

Article

Integrated Multi-Period Optimization of Electric Bus Transition Planning in Urban Mobility

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Abstract

The transition to electric bus (EB) fleets is a critical step towards sustainable urban transportation, offering substantial reductions in greenhouse gas and pollutant emissions relative to diesel buses. However, transit authorities face multifaceted challenges in this transition, including limited driving ranges of EBs, the need for widespread charging infrastructure, and potential strain on the electric grid, alongside opportunities such as governmental subsidies and increased fare revenues. This paper proposes a comprehensive multi-period mixed-integer programming model seeking to optimize long-term EB fleet transition plans in urban contexts while jointly accounting for all inherent financial, technical, and operational factors impacting such a transition. The model is operationalized using real data acquired from Dubai's Roads & Transport Authority (RTA), encompassing 71 bus routes and a 25-year planning horizon to meet a 100% electrification target by 2050. A scenario-based analysis evaluates the robustness of the transition plans under variations in key operational parameters. The results illustrate that optimized long-term planning yields substantial cost savings and emissions reductions, where the incorporation of environmental and social externalities and revenue shifts causes profit maximization to emerge as a more appropriate objective. In addition, it turns out that adequate dwell time is crucial for cost containment and full fleet electrification feasibility. While RTA targets 100% electrification by 2050, the base case is deliberately relaxed to 90% as certain routes, notably double-decker lines, are incompatible with currently available EB configurations. Nevertheless, full electrification is restored under the minimum dwell scenario. Also, a policy of purchasing only EBs accelerates full fleet electrification by roughly a decade with only a marginal increase in total cost, unlike imposing strict interim electrification targets. The optimized transition plans provide actionable insights for transit authorities balancing economic efficiency with sustainability goals.

Keywords: charging infrastructure; electric buses; fleet electrification; multi-period optimization; sustainability; urban mobility



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1. Introduction

Urban transit authorities worldwide are increasingly prioritizing the electrification of bus fleets to mitigate the environmental impacts of public transportation. The transportation sector is a major contributor to urban air pollution and greenhouse gas emissions, generating 15% of total CO₂ emissions [1], and as such, replacing diesel buses with electric buses (EBs) can significantly reduce these emissions. Many cities and transit agencies

across the globe have announced targets for transitioning to 100% EB fleets over the coming decades. Establishing sustainable cities through efficient public transportation is paramount [2] to cater for the world's urban population, which is projected to rise significantly by 2050 [3], and sustainability goals. For instance, Dubai's Roads & Transport Authority (RTA) has set a goal to fully electrify its public bus fleet by 2050, aligning with broader sustainability initiatives [4]. Achieving such ambitious targets requires strategic long-term planning, as transit agencies must balance environmental objectives with financial and operational realities.

While the transition to EBs promises substantial benefits, it also presents several challenges that must be addressed in a comprehensive transition plan [5,6]. EBs have limited driving ranges compared to diesel buses, necessitating careful scheduling and charging strategies to maintain service levels. Developing a robust charging infrastructure is essential to support an electrified fleet whereby agencies must determine the number, type, and locations of chargers (e.g., depot vs. en-route fast chargers) to meet energy demands without causing excessive vehicle downtime. Moreover, large-scale electrification will introduce significant loads on the electrical grid, potentially requiring grid upgrades or smart charging management to avoid capacity issues [7,8]. These technical and operational hurdles occur in parallel with financial considerations. EBs typically have higher upfront costs than diesel buses, including vehicles and batteries, as well as infrastructure investments for charging stations. On the other hand, EBs promise lower fuel (energy) and maintenance costs over their lifetimes. Transit agencies often operate under tight budget constraints, so the capital expenditures for EBs and chargers must be planned alongside operating costs and revenues. Opportunities exist to offset costs where government subsidies can reduce purchase costs [9], and transit authorities may consider modest fare increases given the improved service sustainability [10–12]. Additionally, the societal and environmental benefits of electrification, such as improved air quality, curbed carbon emissions, and reduced noise levels, have economic value that can be monetized through incentive mechanisms (e.g., carbon trading) or considered as part of a broader cost–benefit setting.

Existing studies on bus fleet electrification have typically focused on specific subsets of these issues, such as optimizing charging infrastructure placement, establishing bus-to-route assignment given a fixed fleet composition, or minimizing vehicle and energy costs, in lieu of integrating all aspects into a single decision-making framework. In practice, the transition plan must be holistic, coordinating financial planning, technical requirements, operational considerations, and multi-stakeholder perspectives over a several-year planning horizon. A financial plan must include not only capital and operating costs but also potential revenue changes (e.g., fare policies) and budget limitations. Technical requirements involve selecting appropriate bus types (battery capacity, size) and charger technologies, as well as deciding where to deploy chargers (depots or opportunity charging at terminals). Operational factors include the characteristics of existing bus routes (length, frequency, passenger demand) and fleet utilization. A multi-stakeholder perspective needs to be incorporated as well, including government agencies that might provide subsidies or set electrification mandates, and utility companies that need to coordinate grid capacity and electricity supply for charging infrastructure. Finally, modeling elements such as the temporal dimension (planning over several periods or years) and fleet age dynamics (phasing out old buses and introducing new ones) are crucial for capturing long-term effects.

There is a pressing need for a scalable optimization framework that can simultaneously handle these diverse elements to guide EB fleet transition planning. To that end, this paper aims to develop a comprehensive multi-period mixed-integer linear programming (MILP) model that integrates all key transition planning elements. The specific objectives of the study are to:

- (1) Identify and integrate the critical planning elements (financial, technical, operational, and stakeholder-related) influencing EB fleet transitions;
- (2) Formulate a comprehensive optimization model that jointly optimizes fleet electrification schedules, charging infrastructure deployment, and operational allocation over a long-term horizon;
- (3) Apply the model to a real-world case drawn from Dubai's RTA and validate its effectiveness toward producing a feasible, cost-effective transition strategy;
- (4) Analyze various scenarios to test the model's robustness and derive practical insights on how changes in key input parameters impact the optimal transition plan.

The primary contribution of this work is a unified planning model for EB fleet transition that combines financial analysis, technology selection, strategic fleet deployment, infrastructure planning, and policy levers in one optimization framework. To the authors' best knowledge, this level of integration exceeds that of prior studies, which have not concurrently addressed all these dimensions. Notably, this comprehensive integration is coupled with three specific advances. First, rather than relying on the fixed charger-to-bus ratios common in prior work, this work embraces an endogenous demand-linked energy aggregation approach at depots and terminals that determines the number, type, and placement of chargers from route energy demand. Second, the proposed model explicitly incorporates system feasibility constraints within the strategic planning framework, particularly dwell time availability and charging grid-capacity limits, ensuring that infrastructure deployment and fleet transitions remain consistent with physical and operational service requirements. Third, the proposed model adopts a profit-maximization-based objective that internalizes fare revenue, governmental subsidies, and monetized environmental and social externalities within the fleet transition decision-making process.

The UAE's 2050 net-zero initiative [4] provides an excellent case study that demonstrates how transit agencies can use the model to evaluate trade-offs. For example, the model can determine the cost of accelerating electrification versus the environmental benefits and can help strategize the timing of investments. The scenario analysis provides further insights into the sensitivity of the transition's outcomes to critical factors, guiding agencies on what external support or operational adjustments have the greatest impact. Overall, this work offers a practically applicable yet methodologically rigorous decision support tool that would aid policymakers and transit authorities in planning the complex transition to EBs in an efficient and cost-effective manner.

The remainder of this paper is organized as follows. Section 2 provides an overview of EB research, describes the transition planning elements in more detail and reviews the relevant modeling-based literature on EB transition planning, highlighting this paper's unique contributions. Section 3 presents the mathematical formulation of the optimization model and a detailed description of the problem context. Section 4 provides the practical case study used for implementing the optimization model. Section 5 presents the results of the base case along with a scenario-based assessment and a one-way sensitivity analysis validating the model's effectiveness and practical relevance. Finally, Section 6 presents concluding remarks, draws some managerial implications and outlines potential avenues for future work.

2. Literature Review

Research on EBs has expanded significantly in recent years, driven by declining battery costs and technological advancements that have improved operational and economic feasibility [13]. Manzolli et al. [14] reported a substantial rise in EB-related publications, with the number of studies reaching 486 by 2020. Extending this analysis using the same search string, the total rose to 1113 by 2024, highlighting the growing relevance of EBs

in sustainable transport research. Their bibliometric analysis identified five major research clusters: vehicle technology, sustainability, battery technology, energy management, and fleet operation. These streams address diverse challenges, from improving battery chemistries and charging strategies to reducing environmental impacts and optimizing fleet scheduling. According to [2], the EB planning process spans three key stages: operational (daily adjustments), tactical (months in advance), and strategic (years in advance). Strategic transition planning entails multi-year decisions on fleet electrification scale, charging infrastructure deployment, technology selection, financial forecasting, and alignment with long-term goals. However, despite the growth of research across various streams, most studies focused on operational and tactical domains, with relatively limited attention given to long-term strategic decisions, such as transition planning [15].

2.1. Transition Planning Elements

To ensure a successful transition to EBs, transit authorities must address several transition planning elements, where such elements, along with their sub-elements and components, are depicted in Table 1. Beyond enumerating these elements, the review that follows emphasizes their interdependence and the principal trade-offs they embody, since a decision taken for one element, for example, the charging strategy, propagates into battery sizing, grid load, operating cost, and feasible route assignment.

Table 1. EB transition planning elements.

Transition Elements	Sub Elements	Components	References
Financial Planning	Internal Cost	Bus Purchase Cost	[13,16–18]
		infrastructure Cost	
		Operating cost	
	Environmental and Social Cost	Climate Costs	[9,19]
		Health Costs	
	Revenue	Salvage Revenue	[11,12,20]
Bus Fare Revenue			
Budget Constraints	Budget	[12,21]	
Technical and Infrastructure Requirements	EB Types	Bus Technology Selection	[1]
	Battery Types	Battery Size Selection	[13,20,22]
	Charging Infrastructure	Charging Infrastructure Placement	[15,20,23]
		Charging Infrastructure Types	[2]
Existing Bus Network and Operations	Route Characteristics	Route Assignment	[2,9,14,24]
		Demand Fulfilment	
Current Fleet Characteristics	Available Buses and chargers	[25]	
Multi-stakeholder Perspectives	Electric Utilities	Electric Utilities Constraints	[14,15]
	Government Entities	Government Incentives	[12,26]
Electrification Target			
Modeling Elements	Tracking Elements	Time Tracking	[9,13,21,27]
		Age Tracking	
	Optimization Model	Scalable Model	[28]

2.1.1. Financial Planning

Financial planning for EB adoption is a complex process that requires careful consideration of various factors affecting the transition over time. This includes internal costs where such costs constitute the largest share of the total cost of ownership (TCO). They include bus purchase cost [16], infrastructure investments for chargers and grid upgrades [17], and

operating costs such as energy, battery replacements, and maintenance, where EB operating costs are typically lower than those of diesel buses [13,18]. Environmental and social costs also play a critical role, representing broader societal and environmental impacts, such as adverse public health effects from air pollution and noise (e.g., premature death and respiratory diseases) and climate effects due to greenhouse gas (GHG) emissions [9,19]. These are often overlooked but significantly reduced by EBs. Revenue generation primarily stems from bus fares and fleet salvage, with EBs potentially increasing public willingness to pay and enhancing social welfare [10–12,20]. Finally, budget constraints are a significant factor driving phased electrification, as high initial costs often exceed transit agency capabilities [12,21], necessitating long-term forecasting of costs and revenues for a smoother transition. As it stands now, the financial literature remains fragmented, where most studies optimize a subset of these components, typically internal costs, while holding externalities, revenue, or budgets exogenous. Moreover, monetized externalities rely on damage, avoidance, and replacement cost approaches, and their values vary across regions, rendering their transferability an inherent source of uncertainty.

2.1.2. Technical and Infrastructure Requirements

Ensuring operational feasibility of EBs critically depends on a thorough understanding of their technical and infrastructure requirements. This begins with selecting appropriate EB types like BEBs for zero emissions, hybrid electric buses (HEBs) for extended range, or fuel cell buses (FCBs) for longer ranges despite complex infrastructure [1]. Complementing the bus choice is the battery technology, where Lithium Nickel Manganese Cobalt Oxide (NMC)-based batteries suit depot charging, while Lithium Titanate (LTO)-based batteries facilitate rapid opportunity charging [20,22], with capacity directly influencing cost, weight, and range [13]. Seamless operation then relies on the strategic implementation of charging infrastructure, which involves carefully selecting appropriate battery types and their placement to meet specific operational needs efficiently and cost-effectively [29]. Depot charging (slow, overnight) typically occurs at bus depots [20], whereas opportunity charging (fast, during service breaks) requires placement at terminals [23]. Further solutions include in-motion charging and battery swapping [2]. Regardless of the chosen type and placement, adequate electrical supply and potentially significant grid upgrades at these locations are essential. A recurring weakness across the modeling literature is that charger requirements are approximated by fixed charger-to-bus ratios, decoupled from route energy demand, battery size, and charging rate. This simplification underestimates the interaction between fleet composition and infrastructure and is precisely where strategic plans tend to lose accuracy.

2.1.3. Existing Bus Network and Operations

To effectively integrate EBs, understanding the existing bus network and operations is of paramount importance [24]. This commences with an analysis of route characteristics such as service frequency, run cycle length and time, and dwell time, which are all vital for determining energy consumption and range requirements for EB deployment and ensuring continuous passenger demand satisfaction [2,9,14]. Furthermore, detailed data on current fleet characteristics, including vehicle size, age, powertrain type, and mileage, alongside existing charging infrastructure characteristics, is essential for analyzing operational capacity and assessing electrification feasibility and future replacement needs [13,25]. A thorough analysis of both route and fleet characteristics enables the prioritization of routes best suited for electrification, facilitates efficient EB deployment, and ensures adequate charging infrastructure for the transition. The central methodological tension here lies between granularity and tractability. Disaggregated trip-level representations capture route heterogeneity but do not scale to city-wide multi-decade horizons, whereas highly

aggregated representations scale but may overlook route-specific incompatibilities, leaving the question of which routes are genuinely electrifiable inadequately addressed.

2.1.4. Multi-Stakeholder Perspectives

Successful planning and implementation of EB systems hinges on considering the perspectives of multiple stakeholders [30]. Government entities, for instance, play a pivotal role by providing financial incentives, such as subsidies and tax breaks, to offset high EB and charging infrastructure costs [26]. They also devise supportive policies and raise public awareness, facilitating a smoother transition [12]. Concurrently, electric utilities are essential partners in charge of assessing power grid capabilities and identifying limitations, ensuring necessary upgrades, especially for fast-charging stations [14,15]. Their provision of grid readiness data enables effective charging infrastructure planning, prevents operational disruptions and enhances EB operational efficiency. This collaborative effort is crucial for reducing initial costs, creating a supportive regulatory environment, and ensuring energy availability for growing EB charging demand. These levers are typically studied in isolation, where incentive-focused models rarely incorporate explicit grid constraints, while grid-focused models rarely account for policy instruments such as subsidies. This separation limits the practical applicability of existing approaches, particularly under aggressive electrification mandates, necessitating coordinated planning of subsidies and grid investment to ensure feasible and cost-effective fleet transitions.

2.1.5. Modeling Elements

To facilitate data-driven decision-making in bus-fleet transition planning, key modeling elements are fundamental. These include tracking elements such as time, which is crucial due to the dynamic nature of costs and technological advancements [13], and age, which significantly impacts operating costs, maintenance, and salvage value [9]. A longer planning horizon enhances the benefits of electrification, enabling more realistic and gradual transition plans that account for budget limitations and help identify optimal bus replacement timing for cost-effectiveness [21,27]. An optimization model is then essential for determining optimal transition strategies. Linear programming is particularly effective due to its computational simplicity, which grants superior scalability necessary for modeling extensive, city-wide bus networks [28]. The incorporation of integer variables is inevitable to account for discrete financial and technical choices pertaining to the determination of fleet composition and charger placement, which renders the MILP model the most suitable optimization framework to use. In the existing literature, two relevant issues are seldom addressed explicitly. First, a long horizon magnifies both end-of-horizon distortions and the uncertainty attached to long-range parameters. Secondly, richer nonlinear formulations that capture grid and charging physics quickly become intractable for realistic large-scale instances. The unresolved challenge is therefore to integrate all of the above elements without compromising the scalability that real networks demand.

2.2. Electric Bus Transition Planning Models

Several studies developed optimization models for the EB fleet transitions, despite overlooking some of the aforementioned relevant transition planning elements. Table 2 categorizes the modeling-based studies in light of the key elements, positions this work, and identifies existing research gaps. This section reviews these studies, focusing on each paper's unique approach to EB transition planning. Rather than describing each study in isolation, the following synthesis groups the work by what it optimizes and, more revealingly, by what it omits, using the classification in Table 2 to make these omissions explicit (empty cells) and to identify the gap addressed here.

Table 2. A classification of modeling-based research on EB transition planning.

Reference	Financial Planning			Technical and Infrastructure Requirements			Existing Bus Network and Operations		Multi-Stakeholder Perspectives		Modeling Elements		
	Internal Cost	Environmental and Social Cost	Revenue	Budget Constraints	EB Types	Battery Types	Charging Infrastructure	Route Characteristics	Current Fleet	Electric Utilities	Government Entities	Tracking Elements	Optimization Model
Pelletier et al. [13]	✓			✓	✓	✓		✓	✓	✓		✓	✓
Hanna et al. [15]	✓			✓	✓	✓	✓	✓	✓	✓		✓	
Dirks et al. [18]	✓				✓	✓	✓	✓	✓				✓
He et al. [27]				✓		✓	✓		✓				✓
Islam and Lownes [31]	✓	✓		✓	✓				✓			✓	✓
Zhang et al. [21]	✓	✓		✓		✓	✓		✓	✓			✓
Li et al. [32]		✓		✓	✓				✓				✓
Feng and Figliozzi [33]		✓		✓	✓				✓			✓	✓
Tang et al. [34]	✓	✓		✓		✓			✓			✓	
Zhou et al. [9]	✓	✓		✓	✓	✓			✓		✓	✓	✓
This work	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Dirks et al. [18] proposed an integrated mixed-integer programming (MIP) approach that simultaneously accounts for strategic decisions (such as fleet composition and charging facility locations) and operational constraints (like bus assignments). Their findings indicate that a comprehensive integration of BEBs is not only feasible but also economically beneficial. He et al. [27] examined time-dependent BEB and charging station deployment, proposing a bi-objective integer linear programming model minimizing total electrification costs and non-BEB mileage. It generates a Pareto curve to aid transition planning. Islam and Lownes [31] optimized DB replacement with alternative technologies, primarily BEBs and HEBs. They devised a MIP model to minimize Life-Cycle Cost (LCC) under operational and environmental constraints. Findings show that an optimized fleet (79% BEBs, 21% HEBs) achieves the lowest costs and emissions. The multi-period bus electrification considering seasonal variations and budget constraints is tackled by Zhang et al. [21]. Their MILP model optimizes charging, locations, and fleet transitions. Their findings indicate that optimized long-term planning yields a reduction of the total costs by 17.8% and CO₂ by 39.3%. Li et al. [32] also considered the two objectives of cost minimization and emissions reduction for mixed bus fleets, considering routing and operational constraints. Using a new life additional benefit–cost (NLABC) analysis and integer programming, they identified optimal fleet size, composition, and routing for multi-lines or interlining. This first cluster establishes the value of optimized multi-period planning, but it largely treats fare revenue and monetized externalities as outside the model and sizes charging infrastructure coarsely. As such, its financial picture is partial, and the link between fleet decisions and charger requirements remains approximate.

In another work, Feng and Figliozzi [33] devised a cost minimization model that seeks to determine HEB/DB replacement considering factors such as purchase costs, maintenance costs, and subsidies, which significantly influence the optimal bus type and replacement age. Findings reveal that government subsidies greatly affect optimal replacement periods and the total costs. Tang et al. [34] optimized multi-type EB fleet transition, assuming replacement rates and crowding costs influence strategy. Their mixed-integer nonlinear programming (MINLP) model minimizes life-cycle costs while accounting for subsidies and operational constraints. The findings reveal that larger EBs initially reduce crowding while smaller EBs are advantageous at a later stage. Although this second group sharpens the understanding of when to replace and how incentives aid in this regard, it typically holds the network and charging infrastructure in the background, leaving operational feasibility and grid implications unresolved.

In the existing literature, three studies are particularly relevant to the work presented in this paper. Pelletier et al. [13] tackled the EB Fleet Transition Problem (EBFTP) and proposed a flexible ILP model integrating many transition planning elements. However, it overlooks environmental/social costs, government incentives, and detailed charger placement/maintenance. Furthermore, charger requirements are not accurately estimated due to neglected factors such as battery size or charging rate. In a different approach, Zhou et al. [9] modeled Bus Fleet Replacement (BFR) as an integer programming model, incorporating external costs and incentive impacts. Yet, it ignores existing bus network/operational elements (routes, fleet composition) and falls short of ensuring operational feasibility or accounting for electric utility constraints. Addressing some of these gaps, Hanna et al. [15] proposed a two-stage MINLP model specifically addressing utility constraints and optimizing annual bus/charger purchases. However, its complex and computationally intensive formulation limits scalability and practical use in large-scale networks. The model also does not account for environmental/social costs and government incentives. Moreover, while charger placement at depots/routes is addressed, a more efficient mechanism could involve placing chargers at terminals to improve utilization

and electrical grid capacity at each terminal. These three works reveal a consistent pattern whereby models that broaden financial scope thin out operational and grid detail, models that capture grid physics sacrifice scalability, and none derive charging needs from route-level energy demand. This is precisely the combination that this work targets.

To the authors' best knowledge, and based on a thorough review of the literature, no existing study simultaneously integrates all transition planning elements within a large-scale, strategic, long-term framework (as seen in Table 2). This work addresses these gaps with a scalable profit-maximization model that focuses exclusively on strategic transition planning issues, rather than operational-level decisions, thereby maintaining tractability and the long-term perspective. More specifically, the proposed framework is distinguished by three advances relative to prior work: (i) an endogenous demand-linked determination of charger number, type, and placement that replaces the fixed charger-to-bus ratios common in earlier studies; (ii) the explicit embedding of system-feasibility constraints, namely dwell time availability and grid-capacity limits; and (iii) a profit-maximization objective that internalizes fare revenue, government subsidies, and monetized environmental and social externalities. This claim is made to the best of our knowledge and on the basis of the reviewed literature rather than a systematic review. The strategic outputs of the model, namely fleet composition, charger numbers, types, and locations, and route-class assignments, are intended to serve as inputs to downstream tactical models (timetabling, vehicle blocking and rotation) and operational models (daily dispatch, real-time charge scheduling), where the aggregated route-assignment approximation is adequate at the long-term planning level.

3. Model Formulation

This section presents the MILP model seeking to optimize the EB transition plan for urban transit authorities as depicted in Figure 1. Consider a transition plan taking place over a planning horizon composed of $T = \{1, \dots, Tf\}$ years, and let $J = \{0, 1, \dots, Bj^b + 1\}$ represent all possible ages for a bus of type b . It is assumed that the transit authority makes replacement decisions at the beginning of each year, where age $j = 0$ corresponds to a new bus, and a bus of type b can operate until it reaches an age of $Bj^b + 1$, at which point it must be salvaged. In order to address technical and infrastructure requirements, we introduce sets for bus types B and charging technologies C . Bus types encompass various fuel technologies, models, configurations, and sizes. Let $EB \subseteq B$ denote the subset of EB types, with an example being EB 250 40, referring to a 40-foot electric bus with 250 kWh battery capacity. Charging technologies are primarily categorized into fast chargers $FC \subseteq C$, which are used in terminals and are associated only with fast-charging electric buses $FEB \subseteq B$, and depot chargers $DC \subseteq C$ that support all types of EBs.

To realistically capture the complexities of EB operations, the model includes route-bus assignment with compatibility constraints. These constraints account for factors such as distance, battery capacity, energy consumption, dwell time, and load requirements. As indicated by [13], using an aggregated approach to route assignment helps balance traceability and demand granularity. Let R denote the set of routes, where compatibility between routes and bus types is captured by a binary parameter x_{jtr}^b (1 if bus b of age j is eligible for route r in period t). Furthermore, suitable locations for charging infrastructure are identified by set L , which includes subsets $D \subseteq L$ for depots and $M \subseteq L$ for terminals. Building on the existing network, Lr_{lr} represents the route–location relationship parameter (1 if connected, 0 otherwise). Electric utility constraints are modeled by grid capacity limitations Lg_{ll} at every location. At the beginning of the planning horizon, the fleet consists of Bo_j^b buses of type b and age j , while the charging infrastructure comprises Co_l^c chargers of type c at location l .

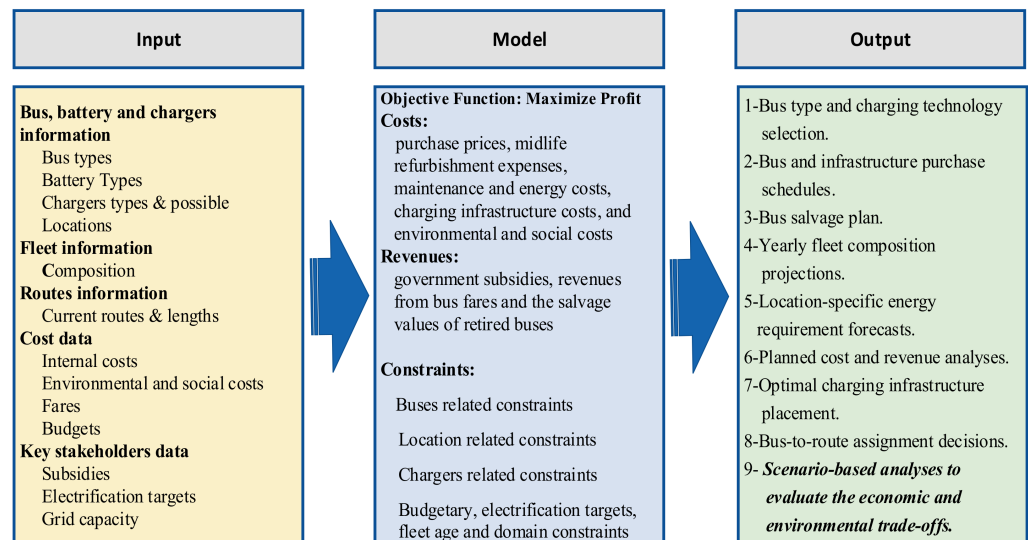


Figure 1. EB transition planning model.

Financial planning encompasses various costs and revenue calculations associated with replacement decisions. These costs cover bus purchases, midlife refurbishments (such as engine or battery replacements), operations (including maintenance and energy), and charger purchase and maintenance. Environmental and social costs are integrated based on the work of [9], capturing the negative externalities of diesel buses in terms of air pollution, noise, and climate change. These costs were estimated using established methodologies, including damage cost, avoidance cost, and replacement cost approaches, and are assigned to each bus type based on its fuel technology. The model also incorporates two government subsidies, including a one-time purchase subsidy, os^b , reducing initial bus purchase costs, and an annual operational subsidy as_j^b based on active buses of type b and age j . The annual budget b_t available for purchasing buses and charging infrastructure in period t may be increased by subsidies and salvage revenues. To account for the time value of money, let i be the periodic discount rate, and let $V = (1 + i)^{-1}$ be the corresponding one-period discount factor. All cash flows gradually incurred over the course of a period, such as bus fare revenues or maintenance and energy costs, are assumed to be made at the beginning of the period. Thus, an amount incurred in period t will be discounted by V^{t-1} .

On the revenue side, the salvage value sv_{jt}^b for retired buses of type b and age j in period t represents the monetary return, influenced by transit authority policy (sell, scrap, or donate). Research also indicates a higher customer willingness to pay for EBs, leading to the bus fare Rbf_r^b for route r when using bus type b as a significant revenue source. As the fleet transitions to more EBs, annual bus fare revenue is expected to rise, contingent on factors such as the number of trips, passenger capacity Bp^b and the route's average load factor RI_r .

As detailed below, eight sets of decision variables are used in the model, seven of which are integers, and one is continuous. These include the number of buses and chargers purchased, salvaged, available and assigned, as well as the allocation of buses to routes and locations. Given that routes connect two terminals, the model allows for flexibility in distributing the number of buses across these terminals, which then influences the number of fast chargers required for EBs. The continuous variable estimates total daily energy demand at each route–location pair, depending on factors such as route distance Rk_r , energy consumption EBx^b , and battery capacity EBc^b , which is then used to determine the required number of chargers. This approach directly addresses the shortcomings in existing studies that often rely on the oversimplified fixed charger-to-bus ratios.

A comprehensive list of all sets, parameters and decision variables used in the development of the mathematical model is included in Appendix A. The model's objective function and constraints are developed next.

Objective function:

The objective function maximizes the total discounted profit of the entire transition plan by incorporating all relevant revenues and costs. The overall structure builds on the formulation in [13] by including internal bus costs such as purchase prices, midlife refurbishment expenses, ongoing maintenance and energy costs, charging infrastructure costs covering charger purchase, installation, and maintenance, and the salvage values of retired buses. It is then extended by incorporating the one-time subsidy that reduces initial purchase costs, the annual subsidy based on the number of operational buses, and the environmental and social cost terms related to air pollution, noise, and climate change as presented in [9]. In addition to these elements, this work adds the revenue generated from bus fares to obtain the profit-based formulation. The profit objective is best interpreted not as commercial profit but as a net social benefit, or public-sector planning objective. Once fare revenue and monetized environmental and social externalities are internalized, it nets the agency's costs against user-borne fares and society-borne externalities, and it reduces to cost minimization when the revenue and externality terms are switched off, as in the base case. Profit maximization was adopted deliberately so that revenue-side levers, fare adjustments (Scenario 6) and subsidy design (Scenario 7) could be assessed, which a pure cost-minimization framework cannot capture.

$$\text{Maximize } \sum_{t \in T} V^{t-1} \left[\begin{array}{l} \sum_{b \in B} \left((os^b - Bc_t^b) P_t^b - \sum_{r \in R} \sum_{j=0}^{B_j^b} moc_{jtr}^b Z_{jtr}^b - mc_t^b A_{Jm^b t}^b \right) + \sum_{b \in B} \sum_{j=0}^{B_j^b} A_{jt}^b as_j^b \\ - \sum_{b \in B} \left(Cc^c W_t^c + \sum_{l \in L} Cm_{tl}^c CL_{tl}^c \right) \\ - \sum_{b \in B} \sum_{j=0}^{B_j^b} \sum_{r \in R} \left((ae^b + ce^b) Rd_r Z_{jtr}^b Bp^b Rl_r + ne^b Z_{jtr}^b Rd_r \right) \\ + \sum_{b \in B} \sum_{j=0}^{B_j^b} \sum_{r \in R} Z_{jtr}^b Ry_r 2Bp^b Rl_r Rb f_r^b + \sum_{b \in B} \sum_{j=1}^{B_j^b+1} sv_{jt}^b S_{jt}^b \end{array} \right]$$

Bus-related constraints:

The following constraints represent standard practice for fleet assignment, availability, and aging throughout the planning horizon, based on the approach in [13]. Constraint (1) ensures that the number of assigned buses matches the required amount over time. Constraint (2) stipulates that route assignments respect bus type and age compatibility, ensuring that only suitable buses operate on specific routes. Additionally, Constraint (3) states that all available buses of a given type and age during a specific period must be assigned to runs to prevent idle capacity. However, the model is flexible enough to accommodate overcapacity by adding dummy routes, ensuring there are sufficient spare buses available for emergencies or scheduled maintenance without incurring additional costs or generating revenue from them. Constraints (4) and (5) determine the availability of new buses of each type based on purchases made at the beginning of each period, including any already owned buses considered new for the first period. The model tracks fleet aging through Constraint (6), which updates the number of buses of each type and age annually, taking into account those that have been salvaged. Once buses reach the maximum age, Constraints (7) and (8) mandate that all buses, whether purchased or preowned, be automatically salvaged, and Constraint (9) ensures that the initial fleet

composition accounts for buses already owned minus those salvaged at the start of the planning horizon.

$$\sum_{b \in B} \sum_{j=0}^{Bj^b} Z_{jtr}^b = Rq_{tr} \quad \forall r \in R, t \in T \quad (1)$$

$$Z_{jtr}^b \leq x_{jtr}^b \cdot A_{jt}^b \quad \forall j \in Bj^b \setminus \{Bj^b + 1\}, r \in R, \\ t \in T, b \in B \quad (2)$$

$$\sum_{r \in R} Z_{jtr}^b = A_{jt}^b \quad \forall j \in Bj^b \setminus \{Bj^b + 1\}, \\ t \in T, b \in B \quad (3)$$

$$P_t^b = A_{0t}^b \quad \forall t \in T \setminus \{1\}, b \in B \quad (4)$$

$$P_1^b + Bo_0^b = A_{01}^b \quad \forall b \in B \quad (5)$$

$$A_{jt}^b = A_{j-1,t-1}^b - S_{jt}^b \quad \forall j \in Bj^b \setminus \{0, Bj^b + 1\}, \\ t \in T \setminus \{1\}, b \in B \quad (6)$$

$$S_{Bj^b+1,t}^b = A_{Bj^b,t-1}^b \quad \forall t \in T \setminus \{1\}, b \in B \quad (7)$$

$$S_{Bj^b+1,1}^b = Bo_{Bj^b+1}^b \quad \forall b \in B \quad (8)$$

$$A_{j1}^b = Bo_j^b - S_{j1}^b \quad \forall b \in B, j \in Bj^b \setminus \{0, Bj^b + 1\} \quad (9)$$

Location-related constraints:

To link buses to their respective locations and account for the resulting energy demand, this study introduces constraints that aggregate daily energy use at depots and terminals and ensure it stays within grid capacity limits. Constraints (10) and (11) assign buses to locations in each period by using Lr_{lr} , a binary parameter that establishes the link between routes and their corresponding locations. However, since routes connect two terminals, this may lead to a varying distribution of energy demands, resulting in different grid capacity and fast charger requirements. Consequently, for terminals specified in Constraint (11), the model manages the assignments to ensure maximum utilization and cost-effectiveness. Constraint (12) calculates each depot's total daily energy demand by combining the energy consumption of EBs that charge solely at the depot with the battery capacity of buses that utilize fast-charging at terminals and depot charging. Constraint (13) calculates each terminal's total daily energy demand by determining the energy consumption of EBs using terminal fast chargers, subtracting the battery capacity that has already been charged at the depot. Constraint (14) ensures that the total daily energy demand does not exceed grid capacity limits at each location.

$$LA_{trl}^b = \sum_{j=0}^{Bj^b} Z_{jtr}^b \quad \forall b \in EB, l \in D, r \in R | LR_{lr} = 1, t \in T \quad (10)$$

$$\sum_{l \in M | LR_{lr}=1} LA_{trl}^b = \sum_{j=0}^{Bj^b} Z_{jtr}^b \quad \forall b \in FEB, \\ l \in M, r \in R | LR_{lr} = 1, t \in T \quad (11)$$

$$LX_{trl} = \sum_{b \in EB | b \notin FEB} LA_{trl}^b \cdot Rk_r \cdot EBx^b + \sum_{b \in FEB} LA_{trl}^b \cdot EBC^b \\ \forall l \in D, r \in R | LR_{lr} = 1, t \in T \quad (12)$$

$$LX_{trl} = \sum_{b \in FEB} LA_{trl}^b \cdot (Rk_r \cdot EBx^b - EBC^b) \quad \forall l \in M, r \in R | LR_{lr} = 1, t \in T \tag{13}$$

$$\sum_{r \in R | LR_{lr}=1} LX_{trl} \leq Lg_{tl} \quad \forall l \in L, t \in T \tag{14}$$

Charger-related constraints:

To coordinate the allocation of chargers at depots and terminals and meet the corresponding energy requirements, this study introduces constraints that establish the number, type, and assignment of chargers over time. Constraints (15) and (16) ensure that the number and type of chargers at each location (depot chargers at depots and fast chargers at terminals) are sufficient to meet energy demands. This is based on their charging rate and the available charging time, which is constant at depots but differs at terminals due to factors such as the number of trips and the dwell time of each route. Contrary to the assumption that fleet growth always requires more fast chargers, Constraint (16) leverages a strategic trade-off, where increasing the number of EBs can reduce the demand on terminal fast chargers by shifting the required energy supplement to cheaper, more available overnight depot charging. Constraint (17) yields feasible fast terminal charging schedules by limiting bus assignment per charger. By calculating the ratio of required charging duration to available operational hours, it determines the minimum number of chargers needed to serve buses during their dwell time, which aligns charging duration with the operational hours of routes connected to that terminal within which charging can be scheduled. Constraints (18) and (19) track the number of EB chargers over time. Constraint (20) prevents the reassignment of chargers to different locations.

$$CL_{tl}^c \geq \sum_{r \in R | LR_{lr}=1} \frac{LX_{trl}}{Cr^c \cdot Dh} \quad \forall t \in T, l \in D, c \in DC \tag{15}$$

$$CL_{tl}^c \geq \sum_{r \in R | LR_{lr}=1} \frac{LX_{trl}}{Cr^c \cdot Rq_{lr} \cdot Ro_r \cdot Rwr_r} \quad \forall t \in T, l \in M, c \in FC \tag{16}$$

$$\sum_{c \in FC} CL_{tl}^c \geq \sum_{r \in R | LR_{lr}=1} \sum_{b \in FEB} \frac{LA_{trl}^b \cdot Ro_r \cdot Rwr_r}{Rhr_r} \quad \forall l \in M, t \in T \tag{17}$$

$$\sum_{l \in L} CL_{1l}^c = \sum_{l \in L} Co_l^c + W_1^c \quad \forall c \in C \tag{18}$$

$$\sum_{l \in L} CL_{tl}^c = \sum_{l \in L} CL_{t-1,l}^c + W_t^c \quad \forall c \in C, t \in T \setminus \{1\} \tag{19}$$

$$CL_{tl}^c \geq CL_{t-1,l}^c \quad \forall c \in C, l \in L, t \in T \setminus \{1\} \tag{20}$$

Budgetary, electrification targets, fleet age and domain constraints:

Constraint (21) ensures that the electrification targets are satisfied. The model assumes that the targets dictate a minimum percentage of buses that should be electric each year. Constraint (22) states that the total purchasing funds available at the beginning of a period are the sum of the budget and salvage revenues from that period, along with any one-time subsidies and annual subsidies. Constraint (23) prevents the excessive accumulation of aging buses by setting a maximum allowable average bus age in the final period Tf. This ensures long-term fleet renewal and sustainability, while also mitigating the end-of-horizon effect, where the model assumes operations will cease at the final period and make decisions without considering any future operations. Finally, Constraints (24)–(30) define the non-

negativity and integrality restrictions on the respective decision variables. In practice, this end-of-horizon effect is further mitigated by re-solving the model on a rolling-horizon basis, whereby the average age constraint acts as a terminal condition, and each re-optimization captures updated parameter values and any change in fleet requirements.

$$\sum_{b \in EB} \sum_{j=0}^{B_j^b} A_{jt}^b \geq e_t \cdot \sum_{b \in B} \sum_{j=0}^{B_j^b} A_{jt}^b \quad \forall t \in T \quad (21)$$

$$\sum_{b \in B} \left((Bc_t^b - os^b) \cdot P_t^b - \sum_{j=1}^{B_j^{b+1}} sv_{jt}^b \cdot S_{jt}^b \right) + \sum_{c \in C} Cc^c \cdot W_t^c - \sum_{b \in B} \sum_{j=0}^{B_j^b} A_{jt}^b \cdot as_j^b \leq b_t \quad \forall t \in T \quad (22)$$

$$\sum_{b \in B} \sum_{j=0}^{B_j^b} j \cdot A_{jTf}^b \leq Ja \cdot \sum_{b \in B} \sum_{j=0}^{B_j^b} A_{jTf}^b \quad (23)$$

$$P_t^b \in \mathbb{Z}^+ \quad \forall t \in T, b \in B \quad (24)$$

$$W_t^c \in \mathbb{Z}^+ \quad \forall c \in C, t \in T \quad (25)$$

$$S_{jt}^b, A_{jt}^b \in \mathbb{Z}^+ \quad \forall j \in B_j^b \setminus \{B_j^b + 1\}, t \in T, b \in B \quad (26)$$

$$Z_{jtr}^b \in \mathbb{Z}^+ \quad \forall j \in B_j^b \setminus \{B_j^b + 1\}, r \in R, t \in T, b \in B \quad (27)$$

$$LA_{trl}^b \in \mathbb{Z}^+ \quad \forall l \text{ in } L, r \in R, t \in T, b \in B \quad (28)$$

$$LX_{trl} \geq 0 \quad \forall l \text{ in } L, r \in R, t \in T \quad (29)$$

$$CL_{tl}^c \in \mathbb{Z}^+ \quad \forall l \text{ in } L, c \in C, t \in T \quad (30)$$

4. Case Study

To assess the performance and applicability of the proposed MILP model, a comprehensive experimental environment is configured, carefully sourcing and processing data to reflect real-world operations in Dubai's bus network. The practical data, including route specifications, were obtained from Dubai's official RTA sources. Additional parameters such as maintenance and energy costs were acquired from relevant studies in the literature (as detailed below). The MILP model for the base case and for the different variants of input parameters was solved to optimality via the CPLEX optimizer within reasonable computational time (as seen below) using commercial hardware (Intel Core i7-11800H processor, 16GB RAM). The use of Microsoft Excel facilitated the input and output data management, alongside the organization and analysis of scenario results. The base-case model comprises 286,681 decision variables and 294,760 constraints, and solution times are reported per scenario in the corresponding results tables.

The study adopted a 25-year planning horizon (2026–2050) in alignment with pre-determined electrification targets [4]. While emphasizing the importance of long-term planning, we also recognize the need for accurate and up-to-date data inputs, especially given the rapid advancements in EB technology. Therefore, to maintain the model's relevance and effectiveness, it should be solved periodically whenever changes occur. The case study is bounded to 71 of the 77 RTA lines, a fixed 406-bus fleet, year-round operation, and a 10 min dwell assumption. When the model is re-solved periodically, an agency would refresh the timetables and route distances, load factors, grid-capacity limits, the battery-cost trajectory, energy and diesel prices, and the fare-response parameters. For reproducibility, the optimization model implementation (solved with CPLEX), the full input dataset, and the route-vehicle compatibility matrices are made available at

<https://doi.org/10.5281/zenodo.20598731>. An explanation of the acquired data for the base-case scenario is provided next.

Network and Route Data: The obtained data comprises detailed schedule and routing information for 71 of the RTA's 77 urban bus lines directly from the Dubai RTA's online timetable portal [35]. Six low-volume or data-incomplete routes were consolidated to avoid distortions in demand estimation. For each route, we extracted the number of daily departures, average trip frequency, average trip duration, first-and-last service times, with the difference indicating operational hours (Rh_r), and nominal trip lengths. Geographic distances between stops were computed via a GIS tool, enabling precise calculation of per-trip energy requirements. Depot charging windows (i.e., the time during which buses are idle and available for charging) were inferred from non-operational hours, as reported in RTA depot operational manuals. Using this data, the number of required buses per route, Rq_{tr} , was calculated using the formula $Rq_{tr} = \left\lceil \frac{Duration + dwell\ time}{frequency} \right\rceil$, where $\lceil x \rceil$ indicates the smallest integer greater than or equal to x . We assumed that the dwell time is 10 min, which is sufficient for passengers to board and alight the bus. Consequently, we derived the daily and annual number of trips per bus (Ro_r and Ry_r), as well as the daily and annual distance traveled per bus (Rk_r and Rd_r), assuming year-round operation. Different bus fares (Rbf_r^b) were allocated for each route, with longer routes assigned higher fares [36]. Typically, higher-passenger-capacity buses are designated for routes with fewer stops, resulting in higher speeds. For bus size distribution, sources indicate allocations of 64% for standard models, 24% for articulated, and 12% for double-decker buses [37].

Fleet and Vehicle Characteristics: The existing fleet consists of 406 Diesel buses with ages following a normal distribution, having a mean of 7 years and a standard deviation of 2 years, with zero EBs or charging installations initially deployed. Ten candidate vehicle configurations were selected, three diesel and seven electric variants, based on a combination of published technical specifications such as [38] and manufacturer data [39]. Electric variants differ by battery capacity (ranging from 250 kWh to 650 kWh), on-route charging capability (depot-only vs. depot + terminal fast-charging), and vehicle length. Compatibility matrices were constructed to ensure that each bus type could satisfy the minimal range requirements of every route under both peak and off-peak load factors. The fleet size is kept constant at 406 throughout the planning horizon. The specific bus types considered in this analysis include 40 ft standard and double-decker buses and 60 ft articulated diesel buses with specifications as indicated in Table 3. The specifications of the EBs are summarized in Table 4.

Table 3. Diesel bus (DB) data.

EB Type	Bus Cost (Million AED)	Passenger Capacity	Energy Consumption (Liter/km)
40 DB Standard	1.643	42	0.48
60 DB Articulated	2.665	55	0.67
40 DB Double-Decker	2.373	70	0.67

This constant fleet assumption is justified on two grounds. First, UAE's population is roughly 10% nationals and 90% expatriates, and projected growth is concentrated in the national segment, whose public bus ridership is extremely low or nonexistent, rendering the ridership base served by the network relatively stable over the planning horizon. Second, as noted above, the model is intended to be re-solved on a rolling-horizon basis, allowing demand drift and any fleet-size adjustment to be absorbed at each re-optimization, whereas the explicit modeling of demand growth is left to future work.

Table 4. Electric bus (EB) data.

EB Type	Bus Cost	Battery Cost	Passenger Capacity	Charging Mode	Energy Consumption (kWh/km)
40 EB 250 *	2.446	0.195	42	Depot only	1.24
40 EB 350	2.446	0.273	42	Depot only	1.3
60 EB 650	4.471	0.508	55	Depot only	1.85
40 EB DD 650	3.285	0.508	70	Depot only	2.2
40 EB 250 FC	2.446	0.195	42	Depot + fast at terminals	1.24
60 EB 550 FC	4.471	0.43	55	Depot + fast at terminals	1.67
40 EB DD 550 FC	3.285	0.43	70	Depot + fast at terminals	1.9

* 40 EB 250 means 40 ft EB with 250 kWh battery; DD: double-decker; FC: fast-charging, costs in million AED.

The bus specifications detailed in Tables 3 and 4 were gathered from various reliable sources. We based our figures on the recent work of [9], which referenced median prices reported by [38]. For EBs, costs are divided into battery and vehicle costs. Diesel bus and vehicle costs are assumed to remain constant throughout the planning period. However, Battery cost is projected to decline annually by 9%, driven by ongoing technological advancements. This decline begins with a baseline cost of 858 AED per kWh in year 0 (initial year), reflective of the 2017 figure of 1825 AED per kWh reported by [40] and adjusted according to market projections from [41]. Bus passenger capacity was obtained from [39], with EB energy consumption figures. For diesel buses, fuel consumption data was sourced from [42] for standard buses and from [38] for both articulated and double-decker buses. It is noted that the assumed lifetime for diesel buses is 15 years [41], while EBs are estimated to have a lifetime of 12 years [18], reflecting the shorter battery life compared to diesel engines.

Environmental and social cost, subsidies, bus fare and load factor: The environmental and social costs for air pollution, noise, and climate change by bus type are presented in Table 5, with values sourced from [9], who cited [43]. These costs reflect only the operational externalities and exclude life-cycle emissions associated with electricity generation for EBs or the production and disposal of the buses themselves. To establish a baseline, these costs were set to zero in the base-case scenario. Since the average load factor influences passenger demand, fare revenue, and related environmental and social costs, we calculated it to be 0.727. This value was based on the RTA's reported 2023 ridership of 173.5 million passengers [44] and the assumption that the selected routes in this study, representing 40% of the total, also constitute 40% of the demand. Although the load factor, along with subsidies, fares, and environmental and social costs, does not affect the base-case scenario, their individual impacts are evaluated in later scenarios. The environmental and social cost values are adopted from [9], which draws on the European Commission external-cost handbook [43], and are assigned by fuel technology. Therefore, their transferability to the UAE is approximate since the local grid mix, climate-driven health burden, and valuation parameters may shift the magnitudes. Consistent with [9], these values capture operational (tailpipe and noise) externalities only and exclude upstream electricity generation emissions for EBs as well as battery production and disposal. Note that this treatment biases the comparison modestly in favor of EBs, and a more carbon-intensive grid would narrow but not reverse the gap. The load factor of 0.727 is a system average estimate derived from

2023 ridership under a proportional demand assumption where route-level load factors vary around this value and constitute a further source of uncertainty examined in the sensitivity analysis section.

Table 5. Environmental and social costs by bus type.

Bus type	Air Pollution Cost (AED per pax km)	Noise Cost (AED per Vehicle km)	Climate Change Cost (AED per pax km)
40 DB	0.00584	0.100813	0.02482
60 DB	0.004015	0.100813	0.028105
40 DB DD	0.004015	0.100813	0.028105
40 EB 250	0.00219	0.065168	0
40 EB 350	0.00219	0.065168	0
60 EB 650	0.00146	0.065168	0
40 EB DD 650	0.00146	0.065168	0
40 EB 250 FC	0.00219	0.065168	0
60 EB 550 FC	0.00146	0.065168	0
40 EB DD 550 FC	0.00146	0.065168	0

Charger-related information: Two charger types are considered: a 100 kW depot charger (292,000 AED) and a 250 kW terminal fast charger (548,000 AED) [41], with maintenance costs set at 1% of the purchase cost [18].

Maintenance and energy cost: Building upon the methodology of [13], total energy and maintenance costs for each bus type and age over the planning horizon were calculated based on the approximate annual distance of each route. For 60 ft diesel buses, maintenance costs were derived from a regression analysis using real transit agency data [33], which modeled maintenance cost per mile as a function of vehicle age. Maintenance costs were assumed to be consistent across different bus sizes of the same type. For EBs, ref. [45] estimated maintenance costs to be 20% to 60% lower than those of diesel buses. In this study, a midway value of 40% reduction in EB maintenance costs is adopted. Energy costs were calculated by multiplying the fuel or energy consumption of diesel and EBs by the route's annual distance, using diesel and electricity prices of 2.77 AED per liter [46] and 0.38 AED per kWh [47], respectively. This facilitated the estimation of energy cost per unit distance for each bus type.

Electrification targets and discount rate: The electrification targets were established in accordance with the RTA's strategic plan [4], outlining the following progression: 10% electrification by 2030, 20% by 2035, 40% by 2040, 80% by 2045, and 100% by 2050. However, due to the identified incompatibility of certain routes with all considered EB types, the base-case scenario was adjusted to achieve 90% electrification by 2050. This adjustment reflects realistic operational constraints and will be further evaluated and refined in subsequent scenario analyses. Furthermore, a yearly discount rate of 3.4% accounts for the time value of money, reflecting regional economic considerations within the UAE [48].

5. Results and Scenario Analysis

In this section, we present and discuss the outcomes of the optimization model under seven distinct scenarios. The purpose is to identify the impact of key parameters, such as technology choice, policy constraints, operational parameters and economic incentives, on the electrification timing, fleet composition, and total cost over the 25-year horizon. Table 6

below provides an overview of all seven scenarios and two sensitivity analyses, listing the key assumptions changed, the electrification year reached, the total discounted cost or profit, and the main fleet and charger takeaways.

Table 6. Summary of the scenario analysis.

Scenario/Sensitivity Analysis	Key Assumption Changed	Electrification Reached	Total Discounted Cost/Profit (Billion AED)	Main Fleet & Charger Takeaways
Scenario 1: Base case	Relaxed 90% target by 2050 (double-decker routes incompatible with available EBs); subsidies and externalities neutralized; unbound budget and grid constraints.	50% by 2032; 90% by 2050 (100% not reached).	Total cost 3.388; objective (profit) 3.33.	Fast-charging EBs preferred for long-range routes; depot-only EBs adopted after 2038 as battery costs fall; diesel buses are isolated to low-mileage routes to shield the operator from high operational costs; charger-to-bus ratios \approx 1:2.2 (depot) and 1:9.3 (terminal); chargers \approx 4% of bus purchase cost.
Scenario 2: Dwell-time extremes	Depot/terminal dwell time set to minimum and maximum extremes.	Minimum dwell achieves full (100%) electrification; selected as the baseline for Scenarios 3–7.	Min dwell: Total cost 3.33, objective 3.409. Max dwell: 3.339/3.40.	Longer operational dwell times allow terminal-charged EBs to draw power over extended windows, making 100% electrification operationally viable; shorter dwell needs 16 fewer fast chargers (–10% charger cost); highlights the role of operational scheduling in charger utilization.
Scenario 3: Pure EB fleet	100% EB purchases from year 1; diesel replacement removed.	Full electrification by 2040 (about a decade earlier than the base case).	Objective \approx 3.401 (–8M AED or –0.24% vs min-dwell baseline).	All-electric procurement is economically feasible given robust charging and falling battery costs, even without subsidies or fare increases; diesel buses retired slightly faster (avg. salvage age 12.93 \rightarrow 12.83 yr).
Scenario 4: Restricted transition plan	RTA interim milestones enforced (10%, 20%, 40%, 80%, 100% by 2030, 2035, 2040, 2045, 2050) to reflect budget and grid limits.	Follows the mandated schedule; up to \approx 60% slower than the unrestricted path in 2036.	Total cost 3.431 vs 3.330 unrestricted (+100M AED, \approx 3%).	Phased out one bus size at a time (double-decker EBs first, standard after 2030, articulated after 2040); 350 kWh battery favored over 250 kWh; fast-charging preference persists.
Scenario 5: Environmental & social costs	Monetized air pollution, noise, and climate externalities (Table 5) added to the objective.	Adoption accelerated by \approx 30% from the start of the horizon.	\approx 50M AED direct cost over the horizon; externalities \approx 5% of total cost.	A small share of total cost but a substantial shift toward earlier EB adoption; improves passenger comfort and community welfare.
Scenario 6: Bus fare increase	5–20% fare uplift applied only to EB-served routes (base fares 3–7.5 AED); ridership held fixed.	20% uplift \rightarrow \approx 60% electrification in year 1 (vs after 2040 under the RTA plan).	Discounted profit rises with each 5% step (revenue-positive).	Fare differentiation is a powerful, internally funded lever for accelerating adoption of cleaner buses.
Scenario 7: Subsidy mechanisms	One-time subsidies; 0–30% of purchase price; an NPV-matched annual subsidy; and a declining-block subsidy (50% in 2026 \rightarrow 10% by 2050, \approx 30% average).	Declining block \rightarrow 50% higher electrification rate in 2026, 35% in 2030, and 15% in 2035 compared to other subsidy types; all policies exhibit minimal impact after 2040.	Objective from 3.409 (no subsidy) to 4.109 (annual 50–10%); declining block +151M AED vs uniform 30% one-time.	Front-loaded subsidies cut net authority expenditure and raise profit; subsidy influence fades after 2040 as battery costs decline.

Table 6. *Cont.*

Scenario/Sensitivity Analysis	Key Assumption Changed	Electrification Reached	Total Discounted Cost/Profit (Billion AED)	Main Fleet & Charger Takeaways
Sensitivity 1: Battery Cost Decline	Annual battery cost decline tested at 3%, 6%, 12%, and 15% variants (min-dwell baseline remains 9%).	100% by 2050 for all decline variants; 3% trace lags by up to 10% in the mid-2030s; 12% and 15% trajectories closely overlap the 9% baseline curve.	For 3%, 6%, 9%, 12%, 15% decline: cost/obj = 3.456/3.28, 3.378/3.36, 3.330/3.409, 3.303/3.43, 3.285/3.45, respectively.	Total system cost drops by 171M AED as decline rate accelerates from 3% to 15%; 12% and 15% traces show diminishing returns on adoption pacing, proving fleet deployment becomes capped by vehicle lifespans rather than battery asset premiums once decline exceeds 9% annually.
Sensitivity 2: Load factor	Baseline load factor (0.727) varied by ±15% and ±30% boundaries (0.509 to 0.945).	100% by 2050; trajectories are entirely identical across all five demand variations.	1.388 at 0.509 up to 5.43 at 0.945 (Total cost remains identical across all variants).	Demonstrates absolute plan robustness where physical fleet rollout and charger infrastructure are entirely invariant to demand volatility. The fuel and maintenance advantages of EBs safely insulate the transition plan from ridership risk, meaning changes in load factor only affect profit linearly.

5.1. Scenario 1: Base Case

In the base-case scenario, we employ the acquired values for all input parameters and impose the relaxed 90% electrification target by 2050 to reflect real-world route compatibility constraints. Under these assumptions, the model gradually replaces diesel buses with EBs, achieving 50% electrification by 2032 and the 90% milestone in 2050. Table 7 presents the 25-year bus purchase plan, while Table 8 outlines the categorized costs, objective function value, and solution time.

Table 7. Base-case scenario purchase plan.

Year	40 DB	60 DB	40 DB DD	40 EB 250	40 EB 350	60 EB 650	40 EB DD 650	40 EB 250 FC	60 EB 550 FC	40 EB DD 550 FC
2026	0	0	0	0	0	0	0	27	3	11
2027	0	0	0	0	0	0	0	28	5	3
2028	0	0	2	0	0	0	0	25	10	0
2029	0	0	1	0	0	0	0	12	12	1
2030	0	0	2	0	0	0	0	17	5	1
2031	6	0	5	0	0	0	0	25	14	1
2032	3	0	6	0	0	0	0	19	9	0
2033	3	0	3	0	0	0	0	17	5	0
2034	12	0	5	0	0	0	0	11	2	0
2035	2	0	3	0	0	0	0	13	0	0

Table 7. Cont.

Year	40 DB	60 DB	40 DB DD	40 EB 250	40 EB 350	60 EB 650	40 EB DD 650	40 EB 250 FC	60 EB 550 FC	40 EB DD 550 FC
2036	3	0	0	0	0	0	0	11	0	0
2037	0	8	7	0	0	0	0	8	0	0
2038	0	0	0	13	0	1	1	4	6	3
2039	0	0	1	7	0	1	0	27	3	11
2040	0	0	0	2	4	0	0	24	5	3
2041	0	0	0	1	2	0	0	23	10	0
2042	0	0	2	0	0	0	0	12	12	1
2043	0	0	3	0	0	0	0	17	5	1
2044	0	0	4	0	0	0	0	25	14	1
2045	0	0	7	0	0	0	0	19	9	0
2046	0	0	5	0	0	0	0	17	5	0
2047	0	0	3	0	0	0	0	17	2	0
2048	0	0	0	3	0	0	0	13	0	0
2049	0	0	0	3	0	0	0	11	0	0
2050	0	0	0	17	0	0	3	8	0	0

Table 8. Base-case scenario model's output.

Category	Value
Bus purchase cost (billion AED)	1.578
Bus maintenance cost (billion AED)	1.014
Bus Energy cost (billion AED)	0.731
Charger purchase and maintenance cost (billion AED)	0.065
Total cost (billion AED)	3.388
Objective function (billion AED)	3.33
Solution time (s)	348

The optimization results consistently favored EBs with fast terminal chargers (FCs), primarily due to their extended range compared to depot-only charging EBs. However, depot-only charging EBs were increasingly selected after 2038, when most of the existing fleet is salvaged and battery costs decline, improving their economic viability relative to diesel buses. EBs demonstrated a significant advantage in maintenance and energy costs, which together exceeded the total bus purchase cost, leading to diesel buses being assigned to routes with lower annual distance. Additionally, the plan includes diesel double-decker buses due to route incompatibilities identified in the base-case scenario. While other bus types appear in smaller quantities, the inclusion of a diverse fleet supports cost optimization efforts. The purchase and maintenance costs of the charging infrastructure accounted for only 4% of the total bus purchase cost. This balanced transition path demonstrates viability under moderate policy targets and realistic cost trajectories. Table 9 depicts the optimal fleet configuration, while Table 10 displays the number of chargers and buses assigned to the top five locations, including the central depot and four terminals.

Table 9. EB base-case scenario fleet configuration.

Year	40 DB	60 DB	40 EB DD	40 EB 250	40 EB 350	60 EB 650	40 EB DD 650	40 EB 250 FC	60 EB 550 FC	40 EB DD 550 FC
2026	242	78	45	0	0	0	0	27	3	11
2027	214	73	42	0	0	0	0	55	8	14
2028	189	63	42	0	0	0	0	80	18	14
2029	177	51	41	0	0	0	0	92	30	15
2030	160	46	40	0	0	0	0	109	35	16
2031	135	32	39	0	0	0	0	134	49	17
2032	116	23	39	0	0	0	0	153	58	17
2033	99	18	39	0	0	0	0	170	63	17
2034	88	16	39	0	0	0	0	181	65	17
2035	75	16	39	0	0	0	0	194	65	17
2036	64	16	39	0	0	0	0	205	65	17
2037	56	16	39	0	0	0	0	213	65	17
2038	39	9	35	13	0	1	1	217	71	20
2039	32	8	35	20	0	2	1	217	71	20
2040	30	8	35	22	4	2	1	213	71	20
2041	29	8	35	23	6	2	1	211	71	20
2042	29	8	35	23	6	2	1	211	71	20
2043	29	8	35	23	6	2	1	211	71	20
2044	29	8	35	23	6	2	1	211	71	20
2045	29	8	35	23	6	2	1	211	71	20
2046	29	8	35	23	6	2	1	211	71	20
2047	23	8	35	23	6	2	1	217	71	20
2048	20	8	35	26	6	2	1	217	71	20
2049	17	8	35	29	6	2	1	217	71	20
2050	0	8	32	46	6	2	4	217	71	20

Table 10. Base-case scenario: charger and bus counts at the top 5 locations

Location	Bus Count	Charger Count
Central Depot	366	166
Al Ghubaiba Bus Stn	55	3
Gold Souq Bus Stn	23	2
Al Rashidiya Bus Stn	17	2
Oud Metha Bus Stn	22	2

It is noted that range compatibility played a crucial role in the selection of EBs. For instance, 40 EB 250 FC buses were compatible with all 40 standard routes, whereas 40 EB DD 650 buses could only serve one route, underscoring the limitations of certain configurations, particularly for double-decker EBs, which remained mostly diesel throughout the transition. Cost was another key factor, where although 40 EB 350 buses were compatible with more

routes than 40 EB 250 buses, their higher battery prices made them less favorable. Fast-charging at terminals improved range feasibility and reduced costs through shared charger use, with average charger-to-bus ratios of 1 to 2.2 at depots and 1 to 9.3 at terminals. High-traffic locations such as Al Ghubaiba and Gold Souq bus stations further enhanced operational efficiency, although they present a scheduling challenge for operators who must coordinate dwell times to ensure timely and adequate charging.

5.2. Scenario 2: Dwell Time Extremes

To assess the sensitivity of charger utilization, we examine two extreme dwell time scenarios at depots and terminals. Dwell time directly influences the number of buses and chargers required. Longer dwell times can increase the number of buses needed to maintain route frequency but also provide more charging time for terminal-charged EBs, which can reduce the overall fleet size. As shown in Table 11, the minimum dwell time scenario reduced charger purchase and maintenance costs by 10% due to 16 fewer fast chargers made possible by shorter charging times. Compared to the base-case scenario, which resulted in higher total costs and incomplete electrification, the minimum dwell time scenario achieves full electrification and attractive financial performance, making it the selected baseline for further analysis. Moreover, the findings highlight the critical role of operational scheduling in maximizing infrastructure efficiency and demonstrate that the long-term total cost of ownership for EBs remains lower than that of diesel alternatives.

Table 11. Dwell time extremes scenario model's output.

Category	Base Case	Max Dwell	Min Dwell
Bus purchase cost (billion AED)	1.578	1.694	1.699
Bus maintenance cost (billion AED)	1.014	0.935	0.933
Bus Energy cost (billion AED)	0.731	0.623	0.619
Charger purchase and maintenance cost (billion AED)	0.065	0.087	0.079
Total cost (billion AED)	3.388	3.339	3.330
Objective function (billion AED)	3.33	3.40	3.409
Solution time (s)	348	2008	958

5.3. Scenario 3: Pure Eb Fleet

The Pure EB fleet scenario enforces 100% EB acquisitions from year 1 onward, removing replacement with diesel options entirely. Figure 2 illustrates that although adoption begins gradually, the transition accelerates after five years and achieves full electrification by 2040.

This aggressive mandate accelerates full electrification by 2040, ten years earlier than in the base case. Despite the accelerated timeline, total discounted profit declines by 8 million AED (representing a mere 0.24% reduction). The outcome associated with retiring diesel buses more quickly reduces the average salvage age from 12.93 to 12.83 years for standard diesel buses. While the solution increases early-period purchases, it yields long-term savings through reduced fuel and maintenance costs. This scenario underscores the economic feasibility of an all-electric procurement policy when supported by robust

charging infrastructure and favorable battery cost figures, even without subsidies and fare increases. The costs are shown in Table 12.

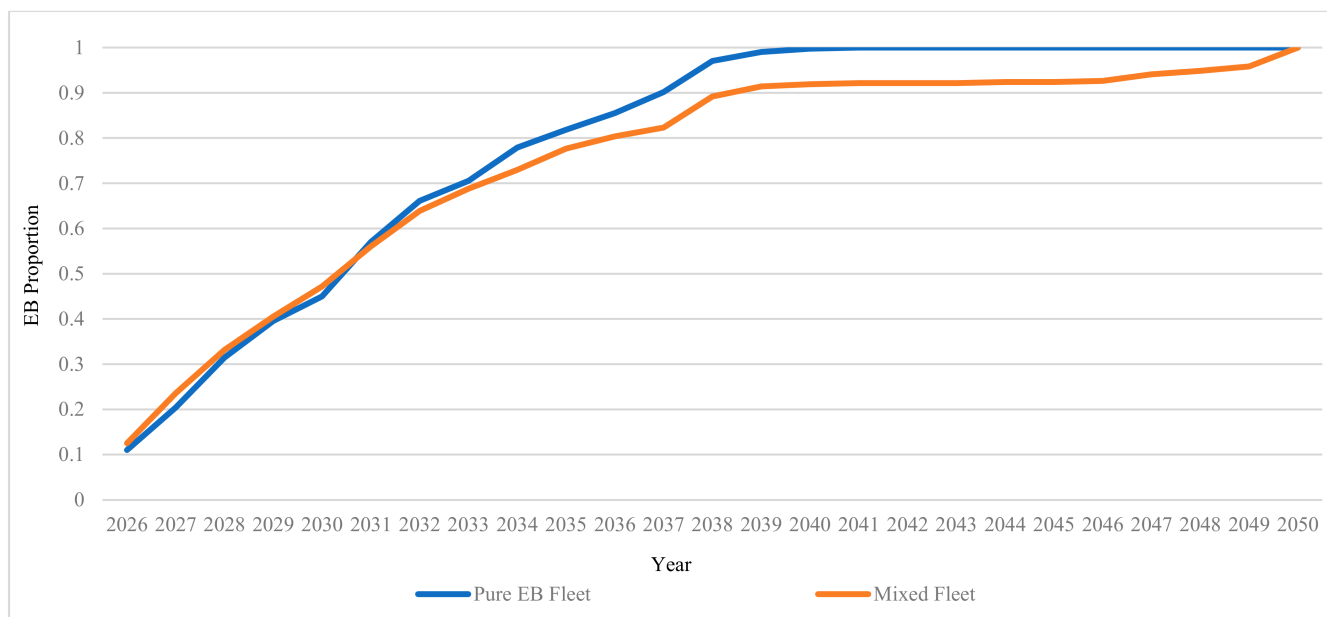


Figure 2. Pure EB fleet scenario electrification rate.

Table 12. Scenario 3 results.

Category *	Pure EB Fleet	Mixed Fleet
Bus purchase cost	1715	1699
Bus maintenance cost	931	933
Bus energy cost	612	619
Charger purchase and maintenance cost	80	79
Total cost	3338	3330
Solution time (s)	369	958

* All costs are in million AED.

5.4. Scenario 4: Restricted Transition Plan

While previous scenarios presented optimal transition plans under specific conditions, they did not consider budget and electrical grid capacity limitations. These constraints can restrict operator purchasing power and charger installation and slow down electrification. Therefore, assuming that the RTA's electrification targets account for such limitations, we enforced these targets within the model, ensuring they were not achieved before their designated dates. The impact of the enforced targets is clearly visible in Figure 3, where the resulting electrification rates differ substantially from the unrestricted scenario, demonstrating a maximal deviation of nearly 60% in the year 2036. The fleet configuration in Table 13 reveals that the adoption rate of double-decker EBs is highest in the initial periods, followed by a surge in standard EBs after 2030, with articulated EBs being introduced last, after 2040. This phased approach aligns with realistic operational strategies, allowing operators to focus on one bus size at a time and incrementally adjust tactical and operational planning. Interestingly, the 350 kWh battery EB seems to be favored over the 250 kWh model, which contrasts with the findings from the base-case scenario in Table 7. This indicates that the choice of battery capacities in EBs can vary, and there is no universal capacity that fits all

needs. However, it is evident that the preference for fast-charging EBs remains consistent across scenarios. Table 14 shows an additional cost of 100 million AED for the scenario with a restricted plan. Operators need to consider this difference and may want to allocate more budget or expedite electrical grid development to facilitate faster EB adoption and mitigate these financial effects. In policy terms, this roughly 100 million AED premium (about 3% of total costs) is the budgetary cost of rigid and date-specific milestones as compared to letting the model choose the timing. Policymakers should therefore either build flexibility into milestone dates or pre-allocate additional budget and accelerate grid development in order to avoid it.

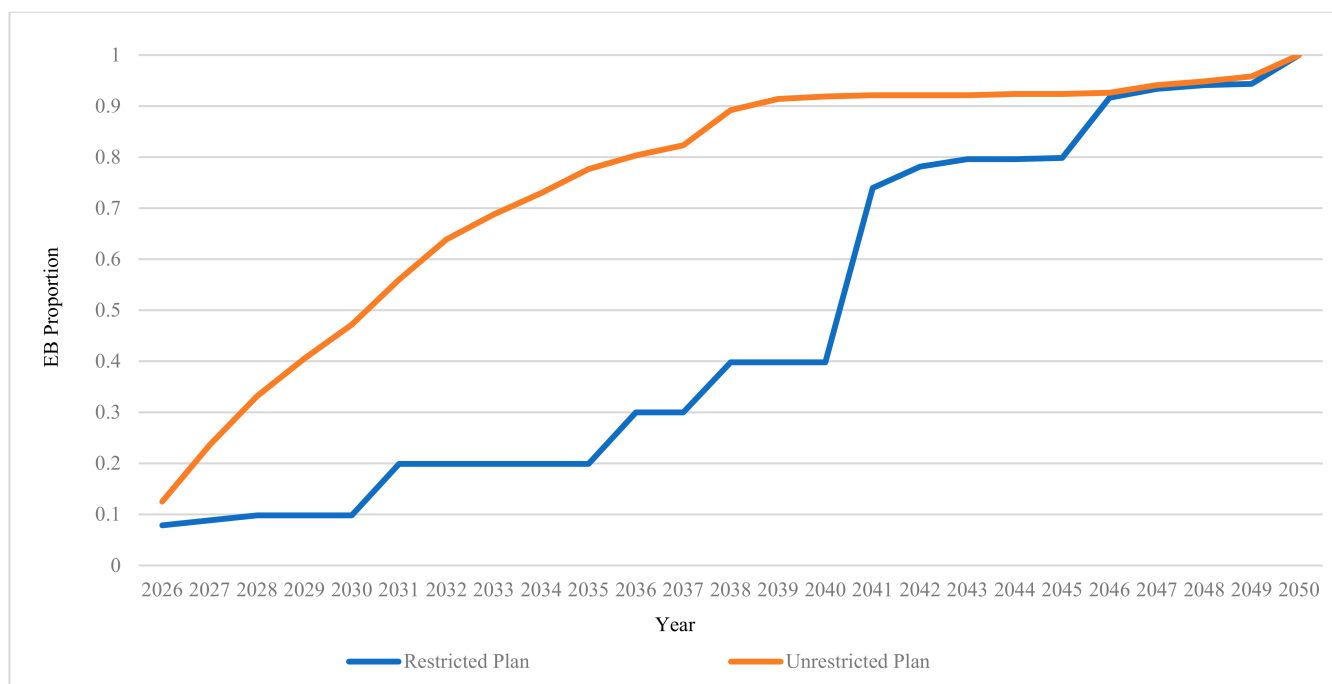


Figure 3. Restricted plan scenario electrification rate.

Table 13. Restricted plan scenario fleet configuration.

Year	40 DB	60 DB	40 DB DD	40 EB 250	40 EB 350	60 EB 650	40 EB DD 650	40 EB 250 FC	60 EB 550 FC	40 EB DD 550 FC
2026	261	81	33	0	0	0	0	8	0	24
2027	261	81	29	0	0	0	0	8	0	28
2028	261	81	25	0	0	0	0	8	0	32
2029	261	81	25	0	0	0	0	8	0	32
2030	261	81	25	0	0	0	0	8	0	32
2031	235	81	10	0	0	0	0	34	0	47
2032	235	81	10	0	0	0	0	34	0	47
2033	235	81	10	0	0	0	0	34	0	47
2034	235	81	10	0	0	0	0	34	0	47
2035	235	81	10	0	0	0	0	34	0	47

Table 13. Cont.

Year	40 DB	60 DB	40 EB DD	40 EB 250	40 EB 350	60 EB 650	40 EB DD 650	40 EB 250 FC	60 EB 550 FC	40 EB DD 550 FC
2036	195	81	9	0	0	0	0	74	0	48
2037	195	81	9	0	0	0	0	74	0	48
2038	169	72	4	0	0	0	0	100	9	53
2039	169	72	4	0	0	0	0	100	9	53
2040	169	72	4	0	0	0	0	100	9	53
2041	87	15	4	0	28	7	0	154	59	53
2042	74	11	4	0	28	7	0	167	63	53
2043	72	7	4	0	28	7	0	169	67	53
2044	72	7	4	0	28	7	0	169	67	53
2045	71	7	4	0	28	7	0	170	67	53
2046	33	1	0	0	28	9	4	208	71	53
2047	27	0	0	0	28	10	4	214	71	53
2048	24	0	0	0	28	10	4	217	71	53
2049	23	0	0	1	28	10	4	217	71	53
2050	0	0	0	24	28	10	4	217	71	53

Table 14. Restricted plan scenario model's output.

Category	Restricted Plan	Unrestricted Plan
Bus purchase cost (billion AED)	1.428	1.699
Bus maintenance cost (billion AED)	1.088	0.933
Bus Energy cost (billion AED)	0.852	0.619
Charger purchase and maintenance cost (billion AED)	0.063	0.079
Total cost (billion AED)	3.431	3.330
Solution time (s)	1130	958

5.5. Scenario 5: Environmental and Social Costs

In this scenario, we introduce monetized environmental and social externalities (e.g., emissions, noise) into the objective function using values from Table 5. As shown in Figure 4, the inclusion of these costs accelerates EB adoption by 30% from the start of the planning horizon, increasing EB numbers to reduce environmental impacts and improve passenger comfort and community well-being. Figure 5 depicts the breakdown of the total cost with and without environmental and social costs. Contrary to expectations of significantly higher costs, Table 15 shows only a 50 million AED increase in the total cost over the planning horizon. Additionally, the earlier retirement of diesel buses could have generated higher salvage revenues, though this was not included in the analysis. The table also illustrates that environmental and social costs (external costs) account for just 6% of the total costs, yet their inclusion substantially influences fleet decisions, highlighting their crucial role in fostering cost-effective and welfare-enhancing transition plans.

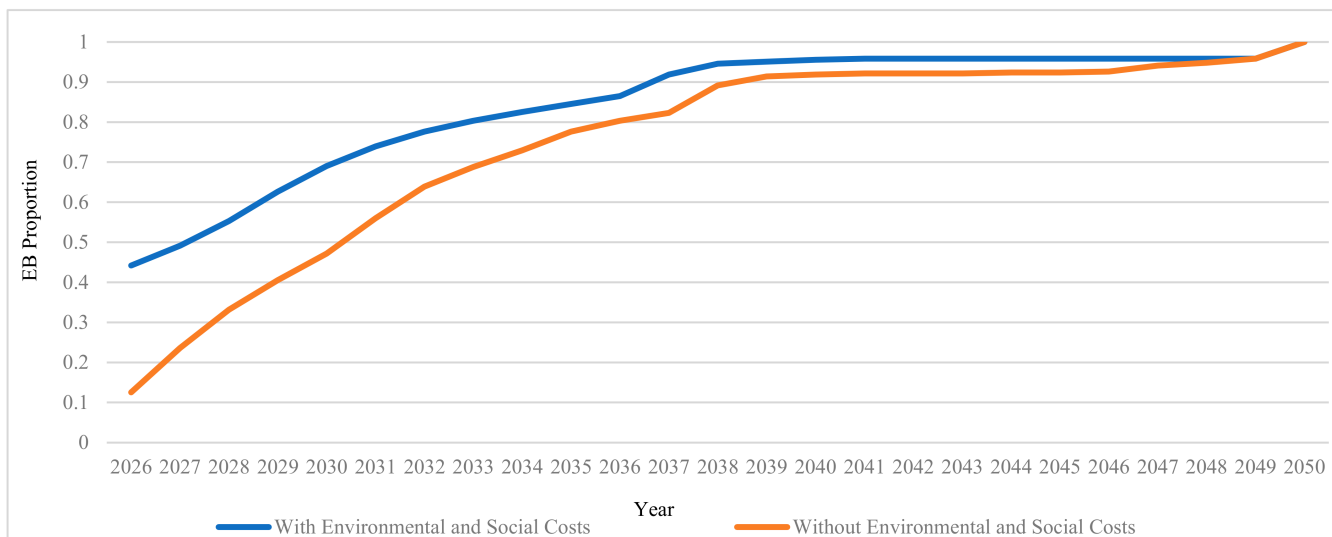


Figure 4. Environmental & social scenario electrification rate.

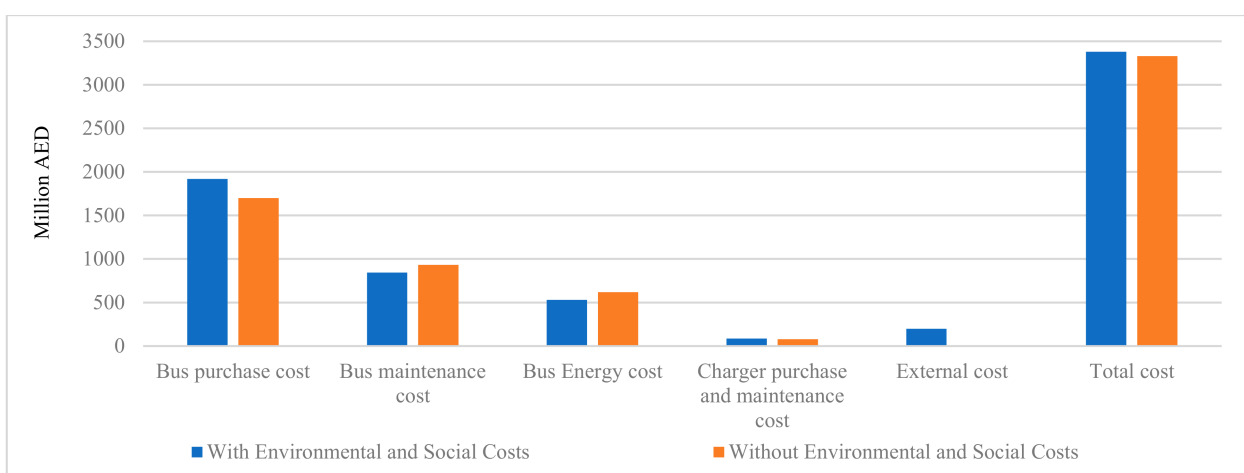


Figure 5. Environmental & social scenario direct total cost.

Table 15. Scenario 5 results *.

Category	With Environmental and Social Costs	Without Environmental and Social Costs
Bus purchase cost	1919	1699
Bus maintenance cost	844	933
Bus Energy cost	531	619
Charger purchase and maintenance cost	86	79
External costs	198	0
Total cost	3380	3330
Solution time (s)	323	958

* All costs are in million AED.

5.6. Scenario 6: Bus Fare Increase

This section examines the impact of increasing fares on EB routes, considering Dubai RTA’s current fares, which range from 3 to 7.5 AED. Recognizing passengers’ willingness to pay more for EBs, we analyze incremental fare increases of 5% up to 20%, applied only

to routes served by EBs and designed to remain reasonable for passengers. As shown in Figure 6, each 5% increase significantly accelerates EB adoption, with a 20% increase enabling 60% electrification in the first year, well ahead of the RTA's current plan to achieve this only after 2040. These results highlight the importance of integrating potential revenue streams from fare adjustments, advertising, and government support into transition planning to avoid missing valuable opportunities. In essence, this suggests that judicious fare differentiation can serve as a powerful mechanism to drive rapid adoption of cleaner technologies. In the model, fare revenue is computed from route fares, trip counts, passenger capacity, and the route load factor. The fare scenarios apply a flat percentage uplift (5%, 10%, 15%, and 20%) to base fares on EB-served routes only, bounded at 20% to remain reasonable for passengers and motivated by documented higher willingness-to-pay for EBs [11]. Ridership is held fixed (no demand elasticity), which is a conservative assumption, where the explicit modeling of fare elasticity stands out as a future research avenue. Costs and profit results are shown in Table 16.

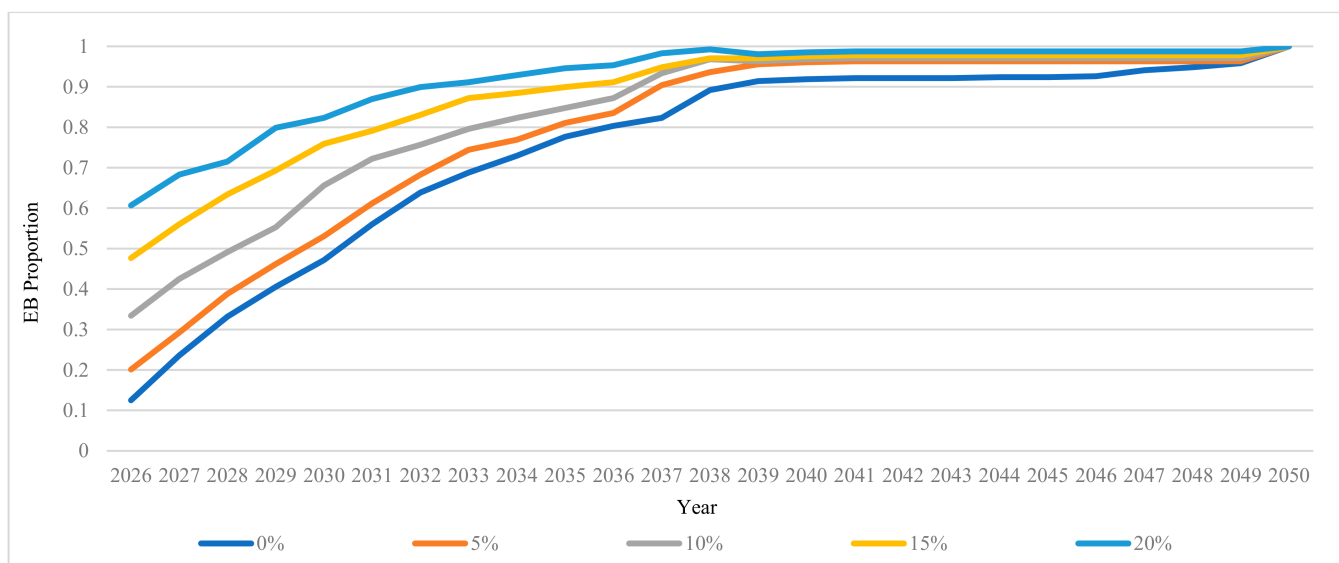


Figure 6. Bus fare scenario electrification rates.

Table 16. Scenario 6 results *.

Category	0%	5%	10%	15%	20%
Bus purchase cost	1699	1765	1872	1990	2086
Bus maintenance cost	933	903	859	819	793
Bus Energy cost	619	590	552	516	489
Charger purchase and maintenance cost	79	82	85	88	90
Total cost	3330	3340	3368	3413	3458
Profit margin	50.59%	52.33%	53.94%	55.40%	56.82%
Solution time (s)	958	339	320	349	310

* All costs are in million AED.

5.7. Scenario 7: Subsidy Mechanisms

Lastly, we assess how targeted fiscal incentives, both lump-sum (one-time) and distributed (annual) subsidies, can expedite the transition to an EB fleet. In this analysis, one-time subsidies of 0–30% of each bus's purchase price were made available in year 0,

alongside an alternative “declining block” subsidy that starts at 50% in 2026 and phases down linearly to 10% by 2050 (for an average subsidy rate equivalent to 30% over the period). In contrast, annual subsidies were calibrated so that their net present value over the 12-year service life of an EB matches that of the equivalent one-time package but were disbursed in equal installments each year. Figure 7 illustrates that by the end of the first decade, the fleet share of EBs under a 30% lump-sum subsidy exceeds the no-subsidy case by nearly 20%, while the steady annual subsidy yields similar early uptake but with smoother budgetary impacts. The declining block subsidy produces the most dramatic early adoption effect, resulting in differences of 50% by 2026, 35% by 2030, and 15% by 2035 relative to the other subsidy schemes. However, as battery costs fall and baseline adoption accelerates, all subsidy regimes converge to virtually identical electrification levels after 2040.

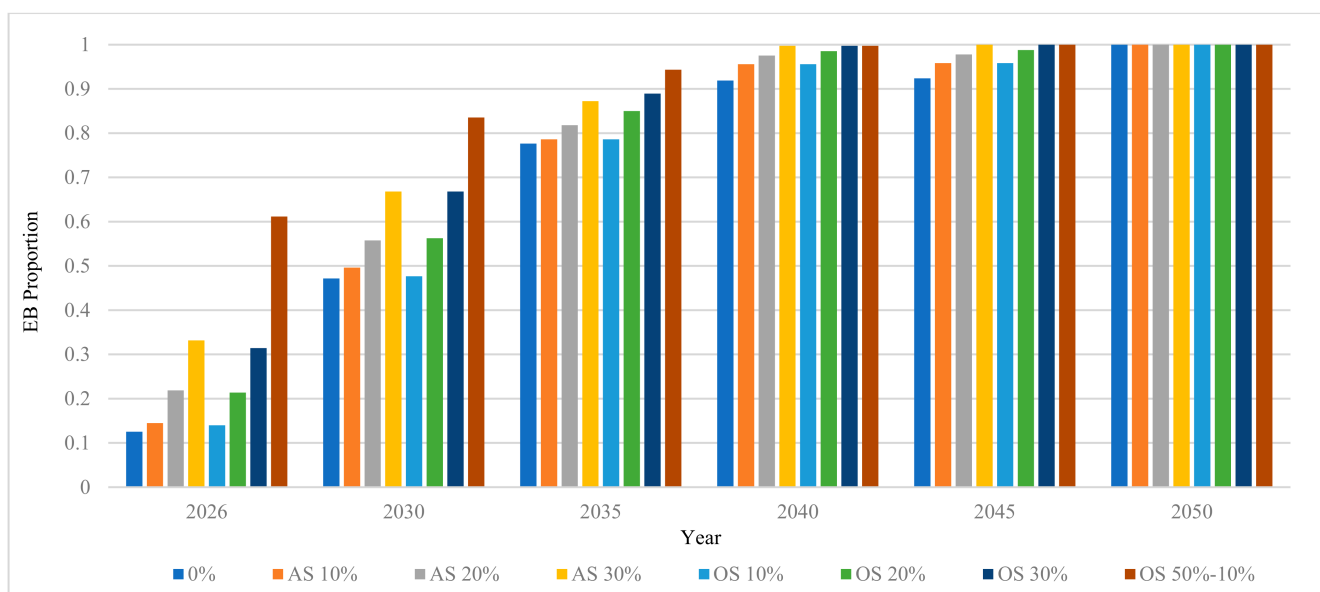


Figure 7. Subsidy scenario electrification rates.

Table 17 confirms that more aggressive subsidies lower net authority expenditures and enhance profitability. In particular, the declining block subsidy generates the highest discounted profit (151 million AED greater than the uniform 30% one-time subsidy). This is attained by concentrating support when marginal cost savings and deployment impact are greatest. These findings highlight that carefully designed subsidy profiles can both accelerate early electrification and optimize long-term financial returns.

Table 17. Subsidy scenario results.

Subsidy Type	0%	AS 10%	AS 20%	AS 30%	OS 10%	OS 20%	OS 30%	OS 50–10%
Subsidy	0	0.153	0.321	0.519	0.177	0.374	0.591	0.830
Cost without subsidies	3.330	3.334	3.347	3.376	3.332	3.349	3.373	3.460
Total cost	3.330	3.181	3.026	2.857	3.155	2.975	2.782	2.630
Profit	3.409	3.558	3.713	3.882	3.584	3.764	3.958	4.109
Solution time (s)	958	527	334	384	354	330	383	356

AS: annual subsidies; OS: one-time subsidy; all data in billion AED.

5.8. Sensitivity Analysis

To further assess the robustness of the transition plan, we conducted a one-way sensitivity analysis on two influential inputs: the annual battery cost decline rate, which is one of the most consequential long-horizon drivers, and the average load factor, which governs fare revenue.

5.8.1. Battery Cost Decline Rate

Since the long-term evolution of EB technology introduces significant capital risk and market volatility, we evaluated the model’s sensitivity to the battery cost trajectory. Building on the minimum-dwell plan as the analytical baseline, the annual battery cost decline rate—originally set at 9%—was tested at 3%, 6%, 12%, and 15%. As shown in Figure 8, the rate of technological advancement exerts a clear leverage effect on the optimal transition timeline, particularly during the main adoption phase between 2028 and 2045. Under a slow 3% decline, the model suppresses early- and mid-stage EB procurement, lagging the other regimes by up to 10% in the mid-2030s as it extends reliance on diesel buses to shield the operator from high upfront premiums. As the decline rate rises from 9% to 12% and 15%, the trajectories exhibit diminishing returns in adoption speed, evidenced by the tight convergence of the 9%, 12%, and 15% curves. Beyond a 9% annual decline, procurement pacing is governed by vehicle lifespans and capacity replacement limits rather than by battery asset premiums. All five rates converge to full (100%) electrification by the year 2050.

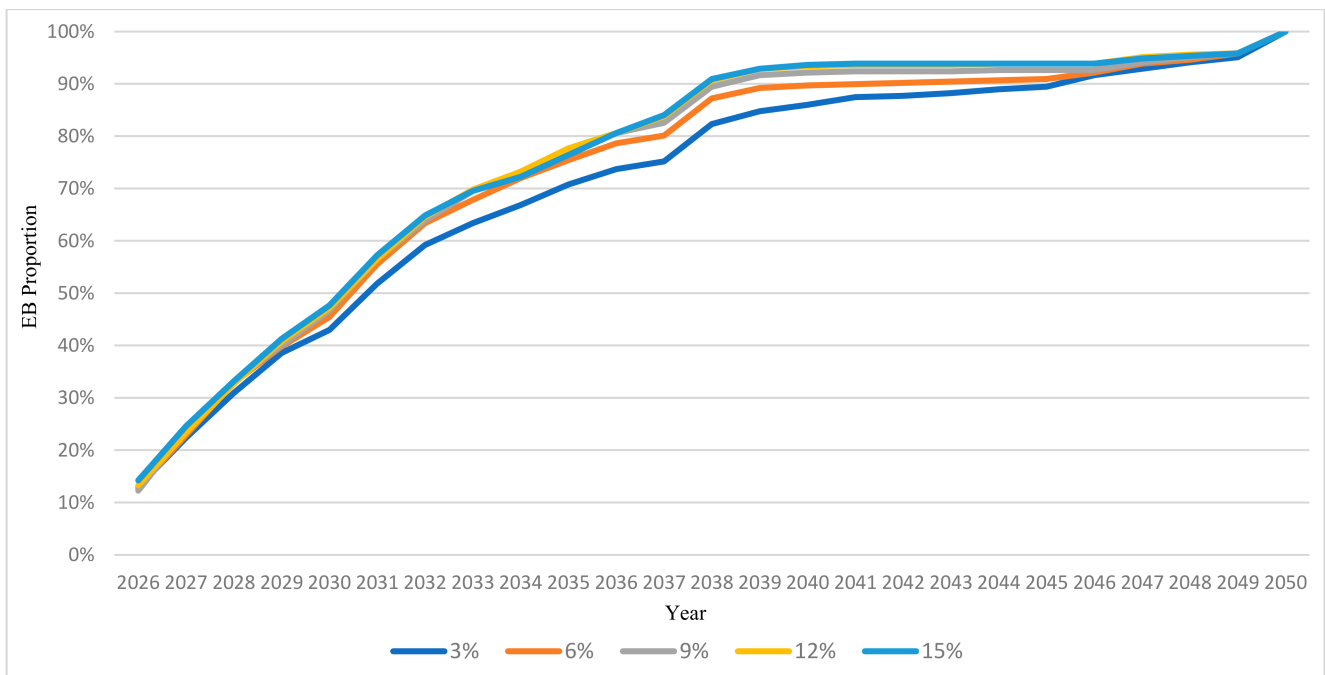


Figure 8. Fleet electrification trajectories under different annual battery cost decline rates.

Table 18 reports the corresponding cost components and objective values. The total discounted system cost scales inversely with the decline rate, falling from 3.456 billion AED under a 3% decline to 3.285 billion AED under a 15% decline, a drop of 171 million AED. This confirms that, while long-term full electrification is robustly feasible across all technology landscapes, the pace of battery cost decay acts as a fiscal optimizer that raises the objective value and protects the transit authority against prolonged, high-cost operational liabilities.

Table 18. Sensitivity of the transition plan to the annual battery-cost decline rate *.

Category	3%	6%	9%	12%	15%
Bus purchase cost	1770	1730	1699	1675	1661
Bus maintenance cost	954	939	933	931	930
Bus energy cost	655	630	619	617	614
Charger purchase and maintenance cost	77	79	79	80	80
Total cost	3456	3378	3330	3303	3285
Objective (profit)	3285	3362	3409	3437	3455
Solution time (s)	367	389	348	363	363

* All costs are in million AED.

5.8.2. Load Factor

We further varied the average load factor by $\pm 15\%$ and $\pm 30\%$ around its baseline value of 0.727. As Table 19 shows, the optimal transition plan is invariant to this assumption, where the individual cost components and the total discounted cost remain essentially unchanged at about 3.330 billion AED in every case, and only the objective value moves. This invariance is structural since the load factor enters the model solely through the fare revenue term and does not appear in the operational, technical, or cost constraints that determine procurement, charger sizing, and timing. Varying it therefore scales total revenue and profit from 1.388 billion AED at -30% to 5.430 billion AED at $+30\%$ while leaving the procurement, charging, and timing decisions intact. The plan is thus insensitive to ridership level uncertainty, indicating that an agency uncertain about future ridership can adopt the recommended plan knowing that only the realized profit, not the optimal decisions, will change.

Table 19. Sensitivity of the transition plan to the average load factor *.

Category	-30%	-15%	0%	+15%	+30%
Bus purchase cost	1699	1697	1699	1699	1697
Bus maintenance cost	933	934	933	933	933
Bus energy cost	619	621	619	620	620
Charger purchase and maintenance cost	79	80	79	79	80
Total cost	3330	3332	3330	3331	3330
Objective (profit)	1388	2398	3409	4420	5430
Solution time (s)	2490	348	348	539	351

* All costs are in million AED.

5.9. Benefit–Cost Analysis (BCA)

To assess the economic viability of transitioning to an EB fleet relative to maintaining the existing diesel fleet, we conducted a BCA summarized in Table 20. The cost of each alternative is the total discounted cost over the planning horizon, which amounts to 3.38 billion AED for the EB transition and 3.53 billion AED for the no-transition (diesel) scenario. The benefits comprise the total discounted revenue from bus fares, equal to 6.73 billion AED in both scenarios. For the EB transition, we additionally monetize the environmental and social benefits, computed as the difference in environmental and social costs between the two alternatives, amounting to 0.79 billion AED. The resulting benefit–cost ratio (BCR) is 2.23 for the EB transition and 1.91 for the no-transition scenario. The

higher BCR indicates that, once monetized environmental and social benefits are included, each AED invested in electrification returns substantially more than continuing with the diesel fleet. Although the upfront investment in electrification appears substantial, its long-term returns, particularly when environmental and social benefits are accounted for, make it the more economically efficient pathway for urban transportation.

Table 20. Benefit–cost analysis for the EB transition.

Alternatives	Cost (AED)	Benefits (AED)	Benefits/Cost
EB Transition	3.380×10^9	7.533×10^9	2.23
No Transition	3.530×10^9	6.739×10^9	1.91

6. Concluding Remarks and Future Research Avenues

This study presented a comprehensive and data-driven optimization model to support transit authorities in planning a cost-effective and operationally feasible transition to EB fleets. We formulated a multi-period MILP model that jointly integrates key inherent transition planning elements, including financial planning, technical and infrastructure requirements, existing bus network operations, multiple stakeholder perspectives, and essential modeling elements (as seen in Table 1). By combining these dimensions, the model better mimics real-world practices, fills a critical gap in the existing literature and offers a practical decision-support tool for transit agencies navigating the shift to zero-emission transport. Beyond this integration, the framework is distinguished by three specific advances: an endogenous, demand-linked determination of charger number, type, and placement in place of fixed charger-to-bus ratios; the explicit embedding of system-feasibility constraints, namely dwell time availability and grid-capacity limits; and a profit-maximization objective, which is interpreted as a net social benefit or public-sector planning objective, that internalizes fare revenue, government subsidies, and monetized environmental and social externalities. The scalability and practical relevance of the proposed model were illustrated via a case study of Dubai’s RTA, where the model generated an actionable transition plan that aligns financial prudence with operational feasibility. The optimized strategy includes a phased bus procurement schedule, prioritization of terminal-based fast-charging infrastructure, deployment of a mixed fleet tailored to route diversity, and a financing structure that evolves alongside battery cost declines and policy shifts. To assess the robustness of this plan, seven different realistic scenarios reflecting technological, economic, operational, and policy variations were developed. Collectively, the scenario analyses demonstrate the model’s capacity to quantify complex trade-offs among technology, policy, and operations. Rather than relying on a single solution, transit authorities can benefit from integrated, scenario-based planning frameworks that adapt to shifting market dynamics, stakeholder goals, and operational constraints, enabling them to design effective electrification roadmaps that balance financial performance, environmental objectives, and operational realities.

In particular, the results of the scenario analysis reveal that charging strategy and dwell time assumptions significantly influence both cost and feasibility. Scenarios with shorter dwell times and terminal-based fast-charging achieved full electrification with reduced infrastructure investment by enabling higher charger utilization and faster vehicle turnover. Furthermore, it turned out that technology choice plays a pivotal role. In range-constrained conditions, fast-charging standard EBs consistently offered better performance than depot-only models. However, as battery prices declined, the model favored more flexible fleet compositions, which demonstrates how cost trajectories can broaden viable options over time.

Policy-related scenarios illustrate that ambitious procurement mandates, such as transitioning to an EB-only fleet, can bring forward full electrification by a decade with minimal financial impact, provided that infrastructure expansion is coordinated. In contrast, scenarios characterized by specific time-phased electrification targets resulted in significant financial implications, highlighting the importance of maintaining flexibility in target-setting, budget allocations, and grid development timelines.

While the incorporation of environmental and social costs contributes a relatively small portion of total direct cost, it did trigger a shift in procurement timelines and technology choices. Notably, profit maximization emerged as a suitable planning objective, as it encompasses both cost savings and revenue generation and yields outcomes well-aligned with public benefit. Revenue-enhancing policies, such as modest EB-specific fare increases and carefully crafted subsidy structures, showed strong potential to improve financial outcomes and accelerate adoption, offering transit agencies an internally sustainable lever for funding cleaner fleets. Over time, as EB technology becomes more economically viable and electrification targets become more ambitious, the relative influence of subsidies diminishes. This highlights the importance of aligning policy support with the most financially sensitive phases of the transition. In this sense, the objective is best read as a net social benefit, or public-sector planning, objective rather than commercial profit, and the framework reduces to cost minimization when the revenue and externality terms are excluded.

For practitioners, these findings translate into several direct recommendations. One shall prioritize terminal-based fast-charging supported by adequate dwell time buffers, favor an all-electric procurement rule over rigid interim milestones, as this brings full electrification forward by roughly a decade at negligible additional cost, concentrate subsidies early through a declining-block design where their marginal impact is greatest, and either build flexibility into milestone dates or pre-allocate budget and accelerate grid development to avoid the cost premium associated with rigid targets.

Several future research avenues can further enhance the model's applicability and depth. One priority is analyzing the interaction between bus requirements, dwell time, and route frequency, particularly as evolving passenger demand may influence fleet sizing and deployment strategies. Furthermore, moving beyond a one-to-one replacement logic toward network-wide optimization could reveal more efficient solutions. In addition, extending the model to account for a broader range of cost and revenue sources, along with the consideration of emerging technologies such as hydrogen fuel cell buses or alternate charging options such as battery swapping (see Fang et al. [49]), would allow for a more holistic evaluation framework. Lastly, closing the loop by considering secondary uses of retired EB batteries and accounting for that as an integral part of the transition optimization framework stands out as a promising avenue for future research. Given that all results reported in this work above are deterministic, the framework could be extended to handle parameter uncertainty in electricity prices, battery cost, and ridership through two-stage stochastic programming or robust optimization, which stand out as a promising avenue for future research. Lastly, further priorities may consider extending the cost accounting to a full life-cycle basis that incorporates upstream electricity-generation emissions as well as battery production and disposal.

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Appendix A. Notation

Table A1. Sets, parameters, and decision variables used in the model.

Symbol	Description
Sets	
D	Set of depots where buses are stored, maintained, and dispatched.
M	Set of terminals where buses stop for boarding and alighting.
L	Set of locations, consisting of depots and terminals.
R	Set of bus routes.
T	Set of time periods (years) in the planning horizon.
C	Set of charging technologies available for EBs.
DC	Set of depot chargers.
FC	Set of fast chargers.
B	Set of bus types.
EB	Set of EB types.
FEB	Set of fast-charging EBs.
J	Set of possible bus ages.
Parameters	
Cc^c	Cost of purchasing and installing charger type c .
Cm_{tl}^c	Maintenance cost for charger type c at location l in period t .
as_j^b	Annual subsidy for buses of type b and age j .
os^b	One-time subsidy for purchasing bus type b .
ae^b	Air pollution environmental and social cost for bus type b .
ne^b	Noise environmental and social cost for bus type b .
ce^b	Climate change environmental and social cost for bus type b .
Bc_t^b	Cost of purchasing bus type b in period t .
mc_t^b	Midlife cost of bus type b in period t .
sv_{jt}^b	Salvage value of bus type b of age j in period t .
moc_{jtr}^b	Maintenance and energy cost for bus type b of age j on route r in period t .
Bo_j^b	Number of buses of type b and age j in the fleet at the start of the planning horizon.
Bp^b	Passenger capacity of bus type b .

Table A1. Cont.

B_j^b	Maximum age of bus type b .
J_m^b	Midlife age of bus type b .
EBc^b	Battery capacity of bus type b (kWh).
EBx^b	EB energy consumption of bus type b (kWh/Km).
e_t	Electrification target in period t .
Co_l^c	Number of chargers of type c owned at location l at the start of the planning horizon.
Cr^c	Charging rate of charger type c (kW).
Dh	The total time available each day for charging buses at depots.
Rh_r	Operational hours of route r .
Rd_r	Annual distance of route r .
Rk_r	Daily distance of route r .
Ro_r	Daily number of trips per bus of route r .
Ry_r	Annual number of trips of route r .
Rw_r	Dwell time of route r .
RI_r	Average load factor for route r .
Rbf_r^b	Bus fare for route r using bus type b .
Rq_{tr}	Number of buses required for route r during period t .
Lg_{tl}	Grid capacity in period t at location l (kWh).
Lr_{lr}	Binary parameter set to 1 if route r is assigned to location l , and 0 otherwise.
x_{jtr}^b	Binary parameter set to 1 if a bus of type b and age j is compatible with the assignment of route r during period t , and 0 otherwise.
b_t	Annual budget in period t .
Tf	Final period in the planning horizon.
Ja	Maximum average bus age in the final period.
V	One-period discount factor.
Decision variables	
P_t^b	Number of buses of type b purchased in period t .
W_t^c	Number of chargers of type c purchased in period t .
S_{jt}^b	Number of buses of type b and age j salvaged in period t .
A_{jt}^b	Number of available buses of type b and age j in period t .
Z_{jtr}^b	Number of buses of type b and age j assigned to route r in period t .
LA_{trl}^b	Number of buses of type b assigned to route r and location l in period t .
LX_{trl}	The total daily energy demand at location l and route r in period t (kWh).
CL_{tl}^c	Number of available chargers of type c installed at location l in period t .

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