ADDIS ABABA UNIVERSITY
COLLEGE OF TECHNOLOGY AND BUILT ENVIRONMENT
SCHOOL OF ELECTRICAL AND COMPUTER ENGINEERING
Master of Science in Electrical Power Engineering

Strategic Scenario-Based Modeling for Optimal Electric Bus Charging Station Deployment in Addis Ababa

By: Melkye Yifru
ID: GSR/1506/16

Advisor: Dr. Dawit Habtu, AAU
Co-Advisor: Dr. Jérémy Dumoulin, EPFL

A thesis submitted to the School of Graduate Studies of College of Technology and Built Environment, Addis Ababa University, in partial fulfillment of the requirements for the award of the degree of Master of Science in Electrical Power Engineering.

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APPROVED BY BOARD OF EXAMINERS

Chairman, Department of Graduate Committee Signature

Advisor Signature

Dr. Jérémy Dumoulin

Co-Advisor Signature

Internal Examiner Signature

Internal Examiner Signature

Declaration

I am a student in the Department of Electrical Power Engineering at the Addis Ababa University (AAU), School of Electrical and Computer Engineering. I hereby declare that the thesis entitled *"**Strategic Scenario-Based Modeling for Optimal Electric Bus Charging Station Deployment in Addis Ababa**"* is entirely my own work. It has not been submitted, in whole or in part, for the award of any degree or diploma at any other university or institution. All sources of data, information, and materials used in the preparation of this thesis have been properly acknowledged and cited.

Melkye Yifru	____________	____________
Name of the Student	**Date(dd/mm/yyyy)**	**Signature**

This thesis work has been submitted for examination with my approval as a university advisor

.

Dr. Dawit Habtu(PhD)	____________	____________
Advisor	**Date(dd/mm/yyyy)**	**Signature**
Dr. Jérémy Dumoulin(PhD)	10/11/2025	____________
Co-Advisor	**Date(dd/mm/yyyy)**	**Signature**

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List of Acronyms & Abbreviations

AAU	Addis Ababa University
BKG	Belayneh Kindie Group
CBE	Commercial Bank of Ethiopia
CO_2	Carbon Dioxide
CS	Charging Station
CTBE	College of Technology and Built Environment
DC	Direct Current
DCS	Depot Charging Scenario
DT4A	Digital Transport for Africa
EB	Electric Bus
ECR	Energy Coverage Ratio
EH	Energy Hub
EEP	Ethiopian Electric Power
EPR	Excess PV Ratio
ETB	Ethiopian Birr
EV	Electric Vehicle
EVCS	Electric Vehicle Charging Station
EV-Fleet-Sim	Electric Vehicle Fleet Simulator
EV-PV	Electric Vehicle – Photovoltaics
GDP	Gross Domestic Product
GHI	Global Horizontal Irradiance
GIS	Geographic Information System
GPS	Global Positioning System
GTFS	General Transit Feed Specification
GTFS4EV	General Transit Feed Specification for Electric Vehicles
ICCT	International Council on Clean Transportation
LCS	Layover Charging Scenario
MCDA	Multi-Criteria Decision Analysis
MCS	Mixed Charging Scenario
MILP	Mixed-Integer Linear Programming
MOO	Multi-Objective Optimization
MoWE	Ministry of Water and Energy
NREL	National Renewable Energy Laboratory
OCS	On-route Charging Scenario
RE	Renewable Energy

SAM	System Advisor Model
SCR	Self-Consumption Ratio
SOC	State of Charge
SSR	Self-Sufficiency Ratio
TOU	Time of Use
USD	United States Dollar

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[1] **New terms used in this study:**

- Energy Coverage Ratio (ECR): Fraction of total EB charging demand supplied by PV generation.
- Self-Sufficiency Ratio (SSR): Proportion of EB charging demand met directly by PV generation, considering only the coincident power.
- Self-Consumption Ratio (SCR): Fraction of PV generation that is consumed on-site for EB charging rather than exported to the grid.
- Excess PV Ratio: Share of PV generation exceeding the charging demand, which is either exported or curtailed.
- Model-based: Denotes the use of the `GTFS4EV` simulation model to quantify charging demand and evaluate optimal station placement across different strategic scenarios.

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Abstract

The adoption of electric buses (EBs) is a critical step toward reducing greenhouse gas emissions and advancing sustainable urban mobility. In rapidly growing cities such as Addis Ababa, the deployment of an accessible, strategically planned, and grid-compatible charging infrastructure is essential to support large-scale EB integration. However, the city currently lacks a charging system that aligns with its transport demand patterns, electricity supply characteristics, and renewable energy potential, creating a significant planning gap.

This study investigates the spatial and temporal deployment of EB charging stations in Addis Ababa, aiming to ease peak loads, improve charger utilization, and enhance fleet reliability, thus strengthening utility efficiency and supporting sustainable urban mobility. It combines General Transit Feed Specification (GTFS) data and bus fleet characteristics with GIS-based simulation models (`GTFS4EV` and `EV-Fleet-Sim`) to estimate travel demand, energy requirements, and charger placement under depot, layover, on-route, and mixed charging strategies. The potential for solar photovoltaic (PV) integration is also assessed to enhance environmental performance and reduce reliance on the grid.

Results indicate that each EB has an average daily energy demand of approximately 401 kWh (1.86 kWh/km). By 2030, EB deployment is projected to increase the city's daily electricity load by 0.8%–2.4% depending on the electrification scenario. Charging strategies strongly influence the spatio-temporal distribution of demand: depot-only charging concentrates load during late-night hours; layover-only charging spreads it across the service day but remains spatially concentrated; and on-route charging disperses demand both spatially and temporally, though with feasibility limitations. Among the examined strategies, a mixed configuration of 47% depot, 27% layover, and 26% on-route offers the best balance between technical feasibility, operational flexibility, and cost efficiency. This strategy also shows the highest PV production alignment, achieving up to 40% self-sufficiency with an average energy coverage capability from 18.9% to 57.7% depending on the PV capacities per bus.

While focused on Addis Ababa, the findings provide transferable insights for other cities pursuing EB electrification. The study demonstrates that strategic charging deployment integrated with renewable energy can optimize costs, reduce peak loads, and enhance system resilience. By quantifying trade-offs among economic, technical, and environmental objectives, this research offers a practical framework for policymakers and planners to design scalable, sustainable EB charging systems in diverse urban contexts.

Key words: EB charging stations, deployment, GTFS4EV, EV-Fleet-Sim, PV integration.

Chapter 1

Introduction

1.1 Background and Motivation

Electric vehicles have been gaining in popularity worldwide due to their environmental advantages and the ability of these vehicles to reduce dependence on fossil fuels [1]. The transportation industry is among the largest contributors to global energy consumption, accounting for about 30% of the world's total energy, which is primarily from hydrocarbons. Naturally, this industry is multifaceted, existing in land, aviation, and maritime sectors, and it is vital to the economy, the environment, energy, and technology [2]. Apart from this, enormous quantities of CO_2 emissions are released, accounting for over one-quarter of all CO_2 emissions globally come from this sector. These emissions therefore harm the environment and contribute to local and global environmental issues, including urban air pollution. As a result, the transport sector has become a core area of focus for decarbonization, because it contributes a large portion of greenhouse gas emissions. In this regard, electric mobility has been the best alternative in moving toward cleaner, low-carbon options [2, 3].

In addition to private EVs, public transportation electrification has become a priority policy for cities for better urban mobility and for attaining sustainability goals. Electric buses (EBs) offer particular promise. They reduce emissions per capita, improve energy efficiency, and promote social equity by providing accessible, low-cost transport for urban residents. An obvious case study is the Shenzhen Bus Group, which has upgraded its entire fleet to electric buses with consequent huge reductions in emissions and operating costs. Furthermore, a comparative study of de-carbonization in public transportation elicits the environmental benefits of substituting diesel with electric buses [4, 5].

Although the transition to electric buses is a wonderful promise for the improvement of public transport systems, it has also some difficulties that need to be addressed. The most crucial obstacles are high initial costs of investments, the need for supporting infrastructure, and existing technologies often limit their widespread adoption. A case study of the economic costs of financing electric buses for a transit agency highlights the importance of taking into account economic feasibility and risk considerations in the fleet electrification [6]. Despite these challenges, global momentum to electrify public transport is alarmingly increasing. The International Council on Clean Transportation (ICCT) reflects that, cities globally are progressively introducing electric buses into their fleets as component of plans to improve air quality and reduce greenhouse gas emissions. This is evidenced by supporting policy regimes and continued technological advancement, which make electric buses more viable and sustainable in the long term for public transport [4, 5].

Building on global advances toward climate-resilient transport, electric mobility has been one of the key pillars of Ethiopia's national transport plan. The long-term vision of the government prioritizes decarbonizing the fleet as one of the primary milestones to reduce emissions from the transport sector. The commitment includes a strong push toward electric vehicles, both in public and private, supplemented by expansion of charging infrastructure for EVs. The strategy specifically appeals to electrify public transport and promote e-mobility in Addis Ababa and the regional cities, and to position electric vehicles at the core of Ethiopia's broader sustainable development and climate ambition goals [7].

With this national impulsion, in Addis Ababa, as the capital and transit center of the nation, these international and continental dynamics are felt sharply. The nation has experienced accelerated urbanization during the recent decades, precipitated mainly by rural-to-urban migration for improved economic opportunities, especially in Addis Ababa [8]. This urbanization, though vital to national progress, has generated several serious issues, the most prominent of which are augmented energy requirements, traffic congestion, air pollution, and emissions of greenhouse gases [8, 9, 10].

Addis Ababa, being the largest city, is currently facing a growing need to transform its urban transport system. The present transport system has not been able to meet the population growth rate and over five million people and still increasing rely on highly congested, fossil fuel-based transportation systems. Low-capacity taxis and minibuses dominate city streets, leading to jams and contaminating the atmosphere [10]. Public transportation is still the most common way to get around in Addis Ababa. Government-owned buses, such as Anbessa and Sheger, cater to the needs of the people for their affordability, availability, and user accessibility [11]. These services increase city mobility by all socio-economic strata and are critical to advancing social equity. In addition, it hugely helps deal with environmental concerns via lower emissions per head compared with individual, more trivial modes of transportation. These fleets, fueled by diesel currently, however, have high emissions and are not very sustainable for future development.

Thus, the transition to electric buses is such a turning point for transformation. EBs with high capacity can disperse traffic congestion, reduce environmental pollution, and offer cheap, reliable, and equitable transport. This is among the general urban design guidelines of making cities livable and accessible to all [11]. Yet, Addis Ababa's EV transition, especially in public transport, is considerably affected by the absence a well planned studies and sufficient charging infrastructure. Although EV adoption is growing, the city lacks a comprehensive network of public charging stations, particularly those capable of supporting heavy-duty vehicles like buses. This lack is a major deterrent to current EV owners and prospective buyers [10].

Recognizing this challenge, the Ethiopian government has launched national programs to build EV infrastructure. These programs include investment in available and reliable charging networks, the use of smart charging technologies, and a set of policy incentives such as tax exemptions, import duty waivers, and financing incentives for the expansion of charging points [12, 13]. These initiatives are intended to reduce the challenges for EV adoption and improve infrastructure readiness in the nation, as well as secure the long-term plan of becoming a smart city.

One of the greatest opportunities for integrating EV infrastructure into urban planning is the Addis Ababa city corridor project, a flagship urban development project for the transformation of the city as a smart and sustainable city [14]. It includes pedestrian walkway development, improvement of public transport infrastructure, and installation of smart technologies to enhance the delivery of urban services. Its objective is directly aligned with the strategic interests of e-mobility. The provision of EV charging points, especially on heavy traffic locations and major transport routes, would be to the benefit of significantly enhance the preparedness of the city to take up the EV revolution. This would have the added benefit of catering to current mobility needs and future expected demand. Though the charging infrastructure may be beyond the technical definition of the corridor project, urban planning in the long term must consider such demands [7, 14].

In the face of such pressing needs and strategic opportunities, the objective of this study is to investigate a model-based framework for the optimal deployment of electric bus charging stations in Addis Ababa by the consideration of energy demand, future fleet growth, spatial suitability, and coupling with solar PV systems. The electric buses are targeted in this research, particularly because they can bring significant benefits in urban, environmental, and social impact. The model used in the present research considers a number of factors, including the existing bus mobility infrastructure, PV supplementation for the demand, and various modes of charging scenarios, so that the impact on the grid and user satisfaction can be guaranteed. Furthermore, the study considers projected consumer demand and the current level of EV infrastructure in the city to inform a data-informed, spatially optimized allocation of deployment strategy. This strategy is designed to be aligned with Addis Ababa's long-term transport and energy visions. Through scenario-based modeling, this study offers a tangible action plan for the rollout of EV charging infrastructure that optimizes the sustainable urban mobility, grid efficiency, and accessibility of the city.

1.2 Statement of the Problem

The Ethiopian government's ambitious ten-year transport plan(2020/21–30)[7] incorporates the national venture of transitioning to sustainable transport through importing large numbers of both electric buses and electric cars EVs by 2030. As well as the corresponding public EV charging stations nationwide, more than half of which will be proposed for Addis Ababa . This reflects the government's plan to eliminate greenhouse gas emissions and decarbonize transport by 2030. However, despite this nationwide momentum, Addis Ababa still lacks an adequate public charging infrastructure for electric buses (EBs). Insufficient planning of a spatially optimized charging network prevents the city from scaling up its electric bus fleet effectively. This constitutes a major barrier to adoption, since uncertainty about the availability of chargers undermines user confidence and operational reliability.

In addition to this, an ongoing Addis Ababa's corridor projects along public transit network provides an opportunity for the incorporation of charging infrastructure without retrofits at higher expense in the future. Even though the charging infrastructure is not officially part of the corridor project , aligning its installation with the corridor project can reduce economic and labor costs, offering long-term benefits through integrated planning.

Given such facts, there is an urgent need to explore how charging infrastructure can best be spatiotemporally distributed to meet the growing need for electric bus transport and harmonize with energy, economic, and environmental goals. In addition, studies for integrating solar PV technology into such charging stations can also help further towards Addis Ababa's resilience and sustainability goals. This research bridges this gap through the development of a model-based method by examining current EB usage patterns, simulating different charging deployment strategies, and analyzing their economic, technical, and environmental aspects. Ultimately, the findings aim to provide policymakers with the best course of action in order to have a clean, efficient, and convenient electric bus system in Addis Ababa.

1.3 Objective of the Research

1.3.1 General Objective

The main goal of this research is to model electric bus charging station deployment in Addis Ababa by examining current usage, future fleet growth, solar PV integration, and the impacts under different charging scenarios.

1.3.2 Specific Objectives

The specific objectives in this thesis are the following:

- To assess Addis Ababa's current EB usage and charging habits, as well as the infrastructure readiness for charging stations.
- To develop a framework for the optimal deployment of electric bus charging stations, considering future fleet penetration by 2030.
- To examine solar PV integration across charging scenarios and estimate the proportion of demand met by renewable energy.
- To evaluate the economic, technical, and environmental impacts of the proposed deployment strategies.
- To provide practical recommendations for policymakers on strategic EB charging station deployment.

1.4 Scope of the Thesis

This thesis, "Strategic Scenario-Based Modeling for Optimal Electric Bus Charging Station Deployment in Addis Ababa", is a critical examination of the energy needs of the EB, and charging stations in accordance with their role in helping the city shift to an efficient and sustainable network of electric public transport. It offers a framework for the planning of the electric bus charging stations strategically and the policies necessary to make the mass use of electric buses popular while maintaining reliability, accessibility, as well as seamless integration into the existing energy infrastructure.

The study starts by examining the existing electric bus (EB) charging infrastructure within Addis Ababa city and assessing its capacity and limitations at present. Projections of electric bus penetration levels up to the year 2030 with in Addis Ababa are evaluated, along with examination of the busiest areas in the city to ascertain demand for charging points.

The research does not involve field deployment; instead, it employs adapted modeling software to indicate the best places for charging stations of EBs within the city. The integration of renewable energy resources in the proposed charging network in this research is also considered, as it can help render the system greener while reducing grid impact.

Further the study investigates the environmental and financial implications of the planned charging facilities. The analysis considers cost-effectiveness, operating efficiency, and conducts a detailed evaluation of the planned system's viability.

1.5 Significance of the Thesis

This MSc thesis ought to provide Addis Ababa utility companies, policymakers, and urban planners critical information through providing actionable outputs on the improvement of the city's electric bus (EB) infrastructure. The research ought to assist the government in its long-term sustainable urban mobility strategy through ensuring the deployment of best charging stations into broader transport and energy policy. Their integration into the current corridor development program is likely to enhance efficiency in resources, and thus labor and financial inputs into infrastructure development. The study also examines the economic and environmental effects of widespread EB adoption, citing its potential to reduce carbon emissions and public transport as clean and efficient. Through overcoming overarching technical, financial, and regulatory challenges, this thesis is part of the overall achievement of sustainable city development in Addis Ababa.

1.6 Thesis Outline

Six interdependent chapters compose this thesis, collaborating to enhance the planning of charging stations for electric buses in Addis Ababa. *Chapter 1* presents the background to the study, the major transport challenges in the city, and the research problem, objective, and scope with clarity. This chapter sets the stage for the necessity to establish sustainable solutions to electric mobility. *Chapter 2* provides an extensive review of the literature on the planning of EV charging stations, electric bus deployment, and the associated modeling approaches. It also positions the current study in the context of overall electric vehicle infrastructure development and identifies information gaps. *Chapter 3* is mostly devoted to Data and Contextual Analysis, explaining the various data sources and the channels through which renewable, operational, and technological data related to the public transport infrastructure of the city were collected. *Chapter 4* outlines the overall methodology employed in this research, along with the modeling framework and simulation tools employed to evaluate various charging scenarios. *Chapter 5* gives the results and discussion, along with an analysis of charger and energy needs, and economic outcomes for various scenarios. The local context is integrated in the explanation of the results, which provides insight into the trade-offs between investment requirements and operational efficiency. Finally, *Chapter 6* summarizes the study by highlighting the applicability of the research to practice and policy, summarizing major findings, and suggesting avenues for further research activities. This thesis contributes significantly to informed decision-making for a sustainable transformation of urban mobility by examining the evaluation of the minimum battery size requirement for the future launch of electric buses in Addis Ababa and the optimization of infrastructure.

Chapter 2

Literature Review

In this chapter, the literature review of electric bus (EB) charging infrastructure, the best deployment model of charging stations, renewable energy integration into e-mobility charging stations, the economic and environmental impact of charging infrastructure, and the spatiotemporal distribution of charging demand are reviewed. The review from interdisciplinary sources forms the state of knowledge of these topics. It is mainly interested in methods, ideas, and outcomes that shape the design and decision-making of EB charging infrastructure.

The review is structured around four themes closely associated with the aims of this thesis. In order to set a context for the methodological decisions and analytical direction adopted in this study, the literature of pertinence is discussed in each theme section. A synthesis of key insights is summarized at the end of the chapter, along with the precise research gaps this study aims to fill.

2.1 Electric Bus Usage and Charging Practices

A comprehensive case study of full electrification of Shenzhen's public bus system, with more than 16,000 buses, was presented by the World Bank [15]. The study states that operational reliability of the EB charging system can be achieved through high charger-to-bus ratio and nighttime depot charging. Furthermore, Liu et al.[16] studies for adaptive planning of location and charging strategies according to local travel demands, emphasizing balancing between locations of fast-charging station planning and random traffic. while Seilabi et al.[17] suggested a bi-level optimization approach to urban EV charging stations infrastructure and demonstrated that, with the assistance of solid traffic and fleet modeling, optimally placed stations can reduce car emissions. Those results align with the needs of conservative infrastructure design, operating policy, and optimization models as EB fleets expand in the city. Hecht et al.[18] as well presents a global EV charging station location analysis model with large empirical data in Germany. Their approach employs neural networks to predict energy demand and place charging stations using OpenStreetMap data.All these studies mainly based on contexts where EV adoption is already mature and well-practiced. However, in the majority of Sub-Saharan African cities,including Addis Ababa, where utilization of electric buses is still in its initial phases, no such comprehensive review of electric bus usage and charging behavior exists. Absence of mature reviews of the city's current EB operations, depot culture, and charging preparedness holds back authorities from comparing or planning for electrification. The inequality introduces into consideration the necessity of local studies such as the present study that aim at creating evidence-based data into Addis Ababa's preparedness in infrastructure and EB utilization patterns.

2.2 Optimal EV Charging Station Deployment

It is highly important to have the best spatiotemporal distribution of electric buses (EBs) charging stations for the design of environmental, eco-friendly urban transport systems. To tackle this, several methods and approaches have been utilized, including multi-criteria decision analysis (MCDA), geographic information systems (GIS)-based simulation methods, and mathematical optimization models. These help in identifying the best way to decide on the location of EB charging infrastructure, the size, and the way to operate them. They also consider constraints such as grid capacity, land use, traffic flow, and energy demand.

To tackle these challenges, several studies [19, 20, 21] utilizes Mixed Integer Linear Programming (MILP) and mathematical optimization models to optimize charger size and placement by minimizing investment and operational costs while accounting for route distances, fleet schedules, and battery dynamics. For instance, the queuing theory, combined with MILP by Momenitabar et al.[22], helps analyze trade-offs between battery sizing and charger availability at terminals. These models most often assume mature transportation systems with large operational datasets and regular trip patterns.

Simulator-based models have also been applied to capture the spatiotemporal distribution of fleet activity and bus energy consumption. Programs such as MATSim and SUMO allow realistic simulation of dynamic vehicle-energy interactions. More recently, EV-fleet-sim, developed by J. Chris Abram et al. [23] utilizes General Transit Feed Specification or GPS datasets to produce high-resolution spatiotemporal energy demand profiles. By incorporating route schedules, topography, vehicle attributes, and consumption profiles, the model simulates the operation of an electric vehicle fleet. A key advantage for cities with emerging EV networks is their compatibility with interactive heatmaps, which allow stakeholders to visualize and identify hotspot areas for charging infrastructure.

Spatial decision support tools based on GIS-integrated multi-criteria decision analysis have also been investigated to analyze optimum locations in terms of proximity to bus routes, grid infrastructure, and land use [24, 25]. For instance, Zhang et al.[26] utilized a spatial–temporal analysis model with transit data for the location of high-demand charging locations within dense urban centers. Likewise, Garau and

Torsæter [27] presented a multi-objective optimization model coupling EV charging stations and renewable energy hubs, trading off coverage, generation potential, and number of stations in Trondheim, Norway.

Despite such advancements, the majority of studies prefer to examine mature EV markets with plenty of historical data, mature transit systems, and mature infrastructure systems. In such settings, traditional optimization methods may not capture the localized complexities or uncertain demand patterns. This thesis bridges this gap by utilizing adapted simulation models specifically for African contexts, together with integrating GTFS data and electric bus energy consumption, and examines various charging approaches. An interactive heatmap is used to locate key hotspot areas, providing decision-making support to policymakers and utility planners. This strategy not only allows for a scalable, localized deployment strategy but also supports national aspirations for low-emission urban mobility transitions.

2.3 Modeling Tools for EB Charging

Electric bus (EB) charging infrastructure deployment requires modeling capabilities that capture complex spatial, temporal, and operational dynamics. Several frameworks have since emerged to support such planning, with different emphases ranging from route-level simulation at depth to system-level energy integration. This section elaborates on four such tools: EV-Fleet-SIM, GTFS4EV, Mixed-Integer Linear Programming (MILP), and Multi-Objective Optimization (MOO), how their basic capabilities relate to the goals of this research: optimal siting of EB charging stations and leveraging renewable energy sources in an urban African context like Addis Ababa.

EV-Fleet-SIM[23, 28] is a fleet-based simulation software tool for electric vehicle analysis. It can handle both GTFS and GPS input data, so it is convenient to use in various situations of data availability. It is capable of producing trip-level estimates of energy consumption and spatial hotspot maps, which can be employed for finding localized patterns of demand along routes and depots. It is highly beneficial in exploring the operational dynamics of electric bus fleets under various traffic and scheduling scenarios. However, EV-Fleet-SIM does not directly estimate charging requirements, such as the number of chargers or charging durations, and its renewable energy (PV) integration feature holds only when GPS data is utilized. Despite this, its ability to monitor vehicle-level behavior demand renders it highly valuable in spatial planning and route-based energy profiling. GTFS4EV[29], in contrast, is an analysis tool at the system level using GTFS data to examine multiple charging scenarios (e.g., on-route, depot, layover) and couple PV generation with charging system design. It simulates charging load profiles for scenarios and estimates the overall energy demand of the system based on provided energy consumption rates. One of the most important aspects of GTFS4EV is that it can generate interactive spatial heatmaps and calculate renewable integration indicators such as PV self-sufficiency and self-consumption, besides dealing with different modes of charging. Although the tool is relatively immature, its focus on renewable integration and scenario planning makes it a significant contributor to strategic infrastructure planning.

While both EV-Fleet-SIM and GTFS4EV accommodate planning with renewable energy and incorporate public transit data, they are used for different analysis purposes. EV-Fleet-SIM is fleet- and trip-based, and it generates high spatial and temporal resolution data appropriate to operational planning. GTFS4EV, in contrast, is top-down planning, suitable for examining larger energy and infrastructure plans within renewable energy constraints. Of anecdotal interest, EV-Fleet-SIM PV integration is only GPS input-based, while GTFS4EV has PV modeling by using GTFS inputs directly, a distinction influencing tool usability based on data feeds available.

Besides these two, optimization models such as Mixed-Integer Linear Programming (MILP)[20] are widely used for siting of charging stations and resource planning. MILP models are best suited for minimizing installation cost, balancing grid constraints, and handling large datasets. They are usually weak in built-in spatial data management but typically need to be supplied with GIS linkage for geospatial analysis. Similarly, Multi-Objective Optimization (MOO)[30, 31] methods enable planners to balance trade-offs among cost, grid load, user access, and environmental impact. Such models are robust in multi-criteria decision-making but can have high modeling complexity and computational expense.

In conclusion, each modeling solution has various strengths for the EB infrastructure planning problem. EV-Fleet-SIM and GTFS4EV both exactly suit the purpose of this research by offering capabilities in spatial analysis, fleet simulation, and PV integration. EV-Fleet-SIM provides tripwise energy mapping with fine detail from real fleet operation, while GTFS4EV provides a system-level insight at broader scale with direct coupling of PV-energy and scenario analysis. Their complementarity supports a multi-level approach to optimal EB charging station positioning in urban areas like Addis Ababa.

2.4 Renewable Energy Integration in EB Charging

Solar photovoltaic (PV) system and electric vehicle (EV) charging system integration has been receiving more attention over the years as a way to lower the grid electricity dependence, increase sustainability, and improve energy consumption in electric bus systems. A number of recent studies have introduced optimization models and simulation-based approaches to the integration of PV into EV charging systems.

Building on optimization techniques, Garau and Torsæter [27] formulate a method for optimal energy hub (EH) placement combining EV charging and renewable energy generation. Based on multi-objective linear programming. The approach reduces the number of EHs, optimizes renewable utilization, and enhances EV charging coverage. which was implemented in Trondheim, Norway, aims to maximize the level of renewable energy generated, enhancing urban sustainability. More specifically, Bokopane, Kusakana, and Vermaak [32] suggested a grid-connected microgrid optimization model for EV charging stations with PV generation, battery storage, and peer-to-peer energy trading. The model tries to optimize costs of operation and enhance system reliability by local energy trades. Even though the proposed microgrid configuration enhances resource efficiency, the model remains generic concerning spatial deployment techniques as well as empirical mobility statistics. Of particular interest, the model does not incorporate transportation-related variables, i.e., charging possibility at bus stops, layovers, or stops.

A model of integrating rooftop solar PV into an electric bus network was also presented by Li et al. [33], specifically applied for electric bus charging systems. In this study, the operational benefits of PV support are described in their model through depot charger location optimization, headways, and stop spacing. Their simulation, performed in Panjin City, China, suggests that rooftop PV can minimize fleet size and maximize daily operating hours with reduced battery capacity needs. For high-irradiance urban locations, this modeling strategy is of benefit.

In a complementary effort, Baldua et al.[34] developed a two-stage stochastic programming model for building solar-integrated EV charging infrastructure under variable renewable generation. Time-of-use electricity tariff, seasonal solar variability, and temperature-based bus energy consumption are all incorporated in their modeling framework ,and achieved high cost savings and solar intermittency robustness when applied to Durham, Canada, and Canberra, Australia, networks. While efficient in coping with environmental uncertainty, the stochastic model relies on set transportation timetables, which may not be readily accessible in still-developing metropolitan cities. It also does not explicitly show the PV utilization variation across different charging scenarios.

Although recent literature focuses on the technical feasibility and economic benefits of solar PV integration with electric bus charging stations, there are certain important gaps, particularly for rapidly urbanizing cities. Most importantly, previous studies do not analyze solar PV integration for varying charging modes such as depot, on-route, and layover charging, each of which can significantly influence energy demand profiles, infrastructure requirements, and PV usage efficiency. Furthermore, neither the size nor the spatial requirements of PV systems tend to be examined in any detail, even though land availability is a critical limiting factor in dense cities. The research is also based mainly on case studies of mature cities with well-developed transit systems and stable operational data, which further limits their applicability to developing urban contexts like Addis Ababa. In addition, the majority of the models overlook the spatial and temporal mismatch between solar power generation and the time-of-need for charging. In order to address these shortcomings, this thesis employs a simulation-based modeling environment, that is able to support scenario analyses of solar PV integration on the basis of real transit operations and site-specific spatial data. With the simulation of different charging scenarios, the research offers a pragmatic estimate of the share of electric bus energy demand that can be served by PV energy in Addis Ababa.

2.5 Techno-Economic and Environmental Impacts

Evaluating electric bus charging infrastructure involves examining deployment mode, cost, grid dependency, and spatial compatibility. Heide et al. [35]showed how charger location affects fleet size, energy needs, and deadhead mileages through simulating terminal and depot charging in an urban transit network. They concluded that hybrid charging enhances schedule flexibility while reducing battery size and depot power requirement. Zhao et al. [36] presented a grid-aware on-route fast-charging design for South King County using mixed-integer second-order cone programming to balance total costs, including hardware, grid upgrades, and operations, within grid capacity limits. Their research emphasizes how on-route pricing impacts operational equity and requires detailed planning for investment.

In France, Nathanael Dougier et al. [37] simulated bus operations under different charger sizes and locations, at depots, termini, and stops, to evaluate effects on peak grid load, battery size, PV self-consumption, and service reliability. They concluded that PV only slightly contributes to charging, particularly in winter, and that charger location plays a significant role in grid stress, delays, and battery requirements. Separately, Mao and Meyer [38] performed a techno-economic analysis demonstrating that uncontrolled EV charging increases grid asset depreciation, calling for the use of smart charging to control infrastructure expenditures and grid stress.

Collectively, these studies confirm that scenario-specific modeling of charging systems, grid constraints, land feasibility, and PV integration is necessary to assess the technical, financial, and environmental impacts of various electrification schemes. To meet this need, this thesis simulates depot, layover, and on-route charging deployments in Addis Ababa with the calculation of the number of necessary chargers, initial charger cost, grid dependency measures, and CO_2 emission reductions while taking into account local operational data and land limits.

2.6 Synthesis and Research Gaps

While global advancements in electric mobility offer valuable insights, significant contextual gaps remain for Sub-Saharan African cities, particularly Addis Ababa. The literature lacks locally grounded evidence on electric bus (EB) usage patterns, charging habits, and infrastructure preparedness (sec: 2.1). Furthermore, although many optimization models exist, they often target mature EV markets with stable data and infrastructure, making them poorly suited for cities like Addis Ababa, where uncertainty and infrastructural challenges prevail (sec: 2.2). In the case of renewable energy integration, particularly solar PV, previous studies seldom account for spatial constraints, charging mode variations, or temporal mismatches with charging demand, factors crucial in urban environments (sec: 2.4). Additionally, the previous research implies that scenario-based modeling of charging infrastructure, grid capacity constraints, land availability, and PV integration is required to examine the technical, economic, and environmental effects of different electrification scenarios (sec: 2.5). To meet this need, we should have to study the techno-economical feasibility and impact of the proposed strategy.

Table 2.1: Mapping of Research Gaps to Thesis Objectives

Research Gap	**Addressed by Objective**
Gap 1: Lack of data-driven assessment of Addis Ababa's EB usage, charging behavior, and infrastructure readiness	**Obj 1**: Assess Addis Ababa's current EB usage and infrastructure readiness
Gap 2: Traditional models overlook uncertainties and localized needs in early-stage EV cities	**Obj 2**: Develop a framework for optimal EB charging station deployment **Obj 3**: Integrate renewable energy (PV) in charging scenarios
Gap 3: Insufficient analysis of PV integration by charging mode and spatial/temporal mismatches	**Obj 3**: Estimate the proportion of EB energy demand met by PV under different scenarios
Gap 4: Limited scenario-based evaluation of grid, cost, and environmental impacts	**Obj 4**: Evaluate economic, technical, and environmental implications of deployment strategies **Obj 5**: Provide practical recommendations for strategic EB charging deployment in Addis Ababa

Chapter 3

Data and Contextual Analysis

3.1 Study Area

Addis Ababa, the capital city of Ethiopia, is located in the central highlands at an elevation of about 2438.0 meters above mean sea level. The geographic coordinates of the city lie at a latitude of 8.8° to 9.1° N and longitudes of 38.7° to 39.0° E. The political, economic, and cultural hub of the nation, Addis Ababa, spans roughly 530 square kilometers. The city is separated into eleven sub-cities for administrative purposes. Each sub-city has a duty of handling infrastructure, urban planning, and service delivery under its administration. Sub-cities such as Kirkos, Bole, Lideta, and Yeka are particularly placed in the middle and form the core of the city; they host a majority of business districts, bus stations, and intersections.

By 2024, a population of over 5 million was estimated for Addis Ababa, making it one of the most populated cities in Africa. It has been highly urbanized in the past 20 years as a result of internal migration, economic reform, and increasing public infrastructure. This is likely to continue putting pressure on urban mobility systems.

In transport terminology, Addis Ababa is the national center of people and goods mobility. There are also significant transit corridors like the Addis Ababa–Djibouti corridor, the Addis Ababa Light Rail Transit (AA-LRT) system, and large networks of city buses and minibuses. Additionally, there are main federal government institutions and international organizations within the city, which further confirm the significance of the city in national and regional mobility planning.

In line with its strategic role as a regional and national mobility nexus and industrial center, the city's 2024 daily energy demand patterns are described in Figure 3.1,based on baseline information sourced from [39]. These profiles illustrate the temporal evolution of the composite electricity load in residential, commercial, and industrial sectors and reflect the city's typical travel pattern and modal composition. The demand profile for 2030 is projected based on the 2024 baseline demand in consistent with the approach in [40], to account for anticipated population growth, economic development, and increased electrification. Although these projections do not yet account for electric vehicle (EV) charging loads, they provide a reference baseline by which the impacts of various charging strategies, evaluated in this research for the widespread adoption of electric buses by 2030, can be assessed.

Figure 3.2 provides an overview of Addis Ababa's main subcity division, and from the figure, it is evident that the city is positioned in the middle of Ethiopia and also houses the administrative center of all the regional states, offering a strategic platform for further infrastructure and network analysis.

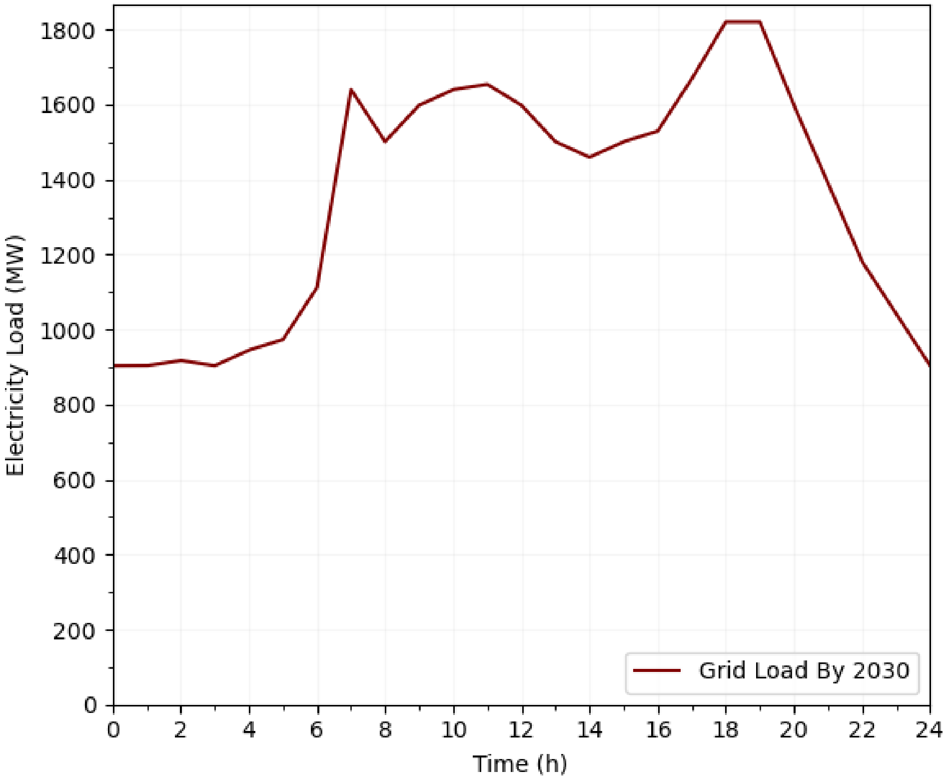


Figure 3.1: Daily Electricity Load Profiles for Addis Ababa, 2024 and Projected 2030

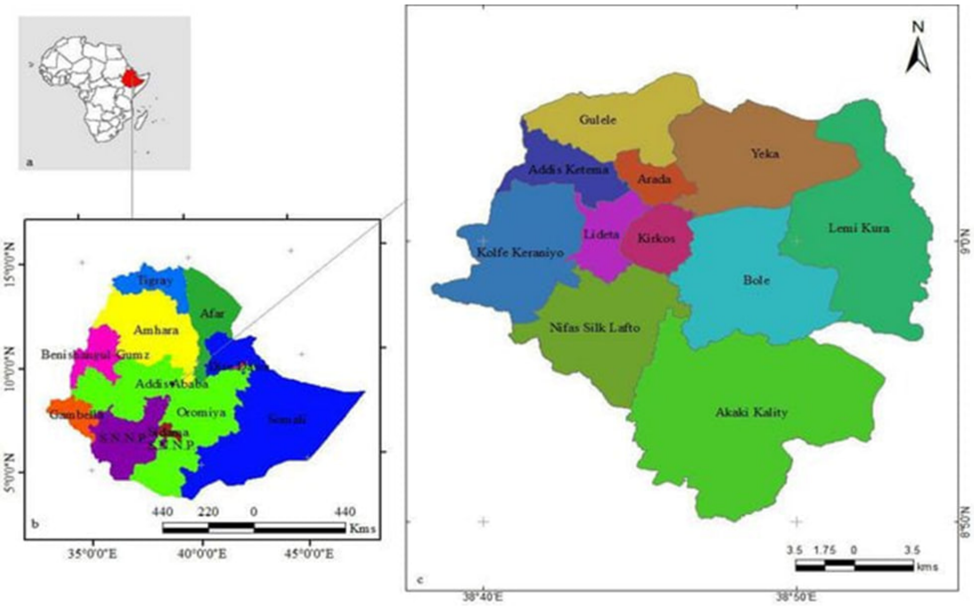


Figure 3.2: The City of Addis Ababa.

3.2 General EV Adoption Trends & Policy Targets

In the last five years, Addis Ababa has witnessed a steady increase in electric vehicle (EV) registrations, marking a wider shift toward sustainable, low-emission urban mobility. The Ministry of Water and Energy (MoWE) provided a comprehensive detail dataset showing electric vehicles registered in the city from 2020 to 2024. The key data points are tabulated in Tables 3.1, 3.2, and 3.3, showing the yearly registration figures, per sub city distributions, and by their type classification. Although the data cover a short time horizon, they provide an essential baseline for evaluating adoption trends and extrapolating future trajectories in Ethiopia's electric mobility market.

Spatially, EV adoption has been strongest in Addis Ababa's dense transport corridors such as Bole,Kirkos, Nefasselk, especially those connected to institutional operations and key commuter paths. This geographic concentration is indicative of the city's role both as a national transportation nexus as well as a testbed for new mobility solutions. Figure 3.3 shows one of the active electric bus corridors in operation, highlighting real-world deployment in urban infrastructure.

These unfold in the context of Ethiopia's ambitious national e-mobility strategy that has set clear quantitative objectives. The government of Ethiopia has committed to putting around 500,000 electric vehicles on the road by 2030, of which 50,000 are electric buses and 148,000 are electric cars. Within this vision, the national strategy seeks to avoid carbon dioxide equivalent (CO_2) emissions by 13.9 million tons by 2022 through decarbonizing the transport system. Charging Infrastructure development is also an integral part of this strategy, where it plans to create more than 2,200 EV charging points across the country. Of these, 1,176 are planned for Addis Ababa, while the rest will be spread out in regional cities [7].

Table 3.1: Distribution of Electric Vehicles by Sub-City in Addis Ababa (2020–2023)

Subcity	Addis Ketema	Arada	Bole	Gulele	Kality	Kirkos	Kolfe	Lemikora	Lideta	Yeka	Nefasselk	**Total**
Total EV	136	380	1026	186	279	960	486	183	270	223	538	**4,667**

Table 3.2: Classification of Electric Vehicles by Type in Addis Ababa (2020–2023)

Category	Automobile	Bus (>11 seat)	Field Vehicle	Dual Purpose Vehicle	Motor Bicycle	Total EV
2020–2023	4626	23	4	8	31	4692

Table 3.3: Yearly Distribution of Electric Vehicles in Addis Ababa (2020–2024)

Year	Registered EV in AA	Total Available EV
2020	143	143
2021	70	213
2022	1009	1222
2023	3470	4692
2024	4047	8739
Total	8739	**8739**

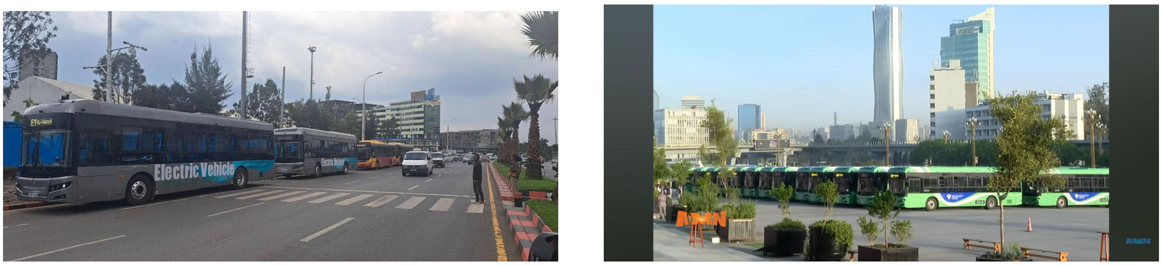
At the city level, Addis Ababa has been given priority as the central hub of electric bus introduction because it has a high concentration of vehicles, with over half of the nation's vehicle fleet. The Addis Ababa City Administration has played an active role in facilitating this shift by ordering 100 electric buses, which are being assembled at the Belayneh Kindie Group (BKG) factory in Debre Birhan, 135 kilometers northeast of the capital. The buses are ready for service by March 2025 (see Fig:3.3b) in Addis Ababa's public transport network, in line with the city's efforts to upgrade its mobility infrastructure and sustainable city.

The capital is also at the forefront of developing key supporting infrastructure, such as EV maintenance centers and intelligent charging stations. This initial investment positions Addis Ababa as a key case study for assessing the operational, environmental, and institutional effects of electric bus rollout. The ten-year transport master plan of the government prioritizes the development of a climate-resilient sector, and Addis Ababa is at the heart of pioneering this transition through corridor-based rollout and urban smart city plans.

As part of continued implementation activities, various private and public actors have started working towards the operationalization of electric mobility. For instance, Velocity Company runs two electric buses on the Bole–Estifanos–4 Kilo–6 Kilo–Shiro Meda routes, providing efficient and clean transport service on one of the city's most busy routes. This is shown in Figure 3.3a. Similarly, Ethiopian Electric Power (EEP) starts operating nine electric buses, comprising five midi buses and four city buses, exclusively for employee transportation services. These cases point to the efforts of institutional and private sector stakeholders towards achieving the transition to electric transport.

Furthermore, regional cities such as Gonder and Debre Birhan have begun adding electric buses to their public service fleets, an early but increasing national trend., reflecting an early but growing national trend. BKG aims to assemble 216 electric mini-buses and 35 regular electric buses through 2024, its company says. Though the numbers reflect significant headway, success in such deployments is predicated on parallel development of smart charging infrastructure and operational preparedness.

In general, the rising EV registration count, the deployment spatial patterns, and the government's strategic targets together define Addis Ababa's new status as a national pioneer in sustainable transport. This policy- and operationally-based primary data offers a basis for assessing infrastructure requirements, investment priorities, and the long-term direction of electric mobility in Ethiopia.



(a) Commissioned Electric Buses (b) The 100 EBs Ready for Service

Figure 3.3: Electric Buses in Addis Ababa

3.3 Electric Buses Characteristics

There are different types of electric buses available in Ethiopia's current fleet. These include the Electric City Bus, Electric Midi Bus, and Electric Mini Bus. These models are designed to address different segments of urban transportation and embody the nation's push towards embracing clean and efficient transportation technologies. The buses' technical specifications are summarized in Table 3.5, including their performance characteristics, energy capacity, and passenger capacity.

The Electric City Bus is the most powerful and has the highest capacity of the these models, and is thus recommended for high-capacity routes. It has a powerful 195 kW motor and 350 kWh battery for a range distance coverage of up to 345 km per full charge. The bus takes a charging time of 1 to 3 hours via 120 kW or 160 kW DC chargers and has a seating capacity of 70 passengers, comprised of 40 seated and 30 standing passengers. It makes a very suitable option for high-demand urban routes with dense ridership demand.

The Electric Midi Bus is designed for medium-capacity routes. It is equipped with a 195 kW motor and a 157 kWh battery pack and has a maximum range of up to 300 km. Among the key advantages, it offers faster charging because it will charge completely in just 20 to 40 minutes from fast chargers. The Midi Bus has a capacity for 29 passengers, and its applications lie in feeder services or medium-density lines.

The Electric Mini Bus is designed for low-to-medium demand corridors and shorter distances. It has an 80 kW motor and a 65.175 kWh battery and provides a range of 270 to 350 km, depending on terrain and load factors. It can be charged within 20 to 40 minutes from DC fast chargers or in around 8 hours from standard AC chargers. The minibus has a maximum seating capacity of 15 passengers and is ideal for suburban or last-mile operations.

All these models of buses have basic comfort and operational needs like air-conditioning, audio-visual systems to communicate with the passengers, and warranty service: 8 years for the battery and 5 years for the electric control system and motor. All these features contribute to reliability, passenger experience, and long-term operation viability.

In addition to the charging and energy demands specified above, the physical and dynamic characteristics of the electric buses are summarized in Table 3.4. The information from the China Golden Dragon Bus Manufacturer and BKG technical reports incorporates required parameters such as vehicle size, curb weight, acceleration and braking, top speed, passenger capacity, and emissions class. Such information is critical in understanding operational fit, infrastructure requirements, safety concerns, and the simulations during the planning of electric bus deployment in urban and intercity settings. Baseline parameters complement the battery and range requirements and all together demonstrate how different bus classes are tailored to operate within Ethiopian traffic and road conditions.

These deployments, along with pilot initiatives operated by both the private and public sectors, are significant early milestones in Ethiopia's broader transition toward electric mobility. They also indicate the flexibility of each bus model to suit different segments of the urban transport system.

Table 3.4: Physical and Performance Characteristics of Electric Bus Classes

vClass	Length	Width	Height	Curb Weight	Min Gap	Accel(m/s^2)	Decel(m/s^2)	Emergency Decel	Max Speed	Desired Max Speed	Person Capacity	Emission Class	Speed Dev
Bus	12 m	2.5 m	3.4 m	12,000–14,000 kg	2.5 m	1.2	4	7 m/s^2	85 km/h	–	80–100	EV	0.05
Coach/Bus	14 m	2.6 m	4 m	13,000–15,000 kg	2.5 m	2	4	7 m/s^2	100 km/h	–	45–70	EV	0.05
Midi Bus	7 m	2.2 m	3.2 m	4,000–6,000 kg	2.5 m	1.5	4	7 m/s^2	80 km/h	–	20–30	EV	0.05
Mini Bus	6 m	2.1 m	3 m	3,500–4,500 kg	2.5 m	1.6	4	7 m/s^2	75 km/h	–	10–15	EV	0.05

Table 3.5: A Summary of The Technical Details and Capacities of Electric Buses

Item	**Electric–City Bus**	**Electric–Midi Bus**	**Electric–Mini Bus**
Driving mileage	345 km	300 km	270–350 km
Motor	195 kW	195 kW	80 kW
Battery capacity	350 kWh	157 kWh	65.175 kWh
Charging hour	3 hr by 120 kW 1 hr by 160 kW charger 10 batteries	40 min by 120 kW 20–30 min by 160 kW 2 batteries	40 min by 120 kW 20–30 min by 160 kW 8 hr if AC charger 2 batteries
Seat capacity	40 + 1 driver seat 30 standing passengers Total of 70	29 + 1 driver seat	15 seats
Roof	Electric AC for EV, with battery water cooling system	Electric AC for EV, with battery water cooling system	Standard with AC
Audio-vision system	MP3 player with radio, 8 speakers	DVD + 19 inch LCD	MP3 player with radio
Warranty	8 years for battery 5 years for motor and controller 1 year for others	8 years for battery 5 years for motor and controller 1 year for others	8 years for battery 5 years for motor and controller 1 year for others
Maximum speed	100 km/h	100 km/h	Not specified

3.4 Estimated Number of Electric Buses by 2030

The forecast of number of electric buses by 2030 is critical for this research for several reasons. First, it helps to determine the total energy demands needed to support the growing fleet of electric buses and, consequently, is an integral part in planning the optimum number and locations of charging facilities. In addition, an understanding of the transition from fuel-based to electric buses allows policymakers and other stakeholders to assess the economic and environmental implications of electrification.

This includes analysis of fuel cost savings, reductions in greenhouse gas emissions, and improvements in urban air quality. Lastly, having a well-structured projection is critical for informing transport policy and investment decisions, thus ensuring that the mobility transition to electric is sufficiently supported by necessary infrastructure and resources.

Using regression model (please refer Appendix A)to predict future bus fleet mix, what comes out is that by the year 2030, Addis Ababa will have a total fleet of 1,928 buses, 632 of which will be electric buses. The estimated calculation is important in the follow-up analysis, especially in calculating the overall energy need for electric buses in 2030. With a correct calculation of the number of fleets, it is now feasible to develop an extensive plan for electric bus charging stations, hence ensuring that there are sufficient charging stations constructed in strategically positioned locations to facilitate smooth operations. This evidence-based approach minimizes the risk of underinvestment or overinvestment in infrastructure, which results in a more effective and sustainable public transport network. The estimated values are summarized in Table 3.6 below.

Table 3.6: The Estimated Number of EBs by 2030

Year	**Regression Forecast (Bus No)**	**Bus Increase (vs 2024)**	**No. of EB**
2025	1296	-134	102
2026	1419	-11	123
2027	1542	112	246
2028	1668	238	372
2029	1799	369	503
2030	**1928**	**498**	**632**

The detailed input data used for the regression analysis is available in Table A.1. This forecast research offers an evidence-based contribution to the comprehension of the shift towards electric mobility in Addis Ababa. The results underscore the significance of economic determinants like GDP growth, fuel price dynamics, and population growth in influencing fleet adoption. The results are a vital guide to this research and infrastructure development, as well as for the energy demand analysis, to conform the projected development of the EB fleet, in light of the governments push for electrification.

3.5 Charging-Infrastructure Landscape

Addis Ababa is currently in the early stages of developing its electric bus (EB) charging infrastructure. These charging stations are vital to support the growing adoption of electric vehicles in the city and align with the government's efforts toward sustainable urban mobility. The following section highlights the various charging infrastructure projects currently present in Addis Ababa, their capabilities, and limitations.

3.5.1 Existing Charging Stations in Addis Ababa

Charging Station at Kotebe (EEP Head Office)

This charging station, located at the head office of Ethiopian Electric Power (EEP) in Kotebe, is currently under construction. It is being developed to serve their own electric buses procured by the company. The station represents a significant step towards expanding the city's capacity to accommodate electric buses.

Figure 3.4: Charging Station at Kotebe (EEP Head Office)

Public EV Charging Station on Bole–Megenagna Road

In February 2025, a high-speed charging station for the general public to charge their electric vehicles was opened at both sides of the Bole-Megenagna road in Addis Ababa. This station showcases one of the latest charging systems available in the city and serves as a solution for the ever-growing need for faster charging services of such vehicles.

The station can charge up to 32 vehicles at a time and has the capacity to charge vehicles through three different charging methods: the use of ultra-fast Direct Current

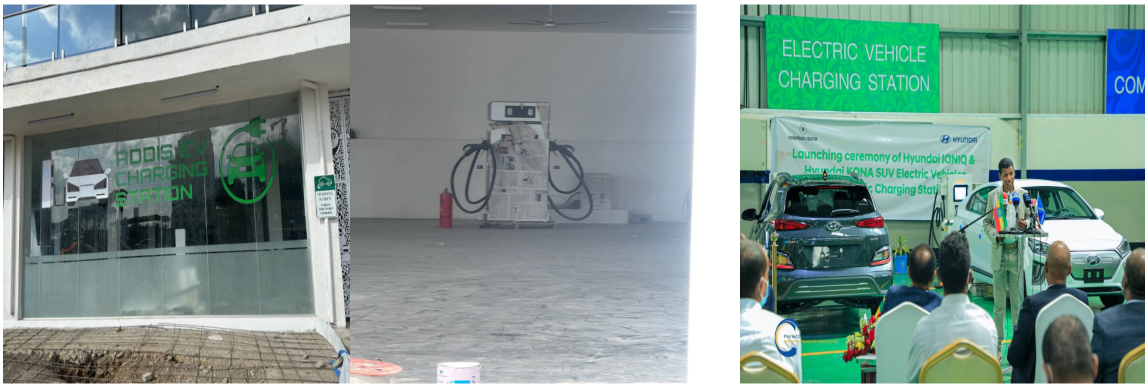
(DC) chargers that can deliver a maximum of 600 kW of power. Such chargers can charge vehicles at their maximum capacity within 15 minutes. Fast 500 kW chargers and Level 2 Smart Pole chargers are also included.

The charging station uses AI to maximize the efficiency of the charging process based on the condition of the vehicle battery as well as the user's preference. This provides faster and more energy-efficient charging. Real-time monitoring of the charging process provides users with information about the status of the charging as well as notification through a mobile app. The station operates 24/7 and has self-service systems. Although this station is publicly available, their charging convenience is limited to the private EVs not suitable for public electric bus.

Figure 3.5: Public Charging Station at Bole–Megenagna Highway Road

EV Charging Stations at Tewodros Adebabay and Hyundai Company

Another charging station is located near Tewodros Adebabay in Piazza. While this station contributes to the city's growing network, its specific charging capabilities and operational details are yet to be fully utilized for larger electric buses. The Hyundai Company has set up its own charging station, primarily dedicated to vehicles manufactured or distributed by the company. Currently, this station is restricted to automobiles produced by Hyundai and does not accommodate electric buses. This limitation highlights the need for more universal charging solutions to meet diverse EV demands.



(a) Tewodros Adebabay Station (Piazza) (b) Charging Station @ Hyundai

Figure 3.6: Charging Stations at Tewodros Adebabay and Hyundai Company

Charging Station at Stadium

A charging station located at Stadium is operational; however, it is equipped with AC charging infrastructure, which is not capable of charging larger electric buses. This restriction highlights a critical gap in infrastructure that needs to be addressed to support the city's growing fleet of electric buses.

Figure 3.7: Electric Vehicle Charging Station at Meskel Flower Stadium

In nutshell, the existing charging infrastructure in Addis Ababa provides a strong foundation for the city's transition toward electric vehicles. However, the limitations observed at various locations, such as restricted access, lack of compatibility with electric buses, and stations under construction, underscore the need for strategic planning and investment. By expanding and upgrading these facilities, Addis Ababa can effectively support the growth of electric buses and achieve its long-term goals for sustainable urban transportation.

3.5.2 Technical Specifications and Cost Overview

The primary data from BKG Business Group indicates that the DC fast chargers and currently installed and operational at the head office of Ethiopian Electric Power (EEP), Kotebe are designed particularly to meet the high-power charging requirements of electric buses and other large electric vehicles (EVs), facilitating effective energy transfer as well as less downtime. The chargers are supplied with an AC 380V (three-phase + neutral) power input, which provides stable and high-capacity power output, thus making them suitable for large-scale fleet applications. The output voltage ranges from 100V to 750V DC, which makes them suitable for a variety of electric bus battery configurations. Additionally, the chargers have a maximum current output of 250A, which encourages high-speed charging, essential to ensure that charging time is kept to a minimum and electric bus operations are maximally efficient.

BKG DC chargers come in four capacities: 60 kW, 80 kW, 120 kW, and 160 kW. All these chargers also support simultaneous charging, which means that they can distribute power to two charging terminals in order to charge more than one car at the same time. The 60 kW option distributes power into 40 kW + 20 kW, which would be efficient enough for average charging requirements. The 80 kW chargers offers the same split of 40 kW + 40 kW, offering equal charging space between two vehicles. The 120 kW variant provides 60 kW + 60 kW, which can be used to charge high-energy-demand buses in quick time. The 160 kW chargers can provide 80 kW + 80 kW, the highest possible power, to charge large electric buses with large battery capacity using fast charging. These facilities help fleet operators to optimize their charging schedule and reduce overall costs of operation.

The physical form factor of the chargers also varies with power capacity. The 60 kW one weighs 220 kg, 80 kW weighs 240 kg, and the 160 kW one weighs 320 kg, which shows their heavy-duty nature and high-power output capability. The structures are made for reliability and stability reasons, ensuring applicability for mass-deployment in the urban public transport system, electric bus depots, and heavy-load charging stations. One of the main benefits of these chargers is that they are highly efficient, with an efficiency rating of over 95%, which reduces energy waste and maximizes the use of power. This makes the process of charging cost-effective and eco-friendly, saving wastage of electricity and minimizing charging time. The feature of real-time power management and secure and efficient charging process is made possible by the smart charging facility of such chargers. Overvoltage protection, short circuit protection, and thermal management enhance the safety and reliability of such chargers since they provide the chargers with the ability to operate flawlessly in any environment.

BKG's DC fast chargers are specifically designed for commercial electric bus fleets, supporting rapid turnaround times by reducing idle periods and ensuring maximum vehicle availability. The ability to charge multiple buses simultaneously enhances operational flexibility and ensures that fleet operators can maintain reliable public transport services. These chargers are particularly suitable for urban transit systems, fleet depots, and high-demand charging infrastructure, where efficiency and reliability are crucial.These chargers are summarized in the Table 3.7 below:

Table 3.7: DC-EV Charger Technical Specifications

Parameter	**60 kW**	**80 kW**	**120 kW**	**160 kW**
Power input	AC 380 V (3-phase + neutral)			
Power output Voltage	DC (100–750) V			
Current	Max 250 A			
Charging way (simultaneously)	(40 + 20) kW	(40 + 40) kW	(60 + 60) kW	(80 + 80) kW
Net weight	220 kg	240 kg	320 kg	
Efficiency	> 95%			

In order to help plan and estimate the cost of charging facilities for electric buses (EB) in Addis Ababa, we also obtained detailed technical and cost data on several direct current (DC) quick chargers from RUIHUN New Energy Technology in Shenzhen. This was done through a personal discussion with the company's sales manager. The chargers are available with rated powers of 120 kW, 360 kW, 400 kW, 480 kW, 500 kW, 600 kW, and 720 kW, utilizing primarily the GB/T interface (a Chinese national standard for DC fast charging), with dual-interface availability at the 360 kW level supporting both GB/T and CCS Type 2 (Combined Charging System Type 2, a European standard) connectors. Prices range from \$3,640 for the 120 kW charger to \$56,000 for the 720 kW charger. For the 360 kW unit, prices differ by interface: \$15,970 for CCS2 and \$6,320 for GB/T. This vast amount of data presented the various kinds of charger technologies along with their cost. It assists in the selection of proper solutions for different charging strategies.

Although the a varity of charger types was seen for reference, just three charger types were utilized for simulation and cost modeling in the project: the 120 kW GB/T charger (\$3,640) for depot charging, where the longer dwell time renders slower charging economically feasible; and the 400 kW GB/T charger (\$6,875) for layover charging applications, which are admirably suited for medium-length stops. For on-route charging, where brief stops necessitate high-power rapid charging, the 500 kW GB/T charger (\$17,703) was selected. These three types, which balance infrastructure cost, operational factors, and compatibility with bus fleet parameters, were judged to be the most realistic and representative for the strategic deployment scenarios examined in this thesis. Although they are not included in the model, the additional charger options are useful standards for future scale-up or regulation requirements.

3.6 Public-Transport Network Profile

The General Transit Feed Specification/GTFS data employed in this study is a very detailed and comprehensive examination of the public transportation services offered in Addis Ababa. It was gathered between August 2022 and March 2024 by AddisMapTransit through financial and technical support from the Digital Transport for Africa (DT4A) Innovation Challenge. The dataset is instrumental in determining the structure, coverage, and operational features of the transit networks in the city and is one of the key tools in optimizing the installation of electric bus charging stations.

The information pertains to the principal transit entities serving Addis Ababa, which are Addis Ababa Transport (Bus), Anbessa City Bus Service Enterprise, Sheger Mass Transport Service Enterprise, and Addis Ababa Transport Authority (Minibus). Each entity serves its own role in the public transport of the city, addressing various routes, passenger needs, and organizational frames. But, minibus services are not covered by this study.

One of the most important elements of the dataset used under this study comprises 193 unique transit routes, with each route corresponding to a specific bus line or service. The routes specify the paths traveled by buses and dictate how transportation is allocated throughout the city. The dataset further assigns 385 geographic trajectories (shapes), which specify the precise routes, those buses take when in movement. Shapes are important for comprehending route structures, establishing areas of potential overlaps, and specifying suitable locations for future route changes.

The data also records 1,340 distinct bus stops, which are designated points where passengers board or disembark from public transport vehicles. Stops are key components of transit planning since they impact accessibility, ridership patterns, and passenger convenience. The stops are distributed across various trips along with its routes.

Furthermore, the data set encompasses 385 distinct trips, where each trip is a case of a bus moving on a particular route. The trips offer valuable information regarding vehicle scheduling, route frequency, and travel of passengers. More significantly, the data set records both spatial and temporal variations in transit operations, thereby enabling a more detailed examination of service performance and demand variation.

The structured format of this dataset enables advanced data processing and analysis by precisely indicating the location and timing of each bus. This information supports a range of activities, including mapping transit routes, identifying areas with high demand for electric bus charging infrastructure, and simulating fleet operations under various deployment scenarios. Figure 3.8 presents the bus network within the study area, where lines represent bus routes and the numbers denote the total bus stops at each location. The map effectively highlights the spatial distribution and density of bus stops across Addis Ababa, providing a solid foundation for analyzing electric bus operations and associated energy demand patterns.

Table 3.8: Summary of GTFS Feed and Trip Characteristics

GTFS Feed Data	Trip Statistics
Trips: 385	Total Trip Length: 5,272.46 km
Routes: 193	Average Trip Length: 13.69 km
Shapes: 385	Min Trip Length: 2.32 km
Stops: 1,340	Max Trip Length: 54.79 km
Temporal Coverage	**Stop Statistics**
Operating Period (hr.): 05:00–22:00	Min Stops per Trip: 3
	Max Stops per Trip: 35
	Avg Stops per Trip: 13
	Avg Stops per Route: 26

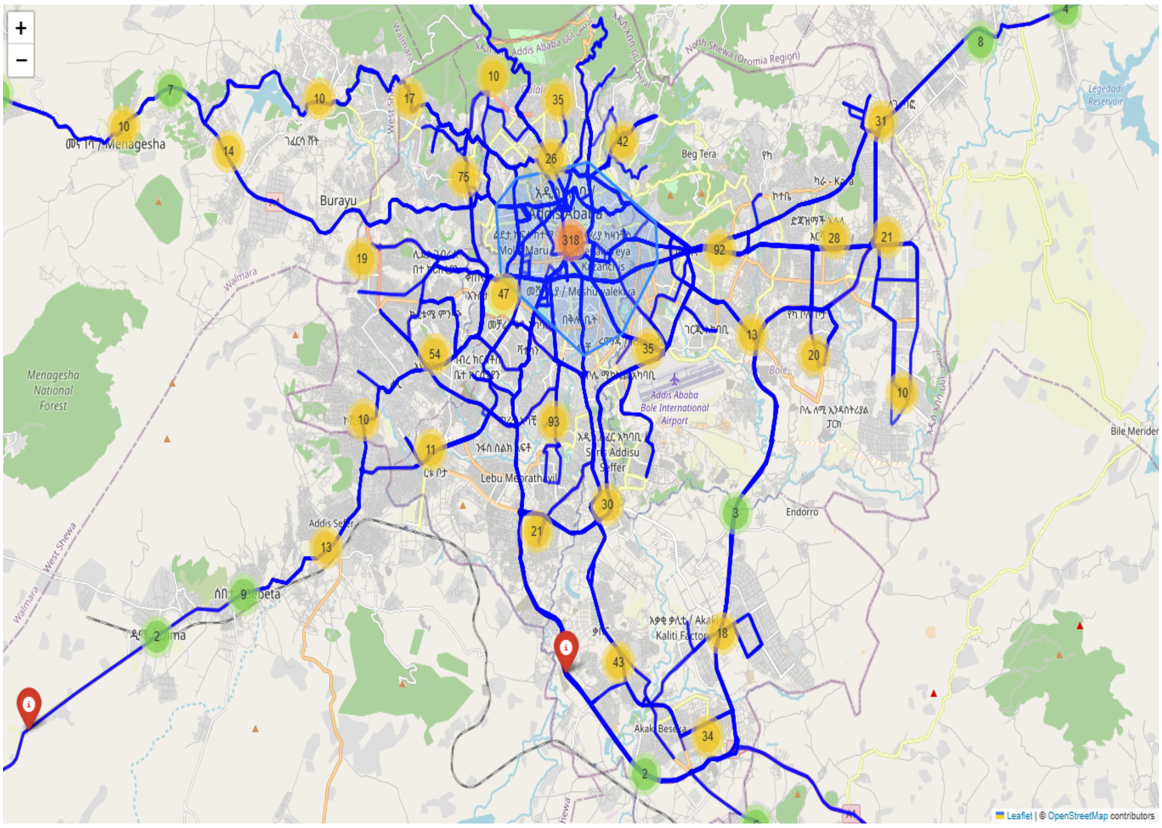


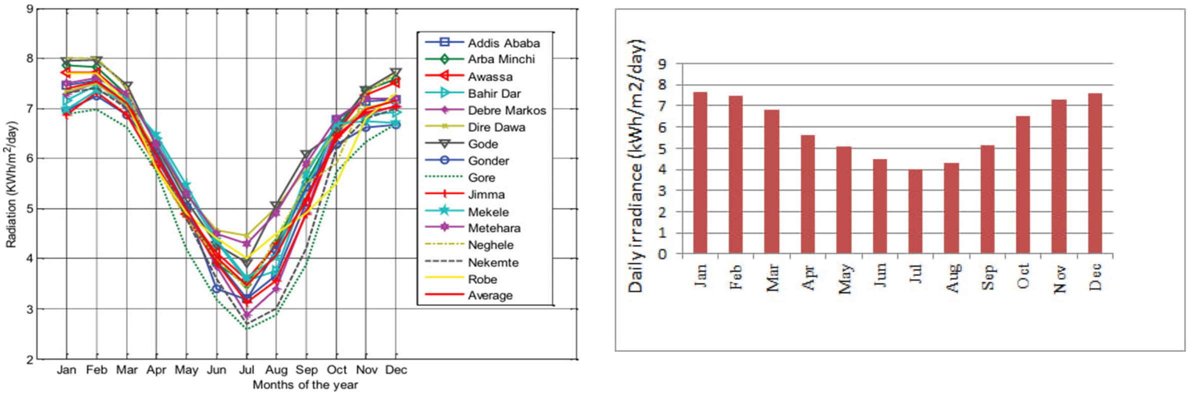
Figure 3.8: Bus Network in Addis Ababa with Stop Density

3.7 Renewable-Energy Potential

Addis Ababa's transition to renewable energy requires a thorough assessment of its solar potential, particularly for electric bus (EB) charging facilities. The city, located at 9.01891°N latitude and 38.7475°E longitude at an altitude of 2,386 meters, has high solar irradiance for most of the year. This geographic location makes it very favorable for photovoltaic (PV) power systems.

To verify this possibility, solar radiation data were obtained using the System Advisor Model (SAM) of the United States National Renewable Energy Laboratory (NREL). Inputting the coordinates of Addis Ababa yielded a daily and monthly average global horizontal irradiance (GHI) values. These data were also compared with results from the study "Estimation of Global Solar Radiation Using Sunshine-Based Models in Ethiopia" [41], in which several empirical models were tested using sunshine duration data. Figure 3.9a shows the monthly mean daily solar radiation at Ethiopian stations from the said study, while Figure 3.9b shows SAM-calculated daily GHI values for Addis Ababa alone.

The study confirmed that Addis Ababa receives sufficient sunlight all year round, with extremely high intensities of sunlight during the dry season (October to March) of about 7.65 kWh/m^2/day and low intensities during the rainy season (June to August) of about 4.01 kWh/m^2/day. The comparison between the SAM output and the empirical model results confirmed that they are very alike, enhancing the credibility of both sources. This confirmed the feasibility of solar-powered charging stations for EBs. Solar-based charging not only minimizes grid dependence and emissions but also addresses the issue of an unreliable power supply in Ethiopia. Therefore, the integration of solar PV systems into EB charging infrastructure expected to offers a sustainable, affordable, and resilient urban mobility option for Addis Ababa.



(a) Monthly average daily global solar radiation for each station in Ethiopia and the average [41]

(b) Daily solar radiation levels in Addis Ababa

Figure 3.9: Solar Resource Data of Addis Ababa

3.8 Key Insights & Data Limitations

This chapter has discussed the study area, provided an overview of the current state of electric mobility in Addis Ababa, analyzed policy aspirations, outlined the early electric bus fleet, charted the city's current charging-infrastructure landscape, characterized the public-transport network based on GTFS data, and assessed the available renewable-energy opportunity for supporting e-mobility. Several important findings emerge from this contextual analysis.

Firstly, According to the data, Addis Ababa is leading the way in the country's significant trend toward the adoption of electric vehicles. The ambitious e-mobility plan of the Ethiopian government, which is targeting 500,000 EVs, including 50,000 electric buses, by 2030, is being complemented by city-level initiatives to electrify mass transit by adding electric bus fleets. Policy momentum is apparent, but current charging-infrastructure provision remains in its infancy: there are only a few pilot chargers installed, and no city-wide public charging network has yet been launched. The gap between planned vehicle uptake and charging-infrastructure readiness highlights a primary implementation gap that must be closed to enable large-scale fleet electrification.

Second, the GTFS analysis of Addis Ababa's public transportation system reveals high-demand corridors with route overlap, dense stop clustering, and long trip lengths. These hotspot segments, especially along central transfer nodes and strategic radial axes, are most opportunistically located for future charging point locations regarding maximizing utilization and convenience. The network measures, including stop densities and route lengths, will be included in the modeling framework developed in Chapter 4.

Third, renewable-energy analysis indicates that there is high solar potential within the metro area that could be harnessed to electrify strategically located charging hubs. This opens up opportunities for solar-assisted charging solutions consistent with Ethiopia's broader low-carbon energy ambitions.

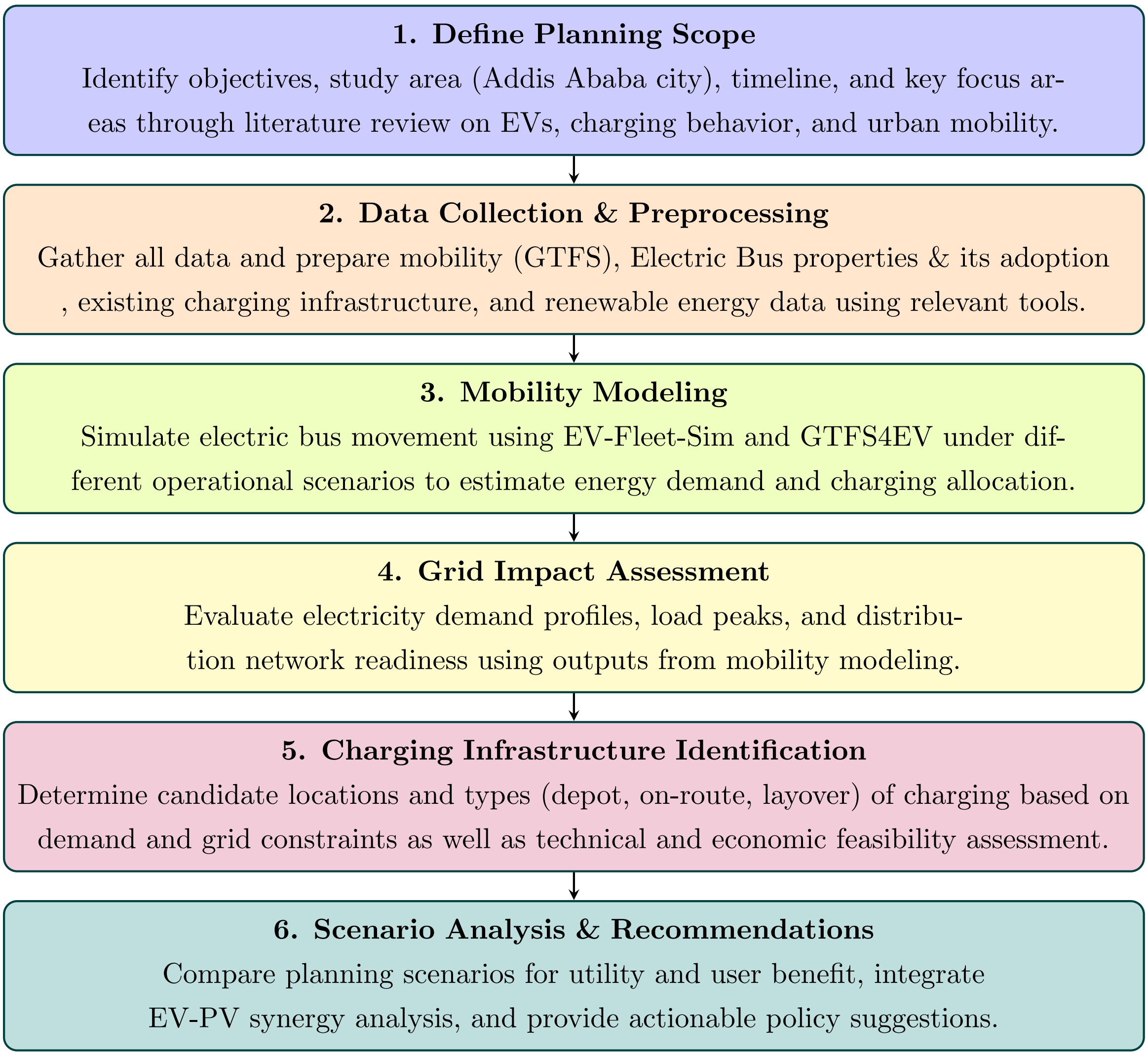
Despite these insights, the study also has several limitations. Publicly available data on charging infrastructure is scant and fragmented, and therefore obliged to rely on direct observation and government statements rather than on full datasets. Similarly, while the GTFS feed provides a complete picture of route structures and frequencies, it represents previously scheduled service rather than real electric bus conditions. Projections of electric bus adoption through 2030 are therefore based on policy ambition rather than fixed procurement plans. But,It is important to acknowledge that these forecasts carry a degree of uncertainty. The rate of uptake of electric buses will depend on a series of dynamic influences, including government policy updates, international trends in battery costs, the speed of charging infrastructure development, and operators' and users' appetite to transition to electric vehicles. Any removal of policy support or disruption of supply chains would slow the rate of adoption compared to current expectations. And the consideration of solar potential assumes that there is urban land available for photovoltaic systems.

In summary, the evidence in this chapter brings to light the fact that Addis Ababa is at the nascent but critical stage of its electric mobility transition. While policy commitments are strong, there is a gaping infrastructure deficit, and the spatial form of the city's transit system reveals clear priorities for targeted interventions. These results and datasets, the GTFS network configuration, electric bus scenarios, and solar resource potential, especially, are the key inputs to Chapter 4's modeling, scenario creation, and infrastructure planning analyses.

Chapter 4

Modeling Methodology

The study methodology begins with defining the planning scope and collecting the required datasets, like GTFS-based mobility, bus, grid data, and renewable energy sources. With these inputs, EV-Fleet-Sim and GTFS4EV are employed to simulate electric bus operations, generate trip-level energy profiles, and perform charging demand calculations under different scenarios. The results are then examined in order to estimate grid impacts, identify candidate charging locations per charging strategies, and examine the role of solar PV. Finally, alternative charging scenarios are compared to gain planning insights and policy suggestions. The entire general methodology is presented in Figure 4.1.



1. Define Planning Scope
Identify objectives, study area (Addis Ababa city), timeline, and key focus areas through literature review on EVs, charging behavior, and urban mobility.

2. Data Collection & Preprocessing
Gather all data and prepare mobility (GTFS), Electric Bus properties & its adoption , existing charging infrastructure, and renewable energy data using relevant tools.

3. Mobility Modeling
Simulate electric bus movement using EV-Fleet-Sim and GTFS4EV under different operational scenarios to estimate energy demand and charging allocation.

4. Grid Impact Assessment
Evaluate electricity demand profiles, load peaks, and distribution network readiness using outputs from mobility modeling.

5. Charging Infrastructure Identification
Determine candidate locations and types (depot, on-route, layover) of charging based on demand and grid constraints as well as technical and economic feasibility assessment.

6. Scenario Analysis & Recommendations
Compare planning scenarios for utility and user benefit, integrate EV-PV synergy analysis, and provide actionable policy suggestions.

Figure 4.1: Overall Methodology for EB Mobility Planning and Analysis

4.1 Overview of Modeling Framework

This study uses a simulation-based modeling approach to simulate and optimize the deployment of optimal charging stations for electric buses in Addis Ababa. The approach integrates two basic simulation tools: EV-Fleet-Sim and GTFS4EV, to simulate electric bus operations and analyze solar energy integration to power electric buses (EBs). The whole process is structured around three key phases: Input Data, Modeling, and Output/post-output Analysis, as shown in Figure 4.2 below.

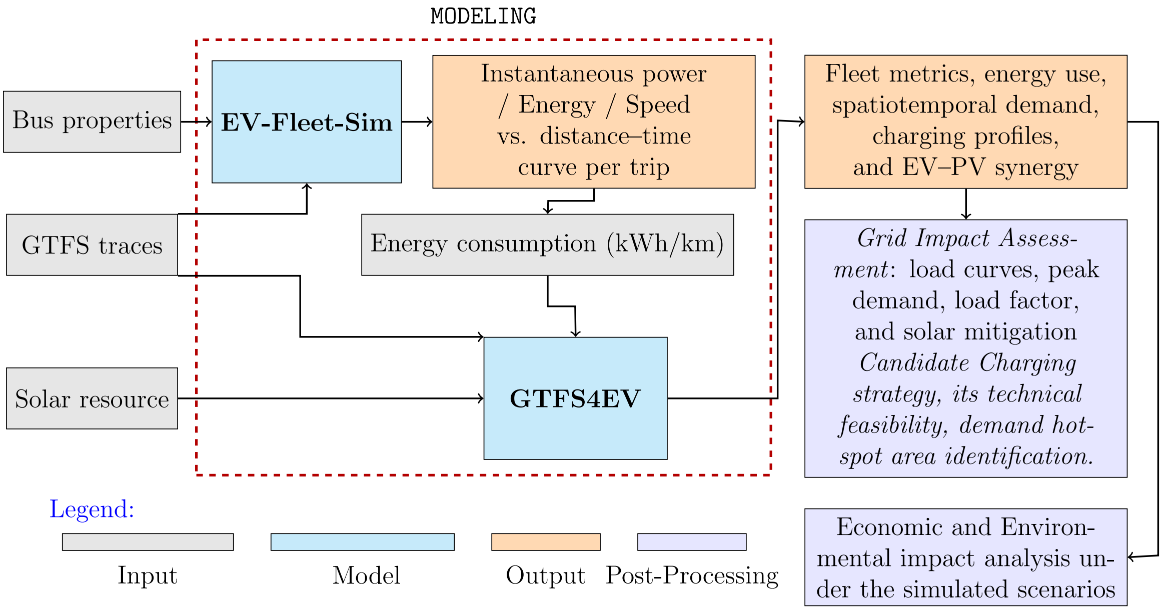


Figure 4.2: Overall System Model Block Diagram

Through this approach, modeling and simulating the most favorable location and infrastructural equipment for charging stations of electric buses in Addis Ababa would be novel. For realistic projection of future demand of the electric bus fleet and the resultant energy requirement, two advanced model software packages, EV-Fleet-Sim and GTFS4EV Model, were utilized. While EV-Fleet-Sim primarily models electric bus travel and energy consumption, the GTFS4EV Model is used for both result comparison and assessing solar integration potential as well as the spatial allocation of charging stations as per the different scenarios(i.e. depot, layover, and on-route), which has yet to be, accomplished with GTFS data in EV-Fleet-Sim. These models enable the study to analyze and visualize both temporal and spatial aspects of fleet operations. In turn, this facilitates the estimation of charging infrastructure requirements, optimal station placement, and the integration of renewable energy into the system.

4.2 Simulation of Bus Per Trip Energy Profiles

To generate detailed trip-level energy profiles for Addis Ababa's public transportation system, this present research utilizes the open-source `EV-Fleet-Sim` model. The software integrates transit schedule information (GTFS), road network boundaries, and electric bus (EB) properties to simulate bus operation and energy consumption.

The simulation begins by preprocessor-cleaning the GTFS feed such that schedules, routes, and stop information are in simulation-formatted presentation. EV-Fleet-Sim then reconstructs vehicle trajectories throughout the network, accounting for traffic conditions, dwell times at stops, and route geometry. On a per-simulated-trip basis, the tool calculates instantaneous power demands and consolidates these into trip-specific energy consumption profiles. The key outputs are include: vehicle-level energy consumption profiles for all scheduled trips, Trip power, and speed for all time distributions.

These outputs are the foundation for further charging-infrastructure planning with `GTFS4EV`. The complete EV-Fleet-Sim workflow is shown in Figure 4.3.

4.3 Simulation of Scenario-Based Charging Needs and Infrastructure Siting

To evaluate charging infrastructure requirements for Addis Ababa's electric bus network, this study employs the open-source novel model `GTFS4EV`, developed as part of the OpenMod4Africa project. The model was completed in parallel with this work, and this thesis represents the first application of GTFS4EV in a real-world context, where it is tested and adapted to local transport and energy data to provide scenario-based simulations of charging demand and inform infrastructure siting decisions.

`GTFS4EV` simulates the energy demand of public transport fleets by combining the operational patterns in GTFS data with per-kilometer energy consumption profiles generated by EV-Fleet-Sim(Fig. 4.2). For each charging scenario (depot, layover, and on-route), the tool estimates spatiotemporal charging requirements, fleet energy use, and the suitability of candidate charging locations.

The simulation framework produces high-resolution (1-minute) load curves, spatial maps, and fleet-level operational metrics that support two key planning tasks: (i) quantifying when and where energy is required, and (ii) identifying charging station siting priorities. A key output is the *charging load curve*, which aggregates system-wide charging power over the day and highlights peak demand periods. Complementary outputs include per-vehicle charging schedules, per-stop charging timelines, interactive maps showing charging hotspots, and PV production profiles to evaluate renewable integration.

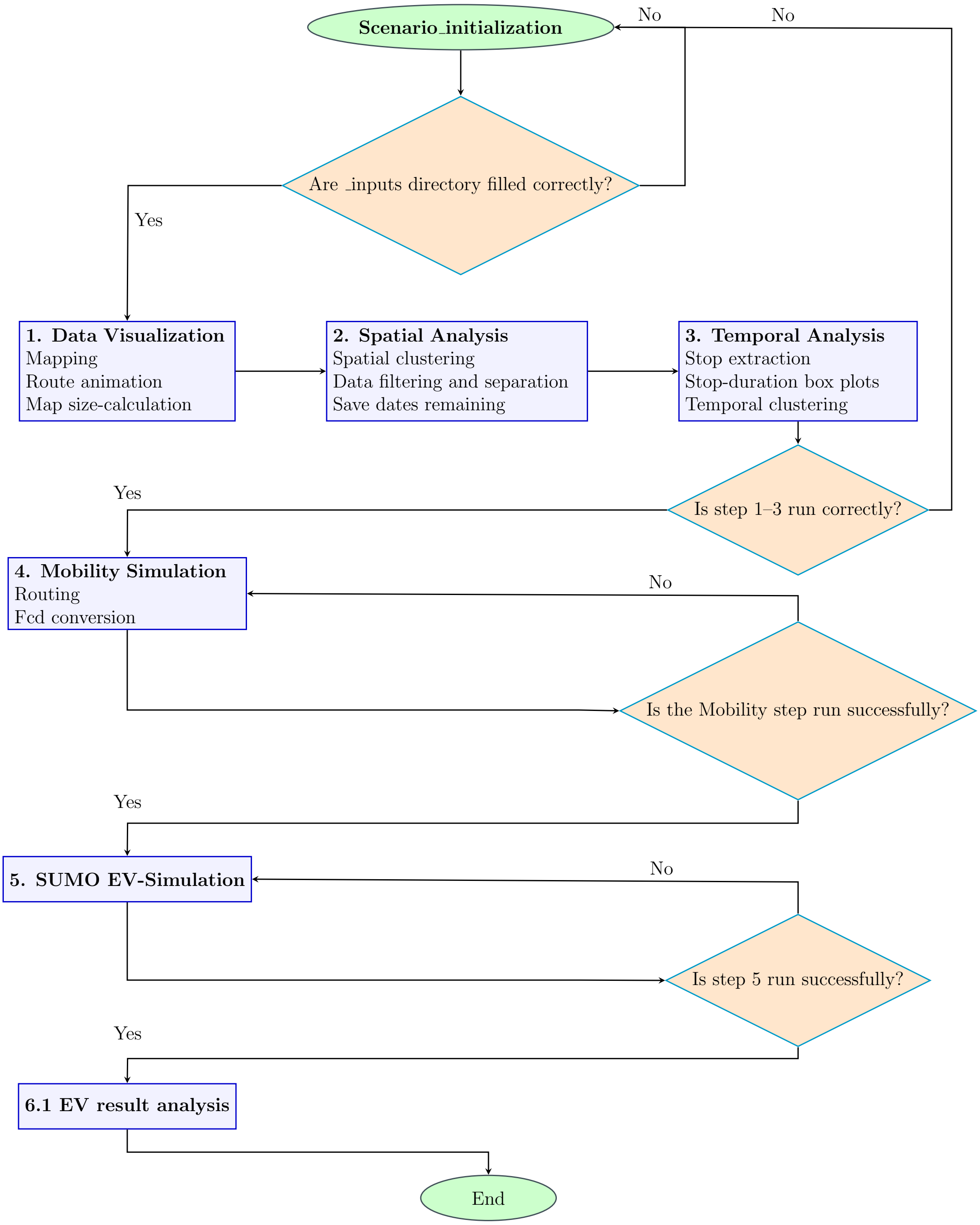


Figure 4.3: Workflow of EV-Fleet-Sim Modeling Process

These findings enable a granular evaluation of fleet size, energy, and infrastructure requirements without the need for real-time telemetry. Outputs from `GTFS4EV` directly feed into subsequent analysis steps in this study, including grid impact assessment (Section 4.5) and the evaluation of alternative charging scenarios. An overview of the GTFS4EV workflow is shown in Fig. 4.4.

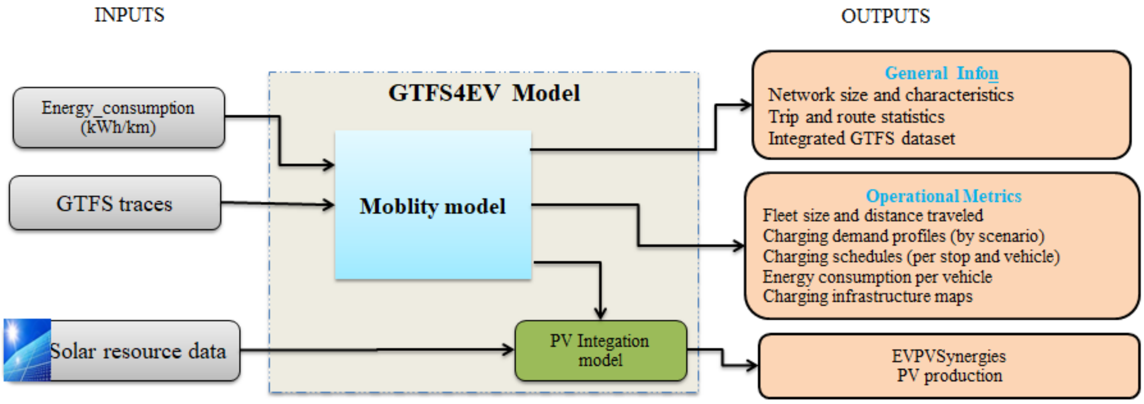


Figure 4.4: GTFS4EV Model Input–Output Workflow

4.4 Load-Based Charging Infrastructure Sizing

Starting from the aggregated load curve $P(t)$ for the entire bus fleet, the total number of chargers for each charging scenario can be estimated as follows:

1. **Determining peak power demand from the load curve**

$$P_{\text{peak}} = \max_t \left(P(t)\right) \tag{4.1}$$

2. **Account for charger efficiency**

$$P_{\text{req}} = \frac{P_{\text{peak}}}{\eta_{ch}} \tag{4.2}$$

   where η_{ch} is the overall charging efficiency (typically 0.90–0.95).

3. **Compute the number of chargers from peak power** For chargers rated at P_{ch} (kW) and an assumed utilization (diversity) factor f_u (0.8–0.95):

$$N_{ch} = \left\lceil \frac{P_{\text{req}}}{P_{ch} \cdot f_u} \right\rceil \tag{4.3}$$

4. **Cross-check with energy delivery in the available charging window** If charging is constrained to a time window T_{win} (hours) and the total required daily energy is:

$$E_{day} = \int_0^{24} P(t)\, dt \tag{4.4}$$

then the charger count must also satisfy:

$$N_{ch} \geq \left\lceil \frac{E_{day}}{\eta_{ch} \cdot P_{ch} \cdot T_{win}} \right\rceil \tag{4.5}$$

Finally, the governing equation used becomes:

$$N_{ch} = \max \left(\left\lceil \frac{P_{\text{peak}}}{\eta_{ch}\, P_{ch}\, f_u} \right\rceil, \left\lceil \frac{E_{day}}{\eta_{ch}\, P_{ch}\, T_{win}} \right\rceil \right) \tag{4.6}$$

where:

- P_{peak} : peak demand from the total daily load curve (kW),
- E_{day} : total daily energy demand (kWh),
- P_{ch} : rated power of a charger (kW),
- f_u : charger utilization/diversity factor,
- η_{ch} : charger efficiency,
- T_{win} : available charging window (h).

This formulation ensures that the number of chargers is sufficient to meet both the instantaneous power demand and the total daily energy requirements.

4.5 Grid Impact Assessment

The grid impact analysis evaluates the effect of electric bus charging demand on the local electric distribution grid. Charging load profiles generated by GTFS4EV for each scenario are summed with the existing load profile over time to yield new total hourly and daily load profiles. The key performance metrics are then calculated by comparing these profiles with the existing grid supply profile, including:

- Peak demand and the timing of peak loads
- Daily load factor and load variability
- Potential overload hours where demand exceeds the assumed feeder capacity

Furthermore, the study considers the potential mitigating effect of incorporating solar PV energy by overlaying standard profiles of solar generation on the overall charging demand. These comparisons highlight times when the system can be de-stressed by using renewable energy to counterbalance peak demand, and the outcome of this step is used in determining scenarios with the least disruptive effects on the grid.

4.6 Proposed Charging Scenarios

To evaluate alternative electric bus charging infrastructure strategies in Addis Ababa, four charging scenarios were examined, each aimed at different operating patterns and infrastructure requirements. The four scenarios were evaluated against a baseline to determine their impact on energy demand, grid capacity, and fleet efficiency. These are Depot Charging (DCS), On-Route Charging (OCS), Layover Charging (LCS), and Mixed Charging Scenarios (MCS).

Depot Charging (DCS): In this strategy, buses are charged primarily overnight or off-peak at depots when out of service [42, 43]. It minimizes on-route charging needs but localizes power demand at depots that require suitable load scheduling to mitigate peak loads [44]. Depot capacity, grid impact, and charger investment needs are examined in the research.

On-route Charging (OCS): This idea enables brief, high-power charging sessions at selected stops or terminals during regular operation [45]. It reduces battery size requirements and enhances bus range, but requires a dense network of fast chargers and planning to handle power spikes, queuing, and grid upgrades. The study examines infrastructure location, power request, and effects on service dependability.

Layover Charging (LCS): Layover charging utilizes planned dwell times for middle or ending stops to partially charge buses [20, 46]. It has the advantages of depot and on-route approaches with minimal timetable disruption but requires sufficient layover time and strategically placed chargers. A feasibility study considers schedule patterns, grid integration, and charger capacity.

In the case of layover and on-route charging, the temporal distribution of charging events can be approximated using a probabilistic formulation. The probability that a bus performs a charging event upon arriving at a layover or stop location is expressed as:

$$p \approx \frac{E_{\text{daily}}}{N_{\text{layover\_visits}} \times E_{\text{per\_charge}}} \tag{4.7}$$

$$p \approx \frac{E_{\text{daily}}}{N_{\text{stop\_visits}} \times E_{\text{per\_charge}}} \tag{4.8}$$

where:

- p = The probability of initiating a charging session at a given layover and stop,
- E_{daily} = Denotes the average daily energy consumption of a bus,
- $N_{\text{layover\_visits}}$ = The average number of times a bus visits layover point per day,
- $N_{\text{stop\_visits}}$ = The average number of times a bus visits stop point per day, and
- $E_{\text{per\_charge}}$ = The amount of energy delivered to the battery in a single charging session.

Mixed Charging Scenario (MCS): To reflect a more balanced and realistic deployment of charging infrastructure, this study incorporates a Mixed Charging Scenario (MCS). Unlike single-location approaches, the MCS considers a combination of depot, layover, and on-route charging, thereby distributing charging activities across time and space. This approach mitigates peak loads on the distribution network, improves the integration of intermittent solar power, and enhances charger utilization, resulting in improved operational flexibility and infrastructure cost-effectiveness.

Charging events are synchronized with night-time depot idle periods, scheduled layovers, and short on-route stops so that vehicle availability and service frequency remain unaffected. The share of charging demand assigned to each location is determined from the proportion of time a bus spends at that location. For a given set of participating charging locations Ω, the demand share for location i is calculated as:

$$S_i = \frac{t_i}{\sum\limits_{j \in \Omega} t_j} \times 100\% \tag{4.9}$$

where:

- S_i is the charging demand share (%) at location i,
- t_i is the available dwell time (hours) at location i,
- Ω is the set of charging locations considered (e.g., depot, layover, on-route).

This formulation distributes the charging demand proportionally to dwell times within the selected MCS.

In this study, charger ratings are selected to satisfy full-charge requirements: depot chargers operate at 120 kW (full charge in ∼3 h for a 345 km range), layover chargers at 400 kW (full charge in 55 min), and on-route chargers at 500 kW (full charge in 45 min) for the currently operating buses of having 350 kWh battery capacity, consistent with industry guidelines [42, 47, 48].

(a) Buses charging at depot (b) Buses at layover (c) Buses at onroute

Figure 4.5: Different Charging Locations of a Bus

4.7 Renewable Energy Integration

This study considers free-standing photovoltaic (PV) installation with a setup tilt of 17° and azimuth angle of 0° as being typical for the usual configurations that would be used in solar farms or autonomous solar-powered charging stations. The configuration of the system picks up on ground-mounted, fixed installations arrayed for optimum collection of solar energy in high-altitude use. The location of the simulation site is Addis Ababa, Ethiopia at 9.036° latitude and 38.756° longitude at an altitude of 2438 meters. Hourly meteorological data, plane-of-array (POA) irradiance, were retrieved from the PVGIS database for the year 2022.

Simulation was done using this data and the pvlib Python library, which allows for comprehensive modeling of PV electricity generation hourly. The PV system was optimized for maximum annual yield, with a free-standing mounting structure and modules specified with a nominal efficiency of 22% [49]. A temperature coefficient of -0.4%/°C[50] was used to account for heat-induced output reduction and system losses of 14% to reflect wiring, inverter, and other balance-of-system inefficiencies in order to incorporate real-world performance issues.

4.7.1 PV Capacity Consideration

To develop realistic, spatially grounded estimates of solar PV capacity for Addis Ababa's electric bus charging network, installations are assessed at two principal urban locations: bus depots and layover sites. The key numerical inputs like land area per bus, usable surface fractions, and module power density and their corresponding sources as well as assumptions used in the PV capacity analysis are comprehensively summarized in Table 4.1.

Table 4.1: Key Parameters Used in the PV-Sizing Analysis

Parameter	**Symbol**	**Value**	**Source**
Buses in each scenario	N_{bus}	632, 1010, 1928	Planning scenarios
Area per bus at depots	A_{bus}	$160\,\text{m}^2/\text{bus}$	Area berakdown for depot[51]
Usable PV fraction (depots)	f_{usable}	0.60	Engineering rule-of-thumb
Max. buses per layover site	N_ℓ	10	Simulation output using GTFS4EV
Layover area per site	A_{site}	$1000\,\text{m}^2$	Engineering estimation + buffer
Usable PV fraction (layovers)	f_ℓ	0.50	Assumption
Module efficiency	η_{module}	0.22	Manufacturer data
System losses	L_{sys}	0.14	Typical for depot PV
Net power density	P_{dens}	$0.189\,\text{kW}/\text{m}^2$	Eq. (4.10)
Specific PV yield (Addis)	Y_{day}	$4.43\,\text{MWh}/(\text{MWp}\cdot\text{day})$	PVSimulator 2022[2]

The net DC power density is obtained from module efficiency and system losses as follow:

$$P_{\text{dens}} = \eta_{\text{module}}\left(1 - L_{\text{sys}}\right) = 0.22 \times 0.86 = 0.189\,\text{kW}/\text{m}^2. \tag{4.10}$$

Depot area and PV capacity. For a fleet of N_{bus} vehicles,

$$A_{\text{depot}} = N_{\text{bus}}\, A_{\text{bus}}, \tag{4.11}$$

$$A_{\text{PV,depot}} = f_{\text{usable}}\, A_{\text{depot}}, \tag{4.12}$$

$$C_{\text{depot}} = \frac{A_{\text{PV,depot}}\, P_{\text{dens}}}{1000} \quad \text{(MWp)}. \tag{4.13}$$

Lay-over PV capacity. The aggregate capacity over all layovers site is then:

$$N_{\text{site}} = \frac{\text{Number of Buses in each Scenario}}{10} \tag{4.14}$$

$$A_{\text{lay}} = N_{\text{sites}}\, A_{\text{site}}, \tag{4.15}$$

$$A_{\text{PV,lay}} = f_{\ell}\, A_{\text{lay}}, \tag{4.16}$$

$$C_{\text{lay}} = \frac{A_{\text{PV,lay}}\, P_{\text{dens}}}{1000} \quad \text{(MWp)}. \tag{4.17}$$

Then, the total PV capacity used for the simulation becomes:

$$C_{\text{tot}} = C_{\text{depot}} + C_{\text{lay}}, \tag{4.18}$$

$$E_{\text{PV}} = C_{\text{tot}}\, Y_{\text{day}}. \tag{4.19}$$

4.7.2 PV–EB Interaction and Performance Indicators

Based on the estimated PV system, the interaction between PV generation and electric bus charging was analyzed using the GTFS4EV model and operational data from Addis Ababa's bus fleet. In this work, four key indicators are evaluated to quantify PV contribution, grid independence, and integration efficiency for public e-mobility:

- **Energy Coverage Ratio (ECR):** Fraction of total EB charging demand supplied by PV generation.
- **Self-Sufficiency Ratio (SSR):** Proportion of EB charging demand met directly by PV generation, considering only the coincident power.
- **Self-Consumption Ratio (SCR):** Fraction of PV generation that is consumed on-site for EB charging rather than exported to the grid.

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[1] PV yield based on PVGIS for the year 2022 & PVSimulator , Results: global POA 2063 kWh/m^2/yr, diffuse POA 795 kWh/m^2/yr, energy yield 355.7 kWh/m^2/yr, specific yield 1616.9 kWh/kWp/yr, performance ratio 0.78, capacity factor 18.5%.

- **Excess PV Ratio:** Share of PV generation exceeding the charging demand, which is either exported or curtailed.

The corresponding expressions for these indicators over a 24-hour period are:

$$\mathrm{ECR} = \frac{\int P_{\mathrm{PV}}(t)\,dt}{\int P_{\mathrm{EB}}(t)\,dt} \tag{4.20}$$

$$\mathrm{SSR} = \frac{\int \min[P_{\mathrm{PV}}(t), P_{\mathrm{EB}}(t)]\,dt}{\int P_{\mathrm{EB}}(t)\,dt} \tag{4.21}$$

$$\mathrm{SCR} = \frac{\int \min[P_{\mathrm{PV}}(t), P_{\mathrm{EB}}(t)]\,dt}{\int P_{\mathrm{PV}}(t)\,dt} \tag{4.22}$$

$$\text{Excess PV Ratio} = \frac{\int \max[0, P_{\mathrm{PV}}(t) - P_{\mathrm{EB}}(t)]\,dt}{\int P_{\mathrm{PV}}(t)\,dt} \tag{4.23}$$

4.8 Technical, Economic, and Environmental Impact Assessment

The integrated PV–electric bus system is evaluated from three complementary perspectives, using data from the GTFS4EV model, scenario simulations, and performance metrics derived from charging and PV generation profiles.

1. **Technical feasibility:** The analysis measures the spatial coverage and density of chargers, their availability throughout the service network, and the operational feasibility of the infrastructure needed. Charger location with respect to bus routes and depots, land availability, and possible deployment limitations are taken into account. The approach further looks at how varied charging configurations affect infrastructure needs, spatial coverage, and operational flexibility.
2. **Economic viability:** The analysis takes into account the capital costs of chargers as well as battery capacity needs per scenarios. The approach entails combining charger investment projections with estimated battery sizes to determine their effect on vehicle procurement expenditures, operational flexibility, and anticipated battery life. The cost trade-offs are examined through comparison of the expenses of infrastructure and anticipated battery life in different charging configurations.
3. **Environmental impact:** To evaluate the environmental benefits of electric bus deployment in Addis Ababa, the analysis quantifies greenhouse gas (GHG) reductions achieved by replacing conventional diesel buses with battery-electric buses. The assessment considers both direct fuel-related emissions from diesel operation and indirect emissions from electricity consumption under different charging strategies. By incorporating the temporal interaction between charging demand and photovoltaic (PV) generation, the framework captures the extent to which renewable energy offsets grid reliance, thereby influencing the net

emission outcome. The CO_2 reduction is formulated by comparing diesel-based and electricity-based operation on a per-bus and fleet-wide basis, and annualized to reflect long-term sustainability impacts. The governing equations are given as:

$$\begin{cases} F_{\text{diesel,day}} & = N \times d \times f \\ CO_{2,\text{diesel,day}} & = F_{\text{diesel,day}} \times e_{\text{diesel}} \\ E_{\text{elec,day}} & = N \times d \times c_{\text{elec}} \\ CO_{2,\text{grid,day}} & = E_{\text{elec,day}} \times e_{\text{grid}} \\ CO_{2,\text{grid,day with PV}} & = E_{\text{elec,day}} \cdot (1 - \text{SSR}) \cdot e_{\text{grid}} \\ \Delta CO_{2,\text{day}} & = CO_{2,\text{diesel,day}} - CO_{2,\text{grid,day}} \\ \Delta CO_{2,\text{year}} & = \Delta CO_{2,\text{day}} \times D \end{cases} \tag{4.24}$$

where:
N = number of buses,
d = daily distance per bus (km/day),
f = diesel fuel consumption (L/km)(For Addis Ababa buses f = 0.179 [52]),
e_{diesel} = diesel emission factor (kg CO_2/L)(e_{diesel} = 2.68 kg CO_2/L, assumed),
c_{elec} = electric energy consumption (kWh/km),
e_{grid} = grid emission factor (kg CO_2/kWh)(e_{grid} = 0.02 kg CO_2/kWh, assumed),
SSR = is the PV self-sufficiency ratio (0–1)
D = number of operating days per year (commonly 365).

In addition, the required land area for PV deployment is estimated based on the selected PV capacity and typical area-per-kW ratios, enabling an assessment of spatial sustainability.

Chapter 5

Results and Discussion

This chapter dives deep into the modeling results of electric bus (EB) operations and their energy dynamics in Addis Ababa, focusing on the strategy at hand. It's laid out in a way that systematically explores both the operational and energy-related facets of the EB system. The discussion kicks off with an analysis of trip-wise operational dynamics, daily energy demands, and the overall bus operating patterns throughout the city. Next, it looks into charging strategies and demand patterns, considering the spatial and temporal variations in energy, infrastructure needs, and battery capacity under different charging scenarios. The chapter also explores how photovoltaic (PV) generation contributes to the charging requirements and the effects of EB operations on the current electrical grid. To wrap things up, it discusses the implications of various charging scenarios, including costs of chargers, technical feasibility, and environmental benefits, concluding with a synthesis of the findings. Altogether, these analyses offer a thorough overview of EB performance and energy needs, aiding in strategic planning and informed decision-making.

5.1 Trip–Level Electric Bus Operational Dynamics

This section illustrates the output of the EV-Fleet-Sim model, which simulates the operational and energy dynamics of an electric bus over a representative trip. Figure 5.1 contains six plots that show the variation in power demand, regenerative braking, cumulative energy consumption, and speed against time and distance. The power profile at the top of the figure shows a highly dynamic profile, with large positive spikes during acceleration and small negative values representing regenerative braking. Such types of variations are typical of the stop-and-go nature of urban driving, with frequent acceleration from a standstill and the presence of hilly terrain creating large short-term demand. Applying a rolling mean to the power curve clarifies the underlying trend in demand, which is consistently high over active service periods.

The speed profile confirms the operating environment that drives this variability. The bus maintains a low average speed of about 11–12 km/h but often slows to nearly zero because of stops, congestion, and intersections. These irregular cycles of speeding up, steady movement, and idling are clearly reflected in the energy curves. Cumulative energy increases nearly linearly with distance, reaching approximately 150 kWh over 200 km. Similarly, against time, it increases in steps that flatten during layovers or standstill periods. Together, the power, speed, and energy plots provide a coherent and comprehensive picture of how Addis Ababa's traffic patterns shape electric bus performance and establishes the foundation for deriving specific energy consumption across the 385 trips analyzed in this study, with detailed results presented in Appendix C.

Based on the trip-level operational dynamics, the distribution of energy consumption across all 385 simulated electric bus trips are extracted. Figure 5.2a shows the statistical distribution of the energy intensity, expressed in kWh per kilometer, as obtained from the EV-Fleet-Sim simulation results. This reveals substantial variability in trip-level energy consumption, ranging from a minimum of 0.53 kWh/km to a maximum of 2.41 kWh/km. On average, it is about 1.86 kWh/km, while the interquartile range (IQR) extends from 1.77 to 2.00 kWh/km. This means that most trips fall close to the higher end of the energy range, while only a few use noticeably less or more energy.

The lower outliers represent trips with extended periods of low-speed operation, flat topography, or favorable regenerative braking opportunities, all of which reduce net energy demand. Conversely, the upper outliers correspond to trips characterized by frequent acceleration, higher speeds, and possibly more stop-and-go dynamics, which elevate traction power requirements. Such variability is consistent with the heterogeneous operational conditions of urban bus routes.

The central positioning of the median (1.87 kWh/km) within a narrow interquartile range underlines the reliability of the average consumption metric, supporting its use as a representative figure for fleet-wide energy demand estimation. At the same time, the observed outliers stress the importance of considering route-level diversity when planning charging infrastructure and scheduling operations. Routes prone to higher energy consumption may require preferential charging capacity or battery oversizing, whereas more efficient routes highlight the potential for energy optimization through eco-driving and regenerative recovery strategies.

Overall, the boxplot analysis indicates that, while the mean energy consumption of 1.86 kWh/km provides a reliable fleet-level benchmark, the variability between individual trips is substantial and must be considered in the strategic planning and operational management of electric buses. The primary outcome of this simulation is the characterization of energy consumption per kilometer, a critical input parameter for the GTFS4EV model.

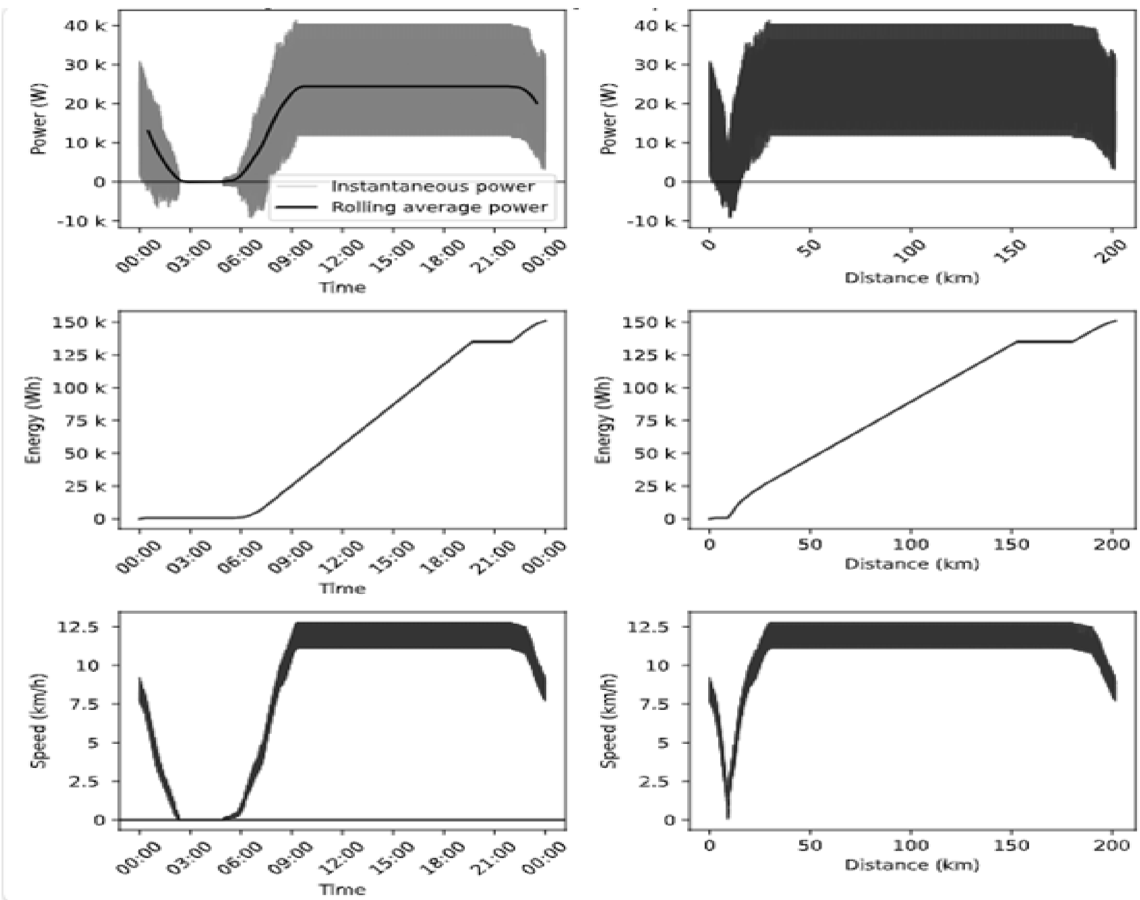


Figure 5.1: Electric Bus Operational Dynamics for a Typical Trip

5.2 Daily EB Energy Demands in Addis Ababa

The daily energy requirement to operate electric buses (EBs) in Addis Ababa was analyzed for three electrification cases: the base year (representative of current GTFS data used for simulation), a projected electric bus by 2030, and full fleet electrification by 2030. The analysis involves the sequential application of two modeling tools: EV-Fleet-Sim and GTFS4EV. The EV-Fleet-Sim model was initially used to forecast trip-wise energy consumption values from spatial-temporal parameters such as trip lengths, stop frequencies, and speed profiles. The output average energy consumption per kilometer (1.86 kWh/km) was feed as a key input to the GTFS4EV model, a simulation of electric fleet performance given the existing GTFS data. Based on this, GTFS4EV estimated that each electric bus consumes approximately 401 kWh/day on average. This benchmark was then utilized for the subsequent system-level energy demand derivation for each electrification case.

For the base year, corresponding to 1,010 buses operating in the GTFS dataset, daily total energy consumption is approximately 405 MWh. In the lowest electrification scenario in 2030, with the forecasted number of 632 electric buses, the estimated demand would be 253 MWh, as 632 × 401 kWh/day. In the full electrification scenario, where all 1,928 urban buses are assumed to be electric by 2030, the daily energy demand would be 773 MWh. These scenario-based forecasts serve as input to charging infrastructure planning, load profiling, and renewable energy integration studies. Table 5.1 summarizes the energy demands for the three fleet configurations.

Table 5.1: Summary of Daily EB Energy Demand under Different Cases

Case	No. of Buses	Daily Energy per Bus (kWh)	Total Demand (MWh)
Baseline year (GTFS data)	1010	401	405
2030 – Only EBs	632	401	253
2030 – Full Fleet Electrification	1928	401	773

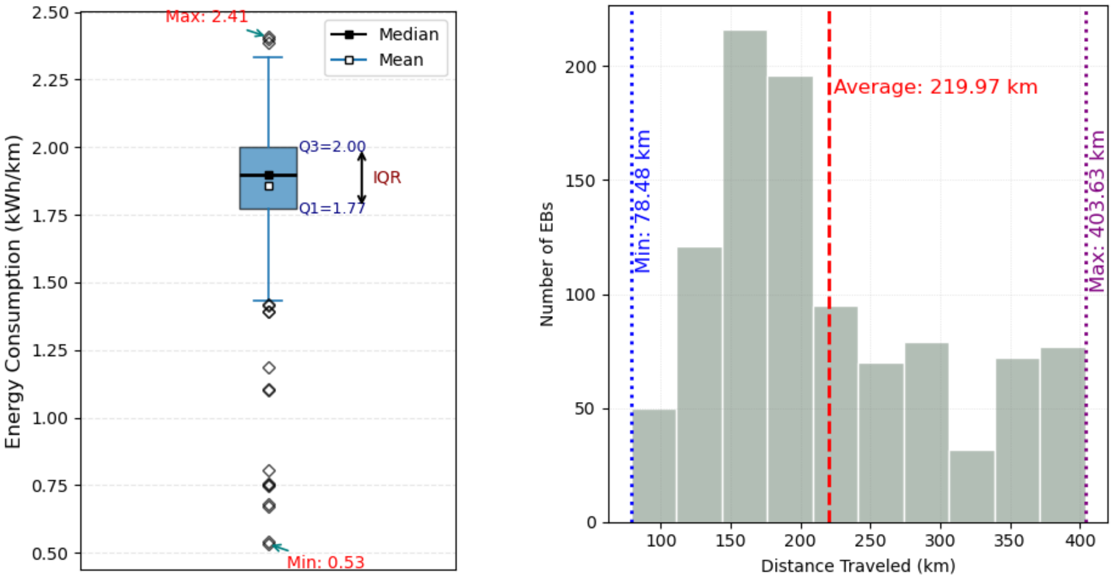
5.3 Daily Bus Operation Patterns in Addis Ababa

The daily operation of Addis Ababa city buses is very variable in terms of distance traveled and time spent in different modes of operation. Analysis of daily distance traveled by each bus indicates a wide range, with some buses carrying out short intra-district loops and others taking long-distance cross-city borders. The plotted distribution ranges from a low of 78.5 km to a high of 404 km, with the mean daily distance at approximately 220 km (see Fig:5.2b). The determinants of this range are primarily route type, peak-hour demand, and the level of bus scheduling frequency.

when we come to operating time, (from early morning at 5:00am to the late evening 10:00pm), is broken down into three broad constituents: travel hours, stop hours, and layover hours, each reflecting different aspects of service dynamics. Buses, on average, requires approximately 9.15 hours of active travel time, 3.8 hours of time spent at regular passenger stops, and 4.05 hours of mid-route layovers. Added to these, a significant amount of inactive time is spent in depots, with a fleet-wide accumulation of depot hours amounting to 7 hours per day, times of vehicle preparation, charging (for electric buses), or overnight parking.

Using Eq. (4.9), the charging demand can be then broken down into mixed scenarios in addition to the independent charging strategy at a specific location. Based on the time-proportionality, the shares of the demand are 47% at depots, 27% at layovers, and 26% at on-route stops, which mirrors the relative duration that buses spend at each location. When charging is concentrated at depots and layovers, the shares become 63% depot and 37% layover, whereas a depot–on-route setup gives 65% depot and 35% stops. By comparison, an opportunity-charging strategy without depot allocation is 52% layover and 48% on-routes. These varying splits indicate the flexibility in allocating charging demand based on infrastructure strategy and operational priorities.

In the case of layover and on-route charging, the temporal distribution of charging events was modeled using the probabilistic formulations in Eq. (4.7) and Eq. (4.8). The probabilities initially worked out to **0.26** for layovers and **0.16** for on-route stops, but these probabilities were not high enough to meet overall daily energy demand. In order to achieve feasibility, the probabilities were adjusted iteratively, and the calibrated values of **0.9** for layovers and **0.6** for on-route stops were used in the simulation.



(a) Energy consumption per kilometer

(b) Daily travel distance of EB

Figure 5.2: Daily EB Operation in Addis Ababa

5.4 Charging Strategies and Demand Profiles

5.4.1 Spatial Energy Demand

Planning effective deployment of electric bus (EB) charging infrastructure needs knowledge of the geographic distribution of charging demand. The georeferenced results of GTFS4EV simulations, which are visualized by interactive Leaflet maps for each charging scenario, are utilized in this research to assess spatial demand. Peak power demand (kW), total energy charged (kWh), and the peak number of vehicles charging at the same time at a given location are all variables provided in the spatial layers. These provide additional insight into how different charging strategies, i.e., depot, layover, on-route, or mixed, impact specific locations in the city, and vary notably across different electric bus charging scenarios in Addis Ababa. The analysis of the top-ranking locations by these metrics reveals distinct operational and infrastructure patterns for each scenario.

With a focus on top ranking demand clusters, this section presents a comparative spatial analysis of the demand characteristics across Addis Ababa. Through an assessment of the heat-map intensity and numerical values for charging terminal nodes, energy demand hot spots are identified. In addition to highlighting the most critical operating areas and sub-cities for investment priority, the results also inform infrastructure planning decisions such as charger location, sizing, and capacity planning. A cross-scenario synthesis of the spatial patterns and their network-wide electrification implications is presented following an independent examination of each scenario.

I. Spatial Comparison of Electric Bus Charging Scenarios

Since *depot charging* typically occurs outside active operational hours (overnight) and is usually centralized, the coordinates for depots are not explicitly represented in the spatial results. But, still the heat-map informs us where the depot should be installed. Consequently, this analysis focuses on locations with geographic references, namely layovers and on-route stops, where charging occurs during active service hours for the base case demand(i.e. 405MWh).

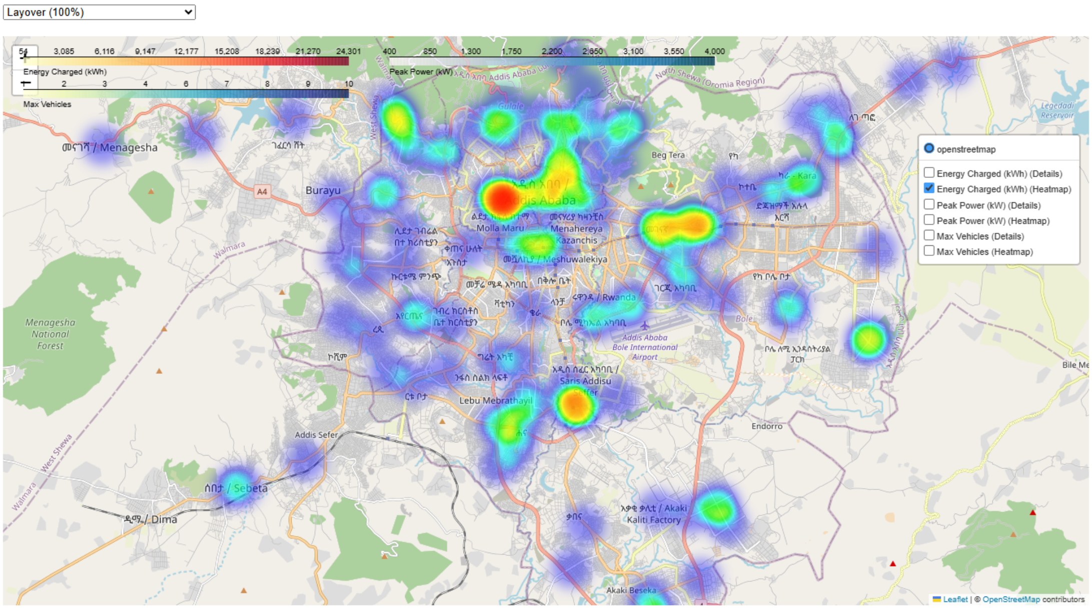
In the *Layover only charging* case, the peak total energy demand is localized at major layover terminals. The highest demand site lies just outside the administrative border of Addis Ababa with around 24.3 MWh, reflecting long-distance operations. Other terminals such as Sheratera, Autobistera, and Addisalem also record very high demand in the range of 21–23 MWh. Besides energy use, some locations show high peak power requirements, such as Leghar in Kirkos Sub-city, with a maximum capacity of 4 MW able to handle ten buses simultaneously. Similarly, locations in Addis Ketema Sub-city record up to 3.2 MW and can support eight buses charging at once (see Fig. 5.3).

The *On-route only charging* case exhibits a distinct spatial pattern of moderate total energy requirements per location, with medium peak power requirements spread across several stops in the city. The highest demand sites record approximately 3.5 MWh, while several others range between 2.7–3.4 MWh. Peak power is somewhat lower than at layovers, though a few locations still reach 2.5–3 MW. These high-power nodes are dispersed across sub-cities, indicating a decentralized fast-charging approach that allows operational flexibility by enabling buses to top up during short on-route stoppages. However, this strategy delivers less aggregate energy overall, making it more suitable for supplementary rather than complete replenishment (Fig. 5.4).

In the Mixed charging scenario of *47% Depot, 27% Layover.and 26% On-Route* (Fig. 5.5), the central depot dominates with nearly 190 MWh of total energy and 73.4 MW peak power, capable of charging up to 612 vehicles simultaneously. This demonstrates reliance on concentrated, high-capacity depot stations to provide the bulk of fleet charging. Complementing this, there are also several layover and on-route sites with more modest yet operationally meaningful loads, typically ranging from 1–3 MWh and 1.2–1.6 MW. This reflects a hybrid strategy where depot charging is effectively supported by strategically located high-power terminals to increase flexibility and reduce stress during peak hours.

Additional mixed configurations further highlight trade-offs between centralization and distribution. A *52% Layover and 48% On-Route* case balances demand across large layover terminals and high on-route stops, avoiding overload at any single site. A *65% Depot and 35% On-Route* model consolidates most energy demand at the depot (about 264 MWh and 103 MW, supporting nearly 859 vehicles), while still using fast charging at key bus stop nodes. Similarly, a *63% Depot and 37% Layover* scenario demonstrates high-capacity depot service (252 MWh and 87 MW, supporting nearly 727 vehicles) supported by layovers contributing up to 3.5 MWh, representing a mature hybrid model with both scale and flexibility.

This geo-spatial analysis highlights the distinct functional roles of depots, layovers, and on-route stops within the electric bus charging network. Depots act as backbone hubs for bulk charging, whereas layovers and on-route stops provide distributed and rapid-charging options across the city. These results improve visualization of demand distribution, informing well-designed infrastructure planning in Addis Ababa.

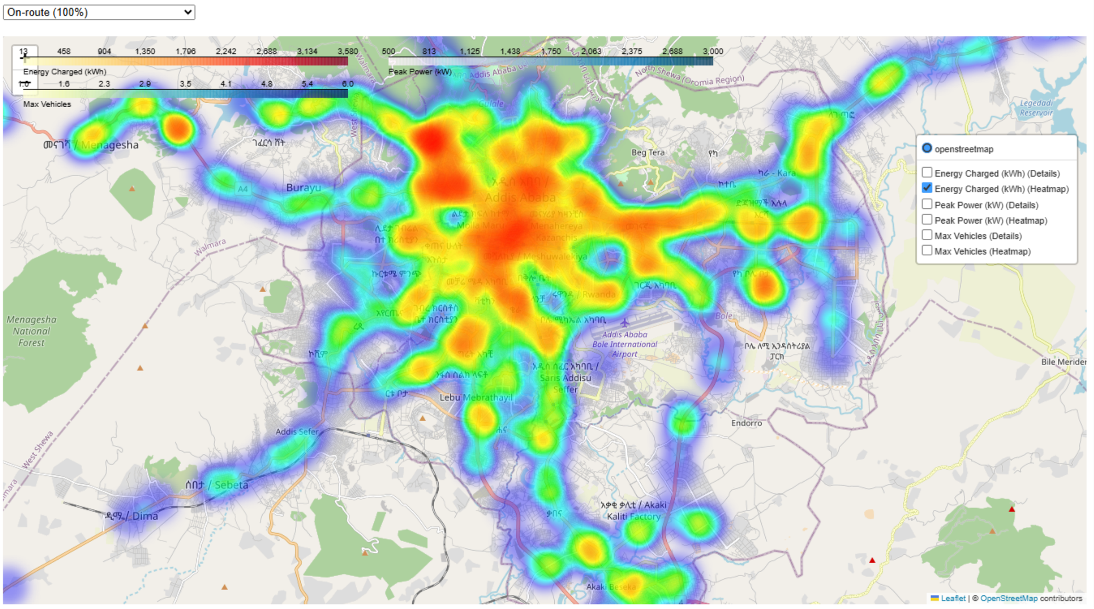


Layover (100%)

○ openstreetmap
☐ Energy Charged (kWh) (Details)
☑ Energy Charged (kWh) (Heatmap)
☐ Peak Power (kW) (Details)
☐ Peak Power (kW) (Heatmap)
☐ Max Vehicles (Details)
☐ Max Vehicles (Heatmap)

Figure 5.3: Spatial Distribution of Demands under the Layover Charging Scenario

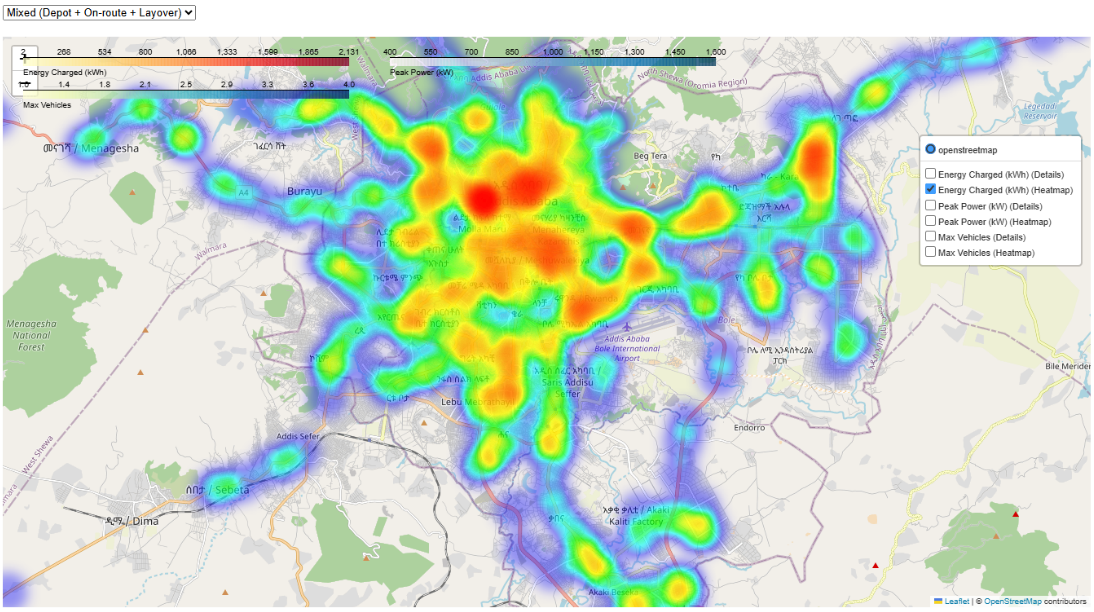
The heat-map shows that there is less activity in the outer areas and that charging is most concentrated inside the city and along main transit corridors. For clarity and easy visual data interpretation, only the Energy charged (Heat-map) layer is enabled for this map. The same analysis technique can be applied to other parameters, such as Peak Power (kW) and Maximum Vehicles, by selecting the respective heat-map and detail layers. This allows stakeholders to compare and analyze different performance parameters effectively.



On-route (100%)

openstreetmap
☐ Energy Charged (kWh) (Details)
☑ Energy Charged (kWh) (Heatmap)
☐ Peak Power (kW) (Details)
☐ Peak Power (kW) (Heatmap)
☐ Max Vehicles (Details)
☐ Max Vehicles (Heatmap)

Figure 5.4: Spatial distribution of demands under the On-route Charging Scenario.



Mixed (Depot + On-route + Layover)

openstreetmap
☐ Energy Charged (kWh) (Details)
☑ Energy Charged (kWh) (Heatmap)
☐ Peak Power (kW) (Details)
☐ Peak Power (kW) (Heatmap)
☐ Max Vehicles (Details)
☐ Max Vehicles (Heatmap)

Figure 5.5: Spatial distribution of demands under the Mixed Charging Scenario.

The heat maps shown are limited to three scenarios for illustration. However, other scenarios also present unique spatial patterns of charging intensity. Adding these would create redundancy without changing the overall results; therefore, they are discussed but not shown here.

5.4.2 Temporal Energy Demand

The comparative demand profiles of charging required to satisfy the daily demand of 405 MWh highlight notable differences in the time distribution of load, peak demand magnitude, and alignment with grid peak hours as shown in Figure 5.6. The demands (773 MWh and 253 MWh) follow the same shape but are scaled proportionally using factors of **1.91** (for higher demand) and **0.63** (for lower demand), respectively. In the *Depot only* case, charging begins immediately after midnight with a significant spike of about 120 MW at 23:00, followed by a steady exponential decline, finishing at about 04:30 AM. This schedule entirely avoids the late afternoon and evening peak-grid time, thereby reducing exposure to higher tariffs under time-of-use pricing. However, the concentrated nighttime load requires significant depot charging capacity, high transformer ratings, and heavy-duty grid connections, which could translate into higher capital investments in infrastructure development.

The *Layover only* case gives the most extreme spike, with a sharp peak in demand around 5.13 hours of ∼165.6 MW, the largest of all the strategies. While charging is spread-out over layover stations, the majority of demand is during morning operating hours, when buses stop back for brief breaks. This activity maintains high demand (∼75–80 MW) well into the late morning and smoother than on-route beyond 7.4 hr, while adding substantial stress to the grid during high-usage hours and escalating operational costs through both demand charges and daylight electricity prices.

In the *On-route only* setup, charging begins at the start of service (∼05:00 AM) with a peak reaches 87.5 MW, then decreases gradually over the course of the day before ending in mid-afternoon. The steady but declining profile lowers depot infrastructure requirements and spreads load more evenly than Layover Only. However, much of the charging is still during the daytime especially in morning, potentially subjecting operators to increased electricity costs and adding to grid congestion during business hours.

Mixed strategies have a more even set of attributes. The *47% Depot, 27% Layover, 26% On-route* mix achieves the lowest daily peak, at around 73.44 MW. Charging follows a smoother profile, with an initial moderate rise which quickly settles to a steady daytime load of ∼10–15 MW, avoiding sharp peaks and reducing overlap with evening peak-grid times. This configuration is an effective minimization of both infrastructure requirements and grid strain and is the best balance of cost-effectiveness and operational feasibility. The *65% Depot, 35% On-route* case shows a very large off-peak depot load (∼103.08 MW at 23:00) combined with moderately steady on-route daytime charging. This approach maintains much of the overnight benefit while smoothing infrastructure requirements relative to a Depot Only configuration. Similarly, the *63% Depot, 37% Layover* profile shows a large overnight charging component (∼87.24, MW) with a smaller secondary rise during the daytime due to layover charging. Both approaches reduce the reliance on peak-grid times; however, they still require substantial depot facilities.

Lastly, the *52% Layover, 48% On-Route* combination holds a fairly steady decline daytime load with a maximum of ∼89.2 MW during morning , which is carried throughout operating hours. Though this strategy evades massive concentrated peaks, it has significant overlap with the 18:00–21:00 peak-grid period, which heightens exposure to high energy costs and possible clashes with system-wide demand management.

From a comparative standpoint, depots-dominant strategies (*Depot only, 65% Depot–35% On-route, and 63% Depot–37% Layover*) are most effective at shifting demand away from expensive peak-grid periods but require heavy investment in high-capacity charging infrastructure. Conversely, layover-concentrated strategies, particularly *Layover only*, possess the greatest risk of causing expensive and operationally difficult-to-manage demand peaks, and therefore are likely to be unsuitable without the application of load-shifting methods like battery energy storage or smart charging management. On-route-dominant or mixed scenarios (*On-route only, 47%–27%–26%, and 52%–48%*) yield more dispersed charging profiles, which can mitigate infrastructure requirements, but leave operators vulnerable to increased daytime and peak-period electricity charges. Notably, the *47% Depot–27% Layover–26% On-route* scenario offers the best compromise between grid impact, infrastructure cost, and operational flexibility, yielding the lowest peak demand even though relatively coincidence with peak-grid times.

These peak demands are relative to the base-case daily energy demand of 405 MWh. In the high-demand scenario, 773 MWh, all peak values scale proportionally by a factor of 1.91, while for the low-demand scenario, 253 MWh, they scale down by a factor of 0.63. In all cases, the time shape of the profiles remains constant, and thus the operational implications developed in this analysis remains valid. Overall, depot-dominant strategies, particularly those that prioritize charging during off-peak nighttime hours, demonstrate the greatest level of coordination with grid stability and economic operation, though at a high expense of infrastructure investment. On-route and layover-heavy strategies permit operational flexibility and reduced vehicle downtime but at increased expense to the grid, notably during peak high-tariff periods. Hybrid strategies, especially those skewed towards night-time depot charging, provide the most balanced solutions by flattening demand, lowering peak-hour pressure, and enabling synergies with renewable integration efforts such as solar PV generation and battery energy storage systems.

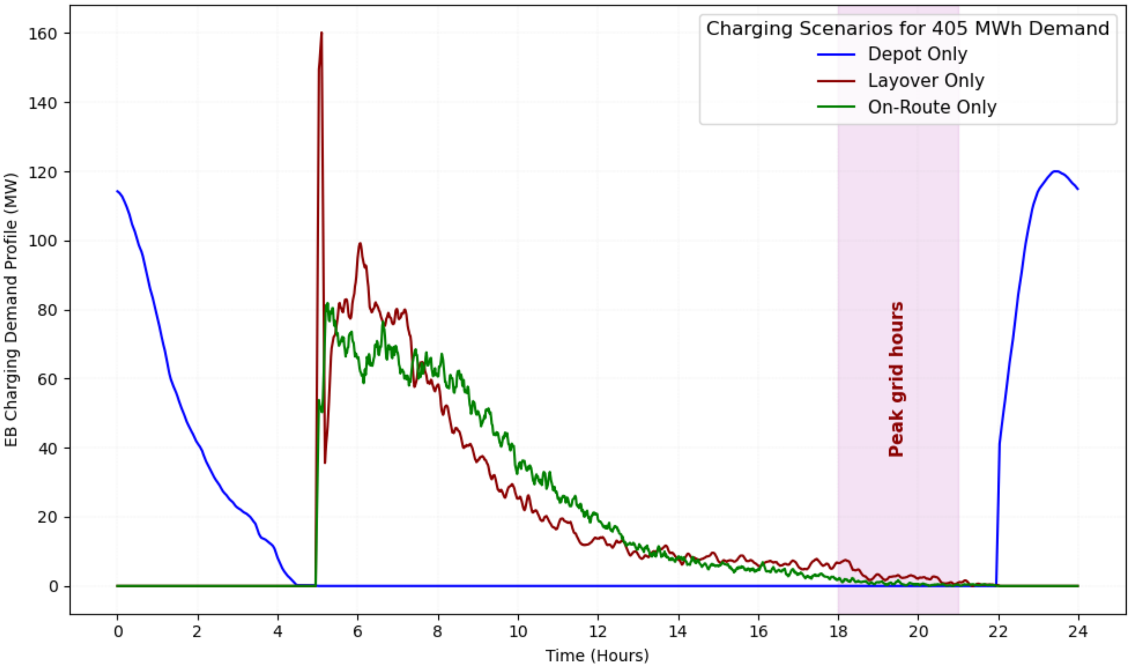


Figure 5.6: Temporal Charging Demand Profiles (in MW) for the 405 MWh Daily Demand, Showing the Three Independent Charging Configurations.

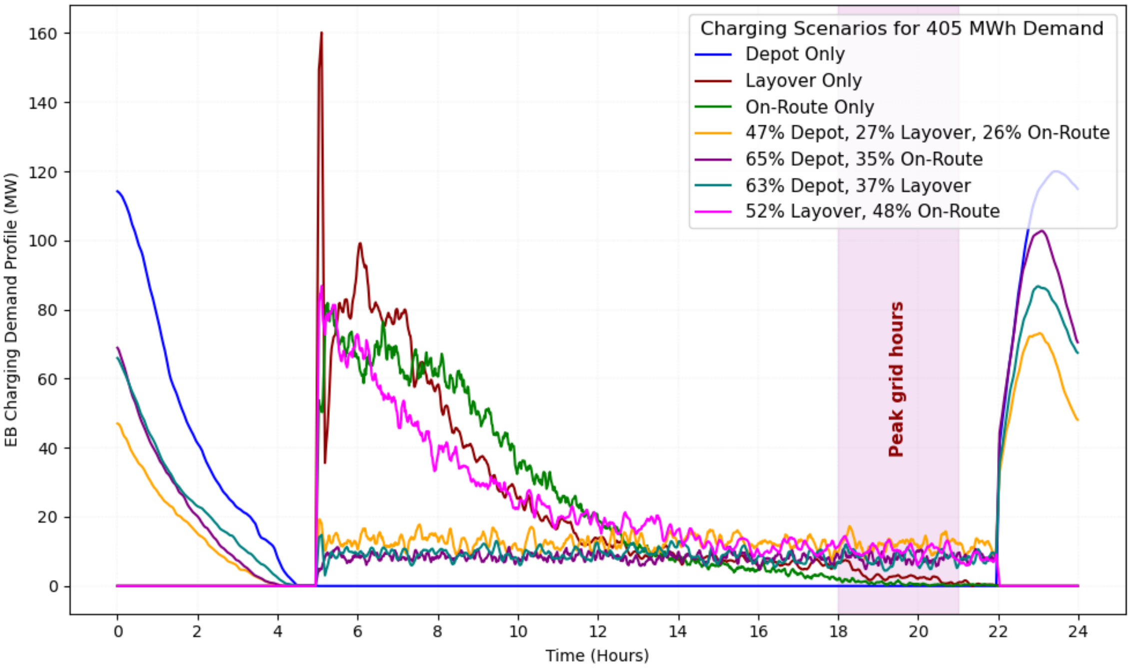


Figure 5.7: Temporal Charging Demand Profiles (in MW) for Electric Buses under Various Scenarios Meeting a 405 MWh/day Base-case for Addis Ababa. Shaded area (18:00–21:00) Indicates Peak Grid Hours.

5.4.3 Charging Infrastructures for Each Charging Scenario

Applying equations (4.1)–(4.6) to the three demand levels (405 MWh, 253 MWh, and 773 MWh) and the considered charging strategies yielded the charging infrastructure requirements summarized in Table 5.2. The calculations account for the peak power requirements, the total daily energy to be delivered, the rated charger power, charging efficiency, and the utilization factor as discussed in the methodology section. The results indicate a strong dependence of the required number of chargers on both the total daily energy demand and the adopted charging strategy.

Depot-only charging (DCS only): In a scenario where all charging is centralized at depots, the infrastructure requirements become substantial due to the need to handle large amounts of energy in a limited charging window. For the 405 MWh case, 1,316 depot chargers are required, and this number increases to 2,514 for the 773 MWh demand. While depot-only charging offers operational simplicity, it leads to very high peak power requirements and the largest investment in charging units.

Layover-only (LCS only) and on-route-only (OCS only): Shifting the charging load to layover locations or on-route stop points significantly reduces the total charger count compared to depot-only charging because the charging events are distributed throughout the operational schedule. For example, in the 253 MWh scenario, 306 chargers are needed when using only layover points, while on-route-only charging requires 123 chargers. However, these strategies require extensive network coverage and depends mainly on the availability of time and space for intermediate charging during operations.

Mixed charging strategies: Combining different charging methods moderately lowers the required number of chargers. This is because mixed strategies distribute both the energy and power demand,relative to the independent strategies, reducing the peak load at any single type of charging location. For instance:

- For 405 MWh daily demand, using a 63% depot + 37% layover approach reduces the total requirement from 1,316 chargers (DCS only) to 1,002.
- Introducing on-route charging as a third component (47% depot, 27% layover, 26% on-route) brings the total number of chargers further down to 869.
- A similar pattern is observed for 773 MWh demand, where the total charger count decreases from 2,514 in the depot-only case to 1,914 for a 63/37 mix and to 1,661 when all three strategies are combined.

Effect of increasing daily demand: As the daily energy demand grows from 253 MWh to 773 MWh, the total number of required chargers increases across all strategies. Nonetheless, the proportional savings achieved by using mixed strategies remain significant, showing that an integrated approach to charging infrastructure planning can mitigate the otherwise steep growth in charger requirements.

In general, the results confirm that:

1. Mixed charging strategies are more infrastructure-efficient than single-mode strategies.
2. Spreading the charging demand across depots, layover points, and on-route chargers helps reduce peak power requirements and total charger count.
3. Higher energy demand scenarios strongly benefit from a diversified charging infrastructure plan.

These findings highlight the importance of strategic planning for charging infrastructure deployment, as they have direct implications for capital investment, grid capacity planning, and operational flexibility of electric bus systems.

Table 5.2: Charging Infrastructure Requirements for Each Demand per Scenarios

C.Scenario	405 MWh				253 MWh				773 MWh			
	DC	LC	OC	Total	DC	LC	OC	Total	DC	LC	OC	Total
DCS only	1316	–	–	1316	829	–	–	829	2514	–	–	2514
LCS only	–	485	–	485	–	306	–	306	–	927	–	927
OCS only	–	–	194	194	–	–	123	123	–	–	371	371
63% DCS + 37% LCS	957	45	–	1002	603	29	–	632	1828	86	–	1914
65% DCS + 35% OCS	1130	–	33	1163	712	–	21	733	2158	–	63	2221
52% LCS + 48% OCS	–	97	170	267	–	62	107	169	–	186	325	511
47%DCS + 27%LCS + 26% OCS	805	40	24	869	508	26	16	550	1538	77	46	1661

Where: DC = Depot Chargers, LC = Layover Chargers, OC = On-route Chargers.

5.4.4 Battery Capacity Requirements Per Charging Scenario

An in-depth evaluation of battery capacity(Fig: 5.8) distributions across different charging scenarios provides crucial insights into temporal energy demand and its implications for electric bus (EB) adoption. As shown in the figure, the *Depot Only* configuration necessitates the largest battery capacities, with a median of approximately 360 kWh, an interquartile range from $Q_1 = 284\,\text{kWh}$ to $Q_3 = 497\,\text{kWh}$, and a maximum outlier reaching 862 kWh. This reflects the temporal concentration of charging into overnight periods, requiring buses to store enough energy to operate the entire day without intermediate recharging. While this centralized strategy simplifies infrastructure planning, it imposes a substantial burden on initial battery investment, which remains one of the most significant cost components in EB procurement. Given the high upfront cost per kWh of battery storage, this scenario could limit large-scale fleet electrification, especially in cities with budget constraints or limited financing options.

In contrast, *Layover only* and *On-route only* strategies, which distribute charging events throughout the day, allow for moderate median battery capacities, 250 kWh and 225 kWh, respectively with narrower interquartile ranges ([218 kWh − 299 kWh] and [191 kWh − 281 kWh], respectively). These lower median capacities, compared to Depot Only, indicates potential savings in battery costs. However, these scenarios come with trade-offs. While smaller battery size reduces upfront procurement costs per vehicle, the operational variability and the need for high-frequency charging infrastructure increase complexity and require robust real-time coordination and scheduling.

Mixed charging configurations offer a middle ground with diverse distribution profiles. *The 63% Depot_37% Layover* and *65% Depot_35% On-route* cases yield median battery capacities of 250 kWh ($Q_1 = 163$ kWh to $Q_3 = 393$ kWh) and 230 kWh ($Q_1 = 159$ kWh to $Q_3 = 366$ kWh), respectively. These medians are slightly higher than pure Layover or On-route strategies but substantially lower than Depot Only. By spreading charging events between depots, layovers, and on-route stops, these strategies reduce the peak demand on any single charging window, enabling buses to operate efficiently with moderately sized batteries. This approach eases pressure on the energy system and reduces capital costs, improving the economic feasibility of EB deployment.

More balanced and distributed scenarios such as *52% Layover_48% On-route* and *47% Depot_27% Layover_26% On-route* further reduce battery size requirements. Their median battery capacities fall to 195 kWh ($Q_1 = 145$ kWh to $Q_3 = 258$ kWh) and 185 kWh ($Q_1 = 126$ kWh to $Q_3 = 308$ kWh), respectively. These configurations enable frequent, opportunistic charging during short dwell times, minimizing the need for large energy storage. This reduces battery-related costs and vehicle weight, improving overall efficiency. However, they demand significant infrastructure investment at multiple urban locations and impose operational dependencies on power grid reliability during service hours. Additionally, the smaller batteries necessitate robust schedule adherence and dynamic energy management systems to ensure operational feasibility.

Ultimately, the analysis highlights that battery size, and consequently battery cost, is directly linked to the temporal structure of charging availability. Larger batteries arise from inflexible or centralized charging schedules, while smaller batteries become viable when energy can be dynamically topped up throughout the day. From a policy and planning perspective, reducing average battery capacity across a fleet directly reduces total capital investment, potentially accelerating the adoption of electric buses in developing urban contexts such as Addis Ababa. Therefore, integrating charging strategies aligned with daily operational rhythms optimizes energy use and grid integration and plays a critical role in reducing one of the key financial barriers to electric mobility adoption.

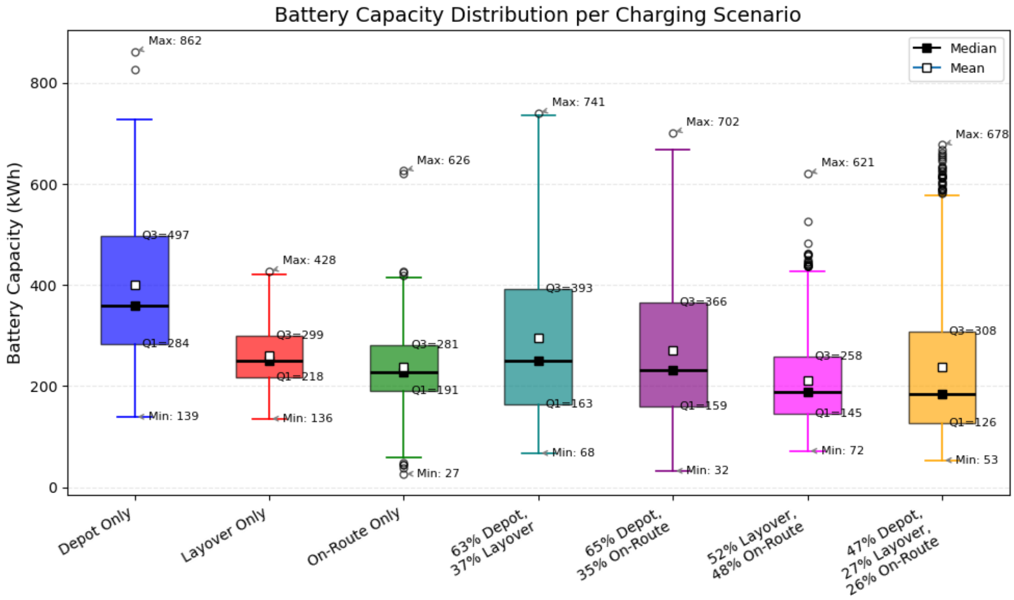


Figure 5.8: Battery Capacity of EBs under Different Charging Scenarios

Table 5.3: Average Battery Capacity and Deviation From the Currently Operating Battery Capacity of EBs under Different Charging Scenarios

Scenario	DCS	LCS	OCS	63% DCS 37% LCS	65% DCS 35% OCS	52% LCS 48% OCS	47% DCS 26% OCS 27% LCS
Average Battery Capacity (kWh)	401	260	238	296	271	210	238
Deviation from 350 kWh (%)	+14.5	-25.8	-31.9	-15.4	-22.5	-39.9	-32.0
Nearest standard EB battery capacity (kWh)	392,400,422	256	220	294	256	210	220

5.5 Synergy Between PV and EB Charging

Applying the PV power density and capacity relations given in equations (4.10)–(4.18), the potential for integrating photovoltaic (PV) generation with electric bus charging infrastructure was estimated. Table 5.4 summarizes the calculated roof areas available at depots and layover sites, together with the corresponding PV capacities for three demand scenarios. The results indicate that the required PV capacity ranges from 17.4 MWp under low-demand conditions to 53.2 MWp for the high-demand case. To ensure adequate coverage for the lower demand and to partially offset the medium and high demands, an average PV capacity of approximately **33 MWp** was used for simulation analyses of PV production and its interaction with the charging load.

Table 5.4: PV Capacity per Depot and Layover Areas

EB Demand	N_{bus}	$A_{\text{PV,depot}}$ (m^2)	$A_{\text{PV,lay}}$ (m^2)	C_{depot} (MWp)	C_{lay} (MWp)	C_{tot} (MWp)
253	632	60,672	31,600	11.47	5.97	17.44
405	1010	96,960	51,200	18.33	9.55	27.88
773	1928	185,088	96,400	34.98	18.22	53.2

As seen in Figure 5.12a, the monthly PV potential for the EB charging of the selected 33 MWp system experiences large seasonality. Generation ranges from a minimum of 26 MWh in July to a maximum of 207 MWh in November. The interquartile range (IQR) is between 110 MWh (Q1) and 190 MWh (Q3), with a median of around 155 MWh. At the same time, the mean (represented by an open square) is marginally lower due to the impact of low-generation months. The longer lower whisker indicates that low-generation months, mainly during the rainy season, are more extreme, whereas high-generation months are relatively stable. These results refer to the dependency of PV generation on seasonal radiance and highlight the need for grid support or storage capacity during periods of low PV generation.

In powering electric bus (EB) charging, the performance of this 33 MW PV system varies considerably across the three demand cases simulated: 253 MWh/day, 405 MWh/day, and 773 MWh/day. For the lowest demand scenario (PV capacity of 52.22 kW$_{\text{p}}$/bus), the PV system offers a high level of support with an average energy coverage of 57.7% (see Fig: 5.9). This implies that, on average, PV generation directly satisfies 57.7% of the daily demand. Coverage ranges from a low of 10.45%, typically occurring during the rainy season (particularly in July, when solar generation is at a minimum), to a high of 81.6% during high-production days, particularly in March and November. The self-sufficiency ratio, or the amount of demand covered without the use of external power reaches averagely 38.9%. Self-consumption, or the proportion of PV energy generated that is directly consumed, also points to quite efficient use of PV, averaging 71.3% and ranging from 55.49% to 100% on a daily basis. In contrast, 28.72% of PV energy, on average, is excess, reflecting the seasonal mismatch between supply and demand and the need for flexible charging or storage to absorb this excess.

When the PV capacity per bus decreases to 32.67 $\mathrm{kW_p}$/bus (i.e. for 405 MWh) (Fig. 5.10), the ability of the system to cover demand reduces. With daily figures ranging between 6.5% and 51%, the average energy coverage reduces to 36%. This shows that the contribution from the PV system is quite modest, especially during low-insolation months like July and August. Similarly, the average self-sufficiency ratio reduces to 27.6%, reflecting the higher dependence on grid electricity. Conversely, self-consumption rises to 79.7%, reflecting the fact that a greater fraction of the PV energy produced is now being consumed due to the increased demand. Although there is less energy wasted, the excess PV reduces to 20.2%, reflecting the fact that the generation is still inadequate to meet the rising load, particularly during low-solar months.

The contribution of the system, when capacity further decreases to 17.12 $\mathrm{kW_p}$/bus, (Fig:5.11) is quite modest. The average energy coverage falls to 18.9%, with a maximum of 26.7% during sunny hours and a minimum of 3.4% in July. This identifies a significant gap between daily energy demand and production. The average self-sufficiency ratio also drops to 14.5%, determining a strong reliance on the grid. Despite the decreased absolute PV contribution, self-consumption stands at its highest average of 80.1 %, and the daily values are between 66.4–100 %, meaning almost all PV energy is used immediately. The surplus PV is extremely low (19.9%), especially in months of weak solar radiation.

Overall, increasing PV capacity per bus substantially enhances self-sufficiency and energy coverage, while self-consumption remains relatively stable across all configurations as seen in the Figure 5.12b below.

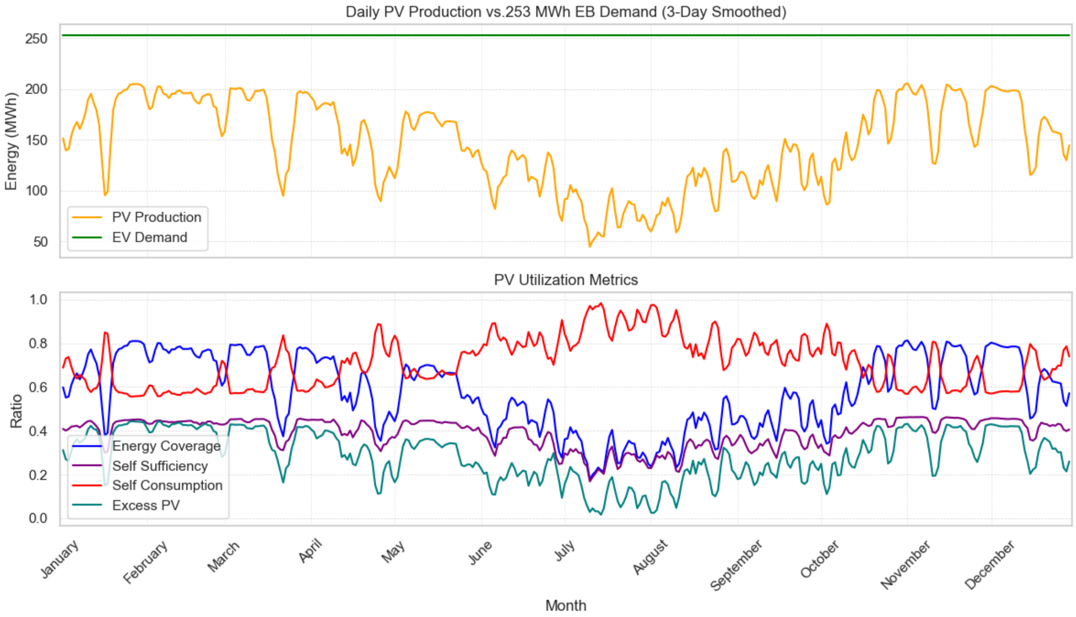


Figure 5.9: PV Production vs. 253 MWh Demand

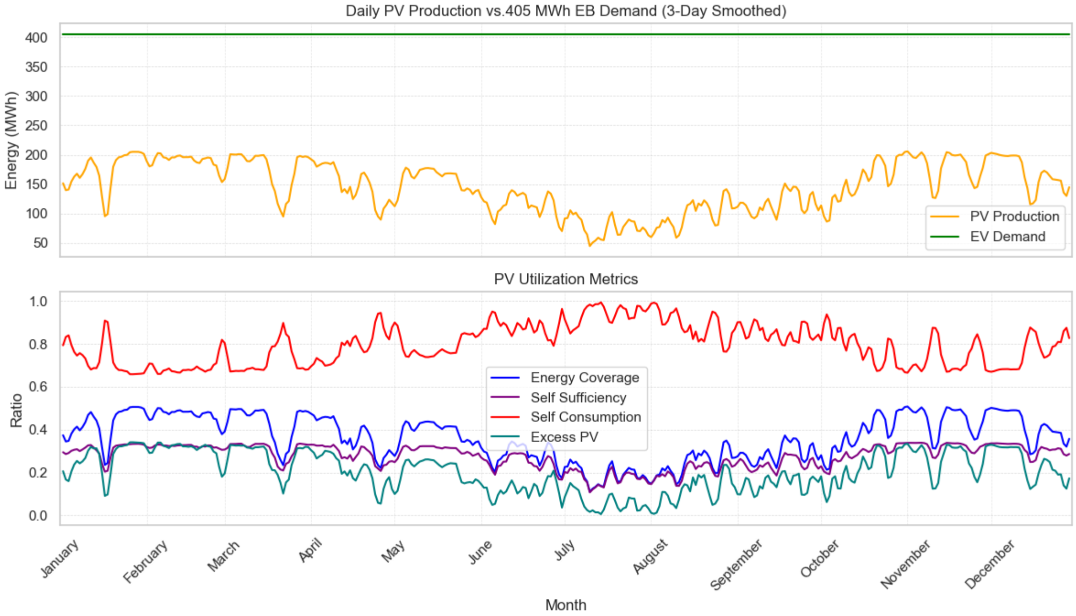


Figure 5.10: PV Production vs. 405 MWh Demand

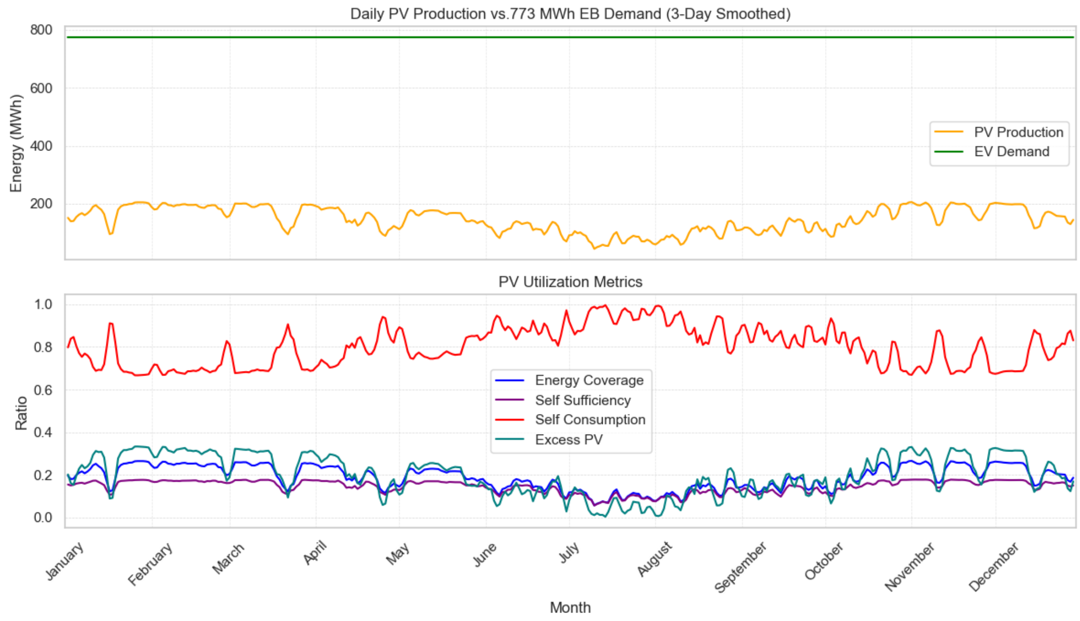
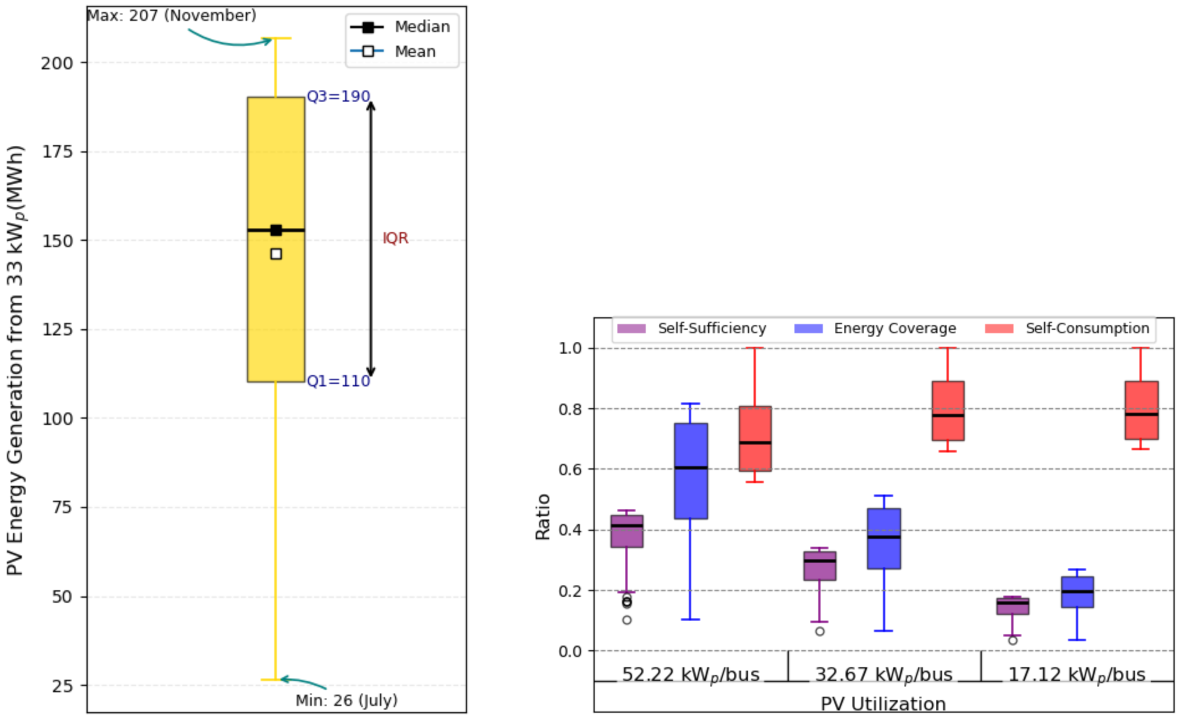


Figure 5.11: PV Production vs. 773 MWh Demand



(a) PV Potential for EB charging

(b) PV Utilization Summary

Figure 5.12: PV Potential and Its Utilization in PV Capacity Per Bus

5.6 Grid Impact Assessment

This section presents a detailed assessment of how the different electric bus charging strategies are projected to influence the 2030 Addis Ababa's electricity grid load profile. The analysis focuses on key grid performance indicators like: *peak load*, *average load*, and *load factor*. The results are, summarized in Table 5.5 and showed in the respective load profile in Figure 5.13,which provides insights into both the magnitude and timing of grid impacts for the different strategies applied.

1. **Peak Load Effects:** The baseline peak load for 2030 is estimated at 1820.9 MW around 19:00 PM night . Charging strategies exhibit varying degrees of impact on this metric. The *depot-only* scenario maintains the peak load at the baseline value, reflecting its deliberate alignment with off-peak nighttime charging windows. Strategies involving *on-route* and/or *layover* charging shift a portion of the demand into daytime hours, slightly elevating peak demand. The highest increase is observed under the mixed strategy of 47% depot, 27% layover, and 26% on-route charging, which raises the peak load to 1839.7 MW.
2. **Average Load Stability:** In all scenarios, the average load only sees a slight increase, reaching about 1383.7 MW. This suggests that the total daily energy consumption stays pretty much the same, no matter which charging strategy is used. This consistency highlights that the key differences between the strategies come from how the load is distributed over time, rather than any shifts in the overall energy needs.
3. **Load Factor Improvement:** The load factor shows a slight improvement in all charging scenarios relative to the baseline value of 0.7506. Notably, the *depot-only* and *on-route-only* scenarios relatively achieves the highest load factors ($\approx$ 0.76), indicating a more uniform distribution of demand over the 24-hour period. Mixed strategies yield load factors closer to the baseline, reflecting moderate variability in demand profiles.
4. **Temporal Load Distribution and Grid Stress:** The timing of charging plays a crucial role in shaping grid impacts. Depot charging exerts most of its load during nighttime hours (22:00–05:00), when system demand is relatively low, thereby reducing competition with other sectors and alleviating daytime stress on the grid. In contrast, *on-route* and *layover* charging concentrate their demand within the operational window of 05:00–22:00, coinciding with existing peak periods and thereby exerting additional pressure on the grid during already high-demand intervals. Whereas, mixed strategies distribute the charging schedule through out the 24 hour period with some additional grid stress.
5. **Potential Overload Hours:** The evening period between 18:00 and 21:00 corresponds to the baseline system peak (1820.9 MW). Several charging strategies introduce additional demand during this interval, compounding grid stress. The largest coinciding increase is observed under the mixed 47% depot, 27% layover, and 26% on-route strategy (+18.8 MW), followed by the 52% layover

and 48% on-route mix (+16.9 MW), and the 65% depot and 35% on-route mix (+15.4 MW). These overlaps with existing peak hours present the highest risk of feeder overload and highlight the need for targeted demand-shifting measures or feeder capacity upgrades.

The observed 1% increase(+18.8 MW) can be fully offset when storage systems are integrated, even with the lowest simulated PV capacity per bus. This demonstrates that storage-enhanced PV systems can be utilized to efficiently offset excess demand, thereby promoting grid stability and operational resilience.

Table 5.5: Summary of Peak Load, Average Load, and Load Factor under Various Electric Bus Charging Strategies Projected for 2030.

Charging Strategy	Peak Load (MW)	Average Load (MW)	Load Factor
Base Load (No EB Charging)	1820.9	1366.83	0.7506
Depot Only	1820.9	1383.66	0.7599
Layover Only	1828.5	1383.71	0.7567
On-Route Only	1824.4	1383.63	0.7584
47% Depot + 27% Layover + 26% On-Route	1839.7	1383.72	0.7521
65% Depot + 35% On-Route	1833.4	1383.73	0.7547
63% Depot + 37% Layover	1833.3	1383.68	0.7548
52% Layover + 48% On-Route	1836.5	1383.77	0.7535

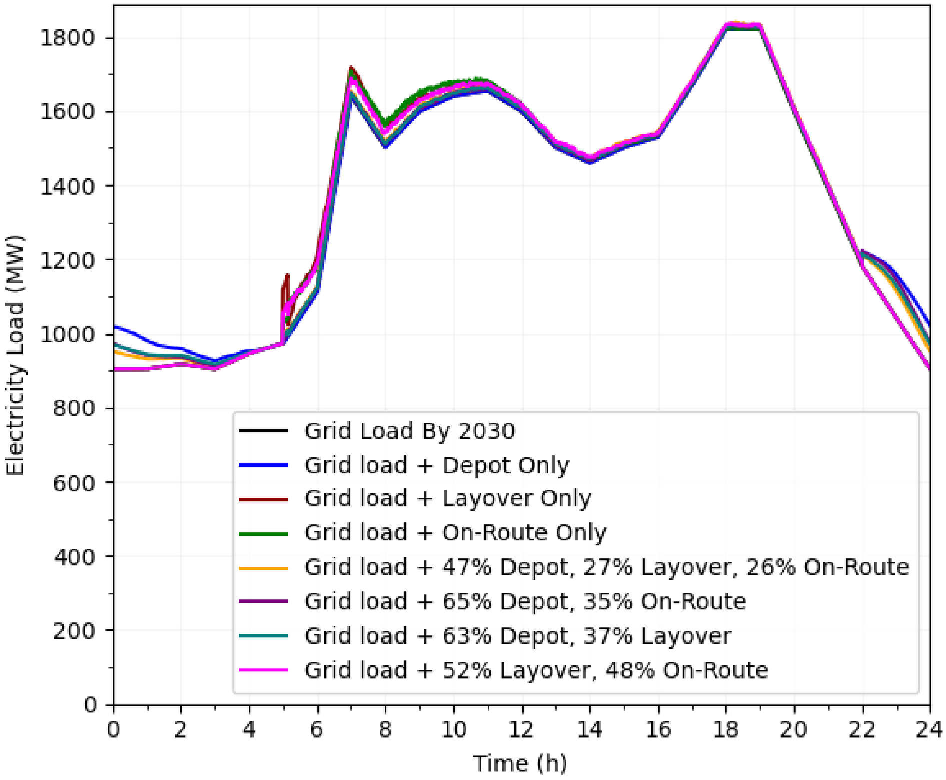


Figure 5.13: Daily Load Profiles with EB Charging Scenarios (2030 Projection)

Overall, the analysis reveals that while the *total* daily energy requirement for electric bus (EB) charging remains broadly consistent across strategies, the *temporal distribution* of this demand is a critical factor influencing grid operation, peak capacity requirements, and system stability. The key implications for grid management and charging strategy optimization are as follows:

- **Depot charging** primarily occurs during the off-peak night hours (22:00–05:00), fully avoiding the daytime system peak. This timing supports load shifting, enables better utilization of base-load generation assets, and minimizes feeder congestion during critical hours, ultimately advantageous for grid stability.
- **On-route, layover, and their combined charging strategies** require careful management and possibly smart charging technologies to prevent exacerbation of peak demand during the day..
- **depot-based mixed charging strategies** provide operational flexibility and can balance depot and in-service charging needs. However, without coordinated scheduling or smart charging algorithms, these strategies risk clustering demand during the most constrained grid periods, reducing system reliability.

5.7 Economic,Technical and Environmental Impact

This section provides a detailed analysis of the monetary terms associated with different electric bus charging setups under different demand levels, along with the technical feasibility and environmental impact assessments. It is focused on three different charger types, i.e., Depot Chargers (DCS), Layover Chargers (LCS) and On-route Chargers (OCS) that have particular unit cost and working features. It should be noted that the economic cost analysis in this work focuses solely on the charger cost under different charging scenarios, without a detailed assessment of other cost factors, and aims to highlight the economic implications of various charging methods.

5.7.1 Economic Impact: Cost Analysis of Charging Scenarios

The total capital cost for each charging scenario and demand level was computed by multiplying the number of chargers of each type by their respective unit costs and summing the results. The unit costs are \$3,640 per unit, \$6,875 per unit, and \$17,703 per unit for depot (DCS), layover (LCS), and on-route (OCS) chargers receptively. Table 5.6 summarizes the total costs for each charging scenario across three daily energy demand levels (253 MWh, 405 MWh, and 773 MWh).

Table 5.6: Total Charger Cost by Scenario and Demand Level

Scenario	**405 MWh**	**253 MWh**	**773 MWh**
DCS Only	$4,790,240	$3,018,960	$9,150,960
LCS Only	$3,334,375	$2,103,750	$6,378,375
OCS Only	$3,431,382	$2,175,469	$6,570,013
63% DCS + 37% LCS	$3,798,855	$2,394,295	$7,249,970
65% DCS + 35% OCS	$4,702,399	$2,963,443	$8,974,509
52% LCS + 48% OCS	$3,676,385	$2,320,471	$7,033,350
47% DCS + 27% LCS + 26% OCS	$3,629,272	$2,311,118	$6,943,233

The economic ranking of charging scenarios from cheapest to most expensive varies slightly with demand level but follows a consistent pattern. For the 405 MWh demand level, the Layover Charger (LCS) only scenario is the most cost-effective, followed closely by the On-route Charger (OCS) only scenario. Mixed scenarios that combine depot, layover, and on-route chargers, such as the 47% DCS + 27% LCS + 26% OCS and the 52% LCS + 48% OCS configurations, rank in the mid-cost range. The 63% DCS + 37% LCS scenario is more expensive than the mixed LCS and OCS options but less costly than scenarios dominated by depot chargers. The 65% DCS + 35% OCS scenario ranks second highest in cost, with the Depot Charger (DCS) only scenario being the most expensive.

A similar trend is observed for the 253 MWh and 773 MWh demand levels, where the LCS only scenario consistently remains the cheapest option. The OCS only scenario follows as the next most affordable. Mixed charger scenarios again fall in the middle range, offering a balance of costs. The DCS only scenario remains the most expensive at both demand levels, emphasizing the higher capital costs associated with depot charging infrastructure.

while this ranking is solely based on initial charger investment, a comprehensive economic assessment must also consider battery requirements and their impact on lifecycle costs. Battery capacity represents a substantial portion of the bus investment, and minimum battery size directly affects both operational flexibility and degradation risk. The Depot Charger (DCS) only scenario remains the least economical due to the highest charger cost and largest median battery capacity of 366 kWh, with a high minimum of 139 kWh. The Layover Charger (LCS) only scenario is the most robust option, combining low infrastructure cost with a moderate median battery capacity of 284 kWh and a minimum of 136 kWh, mitigating early degradation. The On-route Charger (OCS) only scenario, while low in charger cost, has an extremely low minimum battery capacity of 27 kWh, which risks accelerated degradation and consequently lead to higher life cycle costs unless carefully managed. Mixed strategies present a balanced trade-off: LC+OC dominant mixes (e.g., 52% LCS + 48% OCS) achieve low median capacities (199 kWh) but still requires careful management due to low minimums (72 kWh), while DC-heavy mixes (e.g., 63% DCS + 37% LCS and 65% DCS + 35% OCS) incur higher costs due to both infrastructure and larger batteries, despite slightly higher minimum capacities. Overall, the most economically attractive options balance low charger costs with moderate battery capacities, ensuring reduced risk of fast degradation, whereas DCS-only scenarios are the least favorable due to high capital and battery investments.

5.7.2 Technical Feasibility of Charging Scenarios

The technical feasibility of each charging scenario depends on charger availability, spatial coverage, and operational manageability across the city.

- **Depot Charging (DCS) Only:** This scenario requires a very high number of chargers (1316 in the base case) to meet daily fleet demand. While this ensures sufficient energy supply, managing such a large number of chargers at a single depot is technically challenging due to space limitations, land constraints, and maintenance complexity. But, spreading them in two or more depots makes it feasible.
- **Layover Charging (LCS) Only:** Layover-only charging requires fewer chargers than a depot-only setup, making it more manageable in terms of deployment. However, since chargers are only available at layover points, careful scheduling is needed to ensure all buses can access them during short layover times, which could limit operational flexibility.
- **On-Route Charging (OCS) Only:** For the base case, this scenario installs 194 chargers over 1340 stops, providing charging availability at a mere 14.5% of stops, with a maximum of one charger per stop. This limited spatial coverage presents serious technical challenges for city-wide fleet operations since a large number of buses may not have reliable access to on-route charging when required. Similarly for the *52% LCS + 48% OCS* mixed configuration, which, with 267 chargers, can provide a maximum of 19.9% coverage of stops and terminal points throughout the network.
- **Mixed Charging Scenarios:** Depot-based mixed strategies provide a more balanced technical solution. They reduce the total number of chargers compared to depot-only scenarios while improving spatial coverage and operational feasibility compared to LC-only or OC-only setups. For example:

- **47% DCS + 27% LCS + 26% OCS:** Reduces overall charger number compared to DCS-only, while allowing buses to access a combination of depot, layover, and on-route chargers, enhancing operational flexibility.
- **63% DCS + 37% LCS:** Balances depot and layover chargers to minimize the total number of chargers while maintaining good spatial coverage, avoiding the technical difficulty of handling too many chargers at a single depot. As well as PV integration is feasible in this case.
- **65% DCS + 35% OCS:** Combines depot and on-route chargers to reduce depot infrastructure needs while slightly improving access along routes, offering a technically feasible compromise between coverage and manageability. However, only depot stations are supported by PV integration, whereas on-route chargers depend entirely on the grid.

In general, depot-based mixed scenarios provide a trade-off between the high charger density of depot-only configurations and the low availability of layover-only and on-route-only scenarios. With an optimal number and placement of chargers, these configurations improve technical feasibility and operational flexibility for a large urban bus network.

5.7.3 Environmental Impact

The environmental assessment reveals that electrification of the Addis Ababa bus fleet delivers substantial greenhouse gas (GHG) reductions, even without solar photovoltaic (PV) integration. Replacing the entire diesel fleet by 2030, which emits approximately 203,478 kg CO_2 per day (equivalent to 74,270 tonnes/year), with electric buses charged solely from the national grid reduces daily emissions to about 15,779 kg (5,759 tonnes/year). This corresponds to a daily reduction of roughly 92%, primarily attributable to Ethiopia's hydro-dominated electricity mix with a very low carbon intensity. When PV systems are incorporated, the reduction potential improves further, though the incremental effect depends strongly on the charging strategy. Scenarios with higher daytime charging allow better alignment between load and PV generation, as indicated by their Self-Sufficiency Ratios (SSR), thus minimizing reliance on the grid.

Among the strategies evaluated, two stand out. First, the mixed strategy with 47% depot, 27% layover, and 26% on-route charging (SSR = 0.28) reduces annual CO_2 emissions by approximately 70,123 tonnes relative to diesel and achieves an additional 1,969 t/year savings compared to the grid-only electrification case. This scenario balances environmental benefits with operational feasibility, since depot charging remains dominant while daytime charging captures a significant portion of PV output. Second, the strategy combining 52% layover and 48% on-route charging (SSR = 0.34) offers the highest overall environmental performance, reducing emissions by about 70,468 tonnes/year relative to diesel and delivering nearly 1,969 tonnes/year of extra savings compared to grid-only electrification. This configuration maximizes PV utilization due to its strong alignment with daytime load profiles, although it may involve higher infrastructure and operational complexity. Overall, the findings indicate that while electrification itself drives the majority of GHG reductions, integrating PV with appropriately designed charging strategies can yield meaningful additional savings, particularly when layover and on-route charging are prioritized. Applying equation 4.24, the computed daily and annual CO_2 reductions for the full fleet under different charging strategies are summarized in Table 5.7.

Table 5.7: Daily and Annual CO_2 Reduction for Various Charging Strategies, with and without PV Self-Sufficiency.

Scenario	SSR	CO_2 grid/day no PV (kg)	CO_2 grid/day with PV (kg)	ΔCO_2/day no PV (kg)	ΔCO_2/day with PV (kg)
DCS only	0.00	15,779	15,779	187,669	187,669
LCS only	0.27	15,779	11,519	187,669	191,959
OCS only	0.27	15,779	11,519	187,669	191,959
65%DCS 35%OCS	0.20	15,779	12,623	187,669	190,855
63%DCS 37%LCS	0.22	15,779	12,308	187,669	191,170
47%DCS 27%LCS 26%OCS	0.28	15,779	11,361	187,669	192,117
52%LCS 48%OCS	0.34	15,779	10,414	187,669	193,064

These results indicate that electrifying the entire fleet can reduce daily CO_2 emissions by approximately 188 tonnes/day without PV, and up to 193 tonnes/day with PV self-sufficiency, highlighting the substantial environmental benefits of integrating renewable energy with strategic EV charging. Transitioning to electric bus fleets, supported by well-designed charging infrastructure, can substantially reduce greenhouse gas emissions and local air pollutants. However, the extent of these environmental benefits depends on the electricity generation mix and the chosen charging strategy. When electricity is drawn primarily from renewable sources, emissions reductions are maximized. Conversely, in carbon-intensive grids, the timing and distribution of charging demand become critical, as charging strategies directly influence grid integration and the proportion of renewable versus fossil-based electricity consumed.

In a nutshell, an integrated approach considering economic, technical, and environmental factors is essential for sustainable electric bus deployment. The cost analysis highlights that the Layover Charger only scenario is the most cost-effective across all demand levels, followed by On-Route and mixed charger configurations. Depot charger only scenarios incur the highest capital costs. However, technical feasibility and operational flexibility must also guide infrastructure planning. Future research should incorporate grid impact assessments and life-cycle environmental analyses to optimize the transition to electric bus systems.

5.8 Discussion

The results indicate that the average energy consumption per kilometer for a bus is about 1.86 kWh/km, consistent with previous studies [53, 54]. The calculated mean daily distance traveled is roughly 220 km per bus. The relatively high mean distance is due to the fact that the GTFS dataset includes routes that extend outside Addis Ababa to locations like Addisalem, Sebeta, and Sendafa, with some buses traveling up to 403 km daily.

By 2030, three electrification scenarios were considered: the adoption of 632 electric buses (projected number of EBs), the deployment of 1010 EBs (corresponding to the GTFS data set) estimated by the GTFS4EV model (only 0.1% below the actual bus data for the corresponding year), and the full electrification of all 1928 diesel buses. These scenarios would result in daily charging demands of approximately 253 MWh, 405 MWh, and 773 MWh, respectively. Relative to the forecasted 2030 electricity load profile, these demand increases the profile by 0.8%, 1.2%, and 2.4% respectively of total daily consumption. Although seemingly modest, these additional demands require careful planning due to their significant impacts on the grid.

Addis Ababa's electricity system already operates close to its capacity, as reflected in frequent power outages. Spatial analysis further indicates that charging demand is concentrated in the city center, which could exacerbate localized grid stress. Moreover, these projections exclude the rapidly growing demand associated with private electric vehicle adoption, which is likely to intensify pressure on the network.

The choice of charging strategy strongly influences the spatial and temporal distribution of demand. This study evaluates depot-only, layover-only, on-route-only, and mixed charging approaches. For instance, a strategy combining 47% depot, 27% layover, and 26% on-route charging aligns closely with the evening peak load while balancing upfront charger investment, operational flexibility, and battery capacity requirements (Figures 5.7 and 5.8). By contrast, layover-only and on-route-only approaches minimize battery capacity needs but coincide with the morning peak load around 7:00 AM. The layover-only strategy, in particular, creates a sharp demand surge at 5:13 AM, despite having the lowest initial charger cost among the scenarios.

A mixed strategy of 52% layover and 48% on-route charging requires the smallest average battery capacity, followed by the on-route-only approach. However, these configurations needs advanced smart-control systems and may accelerate battery degradation due to frequent daily charging cycles. Depot-only charging, in contrast, requires the largest battery capacity (around 400.8 kWh per bus) and the highest upfront infrastructure cost, but it contributes to stabilizing peak grid loads. In terms of charger requirements, on-route and layover-based strategies rely on fewer, high-capacity DC fast chargers (500 kW and 400 kW, respectively), while depot-based charging requires a larger number of medium-power chargers (120 kW), offset by the longer dwell times available for charging at depots.

The analysis of photovoltaic (PV) integration shows that increasing PV capacity per bus improves self-sufficiency and energy coverage, though the marginal benefits diminish beyond certain thresholds. At the maximum feasible capacity of 52.22 kW_p/bus, constrained by urban land availability, the system achieves a modest self-sufficiency ratio of 0.4 and highly variable energy coverage (0.1–0.8), while maintaining consistently high self-consumption. Reducing PV capacity to 32.67 or 17.12 kW_p/bus lowers both self-sufficiency and coverage, with the lowest case falling below 0.2. Nevertheless, self-consumption remains high (0.7–0.8), indicating efficient use of available PV generation.

With the limited land availability in Addis Ababa, it is not feasible to increase PV capacity beyond the maximum analyzed here. Hence, to take full advantage of PV generation and bring excess energy close to zero, it is crucial to incorporate complementary solutions. These encompass energy storage systems, demand-side management, and smart flexible charging strategies, which together facilitate improved matching of electric buses charging demand and solar generation profiles. These comprehensive strategies optimize onsite renewable energy use and grid independence regardless of natural temporal mismatches between PV generation and charging demand.

Regarding the environmental impact, it should be noted that the CO_2 reductions are not absolute, as the analysis assumes a non-zero grid emission factor that reflects the residual carbon intensity of Ethiopia's electricity mix. In general, the findings provide a foundation for the strategic planning of effective charging infrastructure and highlight the importance of using spatially diverse and flexible charging strategies to achieve the sustainable integration of electric buses in Addis Ababa.

Chapter 6

Conclusion and Recommendations

6.1 Conclusion

This thesis provides a comprehensive, data-driven assessment of electric bus charging strategies in Addis Ababa, examining their economic, technical, and environmental implications. It develops a framework to evaluate trade-offs between infrastructure investment, operational efficiency, and integration with renewable energy sources, offering a structured approach for planning and decision-making in urban transit electrification.

Based on the analysis, several key findings emerge, highlighting the impacts of charging strategies on cost, demand distribution, and renewable energy alignment. These findings are summarized as follows:

1. The analysis indicates that each electric bus has a daily energy demand of approximately 401 kWh, corresponding to an average consumption of 1.86 kWh/km. By 2030, this demand is projected to increase the city's daily electricity load by 0.8%, 1.2%, and 2.4% under three electrification cases: deployment of only the planned electric buses, the number of buses estimated from the GTFS dataset using the `GTFS4EV` model, and full replacement of all diesel buses with electric buses, respectively.
2. The charging strategies strongly influence the spatio-temporal distribution of electricity demand. Depot-only charging concentrates demand at bus depots during late-night hours, layover-only charging distributes demand temporally across the service day while relatively spatially concentrated, and on-route charging disperses demand both spatially and temporally across the city, although its technical feasibility remains limited.
3. A charging mix of 47% depot, 27% layover, and 26% on-route results in the highest evening peak, followed by a 52% layover and 48% on-route mix, while on-route-only and layover-only strategies contribute to increased morning peaks. Across all scenarios, the average daily load increases marginally by 16.87 MW.
4. Depot-only strategy requires the highest initial charger investment, followed by the 65% depot and 35% on-route mix, while layover-only is the most cost-effective.
5. In general, depot-based mixed strategies, specially the 47% depot, 27% layover,

and 26% on-route scenario, provide a trade-off between the high charger density of depot-only configurations and the low availability of layover-only or on-route-only scenarios. With optimal charger number and placement, as well as total cost, these configurations improve technical feasibility and operational flexibility for a large urban bus network.

6. The highest PV production alignment is observed in the 47% depot, 27% layover, and 26% on-route mix, as well as the 65% layover and 35% on-route mix strategies. At the maximum considered PV capacity of 52.22 kW_p/bus, self-sufficiency reaches approximately 40%, with energy coverage ranging from 10% to over 80%, while self-consumption remains consistently high across all capacities, exceeding 70% even in the lowest capacity scenario.
7. Full fleet electrification reduces daily CO_2 emissions by 92% (up to 95% with PV integration), underscoring the environmental benefits of renewable supported EB charging.

Although focused on Addis Ababa, this study provides actionable insights for other cities pursuing electric bus electrification. It demonstrates how strategic charging, cost-efficient planning, and solar integration enhance operational and environmental performance. By quantifying trade-offs between economic, technical, and renewable objectives, this research offers a concise, evidence-based framework to guide policymakers and urban planners in designing scalable, sustainable electric bus systems in diverse urban contexts.

6.2 Recommendation and Future Works

Based on the findings of this study, it is recommended that electric bus operations in Addis Ababa implement a depot-based mixed charging strategy to maximize operational efficiency, cost-effectiveness, and system reliability. The primary recommended configuration consists of 47% depot, 27% layover, and 26% on-route charging, while a secondary configuration of 63% depot and 37% layover charging may serve as an alternative under different operational or demand scenarios. Aligning these strategies with renewable energy (solar PV) can further enhance environmental sustainability and support long-term resilience of the urban transport system. Future work could focus on the following areas:

- Determining optimal electric bus charger capacities for depot, on-route, and layover strategies, including multiple charger sizes at a single location.
- Investigating the effects of charger capacity on electric bus operations from the perspectives of drivers and the power grid.
- Examining the interaction between electric bus battery and charger capacity, including implications for cost and operational efficiency.

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Appendix A. EB Forecasting Method

The transition of the urban bus fleet in Addis Ababa, from conventional fuel-based buses to electric buses (EBs), has been driven by various economic and policy factors. Previously, the growth of the urban fleet has been driven by urbanization and an increasing need for public transport services. From 2010 to 2024, fuel-powered buses followed fluctuating trends depending on economic growth, fuel price fluctuations, and population growth. It is important to understand these historical trends to forecast the future fleet composition of urban buses.

Hence, to predict the number of EBs in 2030, historical data were utilized to conduct multiple regression analysis. GDP Growth (%), fuel price (USD/liter), and population (millions) are the most determining factors of fleet growth and were utilized for the prediction as independent variables. The aforementioned variables were collected from credible institutions: GDP growth data were collected from the World Bank, International Monetary Fund (IMF), and the African Development Bank; fuel price data were collected from TheGlobalEconomy.com, and Energypedia; and population data were retrieved from the World Population Review. Moreover, primary data on the number of buses operational in Addis Ababa were gathered from the Addis Ababa City Bus Service Enterprise.

A key assumption underlying this projection is that, in accordance with government policy, any expansion of the bus fleet beyond 2024 will consist exclusively of electric buses. This assumption is supported by the data presented in Figure A.1, which is sourced from official report [55]. We know that two electric buses were already running on the Addis Ababa streets by 2024 and that another 100 electric buses were already being under assembly. The policy change has been accounted for in the forecasting exercise, therefore making the numbers actually reflect the expected transition to a fully electrified fleet.

The multiple regression model used for this forecast is formulated as follows:

$$\text{Bus\_No} = \beta_0 + \beta_1 \times \text{GDP\_Growth} + \beta_2 \times \text{Fuel\_Price} + \beta_3 \times \text{Population} \tag{A.1}$$

Where:

- β_0 = Intercept
- β_1 = GDP growth coefficient
- β_2 = Fuel price coefficient
- β_3 = Population coefficient

The model was fitted with the aid of Microsoft Excel and yielded a **Multiple R** value of **0.908562** and an **R Square** value of **0.825485** as well as the associated parameters coefficient values of β_0 = -1778.083 (intercept), $\beta_1 = 35.412$ (GDP growth coefficient), $\beta_2 = 411.558$ (fuel price coefficient), and $\beta_3 = 427.942$ (population coefficient). These statistical values indicate a strong level of association between the number of buses and the independent variables, implying that the model accounts for approximately 82.55% of the variance in the number of buses.

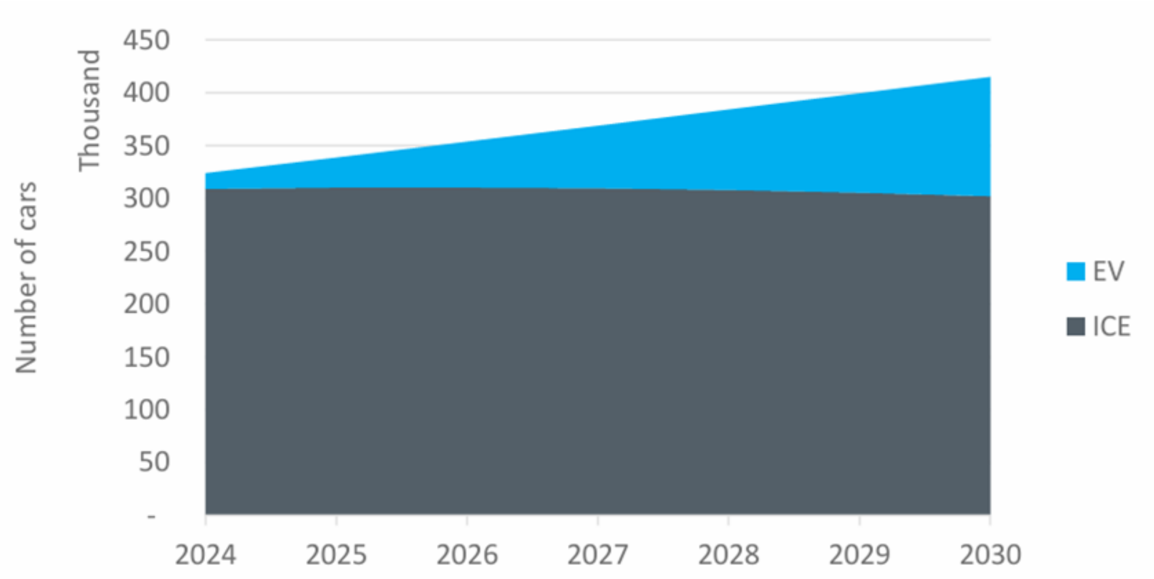

Figure A.1: Projected growth of Ethiopia's Vehicle Fleet (2024–2030) by Propulsion Type (ICE vs. EV)[55]

Table A.1: Input Data Used for Electric-Bus (EB) Forecasting

Year	**City Bus Number**	**GDP Growth (%)**	**Fuel Price (USD/Liter)**	**Population (Millions)**
2010	290	10.6	0.91	3.126
2011	454	11.2	1.00	3.263
2012	604	8.6	1.05	3.405
2013	628	10.6	1.03	3.554
2014	644	10.3	0.99	3.709
2015	650	10.4	0.85	3.871
2016	447	7.6	0.75	4.040
2017	520	10.2	0.83	4.216
2018	608	7.7	0.90	4.400
2019	771	9.0	0.92	4.460
2020	622	6.1	0.88	4.620
2021	944	5.6	1.10	4.780
2022	1020	3.8	1.25	4.940
2023	1162	5.3	1.50	5.160
2024	1430	6.1	0.716	5.703
2025	—	6.5	0.716	5.956
2026	—	6.8	0.716	6.219
2027	—	7.0	0.716	6.490
2028	—	7.2	0.716	6.769
2029	—	7.4	0.716	7.057
2030	—	7.5	0.716	7.352

Appendix B. Depot Area Breakdown

Table B.1 shows the space requirements for individual facilities and components in depots of varying sizes, ranging from 50 to 200 buses. The data serves as the basis for estimating average land area per bus, supporting the assumption of 170 m^2/bus used in the main analysis[51].

Table B.1: Size of Land Parcel for Various Depot Sizes

Component	**50 Bus Depot** Area (m^2)	**100 Bus Depot** Area (m^2)	**150 Bus Depot** Area (m^2)	**200 Bus Depot** Area (m^2)
Fuelling Area	200	200	300	400
Washing Area	100	200	200	300
Maintenance Bays / Pits	–	–	–	–
Inspection Area	160	320	480	640
Workshop incl. Stores	1100	1600	2000	2400
Bus Parking	2500	5000	7500	10000
Admin Area	600	750	1100	1400
Staff Parking	1000	1250	1500	1750
Scrap Yard	250	350	450	600
Sub Station	250	350	450	600
Green Area	600	950	1250	1500
Circulation & Queuing	5700	8200	10500	12500
Total Area	12,460	19,170	25,730	32,090
Land Area (acres)	3.08	4.74	6.36	7.93
Area per Bus (m^2)	250	192	172	161

Appendix C. Electric Bus Trip Statistics

Table C.1: Trip-wise Result of EB Statics From EV-Fleet Simulator

Trip ID	Power (kW)	Energy (kWh)	Dist. (km)	kWh/km	Trip ID	Power (kW)	Energy (kWh)	Dist. (km)	kWh/km	Trip ID	Power (kW)	Energy (kWh)	Dist. (km)	kWh/km
0	54.0	48.0	25.0	1.92	130	75.0	78.0	38.5	2.03	262	37.0	101.0	52.0	1.94
1	60.0	68.0	34.0	2	131	58.0	67.0	38.0	1.76	263	41.0	102.0	53.0	1.92
2	65.0	35.0	18.0	1.94	132	64.0	50.0	24.0	2.08	264	30.0	61.0	36.0	1.69
3	62.0	60.0	28.0	2.14	133	48.0	46.0	27.0	1.7	265	30.0	59.0	29.0	2.03
4	60.0	38.0	18.0	2.11	134	60.0	43.0	24.0	1.79	266	29.0	54.0	31.0	1.74
5	62.0	60.0	27.0	2.22	135	60.0	43.0	24.0	1.79	267	28.0	52.0	31.0	1.68
6	68.0	80.0	38.5	2.08	136	58.0	63.0	37.0	1.7	268	22.0	41.5	24.0	1.73
7	80.0	75.0	37.0	2.03	137	58.0	63.5	34.0	1.87	269	29.0	41.0	22.0	1.86
8	58.0	61.0	32.0	1.91	138	60.0	51.0	26.0	1.96	270	35.0	64.0	37.5	1.71
9	52.0	58.0	28.0	2.07	139	70.0	68.0	38.0	1.79	271	39.5	99.0	51.0	1.94
10	50.0	59.0	29.0	2.03	140	68.0	93.0	49.0	1.9	272	40.0	100.0	50.0	2
11	59.0	59.0	28.0	2.11	141	69.0	80.0	39.0	2.05	273	40.0	100.0	49.0	2.04
12	75.0	78.0	39.0	2	142	43.0	65.0	38.0	1.71	274	75.0	175.0	120.0	1.46
13	70.0	81.0	40.0	2.02	143	77.0	60.0	35.0	1.71	275	55.0	170.0	120.0	1.42
14	43.0	42.0	27.0	1.56	144	58.0	50.0	24.0	2.08	276	39.0	82.0	43.0	1.91
15	57.0	39.0	28.0	1.39	145	50.0	43.0	23.0	1.87	277	40.0	80.0	40.0	2
16	120.0	55.0	29.0	1.9	146	80.0	135.0	70.0	1.93	278	45.0	110.0	59.0	1.86
17	110.0	59.0	33.0	1.79	147	80.0	135.0	70.0	1.93	279	44.0	121.0	62.0	1.95
18	110.0	42.0	23.0	1.83	148	50.0	52.5	27.0	1.94	280	74.0	81.0	44.0	1.84
19	130.0	49.0	27.0	1.81	149	58.0	58.0	29.0	2	281	41.0	81.5	44.0	1.85
20	45.0	39.0	22.0	1.77	150	40.0	82.0	40.0	2.05	282	40.0	22.6	11.0	2.05
21	44.0	40.0	23.0	1.74	151	47.0	83.0	40.0	2.08	283	50.0	25.0	12.0	2.08
22	44.0	65.0	34.0	1.91	152	72.0	52.0	27.0	1.93	284	37.0	11.0	5.5	2
23	45.0	35.0	17.0	2.06	153	61.0	65.0	33.0	1.97	285	39.0	15.0	6.7	2.24
24	40.0	38.0	20.0	1.9	154	47.0	43.0	25.0	1.72	286	60.0	34.0	18.0	1.89
25	42.0	42.0	28.0	1.5	155	41.0	39.0	20.0	1.95	287	60.0	60.0	28.0	2.14
26	45.0	45.0	27.0	1.67	156	60.0	55.0	28.5	1.93	288	80.0	78.0	41.0	1.9
27	41.0	53.0	27.0	1.96	157	58.0	69.0	34.0	2.03	289	60.0	83.0	42.0	1.98
28	41.0	17.0	9.0	1.89	158	47.0	33.0	16.0	2.06	290	40.0	52.0	28.0	1.86

Trip ID	Power (kW)	Energy (kWh)	Dist. (km)	kWh/km	Trip ID	Power (kW)	Energy (kWh)	Dist. (km)	kWh/km	Trip ID	Power (kW)	Energy (kWh)	Dist. (km)	kWh/km
29	42.0	19.5	11.0	1.77	159	52.0	31.0	14.0	2.21	291	40.0	58.0	32.0	1.81
30	40.0	39.0	28.0	1.39	160	53.0	42.0	24.5	1.71	292	60.0	70.0	34.0	2.06
31	51.0	35.0	18.0	1.94	161	41.0	35.0	18.0	1.94	293	52.0	70.0	36.0	1.94
32	45.0	48.0	25.0	1.92	162	45.0	27.0	19.0	1.42	294	38.0	80.0	42.0	1.9
33	47.0	50.0	26.0	1.92	163	40.0	23.5	14.0	1.68	295	60.0	78.0	40.0	1.95
34	45.0	61.0	32.0	1.91	164	58.0	43.0	19.0	2.26	296	60.0	70.0	35.0	2
35	78.0	64.0	32.0	2	165	47.0	39.0	18.5	2.11	297	60.0	75.0	40.0	1.88
36	50.0	24.0	11.0	2.18	168	198.0	161.0	80.0	2.01	298	28.0	31.0	17.0	1.82
37	58.0	18.0	9.0	2	169	108.0	100.0	50.0	2	299	28.0	28.0	16.0	1.75
38	55.0	34.0	17.0	2	170	59.0	60.0	32.0	1.88	300	40.0	35.0	19.0	1.84
39	60.0	35.0	17.0	2.06	171	65.0	61.0	32.0	1.91	301	50.0	38.0	19.0	2
40	60.0	34.0	16.0	2.12	172	50.0	27.0	15.0	1.8	302	27.0	35.0	20.0	1.75
41	48.0	37.0	17.0	2.18	173	59.0	32.0	18.0	1.78	303	20.0	41.0	22.0	1.86
42	115.0	60.0	31.0	1.94	174	101.0	150.0	198.0	0.76	304	26.0	40.0	19.0	2.11
43	58.0	50.0	28.0	1.79	175	120.0	150.0	201.0	0.75	305	24.0	50.0	25.0	2
44	60.0	44.0	29.0	1.52	176	48.0	50.0	24.0	2.08	306	40.0	27.0	15.0	1.8
45	40.0	62.0	35.0	1.77	177	57.0	63.5	32.0	1.98	307	60.0	41.0	24.0	1.71
46	75.0	62.0	38.0	1.63	178	125.0	151.0	137.0	1.1	308	100.0	90.0	45.0	2
47	64.0	64.0	35.0	1.83	179	125.0	152.0	137.5	1.11	309	65.0	80.0	44.0	1.82
48	60.0	53.0	27.0	1.96	180	58.0	67.0	34.0	1.97	310	22.0	40.0	24.0	1.67
49	48.0	42.0	24.0	1.75	181	75.0	70.0	36.0	1.94	311	40.0	70.0	37.0	1.89
50	75.0	165.0	90.0	1.83	182	52.0	70.0	35.0	2	312	30.0	53.0	27.0	1.96
51	75.0	170.0	90.0	1.89	183	43.0	50.0	25.0	2	313	40.0	61.0	32.0	1.91
52	45.0	70.0	45.0	1.56	184	98.0	155.0	100.0	1.55	314	28.0	33.0	17.0	1.94
53	52.0	78.0	47.0	1.66	185	102.0	150.0	90.0	1.67	315	22.0	40.0	18.0	2.22
54	75.0	87.0	44.0	1.98	186	110.0	150.0	220.0	0.68	316	35.0	63.0	35.0	1.8
55	75.0	82.0	40.0	2.05	187	120.0	160.0	135.0	1.19	317	40.0	95.0	50.0	1.9
56	58.0	35.0	18.0	1.94	188	55.0	71.0	35.0	2.03	318	23.0	35.0	19.0	1.84
57	66.0	60.0	30.0	2	189	55.0	60.0	31.5	1.9	319	30.0	52.0	28.0	1.86
58	58.0	39.0	22.0	1.77	190	60.0	62.0	33.0	1.88	320	38.0	40.0	75.0	0.53
59	60.0	44.0	23.0	1.91	191	50.0	65.0	35.0	1.86	321	42.0	80.0	47.0	1.7
60	60.0	33.0	19.0	1.74	192	60.0	75.0	36.0	2.08	322	30.0	38.0	20.0	1.9
61	76.0	48.0	20.0	2.4	193	80.0	80.0	40.0	2	323	37.0	40.0	20.0	2
62	50.0	44.0	19.0	2.32	194	35.0	48.0	23.0	2.09	324	40.0	80.0	42.0	1.9

Trip ID	Power (kW)	Energy (kWh)	Dist. (km)	kWh/km	Trip ID	Power (kW)	Energy (kWh)	Dist. (km)	kWh/km	Trip ID	Power (kW)	Energy (kWh)	Dist. (km)	kWh/km
63	48.0	35.0	18.0	1.94	195	22.0	45.0	23.0	1.96	325	61.0	70.0	37.0	1.89
64	60.0	55.0	28.0	1.96	196	38.0	61.0	30.0	2.03	326	23.0	23.0	12.0	1.92
65	62.0	56.0	29.0	1.93	197	40.0	63.0	34.0	1.85	327	20.0	17.0	9.0	1.89
66	49.0	47.0	24.0	1.96	198	45.0	86.0	45.0	1.91	328	18.0	6.0	3.0	2
67	63.0	50.0	27.0	1.85	199	40.0	87.0	46.0	1.89	329	14.0	8.0	4.0	2
68	67.0	60.0	30.0	2	200	50.0	145.0	67.0	2.16	330	30.0	60.0	38.0	1.58
69	63.0	75.0	37.0	2.03	201	50.0	150.0	70.0	2.14	331	30.0	82.0	50.0	1.64
70	64.0	27.0	14.0	1.93	202	35.0	66.0	35.0	1.89	332	35.5	60.0	32.0	1.88
71	42.0	35.0	18.0	1.94	203	35.0	70.0	40.0	1.75	333	30.0	44.0	21.0	2.1
72	55.0	89.0	44.0	2.02	204	22.0	50.0	28.0	1.79	334	42.0	102.0	57.0	1.79
73	57.0	87.0	43.0	2.02	205	23.0	33.0	19.0	1.74	335	40.0	80.0	40.0	2
74	50.0	50.0	27.0	1.85	206	19.0	14.0	7.5	1.87	336	25.0	40.0	26.0	1.54
75	150.0	49.0	27.0	1.81	207	22.0	13.0	6.5	2	337	26.0	60.0	37.0	1.62
76	58.0	55.0	28.0	1.96	208	30.0	39.0	23.0	1.7	338	38.0	63.0	32.0	1.97
77	42.0	53.0	26.0	2.04	209	10.0	80.0	43.0	1.86	339	60.0	92.0	49.0	1.88
78	41.0	27.0	16.0	1.69	210	25.0	33.0	17.0	1.94	340	38.0	31.0	17.0	1.82
79	58.0	41.0	24.0	1.71	211	23.0	31.0	14.5	2.14	341	25.0	41.5	19.0	2.18
80	40.0	38.0	24.0	1.58	212	30.0	77.0	48.0	1.6	342	40.0	84.0	42.0	2
81	50.0	67.0	45.0	1.49	213	28.0	75.0	47.0	1.6	343	37.0	115.0	66.0	1.74
82	165.0	143.0	75.0	1.91	214	24.0	35.0	19.0	1.84	344	75.0	175.0	122.0	1.43
83	130.0	165.0	95.0	1.74	215	24.0	48.0	26.0	1.85	345	75.0	175.0	121.0	1.45
84	75.0	41.5	23.0	1.8	216	31.0	63.5	32.0	1.98	346	20.0	41.0	23.0	1.78
85	62.0	35.0	19.0	1.84	217	28.0	54.0	28.0	1.93	347	21.0	41.5	24.0	1.73
86	50.0	64.0	37.0	1.73	218	40.0	70.0	39.0	1.79	348	23.0	60.0	30.0	2
87	60.0	63.0	36.0	1.75	219	38.0	63.0	38.0	1.66	349	30.0	60.0	32.0	1.88
88	60.0	58.0	29.0	2	220	55.0	127.0	70.0	1.81	350	38.0	63.0	37.0	1.7
89	43.0	58.0	28.5	2.04	221	65.0	126.0	70.0	1.8	351	30.0	65.0	37.0	1.76
90	64.0	62.0	36.0	1.72	222	42.0	84.0	45.0	1.87	352	30.0	53.0	28.0	1.89
91	44.0	57.0	27.5	2.07	223	40.0	110.0	58.0	1.9	353	31.0	75.0	39.0	1.92
92	42.0	53.0	28.0	1.89	224	40.0	95.0	48.0	1.98	354	29.0	50.0	28.0	1.79
93	45.0	58.0	28.0	2.07	225	50.0	110.0	58.0	1.9	355	30.0	40.0	18.0	2.22
94	98.0	92.0	50.0	1.84	226	32.0	65.0	36.0	1.81	356	28.0	53.0	25.0	2.12
95	110.0	120.0	60.0	2	227	33.0	88.0	50.0	1.76	357	25.0	50.0	24.0	2.08
96	50.0	47.0	29.0	1.62	228	48.0	100.0	53.0	1.89	358	62.0	152.0	80.0	1.9

Trip ID	Power (kW)	Energy (kWh)	Dist. (km)	kWh/km	Trip ID	Power (kW)	Energy (kWh)	Dist. (km)	kWh/km	Trip ID	Power (kW)	Energy (kWh)	Dist. (km)	kWh/km
97	53.0	47.0	24.0	1.96	229	48.0	120.0	61.0	1.97	359	50.0	151.0	80.0	1.89
98	40.0	58.0	30.0	1.93	230	23.0	27.0	13.0	2.08	360	50.0	130.0	75.0	1.73
99	38.0	90.0	50.0	1.8	231	24.0	35.0	15.0	2.33	361	40.0	150.0	83.0	1.81
100	58.0	49.0	25.0	1.96	232	30.0	52.0	27.0	1.93	362	40.0	129.0	71.0	1.82
101	41.0	43.0	27.5	1.56	233	30.0	66.0	34.0	1.94	363	41.0	119.0	61.0	1.95
102	44.0	64.0	32.5	1.97	234	45.0	155.0	86.0	1.8	364	31.0	72.0	38.0	1.89
103	58.0	68.0	37.0	1.84	235	48.0	128.0	65.5	1.95	365	28.0	48.0	23.0	2.09
104	42.5	41.0	20.0	2.05	236	28.0	32.0	16.5	1.94	366	37.0	87.0	52.0	1.67
105	43.0	65.0	34.5	1.88	237	26.0	40.0	19.0	2.11	367	30.0	118.0	71.0	1.66
106	42.0	40.0	22.0	1.82	238	40.0	63.5	34.0	1.87	368	18.0	19.0	11.0	1.73
107	42.5	36.0	18.0	2	239	24.0	62.0	33.5	1.85	369	28.0	20.0	11.5	1.74
108	105.0	58.5	32.5	1.8	240	60.0	165.0	86.0	1.92	370	48.0	148.0	220.0	0.67
109	102.0	52.0	28.0	1.86	241	45.0	165.0	87.0	1.9	371	40.0	150.0	200.0	0.75
110	77.0	64.0	33.0	1.94	242	30.0	52.0	26.0	2	372	58.0	127.0	65.0	1.95
111	45.0	78.0	40.0	1.95	243	23.0	40.0	24.0	1.67	373	41.0	110.0	55.0	2
112	60.0	48.0	28.0	1.71	244	30.0	60.0	39.0	1.54	374	40.0	87.0	47.0	1.85
113	60.0	47.0	22.0	2.14	245	30.0	83.0	51.0	1.63	375	38.0	87.0	46.5	1.87
114	60.0	58.0	29.0	2	246	30.0	81.0	43.0	1.88	376	38.0	60.0	29.0	2.07
115	57.0	50.0	28.0	1.79	247	30.0	78.0	40.0	1.95	377	37.0	60.0	36.0	1.67
116	50.0	50.0	29.0	1.72	248	40.0	80.0	40.0	2	378	30.0	46.0	26.0	1.77
117	50.0	55.0	28.0	1.96	249	50.0	101.0	56.0	1.8	379	29.0	60.0	30.0	2
118	60.0	50.0	27.0	1.85	250	30.0	62.0	26.0	2.38	380	40.0	61.0	36.0	1.69
119	55.0	53.0	27.5	1.93	251	30.0	65.0	27.0	2.41	381	60.0	42.0	24.0	1.75
120	62.0	80.0	43.0	1.86	252	21.0	33.0	19.0	1.74	382	1000	125.0	230.0	0.54
121	50.0	61.0	33.0	1.85	253	23.0	41.0	20.0	2.05	383	1000	185.0	230.0	0.8
122	60.0	27.0	15.0	1.8	254	30.0	59.0	28.0	2.11	384	28.0	27.0	18.0	1.5
123	57.0	37.7	19.0	1.98	255	40.0	52.0	25.0	2.08					
124	62.0	50.0	27.0	1.85	256	37.0	64.0	36.0	1.78					
125	61.0	60.0	30.0	2	257	30.0	65.0	37.0	1.76					
126	75.0	82.0	47.0	1.74	258	30.0	40.0	25.0	1.6				Maximum kwh/km =	2.41
127	54.0	63.0	32.5	1.94	259	30.0	67.0	35.0	1.91				Minimum kwh/km=	0.53
128	60.0	79.0	41.0	1.93	260	40.0	40.0	24.0	1.67				Aggregated Average =	**1.86**
129	60.0	67.0	39.0	1.72	261	28.0	42.0	24.0	1.75					