Document Version
Final published version

Citation (APA)
Khan, M. A., Burghout, W., Jenelius, E., Cats, O., & Cebecauer, M. (2025). Evaluating the Operational and Economic Feasibility of Mobile Charging Pods for Electric Bus Operations. In *2025 9th International Conference on Models and Technologies for Intelligent Transportation Systems, MT-ITS 2025* (2025 9th International Conference on Models and Technologies for Intelligent Transportation Systems, MT-ITS 2025). IEEE. https://doi.org/10.1109/MT-ITS68460.2025.11223571

2025 9th International Conference on Models and Technologies for Intelligent Transportation Systems (MT-ITS) | 979-8-3315-8063-6/25/$31.00 ©2025 IEEE | DOI: 10.1109/MT-ITS68460.2025.11223571

Evaluating the operational and economic feasibility of mobile charging pods for electric bus operations

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***Abstract*—Recent advances in battery technologies and a global push for greener transport have accelerated the development of electrified public transportation systems. Such systems often face challenges due to the need for large battery capacities and the high costs associated with conventional charging infrastructure. This study examines the potential of Mobile Autonomous Charging Pods (MAPs), which are autonomous charging vehicles, as an innovative solution to enhance both the efficiency and cost-effectiveness of electric bus operations in urban environments. Using the case of inner-city trunk bus lines in Stockholm and employing a microscopic simulation-based study, three charging scenarios are evaluated: depot charging only, depot combined with end-station charging, and depot plus MAP charging. The results indicate that the integration of MAPs can significantly reduce the required battery capacities and associated infrastructure costs while enhancing the reliability of the service. By facilitating dynamic, on-the-go charging, MAPs offer a sustainable and economically viable alternative for urban electric bus networks.**

***Index Terms*—Electric Bus, Dynamic Charging, SUMO, Vehicle-to-Vehicle charging, Mobile charging stations**

I. INTRODUCTION

The transport sector is a major contributor to global greenhouse gas (GHG) emissions and energy consumption, accounting for approximately one-third of global carbon emissions, with road transport responsible for nearly 75% of this share [1]. In response to growing environmental concerns, governments worldwide are accelerating efforts toward sustainable transport. Sweden aims to become the first carbon-neutral country by 2045, targeting an 85% reduction in GHG emissions from 1990 levels [2]. Despite progress, road transport remains Sweden's largest emissions source within the transport sector, underscoring the need for further innovation in sustainable mobility.

Advancements in battery technologies have positioned electric buses (EBs) as a viable and energy-efficient option for public transit. However, their widespread adoption is impeded by several challenges, including high costs and increased weight from large battery requirements, and competition for public charging infrastructure with other electric vehicles [3]. A significant barrier is the choice of efficient charging infrastructure. Two primary approaches are prevalent: depot charging and opportunity charging.

Depot charging, which involves recharging buses overnight, requires large battery capacities to sustain daily operations, substantially increasing vehicle costs and weight, while imposing high infrastructure and energy demands [4]. To mitigate these limitations, opportunity charging enables buses to recharge en route through overhead chargers at bus stops or dynamic wireless charging embedded in road segments [5]. This approach reduces battery size requirements by allowing vehicles to charge throughout the day. However, due to long service hours, EBs often require multiple charging sessions, necessitating the installation of multiple charging stations. In some cases, this is not feasible due to location constraints or grid capacity limitations, making reliance on large-capacity batteries a common yet costly alternative.

We explore an alternative approach to charging EBs dynamically consisting of Mobile Autonomous Charging Pods (MAPs), which are autonomous battery-equipped vehicles capable of vehicle-to-vehicle (V2V) energy transfer. MAPs can charge buses while stationary or in motion and return to designated stations after completing charging tasks. Their mobility allows them to serve areas with limited grid infrastructure and adapt to changing charging demands, facilitating efficient energy distribution over time and space.

We assess the operational feasibility and economical benefits of MAPs in Stockholm's public transport network based on microscopic simulation analysis using the open-source tool Simulation of Urban Mobility (SUMO) [6]. We compare three electrification strategies for the rapid inner-city bus lines: Depot Charging Only (overnight charging), Depot + End-Station

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This research was funded by the Swedish Transport Administration grant nr 2022/8287, Project SMART3.

Charging, and with Depot + MAP Charging. In particular, we evaluate reductions in battery capacity requirements and infrastructure costs while ensuring operational feasibility.

The key contributions of this study are:

- proposing a novel dynamic charging approach using MAPs to enhance electric bus charging flexibility and efficiency;
- evaluating economic and operational benefits through a case study in Stockholm, highlighting cost reductions in battery capacity and infrastructure;
- identifying the challenges and future research directions for optimizing MAP deployment, including planning, scheduling, and integration with existing transport networks.

The remainder of this article is structured as follows: in Section II we review the literature, Section III outlines the methodology, and Section IV describes the experimental design. Section V discusses the results, followed by cost comparisons in Section VI. Section VII concludes with key findings and future research directions.

II. Literature Review

Many studies have compared the total cost of ownership (TCO) of EBs with diesel and bio-fuel alternatives. Lajunen and Lipman (2016) [7] found that EBs offer environmental benefits along with lower operating and maintenance costs compared to diesel buses. Similarly, Xylia et al. (2017) [8] demonstrated that reduced operational costs and favorable fuel prices can offset the high initial investment in charging infrastructure, while Borén (2020) [9] reported significant savings in social costs and TCO for EBs, primarily due to reduced noise, zero emissions, and lower energy consumption.

To enhance the operational feasibility of EBs, research has explored various charging strategies, including overnight depot charging, opportunity charging at end-stations, and dynamic charging while in motion. Mohamed et al. (2017) [10] observed that while overnight charging reduces the number of required chargers, it necessitates a larger fleet. Conversely, flash and opportunity charging reduce fleet size but require more strategically placed chargers. Other studies suggest that a hybrid approach combining daytime charging at terminal stops with depot charging, can be cost-effective [4], although grid connection costs need to considered and can account for up to 63% of total installation expenses [11].

Beyond stationary charging, dynamic charging solutions have also been explored, including charging lanes and V2V charging [5]. A micro-simulation-based optimization model comparing traditional charging stations with wireless charging lanes (WCLs) showed that combining static chargers with charging lanes improved service levels and reduced delays but required substantial investment [12]. With these charging lanes, the battery capacity of buses can be reduced by up-to 60% and life-cycle costs of EBs can be reduced by up-to 13% [13].

Despite the advantages of charging lanes in reducing battery capacity requirements, their high investment costs and low flexibility remain major drawbacks. To address this, V2V charging solutions have been proposed, where a vehicle acts as a charger and shares energy with another vehicle. These V2V charging solutions can significantly reduce battery capacities, while also improving travel times and adaptability of the system [14].

Compared to previous works, we propose the use of MAPs to implement V2V charging for EBs. A microscopic simulation using SUMO evaluates the feasibility, benefits, and challenges of MAP-based charging in real networks, providing a comparative analysis with conventional charging strategies.

III. Methodology

We adopt a micro-simulation based approach to analyze the EBs and their charging behavior. To simulate the transport flow of EBs, we employ SUMO, using road network data imported from OpenStreetMap (OSM), and bus routes and schedules from publicly available General Transit Feed Specification (GTFS) and Automated Vehicle Location (AVL) datasets provided by the Region Stockholm public transport authority.

A. Identifying the Number of Buses

For this study, we assume that buses operate on single lines (i.e., no interlining). Determining the precise number of buses is essential for accurately modeling fleet dynamics and estimating energy consumption, which in turn informs infrastructure planning and operational strategies. To achieve this, we incorporate a minimum turn-around time derived from corresponding AVL data, to assign consecutive trips to the same bus when feasible. We then iterate over the GTFS schedule to determine the minimum number of buses and trips per bus required to cover all scheduled trips. The energy consumed during each trip is cumulatively added to the next, simulating continuous operation for each electric bus.

B. Simulating End-Station Charging

To simulate end-station charging of EBs, the buses are charged at the turn-around point when ending a one-way trip. When the bus starts a return trip, it is charged according to the amount of turn-around time it had according to the schedule. For this study, we assume that buses cannot change their schedule based on charging requirements.

C. Simulating MAP Charging

The algorithm for MAP charging is shown in Figure 1, where each MAP enters the simulation and waits at a designated parking spot. These pods provide the necessary charge for buses to complete their trips and operate collaboratively to electrify larger road segments. Due to their compact design, MAPs can be parked vertically [15] to optimize space utilization as shown in Figure 2. When an electric bus requests a charge, the MAP is deployed and follows the electric bus, charging it while moving [14]. The charging stops when either the bus has reached the desired state of charge, or the MAP has reached its stop, or the MAP does not have sufficient energy

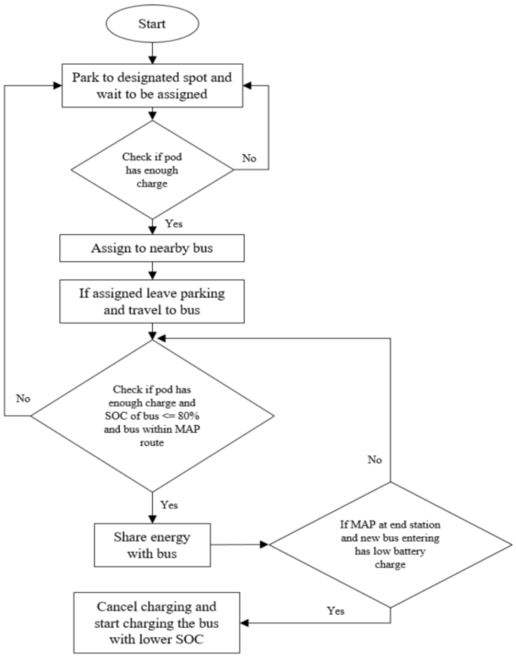

Fig. 1. Charging Algorithm for MAPs for charging buses.

to continue charging the bus. When charging the buses at the end-station, the MAP will prioritize buses with lower State of Charge (SOC) levels.

To simplify the problem, we determine the number of MAPs and their battery capacity based on the energy requirements of bus line operations. Drawing from prior research, the system-level energy transfer efficiency of MAP-based charging systems is typically in the range of 75–80% [14]. 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 expenditure associated with MAP travel, deployment is concentrated near end-stations.

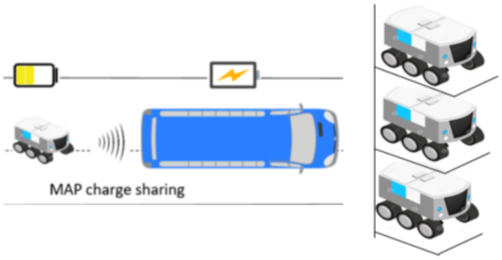

Fig. 2. Illustration of MAP charging, MAPs can charge the buses and then can be stacked together to save space

The distance for deploying MAPs from the nearest end station is determined by ensuring that the energy provided by MAPs is at least equal to the energy consumed by the bus per trip. This relationship is expressed as:

$$E_{endstation} + E_{move} \geq E_{travel}, \qquad (1)$$

where E_{travel} is the energy needed by the electric bus to complete one trip, $E_{endstation}$ 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 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:

$$(c_{rate} \cdot t_{turn}) + 2 \cdot (c_{rate} \cdot t_m) \geq E_{travel}, \qquad (2)$$

where c_{rate} denotes the charging rate at which the MAP transfers energy to the bus, t_{turn} is the turn-around time at the end-station, and t_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 t_m, we derive:

$$t_m \geq \frac{E_{travel}}{c_{rate}} - \frac{t_{turn}}{2} \qquad (3)$$

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

$$d_m \geq \frac{t_m}{s_{bus}}, \qquad (4)$$

where s_{bus} is the bus's speed. Once t_m is determined, the optimal MAP deployment distance from the end station can be computed accordingly using equation 4.

IV. EXPERIMENTAL DESIGN

To assess the feasibility and potential benefits of MAP charging compared to conventional charging strategies, a series of scenarios is conducted. The 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 significant challenges associated with installing stationary charging infrastructure in a dense urban environment, primarily due to space and capacity constraints. For the scope of this study, Line 1 is selected as a representative case for analyzing electric bus operations.

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). 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 determined for trunk line buses. Each bus line is analyzed independently, assuming no interlining of vehicles between routes. Specifically for Line 1, the turn-around time constraint results in a fleet of 21 buses, each

TABLE I
VALUE OF PARAMETERS USED IN THE SIMULATION

Parameter	**Value**
Baseline battery capacity of e-buses	470 kWh
Battery capacity of MAPs	180 kWh
Operational weight of e-buses	30,000 Kg
Operational weight of MAPs	500 Kg
Average speed of e-buses	40 Km/h
Energy consumption e-buses	3.0 kWh/Km
Energy consumption MAPs	0.5 kWh/Km
Minimum turn-around time	5 minutes

completing a maximum of 15 trips per day.Key operational parameters, including energy consumption and charging characteristics, are based on Volvo electric bus specifications [16] and SUMO documentation. The primary parameters used in the simulations are summarized in Table I.

Three different charging scenarios are simulated to evaluate the effectiveness of MAP charging in comparison to conventional approaches:

A. *Depot Charging Only*

In this baseline 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 I. 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.

B. *Depot and End-Station charging*

This 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%, to maintain battery health and optimize charging time. The impact of end-station charging is analyzed in terms of reducing the required onboard battery capacity compared to only depot charging.

C. *Depot and MAP charging*

In this scenario, buses charge overnight at depots and utilize in-motion charging via MAPs during daytime operations. A limited number of two MAPs is considered, strategically positioned near the two end-stations to maximize charging during bus turn-around periods. The MAPs are assumed to charge at 150 kW and have a battery capacity of 180 kWh.

Using Equation 3, the minimum charging time required is computed, where E_{travel} is about 30 KWh, c_{rate} is 41.67 W/sec, and t_{turn} is taken to be around 5 minutes. Considering both stationary and in-motion charging periods, the optimal MAP deployment distance from the end-stations is then calculated using Equation 4.

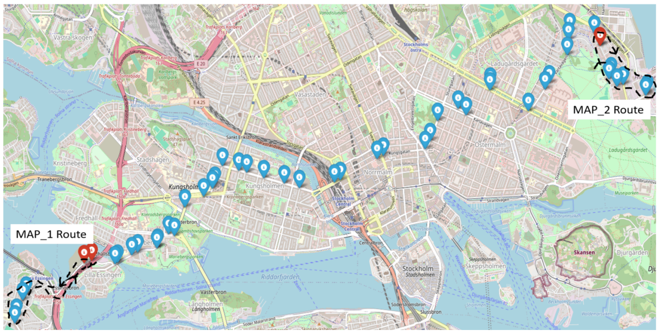

Fig. 3. The charging route of MAPs. The blue stops represent all the stops in line 1, and the red stops represent the end of MAP route. The black line represents the charging route of MAPs.

For Line 1, the identified optimal MAP stop locations are positioned at Primusgatan near the end-station at Essingetorget and at Rökubbsgatan near the end-station at Frihamnen. The MAPs are assigned these specific stop locations from which they are deployed based on real-time charging demand. The corresponding stops and the MAP charging routes are illustrated in Figure 3. When a bus requires additional charge, the nearest MAP is deployed according to the algorithm in Figure 1. For this scenario, we assume that MAPs charge themselves via battery swapping at their charging location.

V. RESULTS

In the following, we present the results obtained from each charging scenario, along with key insights. The 21 buses operating on Line 1 travel a total distance of approximately 2,715 km per day, consuming 8.06 MWh of energy. Each bus operates at an average speed of 20 Km/h and consumes approximately 30 kWh per trip (from one end-station to the other).

A. *Depot Charging Only*

In this scenario, 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 most buses run out of charge before completing their daily operations, as shown in Figure 4.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 analysis shows that a battery capacity of 620 kWh per bus is necessary to maintain this SOC threshold.

Thus, with only depot charging, an additional 32% increase in battery capacity is required to sustain operations without buses running out of charge.

B. *Depot and End-Station Charging*

To reduce battery size requirements, this scenario introduces end-station chargers that allow buses to charge during turn-around times at each end of the route. The simulation assumes 150 kW chargers installed at the end-stations.

From Figure 5, we can see that with end-station charging, the required battery capacity per bus is reduced to 350 kWh,

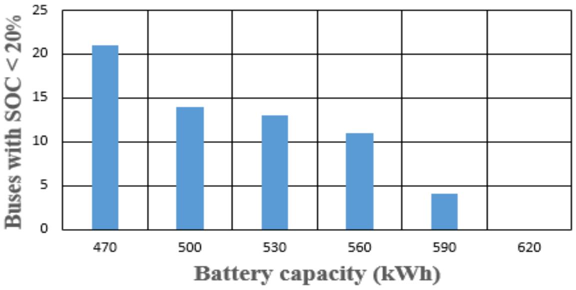

Fig. 4. Battery capacity to maintain daily operation with only depot charging

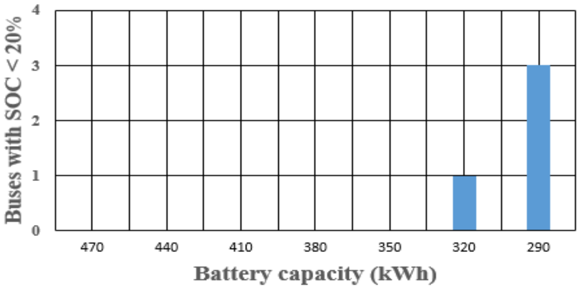

Fig. 5. Battery capacity to maintain daily operation with depot+end-stations

while maintaining an SOC above 20% throughout operations. This represents a 44% reduction in battery capacity compared to the depot-only scenario.

From the experiments, the scenario requires six end-station chargers in total (three at each end-station) to meet the energy demand of Line 1. The total energy delivered at the end-stations is approximately 4.8 MWh for the whole day.

C. 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, buses can maintain their SOC levels above 20% throughout the daily operations. Moreover, the battery capacities can be further reduced to 270 kWh as shown in Figure 6. This translates to a reduction of 56% compared to depot only and about 22% compared to depot plus end-station charging.

The advantage of MAPs over stationary end-station chargers is that they distribute charging both spatially and temporally by traveling alongside buses for a certain distance after they leave the end-stations. As shown in Figure 7, a portion of the energy is charged when the bus is executing the trip, thereby increasing the time to provide the charge while lowering the stress on the grid and corresponding infrastructure. This improves energy utilization, efficiency and enhances the operational flexibility of the charging infrastructure.

VI. ELECTRIFICATION COSTS COMPARISONS

Multiple factors need to be considered when planning and deploying charging technologies for electric bus operations. These include feasibility of deployment, energy requirements, and costs.

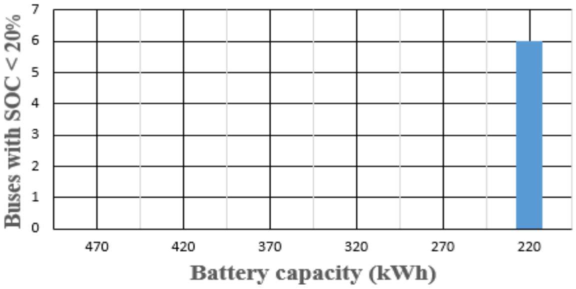

Fig. 6. Battery capacity to maintain daily operation with depot+MAPs

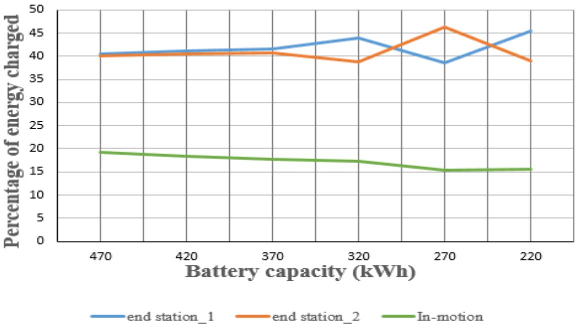

Fig. 7. Shares of energy delivered by MAPs at end-stations and in motion

When considering only depot charging, we see that battery capacity needs to be increased to 620 kWh from currently used 470 kWh. The energy requirement is also 8.06 MWh, as the buses need to be fully recharged before resuming operations the next day.

As the current depots do not have this capacity, this will require the construction of new substations, resulting in costs of about 1.2 M USD [4]. Considering that each bus in line 1 will have a charging station, and that buses are parked for 4 hours before resuming operations, each corresponding charging station will need to be of about 100 kW capacity. For simplification, we consider a cost of 1400 USD/per kW for a charger (considering both equipment and installation costs) [17] and about 115 USD/kWh for batteries [18].

End-station chargers can reduce infrastructure costs by enabling daytime charging and lowering depot load. In this configuration, six end-station chargers meet approximately half of the daily energy demand, thereby reducing battery and charger requirements at depots. However, installing these chargers requires new substations; since one end-station at Frihamnen already functions as a depot, only the remaining end-stations need a capacity of 450 kW. We estimate the cost for these additional substations and grid connections to be around 0.6 M USD [4], [11]. Consequently, depot costs could be reduced by approximately 50% in this scenario.

As grid connection costs can be of great significance, accounting for up-to 63% of the electrification costs [11], we consider an alternate charging strategy using MAPs. From the results obtained, the battery capacities can be further reduced to 270 kWh. As these MAPs are not yet on the market, we assume the cost to be the same as for mobile charging vehicles, about 40,000 USD/vehicle [5].

For this study, only two MAPs were needed, each with a battery capacity of 180 kWh. Moreover, as we assume the MAPs to charge via battery swapping, we consider an additional 360 kWh for charging purposes. For both the parking and charging facility for MAPs, we consider a cost of 0.5 M USD [19], since the majority of the costs are for installation. We consider the grid connection costs to be negligible, as MAPs spread the energy needed spatially and temporally and will not require the construction of additional substations due to the use of batteries.

The resulting costs of electrification per scenario, comprising the cost of charging infrastructure, batteries, and grid connections, are presented in Table II. The analysis reveals that the depot plus MAP configuration is the most cost-efficient, saving approximately 2.25 M USD compared to depot-only charging and about 1.39 M USD relative to end-station charging. Additionally, MAPs offer significant flexibility, as they can be easily deployed in response to increased demand. This adaptability allows for dynamic adjustments in fleet size, scheduling and fluctuations in bus delays, a benefit that static charging solutions cannot provide.

TABLE II
ELECTRIFICATION COSTS PER SCENARIO

Cost component	**Costs (in million USD)**		
	Depot only	***Depot+end-station***	***Depot+MAP***
Chargers	2.94	2.73	2.05
Batteries	1.49	0.84	0.73
Grid connections	1.20	1.20	0.60
Total Costs	**5.63**	**4.77**	**3.38**

VII. CONCLUSIONS AND FUTURE WORK

This study investigates the potential of MAPs, which are autonomous charging vehicles, as a solution to increase the efficiency and cost-effectiveness of electric bus operations in urban environments. Focusing on the inner-city high-frequency bus lines of Stockholm, three distinct charging scenarios are evaluated: depot charging only, depot plus end-station charging, and depot plus MAP charging.

The results show that the depot plus MAP charging scenario can reduce battery capacities by up-to 56% and reduce costs of electrification by about 2.25 M USD. This is due to in-motion charging, which optimizes energy distribution spatially and temporally. The optimal deployment of MAPs is determined based on energy consumption of bus per trip, charging rates, turn-around times, and bus speeds.

The results show the potential for new and hybrid charging strategies to minimize battery size and infrastructure costs while maintaining operational reliability. This study contributes valuable insights for policymakers and urban public transport planners by demonstrating that integrating dynamic charging solutions, such as MAPs, with conventional depot charging can significantly improve the sustainability and economic viability of electric bus networks. Future research should extend these findings to other bus lines and explore further optimization of dynamic charging deployment in diverse urban contexts.

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