

A review of Bus2Grid applications in electric bus systems

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Abstract. Countries around the world are currently striving towards carbon neutrality, requiring the energy and transportation systems to undergo a major transformation. Vehicle-to-Grid (V2G) technology Enables Electric Vehicles (EVs) to feed electricity back into the grid, allowing the energy stored in their batteries to be discharged when the vehicles are not in use. Most current research focuses on private electric vehicles, as their owners can potentially earn additional income while contributing to grid stability. However, private EVs have highly dispersed ownership, no fixed routes, and their parking time is short and fragmented, making it difficult to coordinate and aggregate them to provide large-scale and reliable power supply to the grid. This review argues that electric bus depots, with their large-scale charging infrastructure, are the most suitable targets for implementing V2G. Buses have fixed schedules for departure, and during off-peak hours or at night, large numbers of buses are typically parked at depots and can be centrally managed by bus operators. Operators can therefore determine when batteries are available for grid services and estimate how much electricity can be sent out in advance, making scheduling considerably easier. This paper reviews the basic technologies required to implement V2G at bus depots, including charging stations, communication networks, and control systems. It also explains why bus depots are particularly suitable as distributed energy resources, primarily because they have substantial aggregate battery capacity and operators can accurately identify periods when buses are idle and available for grid services. Finally, this review synthesises academic research and real-world project outcomes, summarising current knowledge and identifying key areas requiring further investigation to enable bus depots to play a greater role in the transition to clean energy.

Keywords: electric bus, Vehicle-to-Grid (V2G), bus depot, battery degradation, carbon neutrality

1. Introduction

1.1. Research background and significance

To address the deteriorating global environment and mitigate climate change, countries around the world are actively pursuing climate goals, which have become a common priority internationally. According to the 2024 Global Carbon Neutrality Annual Progress Report recently released by the Carbon Neutrality Research Institute of Tsinghua University, 151 countries have set carbon neutrality targets, and 120 of these countries have incorporated these targets into their laws or policies [1]. The total carbon emissions of these countries account for the vast majority of global emissions. Against this background, low-energy consumption, low-pollution, and zero-emission electric vehicles play an important role in reducing global carbon emissions. With

the increase in electric vehicles and the advancement of transportation electrification, Vehicle-to-Grid (V2G) technology has emerged. V2G can integrate electric vehicle batteries into the power grid as distributed energy resources. Through bidirectional energy flow, V2G enables electric vehicles not only to draw electricity from the grid but also to feed electricity back into the grid during periods of peak electricity demand. This capability helps stabilise the power grid, facilitates the integration of renewable energy, and can also generate income for electric vehicle owners.

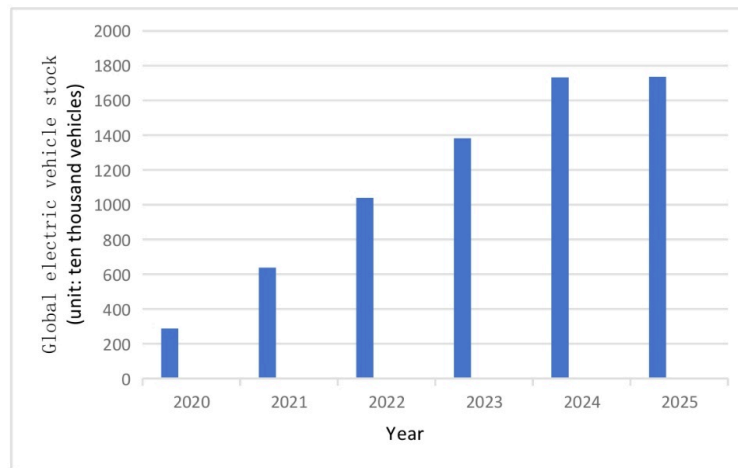


Figure 1. Global number of electric vehicles

With the development of transportation energy systems, the global number of electric vehicles has grown rapidly over the past five years. Figure 1 shows the global number of electric vehicles during this period.

Most existing V2G research focuses on private electric passenger vehicles. Although these studies have demonstrated the technical feasibility and potential economic benefits of V2G, private electric vehicles have inherent limitations for V2G deployment. Their usage patterns are difficult to predict, parking durations vary greatly, and vehicle ownership is highly dispersed, making vehicle scheduling and aggregation extremely difficult. These problems also reduce the value of private electric vehicles as predictable grid assets.

For this reason, electric bus depots, owing to their inherent advantages in load forecasting and scheduling, have become attractive deployment sites for B2G (electric buses supplying power to the grid). Driven by global carbon neutrality goals and the low-carbon transformation of urban transportation systems, the electrification of public transportation has become a major objective in many countries around the world.

1.2. Comparison of core differences between Bus2G and private EV V2G

According to the *Global Electric Vehicle Outlook 2025* released by the International Energy Agency (IEA), by 2025, the global number of electric buses had exceeded 8 million, representing a nearly 12-fold increase compared with 2018 [2]. This has made public transportation one of the fastest-growing segments of the transportation sector in terms of electrification. It is particularly noteworthy that an electric bus typically has a battery capacity ranging from 250 to 500 kilowatt-hours, which is approximately 5 to 10 times that of a private electric vehicle. Moreover, bus operation schedules are very regular, and buses are often parked at depots for extended periods each day. Such a large fleet can therefore be transformed into a reliable and cost-effective flexible energy resource. It can play a significant role in peak shaving and valley filling, renewable energy absorption, and emergency power supply, providing a strong foundation for the large-scale commercial application of Bus2G technology.

Table 1. Comparison of core dimensions between private passenger EV V2G and electric bus Bus2G

Comparison Dimension	Private Passenger EV V2G	Electric Bus Bus2G
Battery Capacity per Unit	50–100 kWh	250–500 kWh (5–10 times the capacity of private EVs)
Average Daily Schedulable Parking Duration	4–8 hours, geographically dispersed and highly unpredictable	12–18 hours, centrally located at depots with fixed, predictable schedules
Ownership and Decision-making Model	Decentralised individual ownership, user participation willingness is highly uncertain	Centralised fleet operation, unified professional decision-making
Resource Aggregation Difficulty	Extremely high: requires aggregation of tens of thousands of vehicles to form MW-level grid resource	Extremely low: 50 buses at a single depot could provide more than 10 MW of aggregated battery capacity
Scheduling Reliability	Low: user travel plans and charging demands are volatile	Extremely high: fixed operation timetables, parking time and state of charge can be accurately predicted

In the context of the large-scale deployment of electric buses, the practice of buses supplying power to the grid (Bus2G) has become a particularly practical application of vehicle-to-grid interaction. However, although both rely on bidirectional charging technology at the technical level, there are significant systematic differences between bus V2G and private electric vehicle V2G in terms of their practical operation.

As summarised in Table 1, these differences cover a wide range of factors, from basic resource attributes—such as battery capacity per vehicle, schedulable parking duration, ownership and decision-making patterns—to scheduling mechanisms, economic costs, and revenue structures, as well as the grid regulation capabilities they can ultimately provide. The most prominent point is that the centralised nature and scheduled operation of electric bus fleets can directly address three core bottlenecks that hinder the large-scale implementation of private electric vehicle V2G: uncertain user participation, highly decentralised and complex scheduling, and low predictability of available resources.

These inherent differences mean that, when designing technical roadmaps, establishing business models, and formulating supporting policies, these two V2G models should not be treated as equivalent. Therefore, it is important to systematically compare the two models. Such a comparison can help clarify their commercialisation potential, suitable application scenarios, and relative priorities for deployment.

1.3. Scope and contributions of this review

As research on Bus2G has attracted increasing attention, this review aims to systematically summarise the current research and practical developments in this field. First, it classifies Bus2G scheduling optimisation methods into several categories. One is the "deterministic" approach, which assumes the relevant parameters are known in advance; another comprises the methods specifically designed to deal with various uncertainties; and the third is the real-time online approach, which calculates while moving and aims to maximise overall benefits. The review then examines representative studies, including small- and large-scale models capable of handling multiple depots and random factors, as well as robust methods designed to withstand uncertainties within a given budget. Furthermore, it compares the strengths and weaknesses of these approaches and identifies the scenarios in which each method is most suitable.

This review also identifies several important gaps in existing research. For example, no model has yet been developed that can incorporate the entire cost cycle of a battery from purchase to disposal. There is also no widely established framework for fairly allocating benefits among all stakeholders, including public transportation operators and grid operators. In addition, areas such as Vehicle-to-Vehicle (V2V) energy transfer for emergency applications and the coordinated integration of bus depots with multi-energy microgrids remain relatively underexplored.

Finally, this review outlines potential research directions for the coming years and provides practical recommendations and a comprehensive reference base for future research. The aim is to contribute to the transition of Bus2G technology from laboratory research towards practical deployment and commercial operation.

2. Bus2G system architecture and core features

2.1. Three-tier technical architecture of Bus-to-Grid (B2G)

The physical layer forms the hardware foundation of the Bus2G system, enabling bidirectional energy flow between the electric bus fleet and the power grid [3]. This layer consists of three interconnected key components: the on-board vehicle system, depot-level charging and control infrastructure, and the interface connected to the power grid. All scheduling and optimisation algorithms operating above this layer must account for these physical constraints [4]. Figure 2 illustrates the overall workflow of Bus-to-Grid, from the vehicle side through the depot to the grid. Figure 3 further presents the detailed physical architecture of the B2G system, including the key components at each layer.

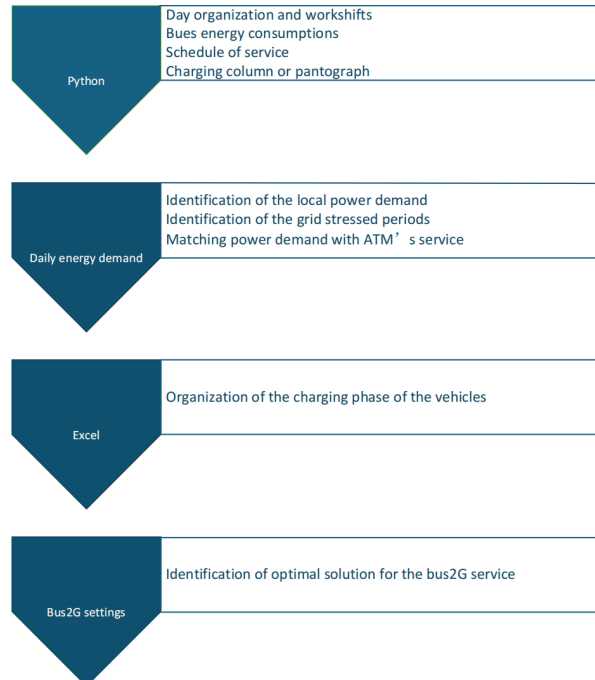


Figure 2. Workflow of Bus-to-Grid

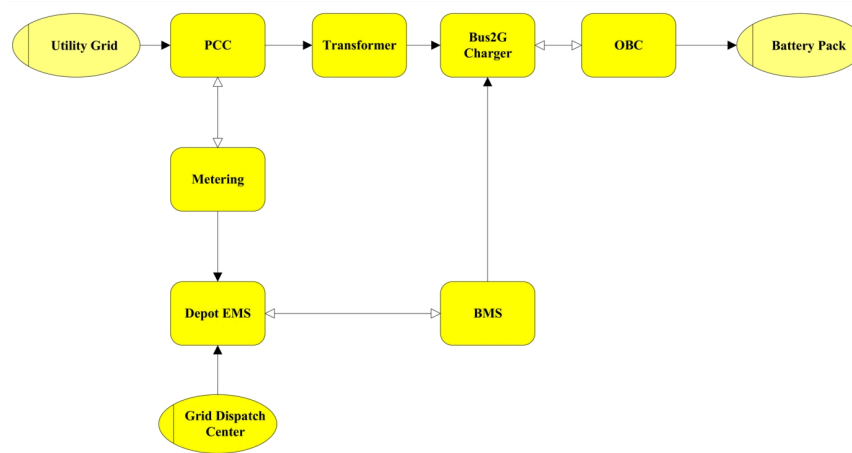


Figure 3. Bus2G physical architecture

2.1.1. On-board vehicle systems

This layer serves as the core energy storage component of the Bus2G system and consists of three key subsystems:

1. **Traction Battery Pack.** The electric buses are equipped with large-capacity lithium-ion battery packs. Each vehicle typically has a battery capacity of 250 to 500 kilowatt-hours, which is approximately 5 to 10 times that of private electric vehicles. Collectively, these batteries form a highly concentrated distributed energy storage resource [5]. For instance, in a large-scale bus fleet study conducted in Seoul, the Hyundai Electric City model used was equipped with a 290.4-kWh NCA (nickel-cobalt-aluminium) battery. To mitigate battery ageing caused by repeated charging and discharging, the study restricted the battery's operating state of charge to between 20% and 80% [6]. In the event of a sudden power outage in the grid, a fully charged electric bus can serve as a backup power source, capable of charging up to 5 private electric vehicles for emergency use. It can therefore be regarded as the most cost-effective mobile backup energy source in the city [5].

2. **Bidirectional On-Board Charger.** Electric buses participating in V2G are equipped with bidirectional DC/AC converters, which can both charge the vehicle from the grid and allow the vehicle to discharge power to the grid. The energy conversion efficiency for this bidirectional energy transfer is generally between 86% and 91% [7]. This bidirectional power interface enables buses to adjust their active power exchange in real time according to the grid dispatch instructions. This is a fundamental hardware requirement for participation in grid services such as peak shaving and load response.

3. **Battery Management System.** The battery management system continuously monitors the battery's state of charge, voltage, temperature, and health status, and transmits operational data to the depot's energy management system [7]. It sets maximum charging and discharging power limits, as well as upper and lower state-of-charge limits, to ensure the safety of the battery during V2G operation. These constraints form the basis of all scheduling optimisation models.

2.1.2. Depot-level charging and control infrastructure

The bus depot is the primary site of Bus2G operations. It brings together the following key equipment and systems:

1. **V2G Bidirectional Chargers.** Unlike the dispersed charging infrastructure for private electric cars, bus depots typically use large-capacity centralised bidirectional chargers. The power rating of each charging interface is typically between 150 and 300 kilowatts. Currently, the commonly adopted advanced dual-port charging station solution is widely used in actual deployments, allowing a single charging station to

simultaneously charge two electric buses and potentially halving infrastructure costs. According to the standard station configuration, for every 10 electric buses, one fast-charging station is provided to meet the operational scheduling requirements [6].

2. Depot Power Transformer. The distribution transformer at the depot is one of the most significant bottlenecks for the large-scale deployment of Bus2G. Its rated capacity directly determines the upper limit of the total power that the entire fleet can charge and discharge simultaneously. All scheduling models must therefore adhere to the transformer's capacity limit and prevent overloading. Transformer capacity is consequently a common hard constraint in Bus2G optimisation research [8].

3. Depot Energy Management System (EMS). The Energy Management System (EMS) acts as the local control centre of the depot. It collects real-time data from all charging stations and vehicle battery management systems, runs scheduling algorithms, and issues charging and discharging instructions to each vehicle. At the same time, it also interfaces with the power grid dispatch centre to receive demand response signals and power information from the grid.

2.1.3. Grid-side interconnection interface

This component enables the electric bus fleet to safely and appropriately connect to the power grid:

1. Point of Common Coupling (PCC). Charging stations within the depot are connected to the power grid through a unified public connection point (PCC). During operation, the net active power exchanged by the depot must remain within the power limits and dispatch requirements specified by the grid operator. This provides an important constraint for real-time scheduling algorithms [4]. The PCC is equipped with standard protection devices and fully complies with the IEEE 1547 grid connection standard to ensure safety during grid connection and in islanding mode.

2. Bidirectional Metering and Communication System. At the PCC, bidirectional electricity meters measure the electricity imported from and exported to the grid, facilitating market settlement. A high-speed communication link connects the depot's Energy Management System (EMS) with the power grid dispatch centre, enabling the exchange of dispatch instructions and operational data with low latency.

2.2. Core constraints of Bus2G systems

Bus2G optimisation models typically involve several important operational constraints. Together, these constraints determine the extent to which the battery fleet can be used as a virtual power plant. Failure to satisfy these constraints can result in infeasible schedules or compromise safe operation.

1. Operational Constraints. These constraints are designed to ensure that the electric buses can first fulfil their primary tasks—providing reliable public transportation services. Specifically, each bus must follow its predetermined operating schedule, including scheduled departure and arrival times. Before departing the depot, the battery must contain sufficient energy to complete the planned route. Energy consumption during operation must be estimated based on factors such as route distance, road conditions, and vehicle characteristics. When buses return to the depot, their remaining state of charge must be sufficient to support the next scheduled operation, including the following day's departure.

The following formula from Fei et al. [8] represents an aggregate-level energy consumption model for large-scale electric bus fleets in Bus2G research:

$$E_c(t) = U(t) \cdot \eta \quad (1)$$

The total energy consumed by the fleet during one operating day can then be calculated as follows:

$$E_{daily} = \sum_{t \in T} E_c(t) \cdot \Delta T \quad (2)$$

The symbols used in the above energy consumption model are defined in Table 2.

Table 2. Nomenclature

Indices and Sets	Description
$E_c(t)$	Total energy consumption of the entire bus fleet at time step t (kWh/h)
$U(t)$	Number of buses in operation at time step t (buses)
η	Average energy consumption rate per bus (kWh/km)
E_{daily}	Total daily operating energy consumption of the fleet (kWh)
T	Set of all time steps in one operating day
ΔT	Length of each time step (hours)

2. Battery Safety and Degradation Constraints. To prevent excessive battery degradation and safety risks, several fundamental constraints must be followed. The battery's state of charge should remain within the industry-recognised safe range, typically between 20% and 80% of full charge. If the charge drops below 20% and the battery continues to discharge, it will suffer irreversible damage; conversely, if the battery is charged above 80% for a long time, its ageing process will significantly accelerate. Additionally, the instantaneous charging and discharging power must never exceed the battery's rated maximum limit, which is controlled by the on-board Battery Management System (BMS). Finally, it is necessary to minimise excessive charging and discharging cycles as much as possible, as additional cycling can cause irreversible capacity degradation and shorten battery life.

3. Depot Infrastructure Constraints. Depot infrastructure constraints depend on the existing hardware configuration and represent another important technical limitation on the large-scale deployment of Bus2G. The number of vehicles that can charge and discharge simultaneously is limited by the number of available charging ports. The total charging and discharging power of all vehicles at the depot cannot exceed the rated capacity of the distribution transformer. At the PCC, the net power exchange cannot exceed the permitted upper limit. Even when dual-port chargers are used, the combined power delivered through the two ports cannot exceed the rated power of the charger itself. Any Bus2G scheduling algorithm must therefore satisfy these physical constraints to ensure feasible and safe operation.

3. Core scheduling and optimisation methods

This chapter reviews three core Bus2G scheduling optimisation methods. It starts with the most well-established method, deterministic optimisation. This can be further divided into Mixed-Integer Linear Programming (MILP), which can model discrete scheduling decisions for single buses, and convex optimisation that looks at the whole fleet all at once.

3.1. Deterministic optimisation

Currently, deterministic optimisation is one of the most widely used methods for B2G scheduling. Its core concept is relatively straightforward: key parameters, such as bus schedules, the amount of electricity consumed for running a route, electricity prices, and battery capacity, are assumed to be known in advance and remain constant once determined. The entire scheduling problem can then be formulated mathematically and solved using standard optimisation solvers to calculate the optimal scheduling plan.

Most existing studies use Mixed-Integer Linear Programming (MILP) as the main tool for modelling. For instance, Manzolli et al. established a MILP model in 2022 focusing on individual buses to determine the most

cost-effective times for charging and discharging their batteries [9]. This model not only calculated the operating costs but also directly incorporated factors such as battery degradation and various operational constraints. This model monitored the power consumption of each bus every minute, ensuring that each vehicle departed on time while minimising the total operating cost over the day. More importantly, its optimisation objective addressed a major limitation of earlier B2G research: previous models only focused on the revenue generated from selling electricity while overlooking the costs associated with battery degradation.

For large fleets consisting of hundreds or even thousands of vehicles, Fei et al. adopted a different approach in 2023 and developed a nonlinear convex optimisation model [8]. Rather than modelling each vehicle individually using MILP, they considered the entire fleet as a single entity, making the problem computationally more tractable. This approach reduces the number of possible combinations that would otherwise become computationally prohibitive as the fleet size increases.

Iuliano and Vaccaro took the MILP approach further in 2024 by formulating the problem as a welfare-maximisation model. In simple terms, the model aims to allocate charging and discharging tasks fairly among the buses while strictly adhering to power instructions from the grid [4].

However, deterministic optimisation has an important limitation: it cannot handle the unpredictable events that occur during real-world operation [9]. These methods are based on the assumption that all data is already known with certainty. In practice, buses may be delayed, weather and road conditions may change, power consumption may vary accordingly, and the demand from the power grid may suddenly change unexpectedly. Under such conditions, a pre-optimised scheduling plan may quickly become infeasible. Therefore, although deterministic methods may perform well in simulation environments with known parameters, their performance may deteriorate when unexpected events occur in real-world operations.

3.2. Uncertainty-aware optimisation

Uncertainty-aware optimisation is specifically designed to address the inherently unpredictable factors that affect Bus2G operations. Its primary purpose is to enable more reliable and risk-aware decision-making. Unlike deterministic models, uncertainty-aware approaches explicitly account for deviations between expected and actual operating conditions. The main sources of uncertainty include fluctuations in electricity prices, changes in energy consumption caused by traffic conditions, fluctuations in passenger demand, and the intermittency of renewable energy output [10].

Related work has extended stochastic optimisation by incorporating photovoltaic generation and battery storage into Bus2G operations in the Swedish city of Skellefteå. Using Benders decomposition to solve the resulting large-scale joint optimisation problem, the study found that, without integrating renewable energy, the high charging demand could cause the voltage of the distribution network to exceed the limit by more than 4% [10].

In terms of handling operational uncertainties, Jiang et al. developed a large neighbourhood search heuristic algorithm for multi-depot vehicle allocation in Shenzhen [11]. This algorithm generates feasible scheduling plans while reducing long-distance empty runs between depots.

The team developed a mixed-integer programming model to address the multi-depot electric bus scheduling problem. The core objective was to minimise the total cost of vehicle operation, idle time, and charging. The constraints of the model covered route allocation, vehicle assignment to specific depots, battery charge levels, charging rules, and temporal and spatial matching.

Objective Function (Formula 3):

$$\min \sum_{k \in K} \sum_{(i,j) \in A} c_{ij} X_{ijk} + \sum_{(i,j) \in A} g_{ij} W_{ij} \quad (3)$$

This is the overall objective of the proposed model, which aims to minimise the total operational cost of the system. It contains two components:

$$\sum_{k \in K} \sum_{(i,j) \in A} c_{ij} X_{ijk} \quad (4)$$

The total cost of bus operation and deadheading, and the overall operational cost.

$$\sum_{(i,j) \in A} g_{ij} W_{ij} \quad (5)$$

The entire model is optimised to achieve the minimum comprehensive operational cost.

Trip Uniqueness Constraint (Formula 6):

$$\sum_{k \in K} \sum_{j: (i,j) \in A} X_{ijk} = 1, \quad i \in T \quad (6)$$

This constraint ensures that each bus trip i is assigned to exactly one bus, preventing trips from being omitted or assigned multiple times.

Flow Conservation Constraint (Formula 7):

$$\sum_{j: (i,j) \in A} X_{ijk} - \sum_{j: (j,i) \in A} X_{jik} = 0, \quad i \in T, k \in K \quad (7)$$

For any trip i and any depot k , the number of buses arriving at trip i equals the number of buses departing from trip i . This guarantees continuous and reasonable connections between consecutive trips and avoids broken bus routes.

Depot affiliation constraints (vehicle relocation constraint, Formulas 8 & 9):

$$\sum_{\beta \in K_k} \sum_{i \in V} X_{o^\beta ik} = 0, \quad k \in K \quad (8)$$

$$\sum_{\beta \in K_k} \sum_{i \in V} X_{id^\beta k} = 0, \quad k \in K \quad (9)$$

These are the core vehicle-depot constraints introduced in this study. In simple terms, each bus must begin its daily service from its home depot and, after completing all assigned trips, return to that same depot. Long-distance deadheading between different depots is strictly forbidden. This rule directly follows the real-world operating regulations of the Shenzhen public bus system.

Battery SOC balance constraint (Formula 10):

$$Y_i - e_i + W_{ij} - e_{ij} + M(1 - \sum_{k \in K} X_{ijk}) \geq Y_j, \quad (i, j) \in A \quad (10)$$

This is the core constraint for battery energy management. After a bus completes trip i , it consumes electricity during deadheading and gets recharged. The remaining battery energy after all these processes must be sufficient to support the subsequent trip j . It maintains the continuity and availability of battery power throughout operation.

Charging duration constraint (Formula 11):

$$W_{ij} - (z_j - z_i - t_{ij} - t_p) r_s \sum_{k \in K} X_{ijk} \leq 0, \quad (i, j) \in A \quad (11)$$

This constraint limits the maximum available charging volume. The actual charged electricity cannot exceed the product of available charging time and rated charging power, which conforms to physical charging limits.

Battery maximum capacity constraint (Formula 12):

$$Y_i - e_i + W_{ij} - u_{max} \leq 0, \quad (i, j) \in A \quad (12)$$

After finishing trips and supplementary charging, the battery energy cannot exceed its full capacity. This prevents overcharging and protects the battery.

Battery safe operating range constraint (Formula 13):

$$u_{min} \leq Y_i \leq u_{max}, \quad i \in V \quad (13)$$

Variable Definition Constraints (Formula 14 & 15):

$$W_{ij} \geq 0, \quad (i, j) \in A \quad (14)$$

$$X_{ijk} \in \{0, 1\}, \quad (i, j) \in A, \quad k \in K \quad (15)$$

$W_{ij} \geq 0$: Charging volume is non-negative, meaning the model only considers charging rather than discharging in this scheduling scenario.

$X_{ijk} \in \{0, 1\}$, where X_{ijk} is a standard 0-1 binary variable, which fits the basic requirement of mixed integer programming.

Table 3. Nomenclature

Symbol	Definition
K	Set of all bus depots
T	Set of all scheduled bus trips
A	Set of service links and connection arcs
X_{ijk}	0-1 binary variable: Bus from depot k travels along arc (i, j)
c_{ij}	Unit cost of operation and deadheading for arc (i, j)
g_{ij}	Time-of-use electricity price
W_{ij}	Charging volume between two consecutive trips
Y_i	Remaining battery SOC after trip i
e_i	Electricity consumption of trip i
u_{min}	Minimum safe battery state of charge
u_{max}	Maximum safe battery state of charge
r_s	Rated charging power of electric buses

The nomenclature for the multi-depot electric bus scheduling model is summarized in Table 3. This is a mixed integer programming model specifically designed for the scheduling of electric buses across multiple depots. Its objective is to minimise total costs, including vehicle operation and charging costs. The model also incorporates real-world constraints, such as vehicle allocation for each trip, depot affiliation, restrictions on long-distance empty runs between depots, battery SOC limits, and the physical constraints of the charging equipment.

3.3. Real-time online scheduling

Real-time scheduling uses bidirectional electricity meters and sensors to obtain real-time information on power consumption and system status. This information, together with pre-set formulas and trained AI models, can be used to estimate bus departure times, battery state of charge, and other operational variables [10]. The system can then dynamically adjust when each vehicle should charge, the charging power level, and the charging location. It can also coordinate the bus fleet with photovoltaic generation and stationary energy storage batteries.

The core purpose of this approach is to maintain reliable bus services, ensure battery safety, comply with grid regulations, and minimise overall operating costs. This scheduling approach can prevent buses from charging or discharging in clusters, thereby making the local grid more stable. However, optimisation models that integrate all these factors involve numerous variables and complex constraints, making them

computationally demanding. Therefore, Benders decomposition can be used to simplify the calculation. This method divides the original complex problem into smaller sub-problems, reducing the computational burden and enabling the model to optimise the system more rapidly in response to the real-time operating conditions of large-scale fleets.

4. Engineering practices and typical cases

4.1. Chinese cases

Shenzhen is a leading pilot city for Bus-to-Grid (B2G) applications in China. The city operates over 13,000 fully electrified public buses, which serve as massive mobile energy storage resources for the urban power grid.

Two typical application modes have been explored in this context. The first is grid demand response. Electric buses at numerous depots can charge during periods of low electricity demand and discharge power back to the grid during peak electricity use, thereby helping to balance grid load and reduce power supply costs. The second is emergency Vehicle-to-Vehicle (V2V) power supply. When local grid faults or power outages occur, electric buses can transmit power to adjacent vehicles or nearby key facilities via V2V and B2G modes, ensuring normal transit operation and improving urban power supply resilience.

Shenzhen's experience with B2G and V2V provides a useful practical reference for the further development of bus-grid integration technologies nationwide.

4.2. Foreign cases

London's Northumberland Park Depot in the UK hosts a Bus2Grid demonstration project run by Go-Ahead London. Supported by the UK government and multiple industrial and academic partners, this large-scale electric bus depot deploys nearly 100 electric buses, with 28 double-decker buses participating in the Bus2Grid trial. Figure 4 shows the depot in London.



Figure 4. Go-ahead London's northumberland park depot

These buses are equipped with bidirectional energy interaction devices. They charge during off-peak periods at night and discharge power to the grid during daytime peak periods, supporting peak shaving and load balancing. The total power output of the trial fleet can reach more than 1 MW. The project demonstrates how a bus depot can function as a virtual power station while exploring potential business models for Bus2Grid. It also serves as a useful case study in support of the UK's carbon-neutrality goals and offers valuable international experience for the further development of Bus2Grid technology.

5. Research challenges and future directions

5.1. Current challenges

Although Bus2Grid has been trialled and deployed in multiple regions worldwide, it still faces several practical challenges to its large-scale deployment. For fleets managed across multiple bus depots, frequent data exchange between different sites also creates potential risks to information transmission and data security [11]. Meanwhile, the industry has not yet established universally adopted technical standards for Bus2Grid equipment, and supporting hardware and infrastructure require further development. From a commercial perspective, tough market access requirements and underdeveloped profit-sharing rules may also hinder the widespread adoption of this technology.

5.2. Future directions

To address these challenges, Bus2Grid research is likely to develop in several directions. Researchers will need to explore full life-cycle battery management, including strategies for controlling battery ageing and degradation, as well as methods for reusing batteries after they are retired from vehicle service. Additionally, integrating photovoltaic power generation and energy-storage equipment with microgrids to create multi-energy integrated systems represents a promising research direction [10].

In terms of system operation, emerging technologies such as artificial intelligence and digital twins could be introduced to make the scheduling and charging of electric buses more intelligent and efficient. By integrating V2G services, grid demand response, and emergency backup power supply functions, Bus2Grid systems could support a wider range of practical applications. Finally, the industry needs to develop a clearer understanding of market rules for balancing the interests of all participating stakeholders.

6. Conclusion

This paper provides a detailed overview of the Bus2Grid technology, covering its current technical architecture, scheduling methods, representative domestic and international applications, current challenges, and potential future development directions.

It first explains the basic concept of Bus2Grid: essentially, electric buses can function as distributed energy-storage resources that help the power grid manage peak demand and respond to emergency situations. In terms of scheduling, existing approaches can be broadly divided into methods that calculate schedules in advance based on known operating conditions and online dynamic scheduling methods that adjust schedules according to real-time conditions. In terms of practical applications, Shenzhen provides a representative example in China, with its large fleet of electric buses and growing deployment of bidirectional charging stations. Internationally, the Northumberland Park Bus Depot project in London provides a well-known demonstration of the potential for converting bus depots into virtual power plants.

However, large-scale deployment still faces numerous challenges. Repeated battery charging and discharging can accelerate battery degradation. Multiple depots may need to coordinate their operations, creating challenges related to data exchange and communication security. Moreover, differences in hardware standards and the slow integration of distributed resources remain obstacles to widespread implementation.

Looking ahead, research should focus on full life-cycle battery management. Photovoltaic generation, energy-storage systems, and microgrids should also be integrated to enable coordinated energy management. In addition, the trading rules of the market must also be carefully revised to ensure that the economic benefits and responsibilities of participating stakeholders are distributed appropriately.

Overall, Bus2Grid represents a promising approach to integrating public transport with electricity-grid management. Despite various challenges, it has considerable development potential. With continuous technological and institutional improvements, this technology could play an increasingly important role in the transition towards low-carbon transportation and energy systems.

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