Metro-Integrated Electrified Campus Shuttles for Green Mobility in Saudi Universities

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***Abstract*—The transition toward low-carbon mobility in Saudi university campuses is gaining strategic importance, particularly in rapidly urbanizing cities such as Riyadh. This paper presents a metro-integrated electric shuttle framework to enhance first/last-mile connectivity and replace diesel-based campus transit at Imam Mohammad Ibn Saud Islamic University (IMSIU). The framework evaluates electrification pathways, battery-sizing requirements, charging coordination, and metro-synchronized shuttle scheduling to ensure reliable service continuity. Results indicate that diesel-to-electric conversion eliminates approximately 79.17 tons of direct tailpipe CO_2 annually while improving on-campus air quality. Battery-sizing and load analyses further show that daily charging minimizes required capacity and peak electrical demand, whereas 12-m buses impose substantially higher energy and grid-load requirements than 8.5-m models. The proposed framework provides a scalable and transferable reference for universities seeking to enhance multimodal mobility and support national sustainability objectives under Saudi Vision 2030.**

***Keywords*-—Green Campus Mobility; Electrified Shuttles; Metro Integration**

I. Introduction

The transition toward low-carbon mobility has become a defining indicator of institutional sustainability, with university campuses increasingly recognized as high-value environments for deploying clean transportation models. In Saudi Arabia, where urban expansion is accelerating alongside national commitments to emission reduction, campus mobility systems must evolve to address environmental and operational inefficiencies. Diesel-based shuttle fleets, though historically dependable, contribute directly to on-campus greenhouse gas emissions, airborne pollutants, noise, and degraded commuter exposure along high-density academic corridors. These impacts highlight the need for a structured, evidence-based pathway toward electrified campus mobility that supports healthier learning environments and advances national sustainability goals. The development of high-capacity public transit in Riyadh, led by the city's expanding metro network, introduces a transformative platform for re-engineering first/last-mile campus transport operations within a multimodal mobility ecosystem. Despite metro availability, transit adoption is often constrained by first-mile limitations and the high rate of private vehicle arrivals at university gates, which intensify traffic congestion, commuter delays, and fuel-based emissions from prolonged idling. Electrified campus shuttle networks, when operationally aligned with metro headways, offer a strategic solution to bridge connectivity gaps, reduce gate traffic, remove diesel tailpipe pollution from internal routes, and enhance localized air quality exposure within the campus. This positions Saudi university campuses not only as users of national green transit infrastructure, but as active contributors enabling sustainable urban commuter flows in Riyadh. Electric buses operating in hot climates face unique performance and reliability challenges, primarily due to intensive thermal loads on batteries, electric drivetrains, and Heating, Ventilation, and Air Conditioning (HVAC) systems. As reported in [1], high ambient temperatures significantly accelerated battery degradation, increased cooling demand, and reduced driving range, making thermal management a critical barrier to widespread battery electric buses deployment in warm regions. A life-cycle assessment was presented in [2], comparing diesel, battery-electric, and hydrogen fuel-cell buses in Saudi Arabia. It highlighted that fuel-cell buses currently offered the largest emission reductions, while the benefits of battery-electric buses increased significantly as the national grid incorporates more renewable energy. It showed the strong influence of local climate, operational loads, and energy-supply pathways on bus performance, emphasizing the need for context-specific modeling. An optimization model was proposed in [3] to jointly consider bus service scheduling and charging strategies, demonstrating substantial cost savings and improved efficiency in large-scale battery electric bus networks. A bus replacement strategy was developed in [4], where buses with low battery levels were swapped with fully charged standby buses at charging stations, allowing continuous service without long dwell times. Using a mixed-integer optimization model, the bus schedules, charging station locations, and charger quantities were jointly determined while meeting service level and passenger-comfort constraints. Recent research in [5] has introduced an aggregator-based charging optimization methodology for multifunctional electric bus charging stations. Using coordinated operational-planning and charging optimization algorithms, the approach integrated normal charging, fast charging, and battery swapping while enhancing renewable energy usage and supporting grid services. A method was developed in [6] to improve real-time energy consumption estimation for electric buses by modeling stochastic operational factors, such as speed, acceleration, and passenger load. Using an enhanced Kalman filter and feature-reduction techniques, the approach achieved accurate acceleration and energy estimates, validated with real transit data. These improvements supported better characterization of power system loading and operational impacts from growing electric-bus adoption. A battery-sizing strategy was examined in [7] for electric apron buses, by modeling powertrain dynamics and auxiliary loads to accurately estimate energy requirements. Multiple commercially available battery capacities were evaluated through simulation and validated using standard drive cycles to meet a 100-km range target. An optimization framework was presented in [8] for electrifying bus rapid transit systems, by jointly determining battery sizes and charging infrastructure to minimize total system costs. Using real-world transit data, the study showed that coordinated planning of battery capacity, charger placement, and operational schedules could significantly reduce both capital and operating costs while maintaining reliable service. The authors of [9] developed a multi-criteria framework to evaluate hybrid charging infrastructure for battery-electric and fuel-cell buses, integrating grid electricity, solar PV, battery storage, and hydrogen systems. Their results highlighted the trade-offs between investment, environmental performance, and operational reliability when planning charging infrastructure for zero-emission bus fleets. The feasibility of replacing diesel buses with electric buses on an Ottawa transit route was evaluated in [10], by modeling energy consumption under Ontario-specific operating conditions. The study designed a mixed charging strategy combining depot fast charging with opportunity pantograph charging and performed a Well-to-Wheel analysis to quantify greenhouse-gas reductions based on the provincial energy mix. A cost assessment further estimated the investment payback period, offering a practical framework for assessing the environmental and economic viability of electric-bus deployment. While existing studies provide valuable insights into electric bus deployment and charging infrastructure design, their direct application to university-scale shuttle systems remains limited. Urban-scale optimization models are often computationally intensive and impractical for early-stage campus planning, whereas many depot-based studies neglect realistic operational constraints such as limited charging windows and battery cycling requirements. To address these limitations, this paper proposes a unified analytical framework that integrates operational constraints, depth-of-discharge limits, and charging duration into a transparent and computationally efficient design methodology for electrified campus shuttle systems. At Imam Mohammad Ibn Saud Islamic University (IMSIU), campus shuttles currently operate as a dedicated fleet covering academic zones and student housing corridors. Transitioning this system to battery-electric propulsion eliminates these tailpipe emissions entirely, providing a measurable carbon reduction gain and an immediate improvement in the exposure micro-environment along shuttle corridors. The main contributions of the paper can be summarized as follows:

- Introduces a metro-integrated campus mobility framework, synchronizing electric shuttle operations with Riyadh Metro train headways to enable reliable multimodal first/last-mile connectivity and reduce on-campus vehicle emissions.
- Develops a structured diesel-to-electric fleet transition model, combining real shuttle-route characteristics, energy consumption modeling for 8.5-m and 12-m buses, and route-specific battery-sizing analysis that incorporates depth-of-discharge constraints, charging frequency, and operational feasibility constraints.
- Incorporates a rigorous well-to-wheel emission analysis that accounts for local electricity grid carbon intensity, enabling a realistic comparison between diesel and electric university shuttle buses under current grid conditions.
- Establishes a fleet-level charging load and infrastructure assessment for the full IMSIU shuttle fleet, quantifying peak power demand, charging energy per event, and grid impacts under multiple charging durations and frequencies.
- Presents a scalable sustainability blueprint for Saudi universities, positioning campus shuttle electrification as an operational mechanism supporting national low-carbon mobility objectives under Saudi Vision 2030.

The remainder of the paper is organized as follows: Section II outlines the proposed metro-integrated electrified shuttle framework. Section III describes the operational data and modeling inputs used in the analysis. Section IV presents and discusses the results, including emissions, battery sizing, charging loads, and fleet-level energy demand. Section V concludes the paper.

II. Proposed Metro-Integrated Electrified Campus Shuttle Framework

This section presents the overall conceptual and analytical structure of the proposed framework, including route topology modeling, fleet sizing methodology, and grid-impact assessment.

A. Metro-Integrated Operational Topology

The framework is established on a “Metro-Integrated” mobility concept, where the campus shuttle network functions as a dedicated first/last-mile feeder system. The operational topology is constrained by the Riyadh Metro service, where all shuttle routes originate and terminate at the campus Metro Station. To quantify the baseline operational demand, the daily distance traveled by each bus (d_b) on route r is determined from the route topology:

$$d_b = \frac{L_r \cdot T_r}{N_r} \tag{1}$$

where L_r is the loop length of route r (km), T_r is the total shuttle trips per academic day on route r, and N_r is the number of buses assigned to route r.

B. Electric Fleet Battery Capacity Sizing

Building on the per-bus daily distance from (1), the daily energy demand for each bus is as follows:

$$E_b = d_b \cdot \xi_{cons} \tag{2}$$

where ξ_{cons} is the specific energy consumption coefficient. The nominal battery capacity (E_{nom}) required to sustain n_d operational days between consecutive charging events is given by:

$$E_{\text{nom}} = \frac{n_d \cdot E_b}{\text{DoD}_{\text{max}}} \tag{3}$$

Figure 1 Yellow route of the shuttle network.

Figure 2 Blue route of the shuttle network.

where n_d is the number of operational days per charging interval and $\text{DoD}_{\max}$ is the maximum allowable depth of discharge, defined by the operator as a design parameter.

C. Infrastructure Load Impact Assessment

The average required charging power per bus ($P_{req,b}$) depends on the accumulated energy demand and the available charging window:

$$P_{req,b} = \frac{n_d \cdot E_b}{\Delta t} \tag{4}$$

where Δt is the designated charging window duration. Increasing n_d or reducing Δt both raise the required power, while daily overnight charging minimizes it. The total fleet charging load (P_{fleet}) is obtained by summing $P_{req,b}$ over all buses in the fleet. The net daily CO_2 reduction achieved by electrifying the shuttle fleet is as follows:

$$e_{\text{CO}_2} = \sum_{b \in B} \left(d_b \cdot \text{EF}_{\text{diesel}} - E_b \cdot \text{EF}_{\text{grid}} \right) \tag{5}$$

where the first term represents the direct tailpipe emissions avoided by displacing the diesel fleet, with $\text{EF}_{\text{diesel}}$ denoting the diesel emission factor (kg CO_2/km), and the second term represents the indirect emissions introduced by grid-based charging of the electric fleet, with EF_{grid} denoting the grid emission factor (kg CO_2/kWh).

III. Input and Simulation Data

To establish a realistic basis for the electric bus network analysis, real operational data from shuttle movements within the IMSIU campus are collected and analyzed. Owing to ongoing construction activities and infrastructure adjustments across the campus, only the Yellow and Blue shuttle routes are presently active. Accordingly, the analysis in this study is limited to these two operational routes. The IMSIU academic calendar comprises 187 operational days per year, which is used to scale daily metrics to annual values throughout the analysis. Figure 1 illustrates the Yellow Route, which follows a 1.6 km loop with five designated stops primarily serving the internal academic blocks. Meanwhile, the Blue Route spans a longer 2.8 km path with eight stops, linking external parking areas to the central campus, as shown in Figure 2. This adjusted configuration reflects the university's effort to sustain mobility efficiency while minimizing disruption during ongoing development works. Table I summarizes the operational characteristics of the Yellow and Blue routes. These parameters form the baseline operational profile of the current fleet and provide the essential foundation for energy-use estimation, emission calculation, and electric-fleet simulation. The operational parameters in Table I, including trips per day and daily distance, are reported on a per-bus basis. In the IMSIU shuttle system, one bus is assigned to the Yellow Route, while three buses are assigned to the Blue Route. To evaluate the environmental performance of the existing diesel fleet, annual CO_2 emissions are calculated for each route using the emission factor of 1.4 kg CO_2/km [2]. The grid emission factor $\text{EF}_{\text{grid}} = 0.55$ kg CO_2/kWh is adopted for Saudi Arabia based on recent ESG performance data from the Saudi Electricity Company [11]. To support the electrification of the current shuttle system, this study adopts two representative electric bus models, 8.5 m and 12 m configurations, selected for their suitability for campus-scale mobility operations. The standard battery capacities for the 8.5-m and 12-m electric buses are selected to be representative of available E-bus models reported in manufacturer datasheets and product brochures for similar vehicle classes. The average market price of traction battery packs for electric buses is provided in [11]. Together, these battery ratings and cost values serve as key input parameters for the battery sizing and economic analysis conducted in this study. The energy consumption rates used in this study are 0.695 kWh/km for the 8.5-m bus and 1.15 kWh/km for the 12-m bus. It is worth noting that the selection of the 8.5-m and 12-m electric

TABLE I OPERATIONAL CHARACTERISTICS

Parameter	Yellow Route	Blue Route
Route distance (km)	1.6	2.8
Number of buses	1	3
Fleet Metrics:		
Total Trips per day	42	84
Total Daily distance (km)	67.2	235.2
Per-Bus Metrics:		
Trips per day	42	28
Daily distance (km)	67.2	78.4

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bus models for each route was intended to replicate the existing diesel bus configuration currently deployed on the respective routes. This like-for-like replacement approach ensures that the electric buses can accommodate passenger demand equivalent to that of the diesel fleet, thereby eliminating the need to modify service frequency or route capacity to maintain the current level of service.

IV. Results and Discussions

This section presents the quantitative evaluation of the proposed framework, including emissions analysis, battery sizing outcomes, charging load behavior, and fleet-level energy implications.

A. Environmental Impact of Existing Shuttle Operations

The estimated annual CO_2 emissions for the Yellow Route, Blue Route, and the total diesel shuttle fleet are presented in Figure 3. The results clearly illustrate the disproportionate contribution of the Blue Route to overall emissions. Although the Yellow Route emits approximately 17.59 tons CO_2/year, the Blue Route alone generates 61.58 tons CO_2/year, accounting for nearly 78% of the fleet's total emissions. This difference is attributed to the significantly longer route length and higher trip frequency of the Blue Route, which results in a substantially higher annual distance traveled. The combined fleet emissions

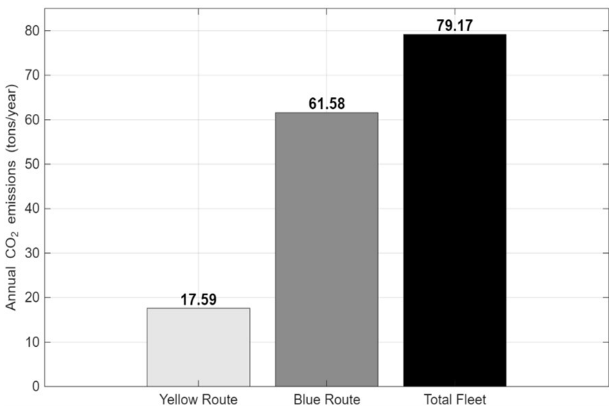

Figure 3 Annual CO_2 emissions by route at IMSIU Campus.

amount to 79.17 tons CO_2/year, highlighting the measurable environmental footprint of the current diesel-based shuttle operation. These findings reinforce the importance of route-specific electrification planning; electrifying the Blue Route yields the largest environmental benefit due to its dominant share of emissions, while the Yellow Route provides additional but comparatively smaller reductions. It is to be noted that transitioning both routes to electric buses would eliminate the entirety of the 79.17 tons CO_2/year currently produced, delivering immediate and quantifiable environmental gains while improving air quality across the campus mobility network.

B. Well-to-Wheel Charging Emissions

While the previous section established that the diesel fleet emits 79.17 tons of CO_2 annually, the net climate benefit of electric buses depends on upstream emissions associated with electricity generation. Therefore, a consistent comparison of diesel-versus-electric should distinguish diesel tailpipe emissions from electric bus charging-related emissions. The Well-to-Wheel analysis is summarized in Table II. The 12-m fleet requires significantly higher charging energy (65,033 kWh) compared to the 8.5-m fleet (39,302 kWh), resulting in higher upstream emissions. Despite the grid's carbon intensity, transitioning to electric buses yields a net emission reduction (e_{CO_2}) of 43.40 to 57.55 tons annually compared to the diesel baseline. These results show that electrification delivers substantial emissions reduction at IMSIU. However, the magnitude of the benefit is sensitive to EF_{grid}, motivating the need for cleaner charging pathways for further decarbonization.

TABLE II WELL-TO-WHEEL EMISSION ANALYSIS: GRID-CHARGED ELECTRIC FLEET VS. DIESEL BASELINE

Bus Model	Annual Energy (kWh)	Grid Emissions (Tons)	Diesel Baseline (Tons)	Net Reduction (Tons)
8.5-m	39,302	21.62	79.17	57.55
12-m	65,033	35.77	79.17	43.40

C. Electrification Readiness Through Route-Specific Battery Sizing

Tables III and IV present the battery sizing requirements for electrifying the shuttle fleet on the Blue Route and Yellow Route, respectively, using two representative e-bus models (8.5-m and 12-m). The results illustrate how route length, daily distance, and charging frequency significantly influence the required energy demand, nominal battery capacity, DoD levels, and corresponding economic implications. It is clear that increasing charging frequency significantly reduces the required battery capacity for both bus types. Daily charging yields the smallest battery sizes, with DoD levels remaining within 46–54% for the 8.5-m buses and 45–77% for the 12-m buses, thereby maintaining operation below the allowable DoD_{max} and supporting improved battery longevity. In contrast, reducing charging frequency substantially increases the required nominal capacity. For instance, on the Blue Route (Table III), the weekly-charged 8.5-m bus requires 340.55 kWh compared with only 68.11 kWh under daily charging, while the 12-m bus increases to 563.5 kWh. This capacity growth directly translates into higher capital costs, with weekly charging adding approximately SAR 185,850 and SAR 315,000 for the 8.5-m and 12-m buses, respectively. Similar trends are observed for the Yellow Route (Table IV), although the absolute capacities are lower due to the shorter daily distance. For instance, the 8.5-m bus requires 58.38 kWh under daily charging and 291.9 kWh under weekly charging. Across both routes, lower charging frequency pushes DoD values toward the design limit of DoD_{max} = 80%, in some cases reaching approximately 75–79%, which reduces the available margin for long-term battery aging. Notably, the Yellow Route 12-m daily case already operates at 77.28% DoD due to the limited sizing buffer between the nominal requirement (96.6 kWh) and the available standard battery (100 kWh). It can be concluded that daily charging combined with adequate

TABLE III BATTERY SIZING ANALYSIS FOR 8.5-M AND 12-M E-BUS FLEETS (BLUE ROUTE)

Charging Frequency	Req. Energy (kWh)	Nominal (kWh)	Standard (kWh)	DoD (%)	Est. Cost (SAR)
		8.5-m e-bus			
Daily	54.49	68.11	100.5	54.22	52,763
3×/Week	108.98	136.22	141	77.29	74,025
2×/Week	163.46	204.33	215	76.03	112,875
1×/Week	272.44	340.55	354	76.96	185,850
		12-m e-bus			
Daily	90.16	112.7	200	45.08	105,000
3×/Week	180.32	225.4	240	75.13	126,000
2×/Week	270.48	338.1	350	77.28	183,750
1×/Week	450.80	563.5	600	75.13	315,000

TABLE IV BATTERY SIZING ANALYSIS FOR 8.5-M AND 12-M E-BUS FLEETS (YELLOW ROUTE)

Charging Frequency	Req. Energy (kWh)	Nominal (kWh)	Standard (kWh)	DoD (%)	Est. Cost (SAR)
		8.5-m e-bus			
Daily	46.70	58.38	100.5	46.47	52,763
3×/Week	93.41	116.76	132	70.76	69,300
2×/Week	140.11	175.14	187	74.93	98,175
1×/Week	233.52	291.90	315	74.13	165,375
		12-m e-bus			
Daily	77.28	96.6	100	77.28	52,500
3×/Week	154.56	193.2	200	77.28	105,000
2×/Week	231.84	289.8	295	78.59	154,875
1×/Week	386.40	483.0	486	79.51	255,150

battery sizing provides the most favorable balance between capital cost and degradation resilience. While deeper DoD enables smaller initial battery capacity, sustained operation near the upper DoD limit may accelerate capacity fade and require earlier battery replacement. The presented analytical sizing therefore represents a minimum feasible design, and practical deployments may incorporate additional capacity margins to maintain operational robustness over the battery lifetime.

D. Grid-Aware Charging Load Analysis for Campus Electrification

The relationship between charging duration, charging frequency, and the resulting electrical load on the campus grid is critical for infrastructure sizing. Based on the daily trip frequency derived in Table I, the fleet operates for approximately 10.5 hours daily. This leaves a consistent 13.5-hour overnight dwell time available for charging. Consequently, the 12-hour charging duration used in this analysis represents a realistic operational baseline that maximizes grid-load reduction without disrupting the daily schedule. Figures 4 and 5 illustrate the relationship between charging duration, charging frequency, and the resulting electrical load for the 8.5-m and 12-m electric bus fleets. It is noted that increasing the charging duration significantly reduces the load imposed on the electrical infrastructure for both bus types. For example, under weekly charging, the 12-m bus fleet imposes a peak load exceeding 430 kW for a 4-hour charging window but drops to below 150 kW when the charging duration is extended to 12 hours. A similar trend is observed for the 8.5-m buses, where the weekly charging load declines from approximately 260 kW at 4 hours to about 90 kW at 12 hours. While the results indicate that the 12-m buses exhibit higher energy consumption and charging demand than the 8.5-m buses, the selection of bus length is primarily driven by passenger capacity requirements rather than energy considerations alone. The 8.5-m buses are suitable for routes and periods characterized by moderate passenger demand, such as internal campus circulation and off-peak operation, whereas the 12-m buses are required to accommodate higher passenger volumes, particularly on routes linking external parking areas to

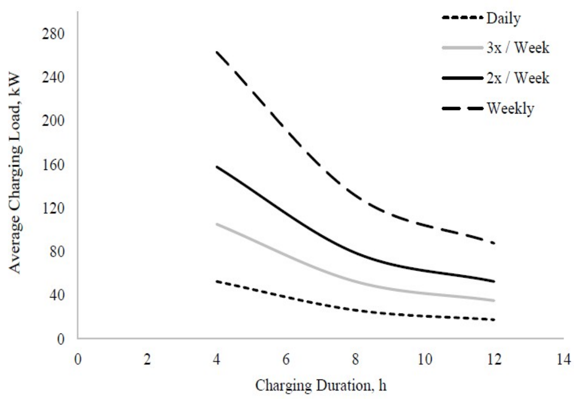

Figure 4 Fleet charging load for the IMSIU shuttle fleet modeled using the 8.5-m e-bus configuration.

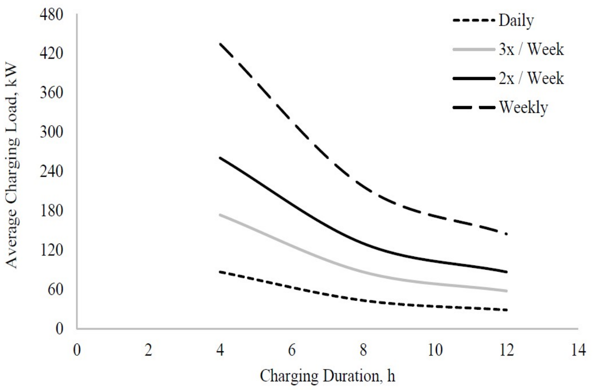

Figure 5 Fleet charging load for the IMSIU shuttle fleet modeled using the 12-m e-bus configuration.

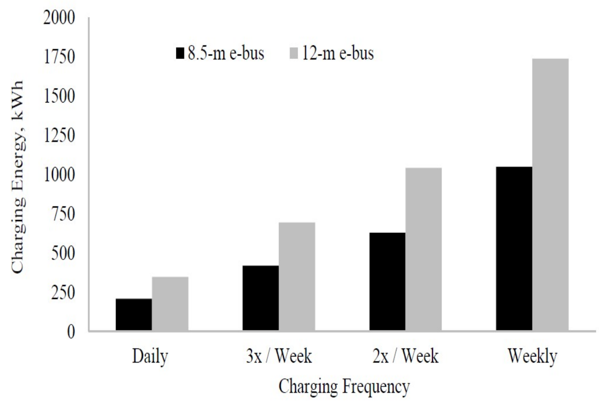

Figure 6 Charging energy per charging event for the 8.5-m and 12-m e-bus models for the full IMSIU shuttle fleet under different charging frequencies.

the central campus during peak hours. Consequently, the higher energy requirements of the 12-m buses represent an operational trade-off between capacity provision and energy efficiency. The mixed deployment of both bus types in the IMSIU shuttle system therefore provides a balanced strategy that satisfies passenger demand while containing overall energy consumption and charging infrastructure requirements. Although the charging durations in Figures 4 and 5 are limited to a maximum of 12 h to represent a conservative and consistent overnight charging window, the results suggest that extending the charging interval during weekend idle periods could further reduce the required charging power without increasing total energy demand. Given that the shuttle buses operate for approximately 10.5 h per day, weekend dwell times may permit charging durations exceeding 12 h, thereby proportionally lowering the average charging load and reducing stress on both the charging infrastructure and upstream electrical components. Nevertheless, the 12-h charging window is retained in this study to ensure a uniform basis for comparing charging strategies and to represent a conservative weekday operating condition rather than relying on extended weekend availability.

E. Fleet-Level Energy Demand Modeling Under Diverse Charging Strategies

The charging energy per event for the full IMSIU shuttle fleet (one Yellow Route bus and three Blue Route buses) is shown in Figure 6. The 12-m e-bus consistently requires substantially more energy than the 8.5-m model because of its larger battery pack and higher energy consumption rate (1.15 kWh/km vs. 0.695 kWh/km). Under weekly charging, the 12-m bus requires approximately 1,740 kWh, compared with 1,050 kWh for the 8.5-m bus. Even under daily charging, the 12-m bus requires roughly 350 kWh, nearly double the 210 kWh needed by the 8.5-m model. These differences emphasize that bus size has a direct and substantial impact on charging infrastructure requirements, influencing transformer sizing, cable ratings, and power scheduling strategies. The findings clearly demonstrate the operational trade-offs between charging frequency, electrical load, and energy demand. Daily charging minimizes peak load, requires the smallest battery capacities, and imposes the least stress on the electrical infrastructure, making it the most grid-friendly strategy. In contrast, weekly charging results in the largest required battery capacities and the highest peak loads under standard overnight charging. However, when extended weekend idle charging is available, the peak load can be significantly reduced due to the longer charging window. The results further show that the larger 12-m e-buses consistently require more energy and generate higher charging loads than the smaller 8.5-m e-buses, emphasizing the need for careful consideration of vehicle size when planning charging infrastructure. These insights highlight the importance of selecting an appropriate charging strategy to ensure a stable, reliable, and cost-effective electrified shuttle network for IMSIU.

V. Conclusions

This paper presented a metro-integrated electric shuttle framework to enhance first/last-mile connectivity and support the transition toward zero-emission campus mobility at IMSIU. Using real operational data from the active Yellow and Blue routes, the analysis showed that electrifying the existing diesel fleet could eliminate 79.17 tons of direct tailpipe CO_2 annually while removing on-campus pollutants and operational noise, thereby improving localized air quality and commuter exposure. Battery sizing results for the 8.5-m and 12-m e-bus models confirmed that charging frequency and route characteristics strongly influence operational feasibility, capital cost, and depth-of-discharge levels. Daily charging emerged as the most efficient strategy, minimizing peak electrical demand and required battery capacity, whereas weekly charging significantly increased capacity requirements and peak power under standard overnight charging, potentially exceeding existing grid limits. The charging-load assessment further demonstrated that longer charging durations reduce average power demand and that larger 12-m buses impose consistently higher energy and load requirements, underscoring the importance of accurate fleet-level planning. The results establish a technically credible pathway for electrifying campus mobility while maintaining service reliability and supporting metro-integrated operations.

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