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A comparative evaluation of mobile charging pods for electric bus operations[☆]

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ABSTRACT

Recent advances in battery technology and the global shift toward sustainable transport have accelerated the adoption of electrified public transit systems. However, the implementation of such systems is often constrained by the need for large battery capacities and the high costs associated with stationary charging infrastructure. This study investigates the potential of Mobile Autonomous Charging Pods (MAPs) which are autonomous mobile charging vehicles as an innovative and cost-effective strategy to support the electrification of high-frequency urban bus lines. Using microscopic simulation for inner-city trunk lines in Stockholm, three charging configurations are evaluated: (i) depot-only charging, (ii) depot charging combined with end-station charging, and (iii) depot charging supported by MAPs. Results show that the MAP-based approach enables a reduction in total battery capacity by up to 67% compared to the depot-only strategy and yields total cost savings of over 7 million USD in total cost of ownership across an 11-year horizon. In addition to reducing capital and grid connection costs, MAPs offer greater operational flexibility and resilience by decentralizing energy delivery and enabling dynamic in-motion or stationary charging. The findings highlight MAPs as a scalable and economically viable solution that complements traditional depot infrastructure, offering a path toward more adaptable and efficient electric public transport networks.

1. Introduction

Electrification of public transport fleets has emerged as a critical component in achieving sustainable urban mobility. Electric buses (EBs) represent an effective solution for decarbonizing public transport networks owing to their elimination of direct tailpipe emissions (Wei et al., 2023; Quttineh et al., 2023). Compared to private cars, the fixed routes, predictable scheduling and passenger loads, and availability of dedicated infrastructure (e.g., bus lanes and priority signals) of bus systems favor electrification. Additionally, recent advancements in battery technologies have significantly improved the operational feasibility, range, and energy efficiency of electric buses, further facilitating their widespread adoption.

Recognizing this potential, governments worldwide have established ambitious targets and supportive policies to encourage fleet electrification. For instance, China, which currently operates over 95% of the global fleet of electric buses, has committed to achieving full electrification of public transit buses by 2035 (Pei et al., 2024; IEA, 2025). Notably, Shenzhen has already achieved complete electrification

of its extensive urban bus fleet, becoming the first city globally to reach this milestone (Weltbankgruppe, 2021).

In Europe, similar momentum is underway, guided by regulatory frameworks such as the EU's Clean Vehicles Directive. This directive mandates that around 45% of newly procured buses by 2025 must be "clean" vehicles, either alternative-fuel or zero-emission, rising further to 66% by 2030 (EU, 2021). Moreover, numerous European cities have adopted even more ambitious targets, with eight major cities aiming for zero-emission bus fleets by 2025 and an additional 19 cities targeting this goal by 2030 (Staff, 2024). Such policy initiatives underscore a growing consensus among policymakers and urban planners that electrification of public transport fleets is imperative for meeting climate goals, reducing urban air pollution, and promoting sustainable urban environments.

Despite these advancements, several barriers continue to impede the large-scale deployment of electric buses. Notable among these are the high initial capital investments required and the increased vehicle mass resulting from substantial battery sizes needed for all-day operations. Such weight increases frequently approach gross operational vehicle

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weight limits, complicating operational flexibility and infrastructure compatibility. Moreover, electric bus fleets face growing competition for limited public charging infrastructure and grid capacity, which presents further logistical and operational challenges (Muhith et al., 2024). One of the most critical barriers in deploying electric buses effectively is the determination of an optimal charging strategy. Since urban buses operate for extended periods with limited downtime, multiple charging sessions throughout the operational day may be necessary, potentially disrupting service continuity, particularly during peak hours (Chiarot and Silvestri, 2022).

Currently, two predominant charging strategies are employed for electric bus operations: depot (overnight) charging and opportunity charging. Depot charging, the most widespread practice, involves recharging vehicles overnight at centralized depots. Although operationally straightforward and reliable, depot charging necessitates large battery capacities to sustain full-day operations without interim recharging, thereby significantly increasing vehicle weight and acquisition costs. This additional weight not only impacts vehicle efficiency and accelerates wear on road surfaces but may also lead to vehicles exceeding legal mass thresholds, further complicating fleet operations (Timmers and Achten, 2016; Dimitriadou et al., 2025). Additionally, depot charging requires substantial infrastructure investment, including high-capacity grid connections, transformers, and extensive physical space at depot facilities, potentially creating logistical and spatial constraints in densely populated urban areas. These limitations underscore the trade-offs inherent in depot-based charging systems and motivate consideration of alternative or complementary solutions, such as opportunity or dynamic charging strategies, to optimize overall fleet performance and infrastructure costs (Karlsson, 2016; Shariff et al., 2020).

Opportunity charging, on the other hand, allows buses to recharge during brief stops at strategic locations throughout their routes, potentially reducing battery size and vehicle weight. However, this method requires the strategic placement of high-power chargers along bus routes, entails more complex scheduling, and introduces logistical challenges associated with frequent short-duration charging intervals. The need for multiple such stations, coupled with physical space constraints and local grid limitations, can hinder their deployment (Lopez de Briñas Gorosabel et al., 2022). Moreover, these systems may not be suitable, particularly for areas prone to heavy snowfall (Rohith et al., 2023). Another form of opportunity charging involves electrifying segments of the route using overhead wires or wireless induction systems, similar to trolleybuses. This allows buses to charge while moving and also allows them to operate with smaller batteries and extended service lives. Nonetheless, this approach is generally infeasible in urban environments due to infrastructural and spatial constraints.

Battery swapping has also emerged as a viable alternative in some regions, particularly in China. Under this model, depleted batteries are quickly replaced at dedicated facilities, significantly reducing vehicle downtime. Despite operational benefits, this approach is constrained by prohibitive capital costs, especially for battery procurement and station installation. Swapping stations in China, for instance, can cost between 1 to 1.5 million USD, with battery costs accounting for 30% to 50% of this total (Ghosh, 2025). Owing to these challenges, cities such as Beijing have shifted from battery swapping to opportunity charging strategies, where buses undergo multiple 10–15 min fast charging sessions per day, aligned with driver breaks (GFA/ HEAT GmbH Habitat, Energy, Application & Technology, 2020).

In light of these limitations, this study investigates an alternative charging strategy using Mobile Autonomous Charging Pods (MAPs), which are autonomous, battery-equipped vehicles capable of vehicle-to-vehicle (V2V) energy transfer. MAPs can charge electric buses either while stationary or in motion and return autonomously to their base stations to recharge. Their flexibility enables them to operate in areas with limited grid access and to dynamically respond to spatial and

temporal variations in charging demand, thereby facilitating more efficient energy distribution.

This study assesses the operational feasibility and economic viability of MAPs through a microscopic simulation-based approach using the open-source tool Simulation of Urban Mobility (SUMO) (Alvarez Lopez et al., 2018). We evaluate and compare three electrification strategies for inner-city trunk bus lines: (1) Depot Charging Only, (2) Depot + End-Station Charging, and (3) Depot + MAP Charging. We perform a series of experiments for the case study of Stockholm's public transit network. Battery swapping and trolleybus systems are not considered due to their limited applicability in the context of our case study.

The primary contributions of this study are as follows:

- Evaluation of an alternate dynamic charging concept involving MAPs, aimed at improving the flexibility, efficiency, and scalability of electric bus operations. This strategy is developed and assessed using a microscopic simulation-based framework;
- Formulation of a baseline charging algorithm for MAPs, grounded in greedy heuristics, which allows for efficient assignment and scheduling of charging tasks.
- Evaluation of the operational and economic performance of the MAP-based charging approach through a case study of Stockholm's urban bus network. The analysis compares MAPs against conventional static charging solutions (i.e., depot-only and end-station configurations), particularly in terms of battery capacity requirements and total cost of ownership.
- Identification of critical challenges and future research directions related to the deployment of MAPs, including charging efficiency, system integration, and logistical considerations. The study highlights the need for further investigation into optimal planning, routing, and scheduling strategies, as well as the integration of MAPs with existing public transport infrastructure.

The remainder of this article is organized as follows: Section 2 reviews the related literature. Section 3 outlines the proposed methodology, and Section 4 describes the case study and experimental design. Section 5 presents the experimental results, followed by a detailed cost analysis in Section 6. Section 7 discusses the results and limitations, and Section 8 concludes the paper.

2. Literature review

The viability of electric buses (EBs) has been extensively studied, with research evaluating both environmental benefits and economic feasibility, particularly through total cost of ownership (TCO) analyses in comparison to diesel and biofuel alternatives. Muhith et al. (2024) investigated the suitability of existing and future battery technologies for EBs in the UK, concluding that although current technologies pose barriers to adoption, anticipated advancements render EBs a promising long-term alternative. Similarly, Sistig et al. (2025) assessed the implications of full fleet electrification on TCO across Germany. While their findings indicated an increase in fleet size by 12% to 13%, these costs were considered manageable through optimized vehicle and crew scheduling, reinforcing the technical and economic feasibility of EBs.

Environmental and operational advantages of EBs have also been substantiated in earlier studies. Lajunen and Lipman (2016) demonstrated that EBs not only reduce direct emissions but also exhibit lower operating and maintenance costs compared to diesel buses. Likewise, Xylia et al. (2017) showed that operational cost savings and favorable electricity pricing could offset the high capital investment in charging infrastructure. Borén (2020) further highlighted the broader societal benefits of EBs, including reduced noise pollution, zero tailpipe emissions, and energy efficiency, which contribute to lower social and lifecycle costs.

To enhance operational feasibility, several studies have explored alternative charging strategies. Verbrugge et al. (2024) examined depot

charging integrated with renewable energy sources, finding that optimized depot microgrids could reduce charging-related costs for public transport operators by up to 30% compared to reliance solely on the distribution grid. Mohamed et al. (2017) compared overnight charging with opportunity charging and concluded that while overnight charging requires fewer chargers, it necessitates a larger vehicle fleet. In contrast, opportunity charging enables smaller fleets but demands the strategic deployment of more chargers. A hybrid approach combining depot charging with daytime charging at terminal stops was found to be cost-effective by Karlsson (2016), although grid connection costs remain a significant concern. Indeed, Lopez de Briñas Gorosabel et al. (2022) reported that grid connection expenses can account for up to 63% of total charging infrastructure installation costs.

Demonstration projects in Barcelona, as reported by Estrada et al. (2017) and Meishner and Uwe Sauer (2020), also revealed that installation costs were a major barrier. In several cases, connecting chargers to the power grid required trenching through pedestrian zones and installing transformers several kilometers from the site, significantly inflating total infrastructure costs. Nevertheless, over a full bus service life, end-station charging was found to be more cost-effective than depot-only charging, particularly when accounting for reduced battery capacity requirements (Meishner and Uwe Sauer, 2020; Lopez de Briñas Gorosabel et al., 2022; Tang et al., 2023).

Beyond stationary charging, dynamic charging approaches have been studied as a means of reducing infrastructure demand and vehicle battery size. These include wireless charging lanes and V2V charging. For example, S. Wang et al. (2023) developed a micro-simulation-based optimization model that integrated static chargers with wireless charging lanes (WCLs). Their results indicated improvements in service levels and reduced delays, albeit at the cost of significant infrastructure investment. Bi et al. (2018) demonstrated that such systems could reduce EB battery capacity by up to 60% and cut lifecycle costs by as much as 13%. Likewise, Bartłomiejczyk and Połom (2019) investigated hybrid systems combining trolleybus and battery-electric bus technologies, suggesting potential TCO reductions of 10%–15%.

Early dynamic charging concepts reveal several limitations that define research gaps. In-road wireless charging (ERS) can reduce the needed on-board battery capacity by continuously charging buses in motion, but it demands costly road infrastructure and precise alignment of inductive components. For example, demonstration projects in Sweden and elsewhere have shown feasibility but underscore the high capital cost and engineering complexity of embedding coils into roadways (Korakianitis et al., 2025). Similarly, trolleybus-style in-motion charging (using overhead wires on segments of the route) allows smaller batteries and fewer stationary chargers, yet it is restricted to routes with catenary wires and lacks route flexibility. These approaches are inherently route-dependent and also on existing infrastructure, and not easily scalable system-wide, creating a gap for more adaptable solutions (Połom and Bartłomiejczyk, 2025).

Other studies such as Du et al. (2025), found that the payback period for dynamic charging lanes may exceed 20 years, longer than the typical service life of electric buses (around 11 years). Moreover, inductive systems are primarily feasible at low vehicle speeds, as higher speeds necessitate the installation of more transmitters, further increasing capital costs.

Overhead catenary charging, where electric buses draw power from overhead wires during operation, has been identified as one of the most cost-effective alternatives in several studies (Shehabeldeen and Mohamed, 2024; Meishner and Uwe Sauer, 2020; Bartłomiejczyk and Połom, 2019). The key advantage lies in the small battery sizes required for trolley-hybrid buses and the extended lifetimes of vehicles operating under such systems, as observed in Hungarian trolleybus networks (Nádasi et al., 2019). Nonetheless, despite its economic merits, the implementation of new overhead wiring infrastructure faces significant political and urban planning resistance, particularly in cities such as

Stockholm, where such systems have not historically existed (Meishner and Uwe Sauer, 2020).

To overcome the inflexibility of infrastructure-based solutions, several studies have proposed V2V charging solutions, whereby one vehicle charges another. An early concept by Maglaras et al. (2015), known as the Mobile Energy Disseminator (MED), involves retrofitting existing public buses or freight vehicles to serve as mobile charging units. Follow-up simulations by Kosmanos et al. (2018) showed that MEDs, when integrated with fixed infrastructure, could significantly extend range and reduce delays.

Emergency V2V applications have also been proposed. For instance, Fan et al. (2024) analyzed the role of EBs as mobile energy sources during large-scale power outages. Their study proposed a data-driven feasibility framework and a low-complexity approximation algorithm for energy allocation. Similarly, Li et al. (2024) developed a joint optimization model for coordinating V2V charging between modular EBs and dedicated charger vehicles, achieving a 10.5% cost reduction compared to conventional EB systems. Yi et al. (2025) proposed another dynamic concept that leverages existing trolleybus infrastructure. Modular EBs form platoons with trolleybuses to receive energy during operation while redistributing passengers, thereby enhancing energy efficiency and operational performance.

Other studies have evaluated the potential of deploying specialized charging vehicles. Zeng and Qu (2023) examined mobile charging vehicles (MCVs) with large onboard batteries (700 kWh) and found that this approach is generally unprofitable due to high energy delivery costs and battery degradation. In contrast, smaller mobile charging units or portable pods, designed to supply enough energy for a single trip, have shown promise. These solutions have been found to reduce peak load demand by up to 67% and operate at 70%–80% efficiency in simulation-based studies (Moghaddam et al., 2021; Khan et al., 2025b).

Despite these encouraging findings, most V2V and dynamic charging studies either focus on private vehicle applications or rely on simplified, idealized traffic conditions. Many models consider energy and routing constraints but omit detailed representations of vehicle kinematics or adherence to traffic rules. As a result, critical challenges such as coordinating charging rendezvous, maintaining safe following distances, and navigating real-time traffic dynamics are overlooked. In practice, forming a charging platoon between two moving vehicles requires complex maneuvers, including merging, synchronization, and interaction with surrounding traffic, factors inadequately addressed in current literature as mentioned in Table 1, which compares the features proposed in this study with previous studies on dynamic charging for electrifying buses.

To address these gaps, the present study considers MAPs, which are dedicated, autonomous electric vehicles capable of delivering energy to electric buses both while stationary and in motion. The study evaluates the operational feasibility and system-level implications of MAP-based charging through a microscopic traffic simulation framework that incorporates realistic traffic dynamics, energy consumption, and bus scheduling. Special attention is given to applications in public transport, using simulations based on real-world bus routes, including variable speed, acceleration, and stochastic energy usage patterns. Furthermore, the performance of MAP-based charging is benchmarked against conventional static charging approaches using a TCO analysis over the operational lifetime of EBs. In doing so, this study contributes to the growing body of literature by providing a more realistic and comprehensive assessment of dynamic charging strategies tailored for public transit systems.

3. Methodology

To evaluate the feasibility and operational performance of the proposed MAP system, we require a modeling framework capable of capturing detailed vehicle-level interactions, energy consumption patterns, and dynamic charging processes. These requirements necessitate

Table 1
Comparative analysis of dynamic charging technologies for EBs.

Model feature	Liu and Song (2017), Bai et al. (2022)	Rohith et al. (2023), Mareev and Sauer (2018)	Shehabeldeen and Mohamed (2024)	Li et al. (2024)	Yi et al. (2025)	This study
Charging facility	DWC	OCC	OCC	V2V	V2V	V2V (MAPs)
Optimizing facility deployment	✓	✓	✓	✓	✓	✗
Comparing charging technologies	✗	✓	✗	✗	✗	✓
Battery size-based consumption	✓	✓	✓	✗	✗	✓
Energy consumption uncertainty	✓	✗	✗	✗	✗	✓
TCO analysis	✗	✓	✓	✗	✗	✓
Continuous charging	✗	✗	✓	✗	✗	✓
GTFS schedule	✗	✗	✓	✗	✗	✓
Modeling of V2V interaction	✗	✗	✗	✗	✗	✓
Model formulation	MILP	MILP	MILP	MILP	MILP	Simulation-based
Model application	City-network	Highway	City-Network	Synthetic-Network	City-Network	City-Network

a simulation environment that can accurately reflect the movement and behavior of both EBs and MAPs within a complex urban setting. For this purpose, we adopt a microscopic simulation approach using the open-source platform SUMO (Simulation of Urban Mobility), which enables vehicle-specific modeling of position, speed, acceleration, and energy usage, and facilitates the representation of dynamic MAP-EB interactions under realistic traffic conditions as proposed in Khan et al. (2025b,c), Khan (2025).

The proposed simulation framework consists of three primary components: (1) modeling the electric bus fleet and operational schedules, (2) implementing dynamic charging scenarios involving MAPs, and (3) evaluating system performance using key indicators such as energy consumption, vehicle state-of-charge (SOC), fleet utilization, and infrastructure requirements. This workflow is designed to be generalizable and adaptable to various network contexts, allowing for comparative assessments of static versus dynamic charging strategies under differing demand and operational settings.

The simulation is instantiated using a real-world road network imported from OpenStreetMap (OSM). Public transport operations are modeled using General Transit Feed Specification (GTFS) data, which includes scheduled routes, stop locations, and timetables. Additionally, Automated Vehicle Location (AVL) data, is used to calibrate and validate vehicle trajectories, ensuring realistic bus movement patterns within the simulation environment. To reduce the complexity, we assume all the buses to be identical in terms of length and battery capacity.

3.1. Composing bus vehicle trip chains

Determining the number of buses required for each line is crucial for modeling fleet dynamics, estimating energy consumption, and informing charging infrastructure planning. In the following, we assume that buses operate exclusively on a single line, i.e., interlining is not considered.

To this end, we generate unique bus identifiers based on vehicle movements within the SUMO simulation, using the GTFS data as input. Specifically, we track each bus as it arrives at its respective end-station, and then identify the subsequent vehicle initiating the return trip. If the time difference between the arrival of one vehicle and the departure of the next exceeds the minimum turn-around time, which is estimated from the AVL dataset, we infer that both trips are operated by the same bus vehicle and assign them the same bus ID.

This approach allows for a consistent representation of vehicle circulation on each individual line, ensuring realistic scheduling and thereby enabling accurate battery SOC tracking and energy demand estimation across the network.

3.2. Charging strategies

We model the following three alternative charging strategies:

3.2.1. Depot charging

In the depot charging scenario, electric buses are assumed to be fully recharged overnight at designated depots, while no intermediate charging opportunities are available during daytime operations. Consequently, each bus must rely solely on the energy stored in its battery at the start of service to complete its daily schedule, as illustrated in Fig. 1(a).

The simulation begins with an initial baseline battery capacity, reflecting the specifications of currently available electric bus models. Using GTFS data, each bus operates according to its assigned timetable and route. For each transit line, the energy sufficiency of the initial battery capacity is evaluated by simulating complete daily operations.

If a bus is unable to complete its scheduled trips without depleting its battery, the battery capacity is iteratively increased until energy sufficiency is achieved across the entire service period. This approach enables the estimation of the minimum required battery capacity for each line under a pure depot charging regime, thereby informing the trade-offs between battery sizing and operational reliability.

3.2.2. Simulating end-station charging

In the end-station charging scenario, electric buses are recharged during scheduled turn-around periods at terminal stops, typically occurring at the end of each one-way trip, as illustrated in Fig. 1(b). Charging is performed opportunistically during these layovers, with the energy replenished determined by the available turn-around time and the rated power of the end-station chargers. Bus schedules are considered fixed and are not altered to accommodate additional charging time.

As in the depot charging case, buses are initialized with a baseline battery capacity derived from current commercial electric bus models. During operation, charging occurs exclusively at end-stations, and the simulation evaluates whether the available layover time suffices to maintain energy adequacy throughout the day.

To estimate the required charging infrastructure, the maximum number of buses charging simultaneously at each end-station is

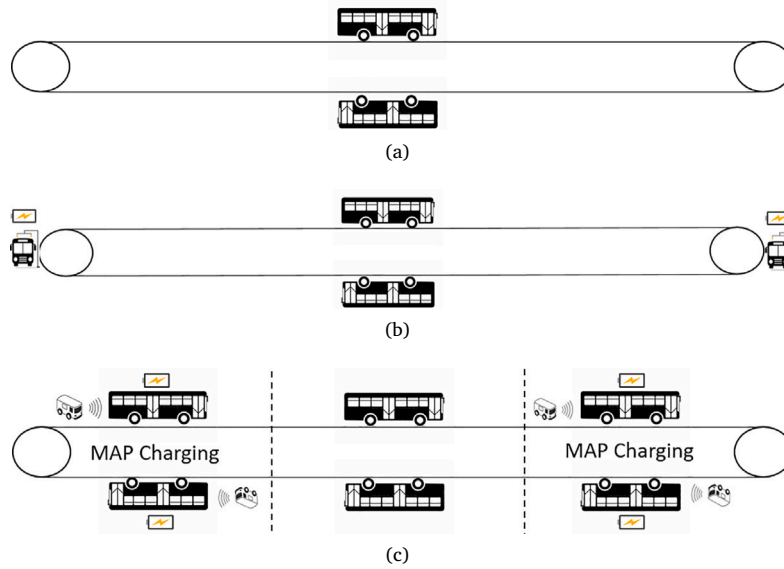


Fig. 1. Different charging scenarios for electrifying buses (a) Only Depot charging (b) Depot with end-station (c) Depot + MAP charging.

recorded, providing an upper bound on charger demand. The potential for battery downsizing is also assessed by iteratively reducing the battery capacity until buses are no longer able to complete their daily operations without energy depletion. This process yields insights into the trade-off between infrastructure deployment and battery sizing under end-station charging conditions.

3.2.3. Simulating MAP charging

We adopt a charging algorithm which is based on greedy heuristics as proposed in Khan et al. (2025b), Alaskar and Younis (2024), due to their computational efficiency in generating baseline solutions (Reisende and Ribeiro, 2013). The MAP charging algorithm is illustrated in Fig. 2. Despite their advantages in terms of simplicity and rapid execution, greedy algorithms suffer from a myopic decision-making process, favoring locally optimal choices without accounting for global system effects, potentially resulting in feasible but suboptimal solutions.

In the proposed charging algorithm, each MAP enters the simulation and initially remains stationed at a designated parking location. Upon receiving an incoming charging request from an electric bus, the MAP is dispatched to follow the bus and transfer energy while both vehicles are in motion (Khan et al., 2025b,c). Charging continues until one of the following conditions is met: (i) the bus reaches its target SOC, (ii) the MAP arrives at its predefined stop, or (iii) the MAP's available energy becomes insufficient to sustain further charging. In the case of end-station charging, MAPs prioritize EBs based on SOC, disengaging from a current assignment if a newly arrived EB has a SOC that is critically lower than a predefined threshold.

These mobile pods collaborate to ensure adequate energy supply for bus operations across the network, particularly on segments that are difficult to electrify with static infrastructure, as depicted in Fig. 1(c). Their compact design enables vertical parking, thus optimizing space utilization in constrained urban environments (Frizziero et al., 2022), as shown in Fig. 3.

To simplify the fleet dimensioning process, the number of MAPs and their corresponding battery capacities are determined based on the energy requirements of the most demanding bus lines. Drawing on prior research, the system-level energy transfer efficiency of wireless MAP-based charging systems is typically in the range of 75%–80% (Khan et al., 2025b, 2022). To enhance this efficiency, we propose a conductive charging configuration in which MAPs physically attach to buses, functioning as compact trailers. Additionally, to minimize energy

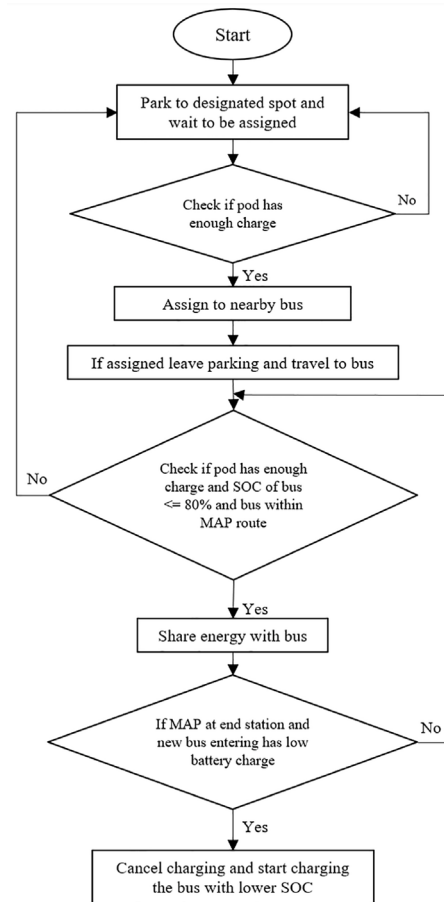


Fig. 2. Charging Algorithm for MAPs to charge buses.

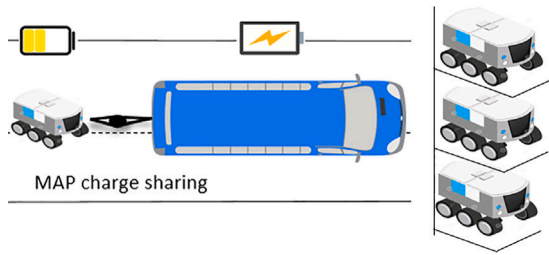


Fig. 3. Illustration of MAP charging, where MAPs attach to buses via a conducting cable and follow it while charging. When the charging is finished, the MAPs stop and charge at the parking spot. Due to their small size, the MAPs can be stacked to save space.

expenditure associated with MAP travel, deployment is concentrated near end-stations. This approach takes advantage of the buses' scheduled turn-around times, thereby reducing MAP travel distances and energy consumption, and ultimately improving system-wide charging efficiency.

The distance for deploying MAPs from the nearest end station is determined so as to ensure that the energy provided by MAPs is at least equal to the energy consumed by the bus per trip.

This relationship is expressed as:

$$E^{\text{endstation}} + E^{\text{move}} \geq E^{\text{travel}} \quad (1)$$

where E^{travel} is the energy needed by the electric bus to complete one trip, $E^{\text{endstation}}$ represents the energy supplied at the end station during turn-around periods, and E^{move} is the energy transferred while the bus is in motion. Notably, the energy transfer while in motion occurs twice: once upon departure from the end station and once again as the bus approaches its destination. Therefore, the overall charging process must provide sufficient energy to meet the bus's total energy demand for a complete trip.

To incorporate charging rates and turn-around times, the following equation is used:

$$(\gamma \cdot \tau_{\text{turn}}) + 2 \cdot (\gamma \cdot \tau_m) \geq E^{\text{travel}} \quad (2)$$

where γ denotes the charging rate at which the MAP transfers energy to the bus, τ_{turn} is the turn-around time at the end-station, and τ_m represents the minimum time required to transfer the necessary charge while the bus is making its trip and also includes time spent at bus stops.

Solving for τ_m , we derive:

$$\tau_m \geq \frac{E^{\text{travel}} - \tau_{\text{turn}}}{2\gamma} \quad (3)$$

The minimum distance required for MAP deployment is then calculated using:

$$d_m \geq \frac{\tau_m}{v}, \quad (4)$$

where v is the bus's speed. Once τ_m is determined, the MAP deployment distance from the end station can be computed accordingly using (4).

3.3. MAP fleet dimensioning

To appropriately dimension the battery capacity of each MAP and the corresponding charging infrastructure requirements, the analysis begins by identifying the most energy-intensive bus line within the analysis area. The battery capacity of the MAP is then scaled to ensure sufficient energy to serve this most demanding (worst-case) line, with the same capacity subsequently extrapolated to other lines for uniformity and operational simplicity.

The total battery capacity of each MAP is calculated by accounting for both the energy it must transfer to an electric bus during a trip

as well as its own energy consumption while traveling alongside the bus. To ensure operational resilience, only 75% of the MAP's battery is allocated for active service, charging the bus and self-propulsion, while the remaining 25% SOC is reserved as a safety margin for returning to a stationary charging facility and for absorbing schedule variability or unforeseen operational disturbances. These values are chosen to maintain the State-of-Health (SOH) of MAPs and extend the battery life (Golder et al., 2023). This energy budgeting strategy is expressed by the following inequality:

$$E^{\text{travel}} + E^{\text{consumption}} \leq 0.75 \cdot E^{\text{mapbattery}}, \quad (5)$$

where:

E^{travel} denotes the energy required to charge the electric bus for a single trip,

$E^{\text{consumption}}$ represents the energy consumed by the MAP during the trip,

$E^{\text{mapbattery}}$ is the total battery capacity of the MAP.

Once $E^{\text{mapbattery}}$ is established, the required power output of the MAP's charging station is determined by examining the time intervals between consecutive charging sessions. The goal is to replenish at least 80% of the MAP's battery capacity during these idle periods to ensure readiness for subsequent assignments. The available charging time is defined as the minimum interval between two successive charging sessions:

$$\tau_{\text{chargingtime}} = \min(\tau_{\text{chargingsession}_{i+1}} - \tau_{\text{chargingsession}_i}), \quad (6)$$

where $\tau_{\text{chargingtime}}$ is the minimum available downtime for recharging.

Based on this available duration, the required charging rate of the static charging infrastructure can be calculated to ensure the MAP is recharged up to an 80% level of SOC:

$$\gamma_{\text{charger}} \cdot \tau_{\text{chargingtime}} = 0.8 \cdot E^{\text{mapbattery}}, \quad (7)$$

where γ_{charger} is the power rating of the MAP charging station. This formulation ensures that MAPs are operationally viable within the system's temporal constraints and do not experience service interruptions due to insufficient battery capacity or prolonged charging durations.

The system-level charging efficiency of MAPs, denoted by η , quantifies the overall effectiveness of energy delivery from the charging infrastructure to EBs. It is defined as the ratio of the total energy successfully transferred to buses (E^s) to the total energy consumed by MAPs from static charging stations (E^c), where E^c accounts not only for the energy delivered but also for the energy expended in MAP mobility operations:

$$\eta = \frac{E^s}{E^c} \quad (8)$$

A high system-level charging efficiency is desirable as it indicates that the majority of energy drawn from the grid is effectively utilized for productive charging of EBs, with minimal losses due to propulsion, idle time, or detours by MAPs. This metric is especially relevant in V2V charging settings, where energy is not only consumed during transfer but also in enabling the charging interaction itself. In the context of MAP operations, maximizing reflects efficient routing and parking location, optimal task assignment, and minimal redundancy in energy use, factors that are critical for reducing operational costs, battery wear, and overall system emissions. Hence, it serves as a key performance indicator in evaluating the techno-economic viability of MAP-based charging systems in real-world deployment scenarios.

4. Case study and experimental design

To assess the feasibility and potential benefits of MAP charging compared to conventional charging strategies, a series of experiments is conducted. Our case study focuses on Stockholm's inner-city trunk bus lines (Lines 1, 2, 3, 4, and 6) as target routes for electrification. These lines were selected due to their high-frequency operations and

Table 2
Number of buses per line with a 5-minute turn-around time.

Bus line	No. of buses	Max trips	Total distance (km)	Total energy (MWh)	Energy per trip (kWh)
Line 1	21	15	2715.00	8.06	30.30
Line 2	15	19	1613.95	5.16	22.90
Line 3	16	18	2286.56	7.60	28.43
Line 4	23	16	3469.83	9.48	31.64
Line 6	10	26	1189.51	3.46	17.81
Total	85	94	11 274.85	33.76	131.08

Table 3
Value of Parameters used in the simulation.

Parameter	Value
Baseline battery capacity of e-buses	470 kWh
Operational weight of e-buses	30,000 kg
Average speed of e-buses (v)	20 km/h
Energy consumption of e-buses	3.0 kWh/km
Energy consumption of MAPs	0.2 kWh/km
Minimum turn-around time (τ_{turn})	5 min

significant challenges associated with installing stationary charging infrastructure in a dense urban environment, primarily due to space and capacity constraints.

The road network of Stockholm, including all trunk bus routes, is imported into SUMO from OSM to ensure an accurate simulation environment. The study simulates bus operations from 05:00 to 23:59 on November 8, 2023, using publicly available GTFS and AVL data from Stockholm's public transport authority (SL). An analysis of this period indicates that 96 buses operated on the selected routes, of which only 13 were electric. However, for this study, it is assumed that all buses on the trunk lines are fully electrified to evaluate the impact of different charging strategies.

Based on AVL data analysis, a minimum turn-around time of five minutes is set for trunk line buses. The corresponding number of bus vehicles along with the maximum number of trips per bus obtained from this turn-around time is presented in Table 2. From the table, we can see that Line 4 has the largest fleet of buses operating, while Line 6 has the highest number of trips being made by each bus. From the distance traveled and energy consumed, we can see that Line 4 is the longest and most energy-intensive line to operate.

Each bus is assumed to operate at an average speed of 20 km/h, which aligns with the municipality's desired service level, and consumes approximately 3 kWh per kilometer. These assumptions underpin the calculation of total energy demand across the network. Table 2 summarizes the total distance traveled and corresponding energy consumption for each bus line, forming the basis for evaluating the charging requirements under each strategy.

Key operational parameters, including energy consumption and charging characteristics, are based on Volvo electric bus vehicle specifications (Volvo, 2025) and SUMO documentation. The primary parameters used in the simulations are summarized in Table 3.

Three different charging strategies are simulated as shown in Fig. 1 to evaluate the effectiveness of MAP charging in comparison to conventional approaches. In the depot charging scenario, buses charge exclusively overnight at depots, with no opportunity for charging during daytime operations. The analysis begins with the current battery capacities as provided in Table 3. The feasibility of sustaining daily operations with depot-only charging is evaluated, and if necessary, the minimum required battery capacities are identified to ensure all buses can complete their scheduled trips.

The second scenario extends the charging options by allowing buses to charge both at depots overnight and at end-stations during turn-around periods. Each end-station is assumed to be equipped with a 150 kW charger, and charging is limited to the bus' turn-around time. For this scenario, we assume that the buses start charging at the end-station when their SOC is below 60% and charge up to a maximum of

80%. The upper SOC limit is imposed to mitigate battery degradation and avoid inefficient charging at high SOC levels. The lower threshold is determined by operational considerations: initiating charging at substantially higher SOC levels (e.g., around 70%) would provide limited usable energy while unnecessarily occupying charging infrastructure, whereas triggering charging at much lower SOC levels (e.g., around 50%) would reduce energy buffers and increase vulnerability to unforeseen delays. The selected 60%–80% SOC window, therefore represents a pragmatic compromise that enables effective energy replenishment within constrained turnaround times.

In the depot and MAP charging scenario, buses charge overnight at depots and utilize in-motion charging via MAPs during daytime operations. A limited number of two MAPs is considered per line, strategically positioned near the two end-stations to maximize charging during bus turn-around periods.

Using (3), the minimum charging time required is computed, where energy consumed per trip (E^{travel}) is taken from Table 2, γ is 41.67 W/sec, and τ_{turn} is taken to be 5 min based on AVL observations. Considering both stationary and in-motion charging periods, the optimal MAP deployment distance from the end-stations is then calculated using (4).

The corresponding stops and the MAP charging routes are illustrated in Fig. 4. The MAPs are assigned these specific stop locations from which they are deployed based on real-time charging demand. When a bus requires additional charge, the nearest MAP is deployed according to the algorithm in Fig. 2.

The energy consumption is determined to be about 0.2 kWh/hr, based on the average energy consumption of electric vehicles (EV Database, 2025). For dimensioning the MAP, we consider Line 4 as it has the highest energy consumption per trip. Based on (5), the MAPs need to have at least 45 kWh battery capacity. For our study, we consider that MAPs have a battery capacity of about 50 kWh.

The required charging power for replenishing MAP batteries is determined based on the available idle time between successive charging assignments. Empirical observations from the simulation indicate that, on Line 4, each MAP experiences a minimum idle period of approximately 600 s between charging events, as illustrated in Fig. 5. Using (7), this constraint translates into a minimum charger power of 240 kW to ensure that MAPs can be fully recharged before their next deployment.

Finally, a sensitivity analysis is conducted to assess the impact of the number of MAPs on system performance. The analysis begins with one MAP deployed at each terminal station and incrementally increases the fleet size until further additions yield no substantial reduction in the required onboard battery capacity of buses.

5. Experimental results

In the following, we present and discuss the simulation results for the three charging strategies: (i) depot-only charging, (ii) depot plus end-station charging, and (iii) depot charging supplemented by MAPs. The analysis is based on the operational profiles of electric buses serving Stockholm's high-frequency inner-city trunk lines.

The following subsections detail the performance of each scenario with respect to key operational metrics: battery capacity requirements, energy supplied by the respective charging systems, and the associated infrastructure needs.

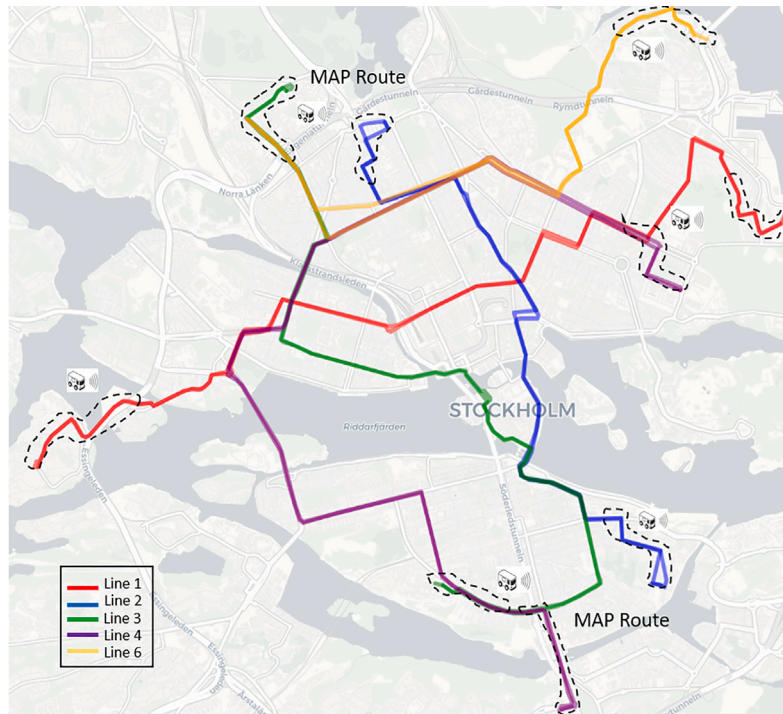


Fig. 4. The charging route of MAPs near the end stations of various trunk bus lines. The black dotted circle represents the area of operation of MAPs near the end-stations.

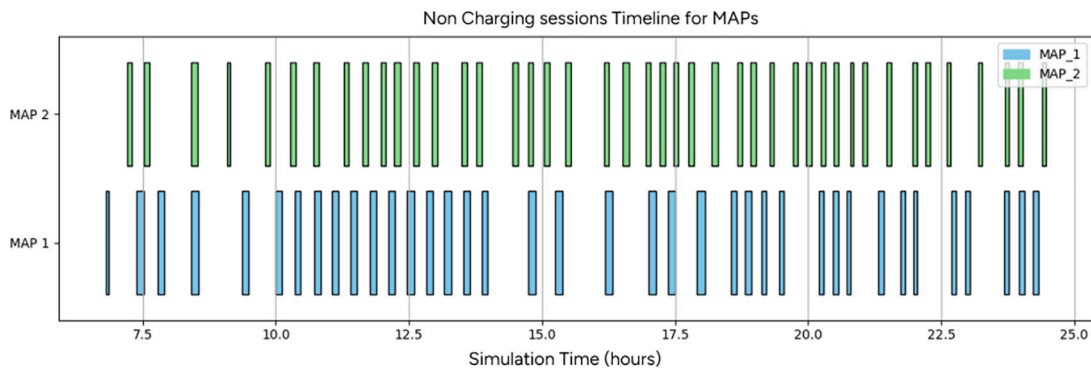


Fig. 5. Non-Charging session timeline of each MAP operating near end-stations in Line 4.

5.1. Depot charging only

In this experiment, buses can only charge overnight at the depot before beginning daily operations. With the baseline battery capacity of 470 kWh per bus, the results show that for each of the bus lines most buses vehicles run out of charge before completing their daily operations, as shown in Fig. 6.

The minimum required battery capacity to ensure reliable operation is determined based on the criterion that the SOC remains above 20% throughout the day.

The minimum battery capacity by each line as well as the total battery capacity required by each line, is shown in Table 4. The results show that Line 3 requires the largest increase in battery capacity to 720 kWh per bus, while Line 2 requires the smallest increase to 530 kWh. Although, Line 3 is not energy-intensive compared to Line 4 and Line 1, as shown in Table 2, it has fewer buses compared to these lines and thus requires a much larger battery capacity. Similarly, Line 2 has a larger fleet of buses than Line 6 and thus can operate with lower battery capacity than Line 6, even though it has higher energy consumption.

Percentage of Buses with SOC Lower Than 20%

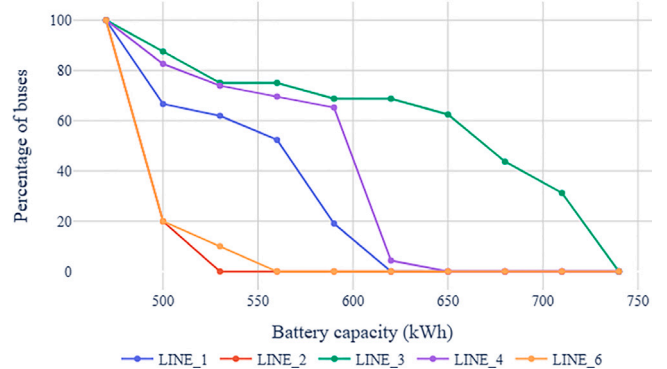


Fig. 6. Battery capacity needed to maintain daily operation with only depot charging available for buses.

Table 4
Battery capacity for buses when only charging at depots.

Bus Line	Required battery capacity (kWh)	Total battery capacity per line (kWh)
Line 1	620	13 020
Line 2	530	7950
Line 3	720	11 520
Line 4	620	14 260
Line 6	550	5500
Total	3040	52250

Required Battery Capacity by Bus Line and Number of End Stations

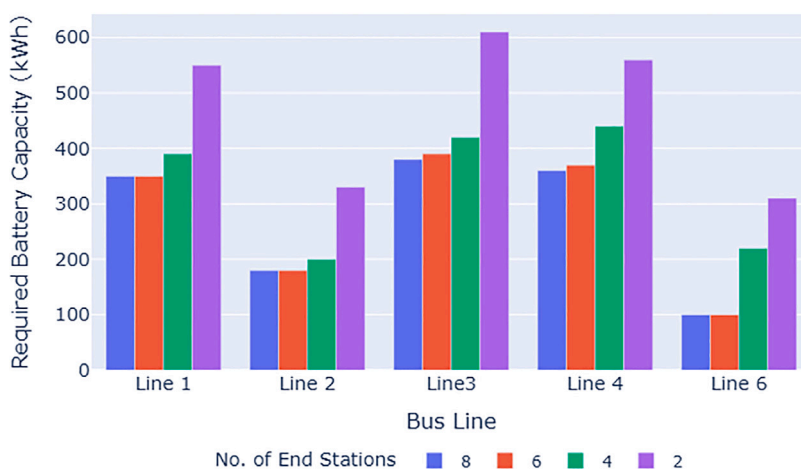


Fig. 7. Relation between required battery capacity by bus line and the number of end-stations.

Thus, with only depot charging, an additional 30% increase in total battery capacity is required compared to the initial capacity of 470 kWh to sustain operations without buses running out of charge.

5.2. Depot and end-station charging

To reduce onboard battery capacity requirements, this scenario considers depot charging with opportunity charging at route end-stations, allowing buses to recharge during scheduled turnaround times. The simulation assumes the installation of 150 kW chargers at each end-station.

For each bus line, the number of end-station chargers was increased iteratively and distributed evenly between the two terminal stops for simplicity. Fig. 7 illustrates the relationship between the number of end-station chargers and the resulting reduction in required battery capacity. In this analysis, the maximum number of chargers that still yields meaningful battery capacity reductions was selected for each line (six chargers in most cases, and seven and eight chargers for Lines 3 and 4, respectively). Beyond these levels, additional chargers provided no significant battery reductions.

Although the number of chargers varies across configurations, grid connection costs were assumed to remain unchanged between four and six end-station chargers. This assumption is supported by prior studies, which indicate that grid connection expenditures are primarily driven by peak power requirements and connection distance rather than the marginal number of chargers of similar aggregate capacity (Estrada et al., 2017; Frieß and Pferschy, 2024). Consequently, configurations that maximized battery capacity reduction were prioritized in the analysis, as additional chargers beyond this point would increase equipment costs without providing commensurate operational benefits.

The resulting battery requirements, charger counts, and energy delivered at end-stations are summarized in Table 5. The results indicate that end-station charging substantially reduces the minimum battery capacity required for daily operations across all lines. The largest

reduction is observed for Line 6, where a battery capacity of only 100 kWh is sufficient. This outcome reflects the relatively low energy demand of this line, which allows most of the required energy to be supplied during terminal dwell times.

5.3. Depot and MAP charging

This scenario evaluates the feasibility of MAP-based charging in combination with depot charging. The results indicate that with only two MAPs per line, buses can maintain their SOC levels above 20% throughout the daily operations. Moreover, the battery capacities can be considerably reduced as shown in Table 6. The total reduction in battery capacity over all the trunk bus lines is about 67% compared to only depot charging and about 32% compared to depot + end-station charging.

To evaluate scalability, additional experiments were conducted with increased MAP availability, considering four MAPs per line (two at each end-station) and six MAPs per line (three at each end-station). As illustrated in Fig. 8, increasing the number of MAPs beyond four per line yields no further significant reduction in required bus battery capacity. This suggests that four MAPs per line represent an upper bound for satisfying operational charging demand under the considered conditions. Moreover, for the least energy-intensive corridor (Line 6), the results indicate that only two MAPs are sufficient to meet charging requirements.

The advantage of MAPs over stationary end-station chargers is that they distribute charging both spatially and temporally by traveling behind the buses for a certain distance after they leave the end-stations. After departing from the end-stations, MAPs can accompany buses for a limited distance and continue delivering energy beyond fixed charging points. As illustrated in Fig. 9, most of the charging energy is supplied while the bus is stationary at end-stations, whereas a smaller share is delivered during in-motion operation. This extension of the effective charging window increases the total time available

Table 5
Battery capacity requirements for buses charging at depots and end stations.

Bus line	Required capacity (kWh)	Total capacity per line (kWh)	Charging stations	Energy charged (MWh)
Line 1	350	7350	6	3.85
Line 2	180	2700	6	3.88
Line 3	380	6080	7	4.40
Line 4	360	8280	8	4.73
Line 6	100	1000	6	3.00
Total	1370	25 410	33	19.86

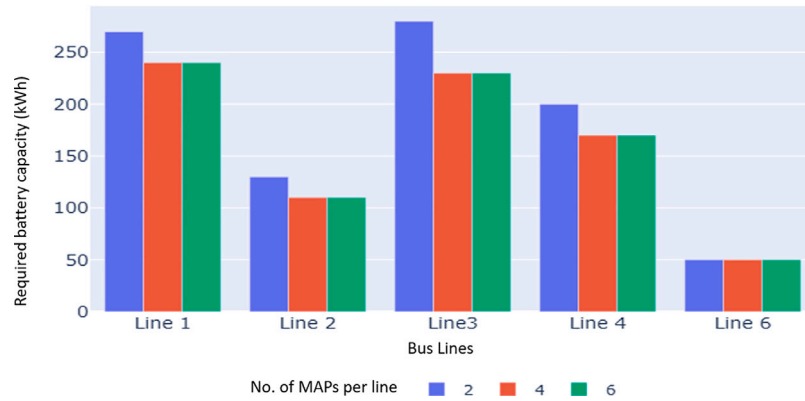


Fig. 8. Relation between required battery capacity by bus line and the number of MAPs.

Table 6
Battery capacity requirements for buses charging at depots with MAP support.

Bus line	Required capacity (kWh)	Total capacity per line (kWh)	Energy charged by MAPs (MWh)
Line 1	270	5670	4.22
Line 2	130	1950	4.24
Line 3	280	4480	5.25
Line 4	200	4600	5.80
Line 6	50	500	3.22
Total	930	17 200	22.73

for energy transfer, enabling lower peak power requirements. Consequently, MAP-based charging improves energy utilization and overall system efficiency, enhances operational flexibility, and may reduce peak demand and associated stress on the electrical grid and charging infrastructure (Moghaddam et al., 2021). The efficiency of MAPs is calculated from (8) and is found to be around 96%. This is due to MAPs being placed near the end-stations and thus provide the majority of charge without moving and consuming energy.

6. Comparative cost analysis of electric bus charging strategies

The deployment of electric bus infrastructure requires careful consideration of multiple interdependent factors, including feasibility considerations, energy demands, and both capital and operational expenditures. This section presents a comparative evaluation of the three charging strategies.

6.1. Energy and infrastructure requirements

Under the depot-only charging strategy, buses must be fully recharged during the overnight dwell period. This requires an increase in battery capacity by approximately 30% over the baseline capacity of 470 kWh, and results in a total daily energy demand of 33.76 MWh. Given that the existing depots in Stockholm lack sufficient grid capacity, this approach would necessitate the construction of new substations, as identified in previous analyses (Karlsson, 2016). Assuming each of the approximately 85 buses in the trunk network is assigned a dedicated depot charger, and that overnight dwell time is

Percentage of Charge Delivered by MAP

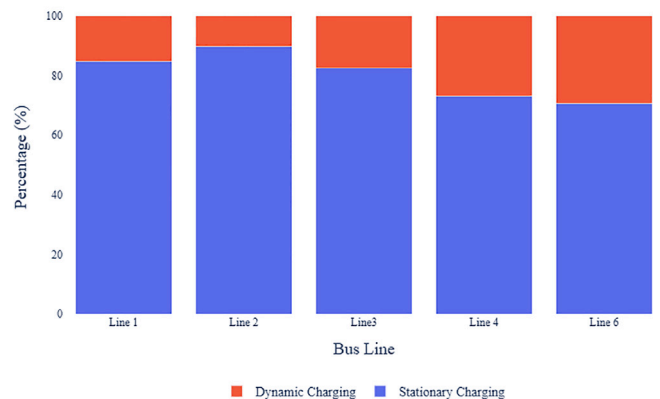


Fig. 9. Shares of energy delivered by MAPs while stationary and moving for each bus line.

limited to 4 h, the required charging power per unit is approximately 100 kW.

In contrast, the depot plus end-station charging scenario distributes the charging load between night and day. As presented in Table 5, a total of 33 end-station chargers provide 19.86 MWh during the

day, thereby reducing overnight energy needs to 13.9 MWh. Consequently, depot charger capacity can be reduced to 40 kW, substantially decreasing infrastructure costs and capacity requirements.

A third configuration incorporates MAPs alongside depot charging. In this setup, 10 MAPs (two per trunk line) provide 22 MWh of energy during the day. As a result, depot chargers are required to supply only 11 MWh, with a corresponding capacity of just 32 kW per unit. This configuration offers greater flexibility and load balancing while maintaining service levels.

6.2. Total cost of ownership analysis

The comparative total cost of ownership (TCO) for each scenario includes capital expenditures (CAPEX) and operational expenditures (OPEX) over an 11-year planning horizon, considering the expected life of an electric bus (Muhith et al., 2024). The cost parameters are drawn from recent literature and industry sources as detailed below.

Battery costs are assumed at 115 USD/kWh for initial procurement, and 80 USD/kWh for replacements, reflecting projected price reductions (Muhith et al., 2024; Statista, 2025). Battery lifetime is estimated at 8–9 years, necessitating one replacement during the bus's 11-year operational life (Muhith et al., 2024; Sistig et al., 2025). The MAP and bus batteries are considered to cost the same per kWh and have the same operational lives.

Depot-only charging relies on 100 kW chargers, each with an estimated unit cost of approximately 60,000 USD (G. Wang et al., 2023). In the depot-plus-end-station configuration, charging demand is split between 40 kW depot chargers, priced at around 30,000 USD per unit, and higher-power 150 kW chargers at end-stations, with an estimated cost of 70,000 USD per unit (Smith and Castellano, 2015; Wright, 2022).

In contrast, the depot-plus-MAP configuration employs lower-power 32 kW depot chargers, costing approximately 20,000 USD per unit, together with 240 kW high-power chargers dedicated to recharging MAPs, each priced at about 120,000 USD. The MAP vehicles themselves are assumed to cost 40,000 USD per unit, based on reported estimates for existing mobile charging vehicles (Khan et al., 2025a). Parking and siting costs for MAPs are assumed to be negligible, as MAPs utilize existing bus routes and associated infrastructure rather than requiring dedicated stationary facilities.

Installation costs are assumed at 900 USD/kW, and annual maintenance at 30 USD/kW (He et al., 2019; Hecht et al., 2022). EB maintenance is assumed at 0.4 USD/km, while MAP maintenance is set at 0.03 USD/km, with all MAPs traveling a total of 5000 km per day during bus operations (Maloney, 2025; Gorzelany, 2024).

Grid connection costs, which include substations, transformers, cabling, and administrative expenses, are highly site-specific and can be a dominant cost component (Lopez de Briñas Gorosabel et al., 2022; Xylia et al., 2017; Energimarknadsinspektionen, 2025). We adopt average connection costs here based on prior Swedish public transport electrification studies (Karlsson, 2016).

The comparative CAPEX and OPEX for each charging configuration over the 11-year operational period are summarized in Table 7. The analysis includes battery costs (initial and replacement), charging infrastructure (hardware, installation, and grid connection), and maintenance costs. Costs related to bus acquisition and general operational expenditures are excluded to isolate infrastructure-related impacts.

6.3. Sensitivity analysis of MAPs

The economic and operational sensitivity of the MAP concept is evaluated by varying both the number of MAPs deployed at each end-station and key cost parameters influencing the TCO. First, the impact of MAP fleet size is examined. As shown in Fig. 8, deploying more than two MAPs per end-station (and more than one MAP for Line 6) does not yield additional reductions in the required battery capacities of buses.

This indicates a saturation effect in which further MAP availability does not translate into operational benefits. The corresponding infrastructure costs for two representative configurations—10 and 18 MAPs, are reported in Table 8. For comparability, the MAP charging infrastructure is assumed to remain unchanged across both scenarios, as we assume the MAPs will not demand charging simultaneously.

Table 8 shows that increasing the MAP fleet from 10 to 18 units raises the 11-year TCO from 18.66 to 19.03 million USD, corresponding to an increase of 0.37 million USD. While higher MAP availability enables a reduction in battery-related expenditures due to smaller required onboard bus batteries, this saving is outweighed by increased capital and operational costs associated with the MAP fleet itself. In particular, charger hardware costs increase from 3.30 to 3.60 million USD, and MAP maintenance costs rise from 0.62 to 1.08 million USD. As a result, the net system cost increases with additional MAPs beyond the identified threshold of 2 MAPs per line.

These results indicate diminishing economic returns from increasing the MAP fleet size beyond the tested range. For the parameterization and operational conditions considered in this case study, additional MAP deployments lead to higher total system costs, as the marginal cost of deploying extra MAPs outweighs the marginal savings achieved through reduced bus battery capacities. The present analysis is based on a scenario-driven evaluation rather than a full parametric or mathematical optimization. A comprehensive optimization of MAP fleet size, placement, and associated infrastructure costs remains outside the scope of this study and is identified as an important direction for future research.

To gain further insights into the elasticity of these findings, a one-at-a-time sensitivity analysis is conducted on the principal cost components of the MAP system. Fig. 10(a) illustrates the TCO response when battery costs, MAP hardware costs, and its maintenance costs are independently varied between 40% and 160% of their baseline values, in 10% increments. The results show that battery costs and charger hardware costs are the dominant drivers of the overall TCO. Both parameters exhibit nearly identical sensitivity slopes, indicating that proportional changes in either cost component lead to comparable changes in total system cost. This highlights battery procurement and charging hardware as first-order determinants of the economic performance of MAP-based charging infrastructure.

In contrast, MAP maintenance costs have a comparatively limited influence on the TCO. The maintenance sensitivity curve is considerably flatter, suggesting that uncertainties in routine operational expenditures are less critical than uncertainties in capital-intensive components such as batteries and chargers.

The combined effect of battery and MAP hardware cost variations is further illustrated by the iso-cost curve in Fig. 10(b). The results indicate that, under favorable cost assumptions, the total system cost can decrease to approximately 15 million USD, whereas under pessimistic assumptions it may increase to around 22 million USD. Despite this wide range, the MAP-based charging strategy remains economically competitive across most of the tested parameter space.

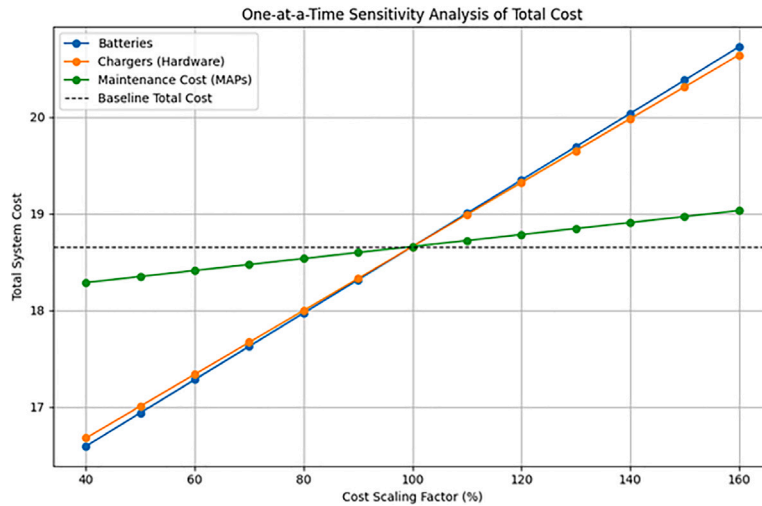
Overall, the sensitivity analysis demonstrates that even under substantial cost escalation—up to approximately 60% above baseline values for battery and hardware components, the MAP solution retains its economic advantage relative to depot-only and depot-plus-end-station charging strategies. This resilience is primarily driven by the scalable reduction in required bus battery capacities enabled by MAP deployment, which offsets a significant portion of the associated infrastructure costs.

7. Discussion and limitations

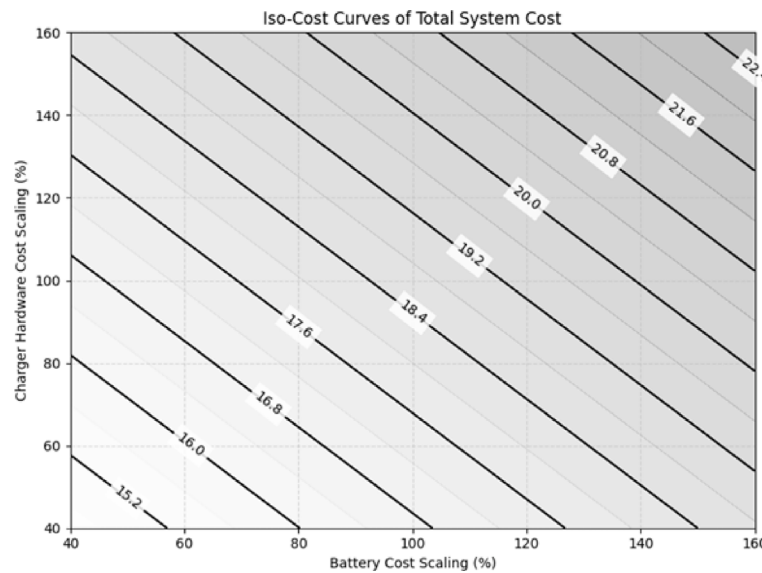
This study highlights the central role of battery sizing and infrastructure costs in determining the TCO for electric bus systems and provides comparative insights into how different charging strategies redistribute costs across vehicles and infrastructure. The depot-only

Table 7
Total cost of ownership of charging infrastructure (in million USD).

Cost component	Depot only	Depot + end-station	Depot + MAP
<i>Capital Expenditure (CAPEX)</i>			
Batteries	6.00	2.90	2.03
Chargers (Hardware)	5.10	4.89	3.30
Chargers (Installation)	7.65	7.51	4.60
Grid Connections	4.06	6.31	5.02
<i>Operational Expenditure (OPEX) – 11 years</i>			
Maintenance Cost (MAPs)	–	–	0.62
Maintenance Cost (Chargers)	2.80	2.75	1.68
Battery Replacement	4.18	2.03	1.41
Total costs	29.79	26.39	18.66



(a)



(b)

Fig. 10. Sensitivity analysis of MAPs to price changes of various parameters (a) One-at-a-time analysis (b) Iso-cost curve of cost sensitivity.

charging configuration illustrates the economic consequences of large battery dependence. Although centralized overnight charging offers operational simplicity and reliability, its reliance on oversized batteries leads to high capital expenditures. These findings are consistent with earlier techno-economic assessments, which have shown that battery costs account for a substantial share of life-cycle costs under

overnight charging regimes (Meishner and Uwe Sauer, 2020; Lajunen and Lipman, 2016). Together, these results reinforce the broader conclusion that depot-only charging is economically disadvantaged unless accompanied by significant reductions in battery costs.

Introducing end-station charging partially mitigates these challenges by enabling opportunity charging during scheduled layovers,

Table 8
Total cost of ownership of MAPs (in million USD).

Cost component	10 MAPs	18 MAPs
CAPEX		
Batteries	2.03	1.80
Chargers (Hardware)	3.30	3.60
Chargers (Installation)	4.60	4.60
Grid Connections	5.02	5.02
OPEX – 11 years		
Maintenance Cost (MAPs)	0.62	1.08
Maintenance Cost (Chargers)	1.68	1.68
Battery Replacement	1.41	1.25
Total costs	18.66	19.03

thereby reducing required battery capacities. However, the economic gains from smaller batteries are offset by the capital and grid connection costs associated with deploying multiple high-power chargers at terminal locations. This trade-off highlights a key limitation of stationary opportunity charging: while it reduces vehicle-level costs, it shifts investment burdens toward geographically dispersed and often grid-constrained infrastructure.

The MAP-based charging strategy further extends the principle of opportunity charging by decoupling energy delivery from fixed locations. The mobile nature of MAPs allows charging capacity to be flexibly allocated where and when it is needed, substantially reducing battery capacity requirements across the fleet. However, rather than viewing these results as a definitive cost ranking, they should be interpreted as evidence that mobility and flexibility in charging infrastructure can fundamentally alter the cost structure of electric bus systems.

A limited sensitivity analysis was conducted to assess the robustness of the MAP-based approach under uncertainty in key cost parameters. Varying battery costs, MAP hardware costs, and maintenance expenses shows that total system costs are most sensitive to battery and charger hardware prices, while maintenance costs play a comparatively minor role. Importantly, even under pessimistic assumptions, where battery and hardware costs increase by up to 60%, the MAP based solution remains economically competitive relative to conventional charging strategies.

An additional operational dimension not fully explored in this study is the potential impact of increasing MAP charging power. Higher charging rates would allow a larger share of energy transfer to occur while buses are stationary at end-stations, thereby reducing the need for prolonged in-motion charging. This could improve overall system efficiency, reduce the operational complexity of MAP-bus interactions, and enable smaller MAP battery capacities. Future research should therefore investigate the techno-economic trade-offs associated with higher-power MAP chargers, including implications for battery degradation and grid integration.

Despite these potential advantages, several practical challenges must be acknowledged. Following a bus during in-motion charging may affect vehicle dynamics, operational flexibility, or lane usage, particularly in dense urban traffic. Ensuring safe and reliable MAP-bus coordination may require advanced control systems, dedicated operating protocols, as well as regulatory adaptations. Moreover, MAPs will require dedicated charging locations, parking space, and dispatching systems, which were only implicitly considered in this study. Future work should therefore incorporate traffic-level simulations, safety assessments, and infrastructure layout studies to evaluate the real-world feasibility of large-scale MAP deployment.

In addition, several limitations must be acknowledged, particularly concerning methodological assumptions and the overall scope of the analysis. The proposed results do not stem from a formal optimization of infrastructure sizing, MAP allocation, or charging schedules. Instead, the analysis is based on a scenario-driven evaluation, where charging

configurations, MAP fleet sizes, and placement strategies are predefined and assessed through detailed simulation. Battery capacities and MAP quantities are progressively adjusted until operational feasibility criteria, such as maintaining minimum SOC thresholds are satisfied. Consequently, the reported outcomes should be interpreted as feasible and cost-efficient configurations rather than globally optimal solutions. While a limited sensitivity analysis showed the effect of costs and the number of MAPs, future work could explore optimization of many such aspects, including but not limited to deployment, planning, location, and fleet size of MAPs for these configurations.

Finally, the economic assessment relies on cost parameters derived from existing literature and prior infrastructure studies, including grid capacity assumptions based on Karlsson (2016). Given ongoing investments in urban power systems and electrification, these assumptions may not fully reflect current or future grid conditions. Updating grid capacity assessments and incorporating evolving regulatory and market contexts represent important directions for future research. Moreover, the present analysis does not consider vehicle-to-grid (V2G) integration, which could further enhance system flexibility and economic performance. Evaluating the interaction between MAP-based charging and V2G services therefore constitutes a promising avenue for future investigation.

8. Conclusions

This study examined the feasibility and cost-effectiveness of three electric bus charging strategies, applied to Stockholm's inner-city trunk lines. The configurations evaluated included: (i) depot-only charging, (ii) depot charging combined with end-station charging, and (iii) depot charging supplemented by Mobile Autonomous Charging Pods (MAPs). Using a microscopic simulation-based approach, the assessment considered operational constraints, energy demand profiles, and key infrastructure and vehicle cost elements over an assumed operational period of 11 years.

The depot-only strategy serves as a baseline and represents the simplest implementation, relying exclusively on centralized overnight charging. While operationally straightforward, this configuration imposes significant energy storage demands, requiring battery capacities approximately 30% larger than the initial capacity available in the current bus models. These requirements translate into high capital costs due to both battery procurement and future replacements, as well as increased vulnerability to depot-level grid congestion and single-point infrastructure failures.

The depot plus end-station charging strategy improves upon the depot-only model by enabling energy replenishment during daytime turnaround periods. This allows for the downsizing of onboard batteries, thus reducing battery-related expenditures. However, the savings are partially offset by the cost and complexity of installing 33 stationary chargers across terminal points, which are associated with substantial grid connection and installation costs, particularly in dense urban environments where access to high-capacity grid nodes is often limited.

The MAP-based strategy demonstrates the most favorable trade-off between operational flexibility and total cost of ownership. By facilitating on-the-go and opportunistic charging, MAPs significantly reduce dependency on large onboard batteries, resulting in up to a 67% decrease in total battery capacity relative to the depot-only baseline. Despite requiring upfront investment in high-power charging infrastructure (240 kW) and autonomous vehicle systems, the overall TCO is 11.13 million USD lower than depot-only charging and 7.73 million USD lower than the end-station strategy. These savings stem from both reduced battery investments and minimal grid connection costs, as MAPs can be flexibly deployed in locations with favorable grid access.

Moreover, a limited sensitivity analysis demonstrates that the economic viability of the MAP-based strategy is robust to uncertainty in key cost parameters, where battery prices and MAP hardware costs

emerge as the dominant cost drivers. Importantly, even under pessimistic assumptions with cost increases of up to approximately 60%, the MAP-based configuration remains competitive relative to both depot-only and depot plus end-station strategies. These findings suggest that the observed advantages of MAPs are not contingent on optimistic cost assumptions, but rather stem from structural shifts in how energy is delivered and stored within the system.

From a system design perspective, these findings underscore the potential of hybrid and dynamic charging strategies in enhancing the scalability, reliability, and resilience of electric bus networks. The MAP-based approach, in particular, decouples charging infrastructure from fixed spatial locations, enabling responsive deployment based on temporal and spatial energy demands. This increases robustness to disturbances and reduces reliance on costly grid upgrades at constrained urban sites.

From a policy and planning standpoint, MAPs can support more adaptive energy management, potentially easing peak load pressures and providing redundancy in the event of infrastructure failures. Furthermore, the mobile charging units can be integrated with second-life batteries from retired bus fleets, reducing environmental impact and improving lifecycle sustainability.

In conclusion, this study demonstrates that incorporating dynamic, mobile charging solutions such as MAPs alongside traditional depot infrastructure can significantly enhance the economic and operational performance of electric bus networks. The results offer a compelling case for rethinking conventional charging paradigms and adopting flexible, distributed energy delivery models in the transition toward sustainable urban mobility.

CRediT authorship contribution statement

Mohd Aiman Khan: Writing – review & editing, Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **Wilco Burghout:** Writing – review & editing, Visualization, Methodology. **Oded Cats:** Writing – review & editing, Supervision, Methodology. **Erik Jenelius:** Writing – review & editing, Supervision, Methodology. **Matej Cebecauer:** Writing – review & editing, Supervision.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT in order to improve readability and language. After using these tools, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Declaration of competing interest

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