vehicle itself is still operational, the user will replace the battery. The battery degradation model quantifies the frequency of battery replacement throughout the EV's lifecycle, both with and without V2G participation. The detailed calculation process for the battery degradation model is provided in the Supplementary Material.

Life cycle assessment of V2G technology

This study employed the LCA methodology to evaluate the additional lifecycle GHG emissions of V2G technology. The global warming potential (GWP) midpoint factor from the ReCiPe 2016 method was used to assess GHG emissions[27]. Using V2G-based EV distributed energy storage introduces two additional GHG emissions compared to directly using grid electricity. The first source comes from the materials and manufacturing of related equipment, including bidirectional chargers and EV batteries. The second source is electricity losses during charging and discharging due to the battery's round-trip efficiency. Additionally, for plug-in hybrid electric vehicles (PHEVs), participating in V2G causes additional battery degradation, which leads to increased fuel consumption and corresponding GHG emissions.

Life Cycle GHG Emission (LCE) is adopted as the evaluation metric to assess the additional GHG emissions resulting from V2G technology. LCE refers to the GHG emissions generated per kilowatt-hour of electricity discharged from an energy storage system and is widely used in the environmental impact analysis of energy storage technologies[20,28]. The detailed calculations for the LCA model are provided in the Supplementary Material.

Input data

The additional GHG emission of V2G technology is determined by multiple factors. On one hand, the EV's energy storage potential is shaped by technical specifications and user behavior. On the other hand, the grid and end-use loads, as the demand side for energy storage, determine the amount of energy storage services provided by scheduling strategies and policies. Given the substantial regional heterogeneity of these factors, this study analyzed the additional GHG emissions of V2G technology across various cities in China, considering multiple perspectives.

China's EV market exhibits significant regional variation. To capture this heterogeneity, a multidimensional database was developed using 2023 EV sales data in China[29]. The database characterizes the market by spatial distribution, vehicle types, powertrain configurations, and battery chemistries. It covers 337 cities across 31 provinces, excluding Hong Kong, Macau, and Taiwan. Vehicle types are categorized into cars (C), SUVs (S), and MPVs (M), with each divided into five segments: mini, small, medium, large, and executive[30]. In this study, these five segments were denoted by segment 1 to segment 5. The database also includes both PHEVs and BEVs, with distinctions based on battery chemistry.

User behavior is a key factor in determining the V2G potential of EVs. This study constructed a city-level EV commuting distance distribution database using statistical driving behavior big data[31]. Additionally, regional and temporal variations in temperature and policies significantly affect the results. TOU tariff policies across regions define the periods of charging and providing PSVF services. Temperature influences both real-time energy consumption and battery degradation. The 2023 city-level hourly average temperatures and monthly provincial TOU tariff policies were compiled from available statistical data[32].

The life cycle inventories (LCI) of LIBs, including lithium iron phosphate (LFP) and nickel cobalt aluminum (NCM) batteries, were sourced from the GREET model (2023 version)[33-35], and those of EV chargers were sourced from ECOINVENT database (version 3.8)[36]. The LCIs of electricity were localized based on the related report[37]. In this study, it is assumed that NCM and nickel-cobalt-manganese (NCA) batteries have the same emission intensities. Details of the aforementioned data are shown in the Supplementary Material.

RESULT

Geographic heterogeneity of V2G's additional GHG emissions in China

Figure 2 illustrates the additional GHG emissions of V2G technology in China. Figure 2A and B present the results for providing FR and PSVF services, respectively. The results highlight significant geographic heterogeneity in the LCE across the country. For FR services, the LCE values range from 0.046 to 0.152 $kgCO_{2\text{-eq}}$/kWh. Southern and western regions exhibit lower LCE values, primarily due to the higher proportion of low-carbon renewable energy, such as wind and solar power, in the local grid. In contrast, northeastern regions, which rely predominantly on fossil fuel-based power generation, exhibit higher electricity GHG emission intensities, leading to relatively higher LCE values. For EVs providing PSVF services, the overall LCE is lower than that for FR service, ranging from 0.036 to 0.148 $kgCO_{2\text{-eq}}$/kWh. The regional distribution of LCE for PSVF services mirrors that for FR services, reflecting the influence of regional differences in the power generation mix.

Figure 2C presents the results of ranking V2G's additional GHG emissions based on LCE values. The distribution of LCE values across cities is relatively uniform, with a few notable spikes due to the stepwise increase in the provincial GHG emission intensities of electricity. By averaging the LCE values of different cities according to the scale of local EV markets, the national average LCE of V2G technology is found to be 0.101 $kgCO_{2\text{-eq}}$/kWh for FR services and 0.091 $kgCO_{2\text{-eq}}$/kWh for PSVF services. The higher LCE for FR services is primarily attributed to the frequent charging and discharging involved in grid scheduling, which results in higher battery energy throughput and, consequently, more significant additional battery degradation. This leads to a higher carbon footprint associated with battery materials and manufacturing. The composition of additional GHG emissions for different V2G services will be further analyzed in the subsequent sections.

Breakdown analysis of V2G's additional GHG emissions in China

By aggregating the LCE results of V2G technology across cities and input data dimensions such as vehicle type and battery chemistry, a comprehensive comparative analysis of LCE is obtained, as shown in Figure 3. Specifically, Figure 3A shows the LCE breakdown with the results weighted by local sales data. The comparison distinguishes PHEV and BEV powertrains, 5 types of battery chemistries, and 11 vehicle types

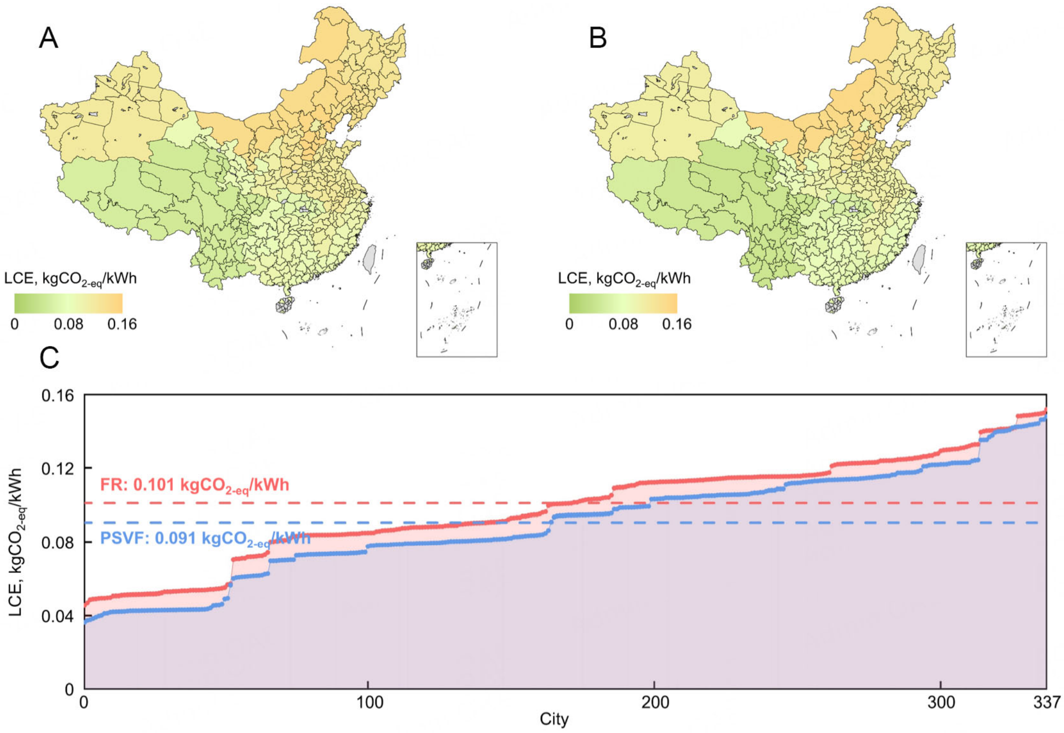

Figure 2. Geographic heterogeneity of V2G's additional GHG emissions in China. (A) City-level additional GHG emissions for FR services. (B) City-level additional GHG emissions for PSVR services. (C) Distribution of city-level additional GHG emissions. The map used in the figure is the latest version of the official map of China [GS(2024) 0650][38].

and segments (C1-C5, S1-S5, M). Battery chemistries considered in this study include LFP, NCM-L (NCM111), NCM-M (NCM523, NCM622), NCM-H (NCM811), and NCA. The findings indicate that the LCE values for FR and PSVF services range from 0.084 to 0.217 $kgCO_{2-eq}$/kWh and 0.077 to 0.272 $kgCO_{2-eq}$/kWh, respectively. Notably, PHEVs equipped with NCM-L and NCM-H batteries at the C3 level exhibit the highest LCE, which is due to the characteristics of prevalent EV models in the market. In particular, the average battery capacities of C3-level PHEVs with NCM-L and NCM-H batteries in China are 5.8 and 5.7 kWh, respectively. The limited battery capacity restricts the surplus capacity available for V2G participation, which in turn prevents the full allocation of the GHG emissions associated with battery materials and manufacturing. In contrast, BEVs, which generally have larger batteries, exhibit more consistent LCE values across different models.

The LCE results were then weighted according to the sales of EVs with different battery chemistries within each vehicle type, enabling an analysis of LCE from the perspective of powertrain and vehicle type, as shown in Figure 3B. The LCE values when providing FR services range from 0.099 to 0.108 $kgCO_{2-eq}$/kWh for PHEVs and from 0.096 to 0.108 $kgCO_{2-eq}$/kWh for BEVs. For PSVF services, the LCE values range from 0.091 to 0.108 $kgCO_{2-eq}$/kWh for PHEVs and from 0.080 to 0.097 $kgCO_{2-eq}$/kWh for BEVs. The key distinction between PHEVs and BEVs lies in the contribution of charger-related emissions. PHEVs, with smaller battery capacities, support lower energy throughput over their entire lifecycle, which limits the ability to amortize emissions from the EV charger. As a result, GHG emissions associated with the charger account for a larger share of the total emissions in PHEVs, which range between 3%-12% for FR services and 4%-19% for PSVF services. In contrast, BEVs, with larger batteries and more available capacity for V2G, are better able to amortize charger-related emissions. The share of GHG emissions attributable to the charger for BEVs ranges between 2%-4% for FR services and 1%-6% for PSVF services.

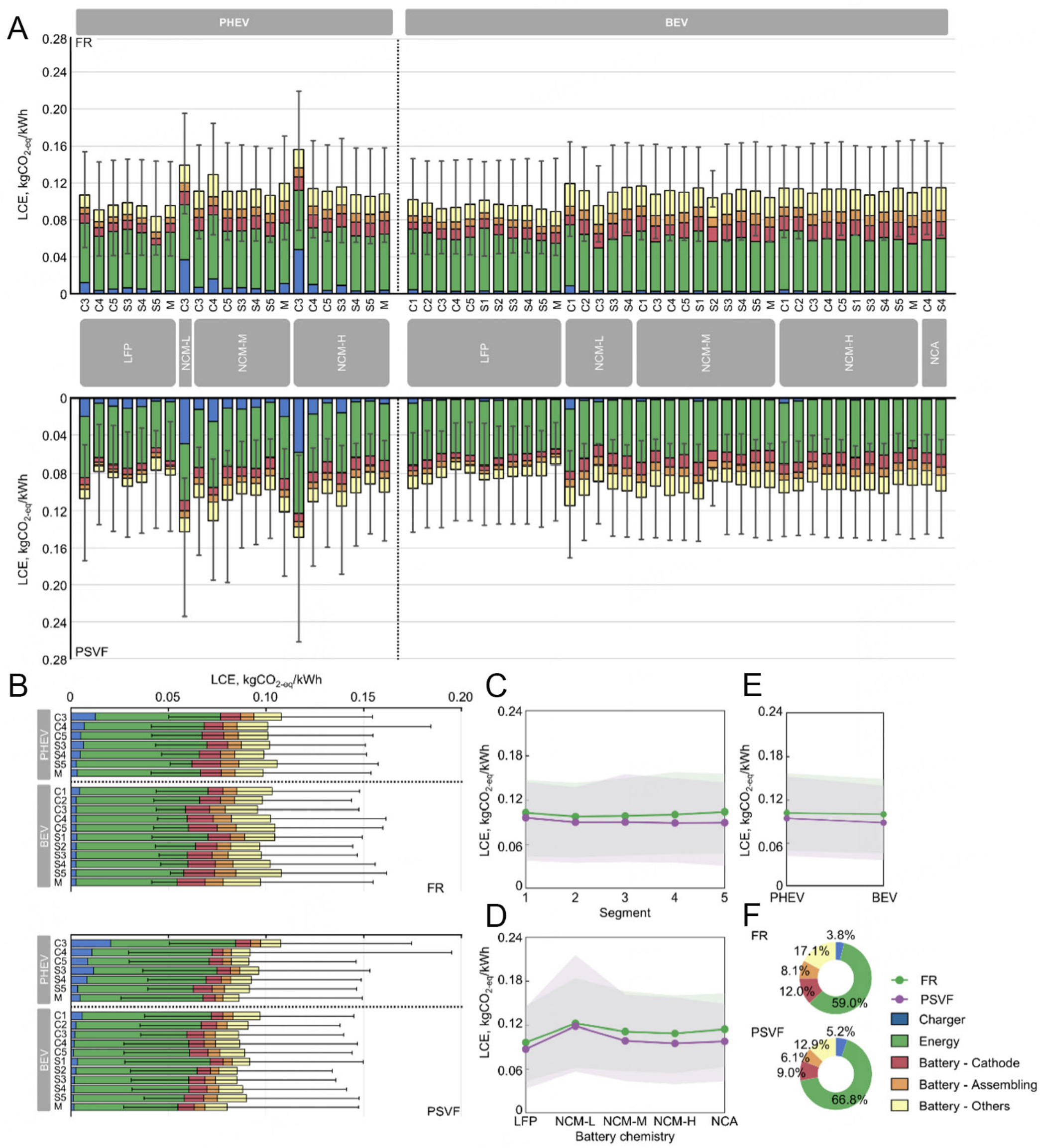

Figure 3. Breakdown analysis of V2G's additional GHG emission in China. (A) LCE breakdown of V2G considering different EV powertrains, segments, and battery chemistries. (B) LCE breakdown of V2G considering different EV powertrains and segments. (C) LCE of V2G from the perspective of EV segments. (D) LCE of V2G from the perspective of EV battery chemistries. (E) LCE of V2G for PHEV and BEV. (F) LCE breakdown of V2G under the national average. The black bar in the subfigure represents the LCE range of different cities in each dimension.

Figure 3C compares the LCE values across different segments. For FR services, the LCE values range from 0.098 to 0.104 $kgCO_{2-eq}$/kWh, with Segment 2 vehicles exhibiting the lowest LCE. This can be attributed to the relatively modest battery capacity requirements for FR services, which involve frequent charging and discharging within a narrow SOC range. In contrast, larger vehicles with higher battery capacities incur greater LCE due to the associated GHG emissions associated with battery materials and manufacturing. For PSVF services, the LCE range is between 0.089 and 0.096 $kgCO_{2-eq}$/kWh, with values for Segment 2 through Segment 5 remaining fairly consistent. The larger battery capacities enhance the energy storage potential for PSVF services, thereby enabling a more effective amortization of the emissions associated with battery materials and manufacturing.

Figure 3D compares the LCE values of EVs equipped with different battery chemistries. The LCE ranges for providing FR and PSVF services are 0.097-0.123 and 0.088-0.119 $kgCO_{2-eq}$/kWh, respectively. In both cases, LFP batteries demonstrate the most favorable LCE performance, while NCM-L batteries exhibit the highest values. This difference can be attributed to the lower GHG emissions associated with the materials and manufacturing of LFP batteries. Additionally, EVs equipped with NCM-L batteries tend to have smaller battery capacities, further leading to higher LCE values.

Figure 3E further compares the LCE values of PHEVs and BEVs. The results indicate that BEVs exhibit superior LCE performance. For both services, the weighted average LCE values of PHEVs are 0.102 and 0.095 $kgCO_{2-eq}$/kWh, respectively. For BEVs, the corresponding values are 0.100 and 0.089 $kgCO_{2-eq}$/kWh. Overall, BEVs, benefiting from their larger battery capacities, are better suited for V2G technology.

Figure 3F presents the LCE breakdown of FR and PSVF services. The results indicate that energy-related GHG emissions contribute 59.0% and 66.8% of the total, highlighting that electricity losses due to battery round-trip efficiency and fuel consumption alterations of PHEVs due to V2G participation are the primary sources of additional GHG emissions. Emissions related to battery materials and manufacturing also contribute significantly, accounting for 37.5% and 25.3%, respectively. In contrast, GHG emissions from charger materials and manufacturing are relatively small, standing at 3.8% and 5.2%, respectively.

Multi-scenario analysis

The results above are based on the current technical landscape and GHG emission intensity in China, representing the "Baseline" scenario. With the acceleration of transportation electrification, the market share of BEVs is expected to rise significantly in the future. Simultaneously, clean energy generation is anticipated to grow rapidly, with a higher proportion of renewable energy sources like wind and solar power. To explore the potential future development, this study extended the Baseline scenario by analyzing LCE values under several alternative scenarios, as shown in Figure 4. The BEV-dominant scenario envisioned a future where BEVs become the dominant powertrain with 100% market penetration. The High RE scenario modeled a future with a substantial increase in clean energy generation, resulting in a higher share of renewables and a corresponding reduction in electricity GHG emission intensity. Projections for provincial electricity GHG emission intensity in China by 2030 are used for this scenario. Additionally, EVs equipped with LFP batteries demonstrated superior environmental performance in V2G applications. Given the growing market for LFP-equipped EVs in China, the LFP-dominant scenario was also explored, where 100% of the EV fleet is powered by LFP batteries. Finally, the Aggressive scenario combined the effects of all scenarios for a more holistic analysis.

In the BEV-dominant scenario, LCE values exhibit only slight variations. Specifically, the LCE for FR services increases marginally from 0.101 to 0.102 $kgCO_{2-eq}$/kWh, while for PSVF services, it decreases from 0.091 to 0.089 $kgCO_{2-eq}$/kWh. The contrasting trends can be attributed to the larger battery capacity of BEVs. For FR services, the increased battery size leads to higher emissions associated with battery materials and manufacturing. However, for PSVF services, the larger battery capacity facilitates a more effective amortization of GHG emissions across a greater volume of V2G services. In the LFP-dominant scenario, LCE values decrease for both services due to the lower GHG emissions and longer cycle life of LFP batteries. Specifically, the LCE values fall to 0.096 $kgCO_{2-eq}$/kWh for FR services and 0.086 $kgCO_{2-eq}$/kWh for PSVF services. The High RE scenario shows a more significant reduction in LCE, as electricity-related GHG emissions serve as the dominant factor. In this scenario, LCE values drop further to 0.086 $kgCO_{2-eq}$/kWh for FR services and 0.075 $kgCO_{2-eq}$/kWh for PSVF services. In the Aggressive scenario, where the combined effects of all three developments are considered, LCE values decrease even further, reaching

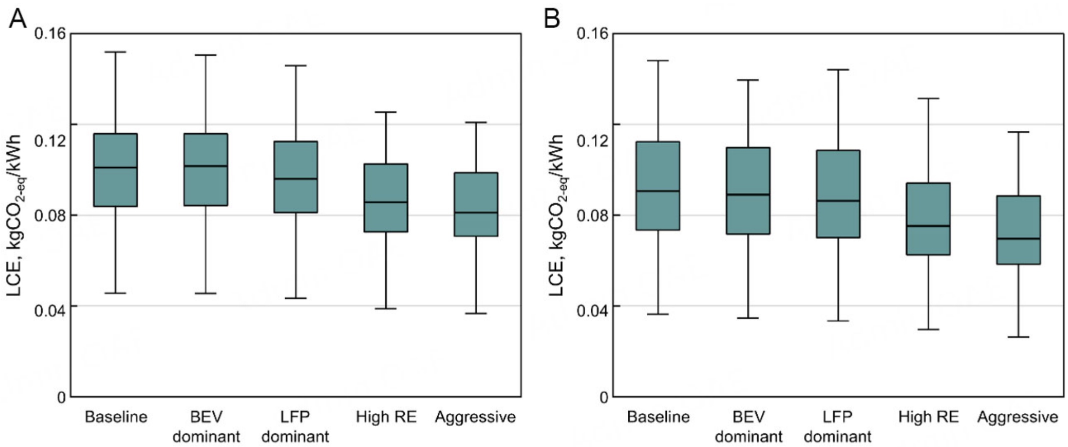

Figure 4. Multi-scenario analysis of V2G's LCE. (A) FR services. (B) PSVF services.

0.081 $kgCO_{2\text{-eq}}$/kWh for FR services and 0.070 $kgCO_{2\text{-eq}}$/kWh for PSVF services, representing reductions of approximately 19.7% and 23.2%, respectively. Overall, the multi-scenario analysis suggests that with the ongoing development of transportation electrification and renewable energy integration, the environmental impacts of V2G technology are expected to improve significantly in the future.

DISCUSSION

The deployment of distributed energy storage systems based on V2G technology constitutes a complex system involving multiple stakeholders. The environmental impacts of such systems are shaped by various factors, such as market structures, technological advancements, policies, and geographical variations. Geographically, these factors exhibit significant heterogeneity. A key determinant of the geographical variation in V2G's LCE values is the disparity in provincial electricity GHG emission intensities. In regions where power generation is still dominated by high-carbon resources, such as thermal power, V2G incurs higher additional GHG emissions. Conversely, regions that rely more on clean energy resources like wind, solar, and hydropower experience lower additional environmental impacts from V2G. Notably, the cities with the lowest LCE value in China exhibit only 24.6%-30.0% of that in the cities with the highest GHG emissions. Overall, a clear geographic trend emerges, with southern regions exhibiting lower LCE values compared to northern regions, and western regions showing lower values than eastern regions. The northeastern regions of China, characterized by the highest electricity emission intensities, bear the highest additional GHG emissions of V2G technology. In order to ensure the sustainable development of V2G technology and promote its widespread adoption across the country, tailored strategies should be developed based on the local electricity market structure, climate conditions, and policies.

Within each province, variations in the EV market structure across cities contribute to varying environmental impacts of V2G. From the perspective of powertrain, BEVs are more suitable for V2G compared to PHEVs. Larger batteries provide more available capacity for energy storage services, which helps amortize the GHG emissions associated with the production of batteries and bidirectional chargers. However, excessively large battery capacities do not necessarily lead to a reduction in V2G-related emissions, especially in the case of FR services. Larger batteries do not increase the amount of FR services provided throughout the vehicle's lifespan, yet increasing the emissions associated with battery materials and manufacturing. Therefore, from an environmental perspective, EVs in Segment 2 and Segment 3 are more favorable for V2G applications. In terms of battery chemistry, LFP batteries offer particular advantages for V2G due to their lower emission intensities. Moreover, their longer cycle life allows EVs to participate in V2G with fewer battery replacements over the vehicle's lifespan. During the implementation of V2G demonstration projects, priority should be given to BEVs with suitable battery capacities to minimize the GHG emissions associated with V2G technology.

Based on the multi-scenario analysis, the environmental impacts of V2G are expected to improve significantly with the ongoing expansion of renewable energy and the electrification of transportation. The widespread adoption of LFP batteries will substantially reduce the additional carbon emissions associated with V2G technology. Supplementary Figure 6 compares the results of this study with existing research on the additional GHG emissions of stationary battery storage technologies. The results indicate that the additional emissions from V2G are significantly lower than those from stationary storage technologies, positioning V2G as a crucial energy storage solution for the future power system. The focus of this study is the additional GHG emissions from EVs providing distributed energy storage services via V2G, without accounting for the emission reduction benefits associated with the optimization of the overall grid system. However, it is important to acknowledge that energy storage systems also play a role in reducing the overall GHG emissions of the power system. On one hand, the integration of energy storage with renewable energy generation helps to mitigate the intermittency and variability of resources such as wind and solar power, thereby facilitating their integration into the grid and reducing the overall emission intensity of electricity. On the other hand, traditional grid services are predominantly supplied by high-carbon thermal power plants, while EVs and other battery storage systems provide a low-carbon alternative. According to the latest report from the International Energy Agency (IEA), failing to achieve large-scale deployment of battery energy storage systems within the power system represents a substantial risk to the clean energy transition[39]. In scenarios with low penetration of battery storage, the integration of photovoltaic (PV) generation will face considerable obstacles, and a substantial portion of electricity demand will need to be met by high-carbon energy sources, such as coal and natural gas. Under such circumstances, the decarbonization of the power system is expected to decelerate around 2030, resulting in an additional 83 Gt of cumulative global GHG emissions by 2050. This would substantially hinder the global target of limiting the average temperature rise to 1.5 °C by the end of the century. In future research, a more comprehensive evaluation of both the additional emissions and the system-wide emission reduction benefits will be essential to better understand the potential of V2G technology in advancing the sustainability of the power system.

CONCLUSION

This study focuses on the additional greenhouse gas emissions associated with electric vehicles providing energy storage services by vehicle-to-grid technology. A data-driven life cycle assessment for vehicle-to-grid technology is developed specifically for the Chinese market. The model integrates statistical data on various factors, including China's EV market structure, driving behaviors, relevant policies, and geographical indicators, enabling a comprehensive analysis of the geographical heterogeneity in lifecycle greenhouse gas emissions of V2G technology at the city level.

The results indicate that the additional lifecycle greenhouse gas emissions associated with electric vehicles providing frequency regulation as well as peak shaving and valley filling services in different cities range from 0.046 to 0.152 $kgCO_{2\text{-eq}}$/kWh and 0.036 to 0.148 $kgCO_{2\text{-eq}}$/kWh, respectively. Among all components, energy-related greenhouse gas emissions constitute the largest proportion, accounting for 59.0% and 66.8%, respectively. Overall, the additional greenhouse gas emissions from vehicle-to-grid technology in China exhibit a geographical distribution, with the lowest values in the southwest regions and the highest in the northeast regions. The greenhouse gas emissions of vehicle-to-grid technology can be improved by cleaner electricity generation, optimal battery capacities, and longer battery lifecycles. These findings provide valuable insights into the environmental impact of vehicle-to-grid technology and its geographical variability, providing a theoretical foundation for developing region-specific policies.

This study has the following limitations. In V2G technical model, due to the data availability constraints, a droop model based on normally distributed random arrays and a grid scheduling model based on TOU tariff policies are adopted to simulate the charging and discharging process of EV batteries. While these methods have been widely used in existing research, they may still deviate to some extent from actual operating conditions. Another limitation stems from the input data. Specifically, the user behavior data utilized in this study is derived from historical operating records of over 1,000 sample EVs. Due to the limited sample size, the statistical outcomes may not fully capture the actual behavioral patterns of EV users in different regions. Furthermore, the underlying data used in this study come from multiple sources, which introduces temporal inconsistencies across datasets. To ensure overall consistency, this study uniformly adopts data from the year 2023. Future research should prioritize ongoing model refinement and continuous data updates to enhance the timeliness, accuracy, and reliability of the results.

DECLARATIONS

Authors' contributions

Methodology, investigation, formal analysis, writing - original draft: Geng, J.
Methodology, investigation, writing - review & editing: Dou, H.
Methodology, writing - review & editing: Hao, X.
Conceptualization: Liu, Z.; Zhao, F.
Conceptualization, methodology, writing - review & editing, project administration, supervision, funding acquisition: Hao, H.

Availability of data and materials

The data supporting the findings of this study are available within this Article and its Supplementary Material. Further data are available from the corresponding authors upon reasonable request.

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Conflicts of interest

Hao, H. is the Guest Editor of the Special Issue "Challenges and Opportunities for Transport Carbon Neutrality" and the Associate Editor of the journal *Carbon Footprints*. Hao, H. was not involved in any steps of editorial processing, notably including reviewer selection, manuscript handling, and decision making, while the other authors have declared that they have no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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