

Energy Consumption and Charging Infrastructure Analysis for Electric Bus Deployment in Urban Transportation Systems

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Abstract: The electrification of urban public transportation has become a key strategy for reducing energy consumption and greenhouse gas emissions while improving overall system efficiency. This study develops a comprehensive modeling framework to evaluate the energy consumption and charging infrastructure requirements of electric bus fleets operating in urban environments, incorporating key operational parameters such as travel distance (126 km/day), vehicle energy efficiency (1.2–1.5 kWh/km), fleet size (5–30 buses), and regenerative braking efficiency (25%). The results indicate that a single electric bus consumes approximately 151.2 kWh/day under typical operating conditions, which can be reduced to 113.4 kWh/day through regenerative braking, representing a 25% improvement. At the fleet level, electricity demand increases proportionally, reaching 0.76 MWh/day (5 buses), 1.51 MWh/day (10 buses), 2.27 MWh/day (15 buses), and 3.02 MWh/day (20 buses). Furthermore, fast-charging systems with a capacity of 150 kW can deliver up to 300 kWh within 2 hours but may introduce peak load demands of up to 0.75 MW. These findings highlight the importance of integrated energy modeling, smart charging strategies, and grid-aware planning.

Keywords: Charging infrastructure; Electric bus; Energy consumption modeling; Regenerative braking; Urban transportation

Introduction

Urban transportation systems are among the largest consumers of energy worldwide and play a significant role in global greenhouse gas emissions. Rapid urbanization, population growth, and increasing mobility demand have led to a continuous rise in transportation energy consumption, particularly in developing countries (Chan, 2007; Shao et al., 2009; Clement-Nyns et al., 2010; Lajunen, 2014; Santos & Davies, 2020; Kamal & Irfan, 2025). Globally, the transportation sector accounts for approximately 30% of total final energy consumption, with road transportation representing the dominant share of this demand (Creutzig et al., 2015; Mahmoud et al., 2016). In many urban areas, the growing number of private vehicles has intensified energy use and environmental pollution, raising serious concerns regarding sustainability, air

quality, and energy security. These challenges have encouraged governments and researchers to explore alternative transportation technologies capable of reducing energy consumption and emissions.

Public transportation systems are widely recognized as an effective strategy for improving energy efficiency and reducing environmental impacts in urban transport networks (Zhou et al., 2020; Deb et al., 2018; Li et al., 2018; Maulidiana et al., 2023). Compared with private vehicles, buses can transport a larger number of passengers with lower energy consumption per capita, making them a key component of sustainable mobility systems. However, most conventional bus fleets in developing countries still rely on diesel engines, which contribute significantly to urban air pollution and greenhouse gas emissions (Rompegading & Handayani, 2023; Anshori et al., 2024; Wahyudi et al., 2024; Syaiful et al., 2024; Charis et al., 2025; Supranartha et al., 2025). The

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continued dependence on fossil fuel-based transportation therefore remains a critical challenge for urban energy management and environmental

protection (Pagany et al., 2019; Rahman et al., 2020; Afraah et al., 2021; Hanun et al., 2023).

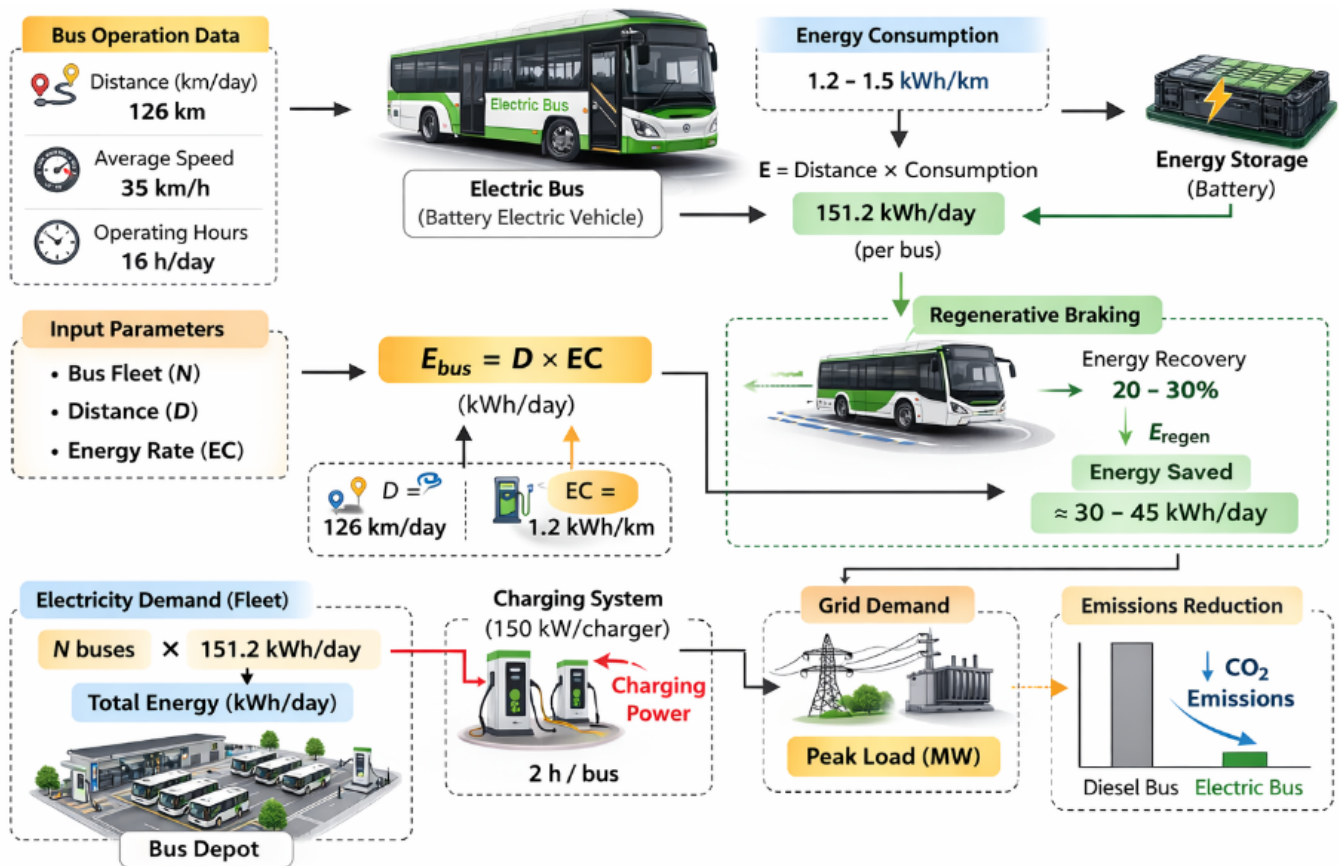


Figure 1. Conceptual framework of electric bus energy consumption and charging infrastructure analysis, illustrating the relationship between operational parameters, energy demand, regenerative braking, and grid impact

In response to these challenges, the electrification of public transportation has emerged as one of the most promising solutions for achieving low-carbon mobility. Electric buses (EBs) have gained considerable attention due to their high energy efficiency, zero tailpipe emissions, and potential to integrate with renewable electricity systems (Wang et al., 2019). Compared with internal combustion engine vehicles, electric buses are capable of converting a higher proportion of input energy into useful traction power, while also enabling energy recovery through regenerative braking systems (Zhang et al., 2020). As a result, the deployment of electric buses in urban transport systems offers significant potential to reduce energy consumption and emissions while improving overall transportation sustainability. Despite these advantages, the large-scale adoption of electric buses introduces new challenges related to electricity demand and energy management. Electric buses require substantial electrical energy for daily operation, particularly in large urban fleets. Understanding the energy consumption characteristics of electric buses is therefore essential for planning

charging infrastructure, managing electricity demand, and ensuring reliable operation of urban power systems.

Several studies have examined transportation fuel consumption and emissions using system-based modeling approaches (Anshori et al., 2024). These studies provide valuable insights into transportation energy demand but primarily focus on conventional fossil-fuel vehicles. However, limited research has investigated the electrical energy consumption characteristics of electric bus fleets within the context of urban transportation systems in developing countries. In particular, there is still a lack of quantitative models that estimate the electricity demand of electric buses based on operational parameters such as travel distance, fleet size, and vehicle energy efficiency. Without such models, it becomes difficult for city planners and power system operators to accurately estimate the additional electricity demand associated with transportation electrification or to design appropriate charging infrastructure for electric bus deployment.

Therefore, this study aims to develop an energy consumption modeling framework for electric buses

operating in urban transportation systems. Using transportation activity data derived from previous transportation studies, the proposed model estimates the electrical energy demand of electric bus fleets based on operational parameters such as route distance, vehicle efficiency, and fleet size. In addition, the model evaluates the potential energy recovery from regenerative braking and examines the implications of electric bus deployment on urban electricity demand. The results provide valuable insights into the energy requirements of electric bus systems and contribute to the development of sustainable urban transportation.

Method

Study Framework and Data Assumptions

This study develops a modeling framework to estimate the electrical energy demand of electric bus (EB) fleets operating in urban transportation systems. The approach is based on a system-level analysis, where

vehicle operational parameters are used to quantify energy consumption and charging requirements (Chan, 2007; Lajunen, 2014). Transportation activity data are derived from representative urban transport conditions reported in previous studies on public transport electrification. The analysis assumes an average daily travel distance of 126 km per bus, with an average operating speed of 35 km/h and a daily operation time of approximately 16 hours. These parameters are consistent with operational observed in worldwide bus systems (Zhou et al., 2016).

Technical specifications of electric buses are defined based on commonly reported values in the literature. Each bus is assumed to have a battery capacity of 350 kWh and an average energy consumption rate of 1.2 kWh/km under efficient driving conditions (Xylia et al., 2017). Charging infrastructure is modelled using fast-charging systems with a rated power of 150 kW per charger, which reflects current industry in electric charging systems (Deb et al., 2018).

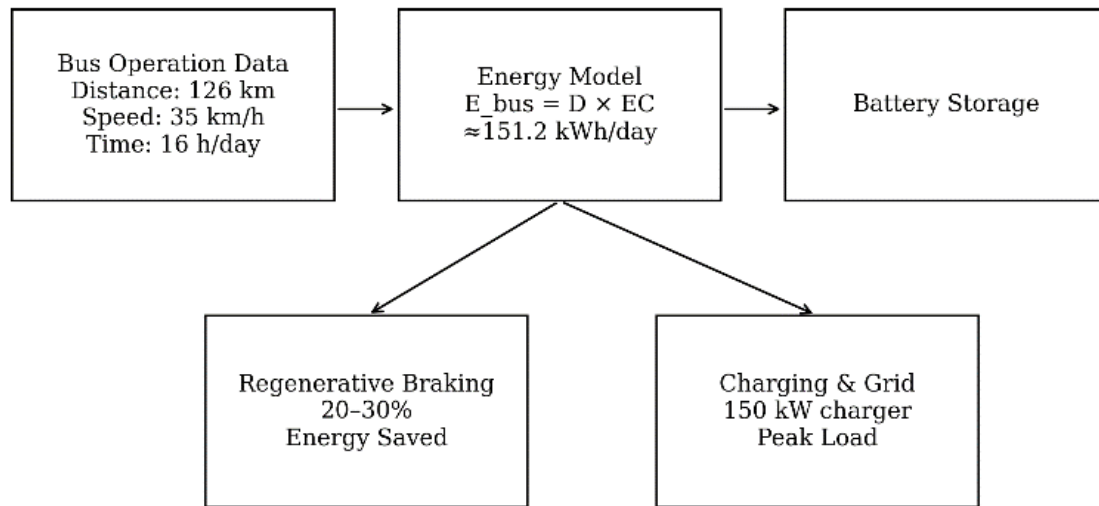


Figure 2. Schematic representation of electric bus energy consumption and charging system analysis

Electric Bus Energy Consumption Model

The daily electrical energy consumption of an electric bus is determined by the relationship between travel distance and vehicle energy efficiency. This relationship can be expressed as equation (1).

$$\text{Energy}_{\text{bus}} = D \times EC \tag{1}$$

This formulation is widely used in transportation energy modelling, where total energy demand is directly proportional to travel distance and specific energy consumption rates (Lajunen, 2014). In this equation, E_{bus} represents the daily electrical energy consumption (kWh/day), D denotes the travel distance (km/day), and EC is the energy consumption rate (kWh/km). Based on the baseline operational parameters, the energy consumption per bus is 151.2 kWh/day.

This value is consistent with empirical findings from real-world electric bus operations, where energy consumption typically ranges between 1.2 and 1.5 kWh/km depending on traffic conditions and driving patterns (Xylia et al., 2017; Tong et al., 2017; Yusnidah et al., 2023; Zainuri et al., 2024). The model assumes steady-state operation, where variations such as road conditions, passenger load, and driving behaviour are implicitly captured through the selected energy consumption rate.

Regenerative Braking and Fleet Energy Demand

Electric buses are equipped with regenerative braking systems that enable the recovery of kinetic energy during deceleration. This feature explains vehicle efficiency, particularly in urban environments characterized by frequent stop-and-go traffic conditions

(Deb et al., 2018; Wang et al., 2019). The amount of recoverable energy is estimated as a fraction of the total energy consumption, expressed as equation (2).

$$E_{\text{regen}} = \eta_{\text{regen}} \times E_{\text{bus}} \tag{2}$$

This formulation reflects the proportional relationship between total energy usage and recoverable braking energy, as commonly applied in electric vehicle energy analysis (Yao et al., 2020). Here, E_{regen} represents the recovered energy (kWh/day), and η_{regen} denotes the regenerative braking efficiency. In this study, a nominal efficiency of 25% is assumed, which falls within the typical range reported in the literature. Furthermore, the net energy consumption of the electric bus is therefore calculated as equation (3).

$$E_{\text{net}} = E_{\text{bus}} - E_{\text{regen}} \tag{3}$$

This equation represents the effective energy demand after accounting for energy recovery, providing a more realistic estimate of electricity consumption during actual operation (Chan, 2007). At the fleet level, the total electricity demand is determined by scaling the per-bus energy consumption with the number of operating units as expressed by equation (4).

$$E_{\text{total}} = N \times E_{\text{bus}} \tag{4}$$

This linear scaling approach is widely used in fleet energy modeling and enables the estimation of total system demand under different deployment scenarios. It also facilitates the evaluation of how fleet size influences overall electricity requirements and infrastructure planning.

Charging Infrastructure and Grid Demand Analysis

The charging requirements of the electric bus fleet are evaluated based on charger capacity and operational schedules. The total energy supplied during charging is calculated as equation (5).

$$E_{\text{charge}} = P_{\text{charger}} \times \text{time} \tag{5}$$

This equation represents the relationship between power and time in energy delivery systems for electric vehicle analysis (Yao et al., 2020). In this formulation, P_{charger} is the charging power (kW), and t is the charging duration (hours). With a fast-charging system rated at 150 kW and a charging duration of 2 hours, each charger can deliver up to 300 kWh of energy. To assess scalability, three operational scenarios are considered: small-scale (5 buses), medium-scale (10 buses), and large-scale (20 buses).

Result and Discussion

Energy Consumption Characteristics of Electric Buses

The energy consumption of electric buses is directly influenced by operational parameters such as travel

distance, vehicle efficiency, and driving conditions. Based on the baseline case (126 km/day and 1.2 kWh/km), the energy consumption is calculated as 151.2 kWh/day per bus. This value falls within the typical range reported in urban electric bus systems, where energy consumption varies between 1.2 and 1.5 kWh/km depending on traffic conditions, road gradient, and passenger load. The linear relationship between energy consumption and distance indicates that route optimization and driving efficiency are critical factors in minimizing electricity demand (Lajunen, 2014; Mahmoud et al., 2016).

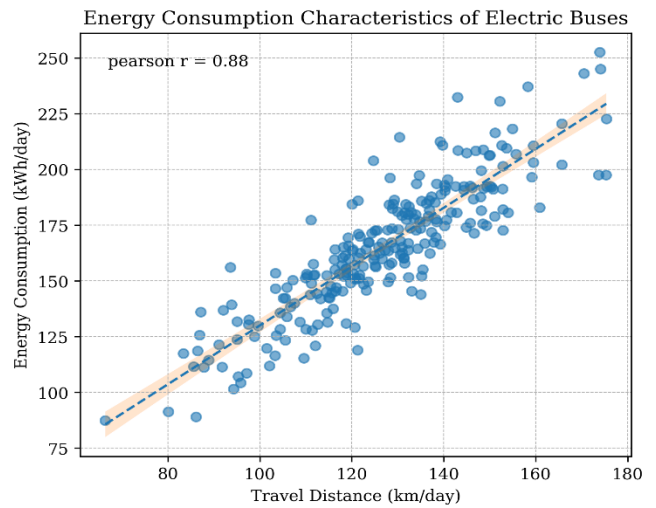


Figure 3. Relationship between travel distance and energy consumption of electric buses, showing a strong positive linear correlation derived from the energy consumption model ($E = D \times EC$), where the scatter distribution represents variability under operational conditions and the dashed regression line with 95% confidence interval

Table 1. Comprehensive energy consumption analysis

EC	Distance (km/day)	Energy (kWh/day)	Increase (%)
1.2	126	151.2	0
1.3	126	163.8	+8.3
1.4	126	176.4	+16.7
1.5	126	189.0	+25.0

A sensitivity analysis was conducted to evaluate the impact of different energy consumption rates. The results show a significant increase in energy demand as efficiency decreases. For example, increasing the energy consumption rate from 1.2 to 1.5 kWh/km leads to an increase of 37.8 kWh/day per bus, representing a 25% rise. This highlights the importance of vehicle technology, driving behaviour, and route characteristics in determining overall system performance (Zhou et al., 2016; Li et al., 2018; Sathiyar et al., 2022).

Impact of Regenerative Braking on Energy Efficiency

Regenerative braking significantly enhances the energy efficiency of electric buses by recovering kinetic energy during deceleration (Clement-Nyns et al., 2010; Deb et al., 2018; Wang et al., 2019). Under urban driving conditions, where frequent stops occur, this system becomes highly effective. Using a recovery efficiency of 25%, the recovered energy is estimated at 37.8 kWh/day per bus, reducing net consumption to 113.4 kWh/day.

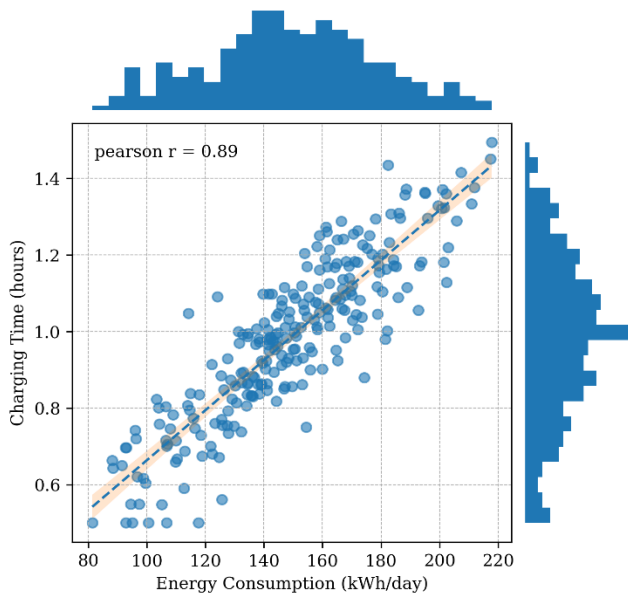


Figure 4. Effect of regenerative braking on electric bus energy consumption, illustrating the proportional reduction in net energy demand as a function of energy recovery efficiency and highlighting the significant contribution of regenerative braking

The impact becomes more pronounced when scaled to fleet level. For instance, a fleet of 20 buses can recover approximately 756 kWh/day, which is equivalent to the daily energy consumption of several additional buses. This demonstrates that regenerative braking not only improves vehicle efficiency but also reduces overall electricity demand and operational costs.

Fleet Electricity Demand Analysis

The total electricity demand increases proportionally with fleet size. For a baseline consumption of 151.2 kWh/day per bus, a fleet of 20 buses requires approximately 3.02 MWh/day. This represents a substantial energy demand that must be considered in urban energy planning (Yao et al., 2020; Zhang et al., 2020; Feng et al., 2021). The results clearly indicate that large-scale electrification of public transportation can significantly increase electricity consumption.

However, when regenerative braking is included, total demand is reduced by approximately 25%. This reduction becomes increasingly important for larger fleets. For example, a fleet of 20 buses reduces demand

from 3.02 MWh/day to 2.27 MWh/day. This highlights the importance of incorporating energy recovery technologies in system design, particularly for large-scale deployment scenarios (Creutzig et al., 2015; Santos & Davies, 2020; Alanazi, 2023; Veza et al., 2022).

Table 2. Fleet electricity demand (extended)

Fleet Size	Energy/Bus (kWh/day)	Total (MWh/day)	With Regen (MWh/day)
5	151.2	0.76	0.57
10	151.2	1.51	1.13
15	151.2	2.27	1.70
20	151.2	3.02	2.27
30	151.2	4.54	3.40

Charging System and Grid Impact

The integration of electric bus charging infrastructure introduces significant electrical loads to the distribution network. Each fast charger operates at 150 kW, and simultaneous charging can lead to substantial peak demand. For example, five chargers operating simultaneously result in a load of 0.75 MW.

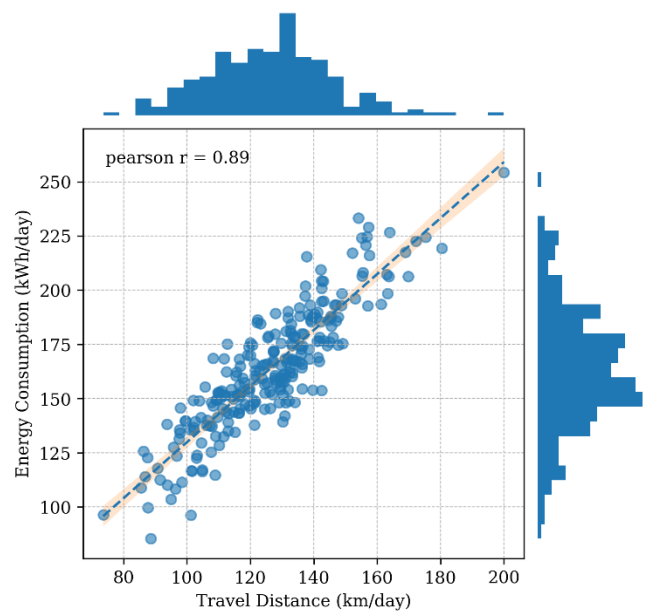


Figure 5. Relationship between energy consumption and charging time under fixed charging power conditions, demonstrating a strong positive linear dependency based on the charging equation ($E = P \times t$), with regression trends and confidence intervals indicating consistent system across operational scenarios

Table 3. Charging and grid demand analysis

Chargers	Power (kW)	Power (MW)	Buses Served	Grid Impact
1	150	0.15	2	Low
2	300	0.30	4	Moderate
3	450	0.45	6	Medium
4	600	0.60	8	High
5	750	0.75	10	Critical

The results emphasize the importance of smart charging strategies to avoid peak load issues. By scheduling charging during off-peak hours or implementing staggered charging, the grid impact can be minimized. Without proper planning, high-power charging systems may lead to grid instability, especially in developing urban networks (Yu & Wei, 2021).

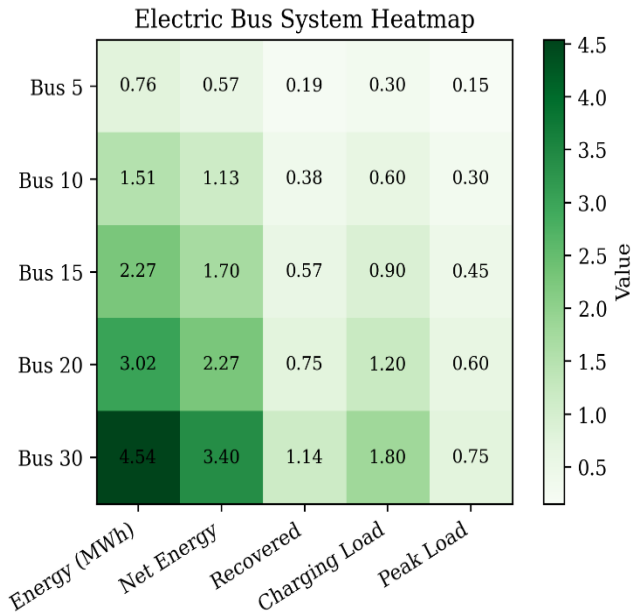


Figure 6. Heatmap visualization of electric bus system parameters across multiple fleet scenarios, illustrating variations in total energy demand, recovered energy, charging load, and peak grid demand, where the colour gradient enables rapid comparison and highlights increasing infrastructure requirements

As shown in Figure 6, the variation of system parameters across different fleet sizes reveals a clear scaling behaviour in electric bus deployment, where increasing fleet size leads to a substantial rise in total energy demand, charging load, and peak grid requirements, while energy recovery through regenerative braking partially offsets this increase. This interconnected behaviour reflects the complex interaction between transportation operations and electrical infrastructure, where system performance depends on the balance between energy demand and supply capacity (Rahman et al., 2020; Afraah et al., 2021; Putri et al., 2022, 2024; Ramadhina & Najicha, 2022; Kusuma et al., 2023; Hanun et al., 2023; Anshori et al., 2024).

Similar interactions have been observed in electric vehicle integration studies, where charging demand, load distribution, and grid stability are tightly coupled

within a dynamic network of dependencies (Clement-Nyns et al., 2010; Shao et al., 2009; Khaharsyah et al., 2025). Therefore, understanding these relationships is essential for designing resilient and efficient electric bus.

Furthermore, as illustrated in Figure 7, these interactions can be understood more comprehensively when energy consumption characteristics, charging strategies, and grid constraints are evaluated within an integrated framework (Wahyudi et al., 2024; Siombo & Adi, 2025).

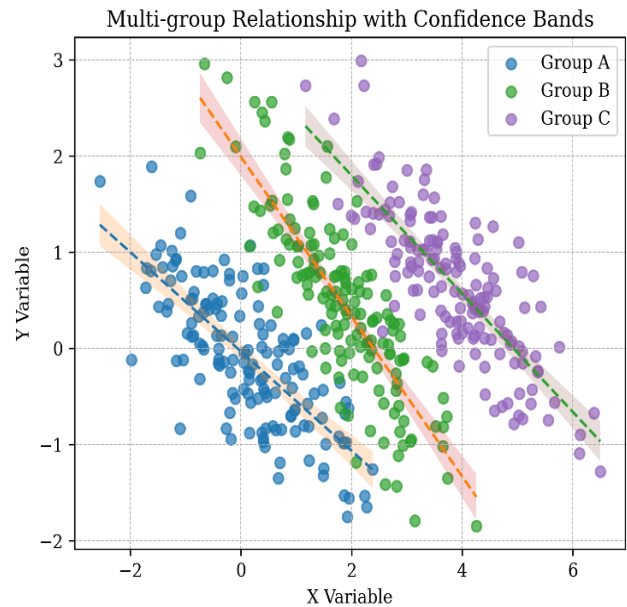


Figure 7. Network representation of interdependencies among key electric bus system parameters, where clustered nodes correspond to energy, charging, fleet, and grid components, and interconnected links illustrate the complex interactions

The results suggest that optimizing individual components alone is insufficient, as improvements in one area may shift the burden to another part of the system (Wang et al., 2019; Yao et al., 2020; Alanazi, 2023).

Instead, coordinated energy management, including smart charging and load balancing, is required to ensure stable and efficient operation under increasing demand (Chan, 2007; Lajunen, 2014; Zhou et al., 2016; Li et al., 2018; Anggriani et al., 2024). This holistic perspective aligns with recent developments in transportation electrification, which emphasize the importance of integrated planning and intelligent energy management systems in supporting large-scale electric mobility. Ultimately, a system-level understanding is crucial for enabling sustainable and scalable deployment of electric bus in urban environments.

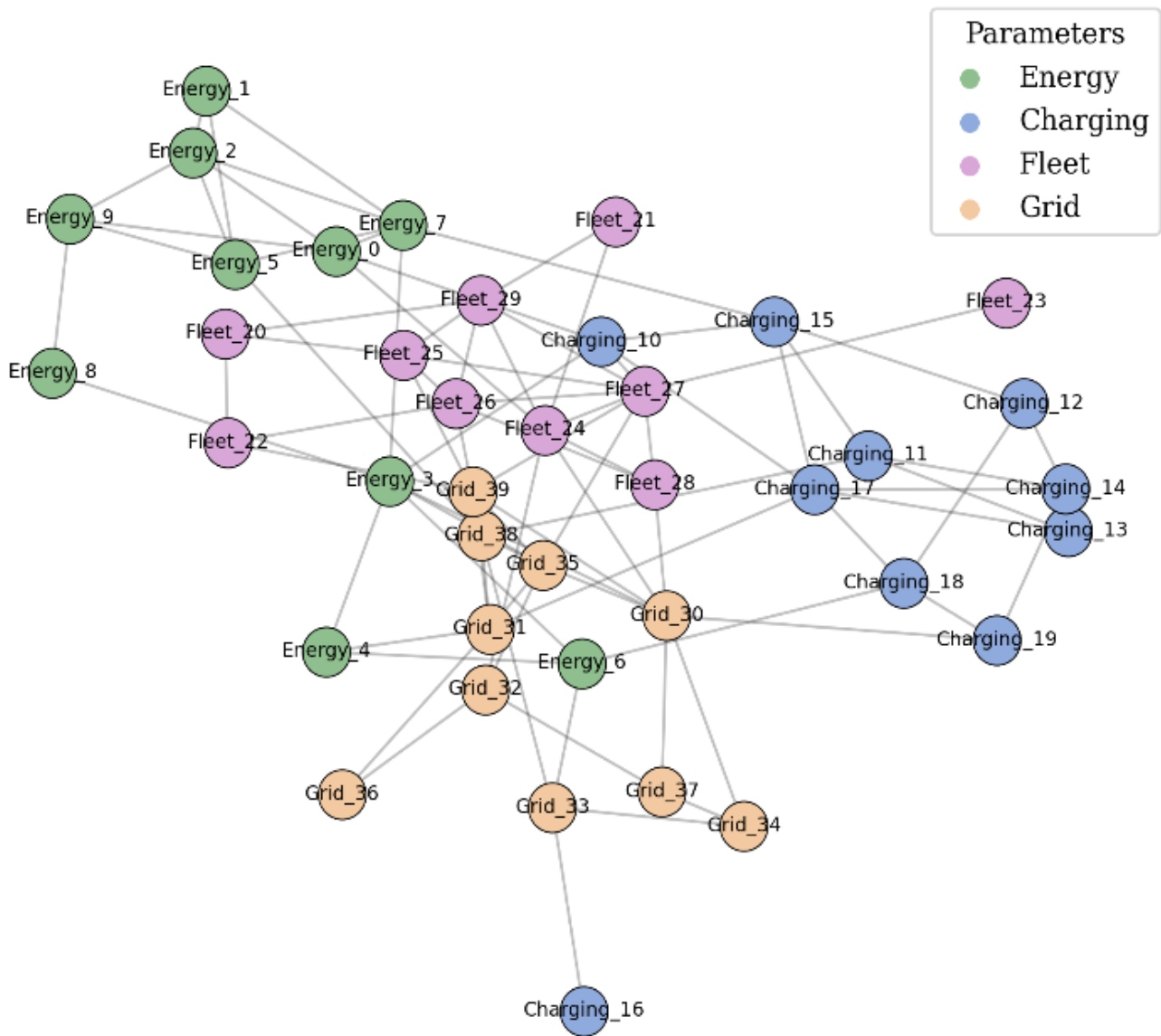


Figure 8. Integrated multi-parameter visualization of electric bus system performance, combining energy consumption characteristics, charging requirements, and grid impact analysis.

Conclusion

This study developed a comprehensive modelling framework to evaluate the energy consumption and charging infrastructure requirements of electric bus systems in urban transportation environments, demonstrating that energy demand is primarily influenced by operational parameters such as travel distance and vehicle efficiency, with a baseline consumption of approximately 151.2 kWh/day per bus under typical conditions; the strong linear relationship between distance and energy consumption confirms the importance of route characteristics and driving efficiency in determining electricity demand. The incorporation of regenerative braking significantly improves system performance by reducing net energy consumption by approximately 25%, particularly under

urban stop-and-go conditions, while at the fleet level, electricity demand increases proportionally with the number of buses, reaching several megawatt-hours per day for large-scale deployment. In addition, the analysis shows that high-power fast-charging systems are capable of supporting operational requirements but may introduce substantial peak load demands on urban distribution networks, thereby highlighting the necessity of implementing smart charging strategies such as load scheduling and staggered charging to maintain grid stability. Overall, the findings emphasize that electric bus deployment must be approached from an integrated system perspective, where energy consumption, charging requirements, and grid constraints are considered simultaneously, and that a coordinated approach combining efficient vehicle operation, energy recovery technologies, and intelligent

energy management is essential to support sustainable and scalable urban transportation electrification.

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Author Contributions

Conceptualization, A.M.P. and D.H.S.N.; methodology, A.M.P., D.H.S.N., and M.W.L.; software, D.H.S.N. and J.S.; validation, A.M.P., M.W.L., and A.A.M.; formal analysis, A.M.P., D.H.S.N., and N.F.H.; investigation, A.M.P., M.W.L., and E.H.; resources, J.S. and E.H.; data curation, D.H.S.N. and N.F.H.; writing—original draft preparation, A.M.P.; writing—review and editing, D.H.S.N., M.W.L., and A.A.M.; visualization, J.S. and N.F.H.; supervision, A.A.M.; project administration, A.M.P. and E.H.; funding acquisition, A.M.P. and A.A.M. All authors have read and approved the published version of the manuscript.

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Conflicts of Interest

The authors declare that there are no conflicts of interest in this research. The entire process, from data collection and analysis to manuscript writing, was conducted independently without any external influence that could influence the results or interpretation of the research.

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