

“Fleet Electrification for Public Transit: An Economic Assessment of Intercity Bus Operations in Kutch”

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Doctor of Philosophy

in

Civil Engineering

By

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under supervision of

Prof. Dr. Nipa A. Desai



**GUJARAT TECHNOLOGICAL UNIVERSITY
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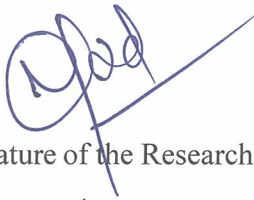
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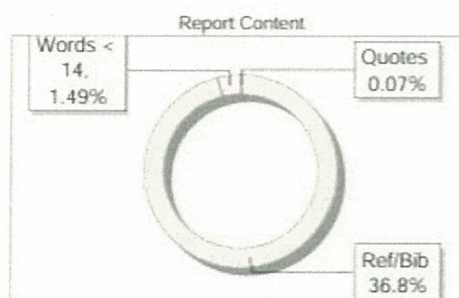
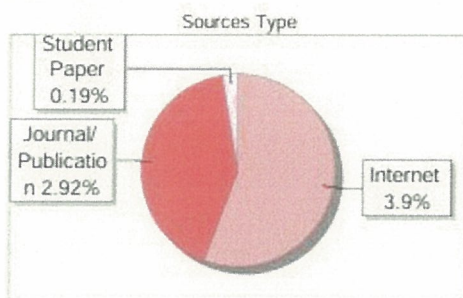
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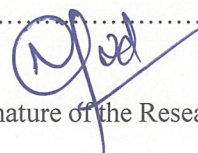
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ABSTRACT

The extensive use of fossil fuels in transit buses has led to both environmental problems and fuel scarcity. Many countries worldwide have already adopted sustainable development to address these challenges. Similarly, the Indian government has initiated e-vehicle adoption in various sectors through subsidies to reduce dependence on conventional fuels. This research investigates the key areas: fuel consumption dependency and air quality impact assessment for diesel-operated public bus fleet (GSRTC), while exploring fleet electrification possibilities through the replacement of diesel buses with EV-buses. This research employs a three-stage energy modeling methodology: Route Energy Planning (REP), Charging Infrastructure Planning (CIP), and Total Cost of Ownership (TCO) and relevant analysis. The study explores the potential for fleet electrification for Kutch division of GSRTC, aiming to replace existing diesel-powered internal combustion engine (ICE) buses with environmentally friendly EV-buses. This study focuses on planning fleet electrification for 183 buses of 8 major depot out of total 381 buses operating over 82,196 km route length in Kutch. Using a 25% minimum SOC (state of charge) threshold, 119 ICE-buses were shortlisted, and after optimizing charging schedules, 66 were finalized as priority buses. An analysis of annual costs for both ICE diesel and EV-buses was conducted, considering bus capitalization, battery capitalization, charging infrastructure, and annual operating costs. The findings revealed that the TCO for an EV-bus is lower than that of a diesel bus (31.00 Rs/km vs. 32.01 Rs/km). This study evaluates the viability of implementing electric mobility for the Gujarat State Road Transport Corporation (GSRTC) in Kutch District, India, to promote sustainable transportation and reduce

emissions. The methodology involved assessing Net Present Value (NPV) and Internal Rate of Return (IRR) using a functional unit of one bus travelling 220 km daily. The bus stations and routes were digitized in GIS format, enabling precise mapping and spatial analysis. The economic assessment indicates that electric bus deployment is financially viable compared with diesel-operated buses. For the 30% fleet replacement scenario, The EV-with-charging scenario achieves NPV of EVs with charging infrastructure increases from ₹1,927 lakh to ₹6,169 lakh across the 10%–30% electrification scenarios. The corresponding IRRs are 29.52%, 31.13%, and 31.68%, compared with 41.87% for diesel buses and 31.53% for EVs without charging infrastructure. The NPV of diesel buses increases from ₹1,469 lakh to ₹4,331 lakh, while EVs without charging infrastructure increase from ₹2,015 lakh to ₹5,939 lakh across the respective scenarios.

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List of Abbreviation

EV – Electric Vehicle E-Bus – Electric Bus

ICE – Internal Combustion Engine

VKT – Vehicle Kilometers

Travelled PKM – Passenger Kilometers

SoC – State of Charge

BRT – Bus Rapid Transit

GHG – Greenhouse Gas

CO₂ – Carbon Dioxide

NO_x – Nitrogen Oxides

GSRTC – Gujarat State Road Transport Corporation

PM – Particulate Matter

NPV – Net Present Value

IRR – Internal Rate of Return

BCR – Benefit-Cost Ratio

PBP – Payback Period

LCC – Life Cycle Cost

TCO – Total Cost of Ownership

CAPEX – Capital Expenditure

OPEX – Operating Expenditure

DCF – Discounted Cash Flow

SDGs – Sustainable Development Goals

ULB – Urban Local Body

FAME – Faster Adoption and Manufacturing of Electric Vehicles

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CHAPTER – 1

Introduction

1.1 General

The rapid growth in transportation demand in India has significantly increased fuel consumption and emissions from diesel-operated buses. In this context, electric mobility has emerged as a sustainable alternative to public transport. This study evaluated the environmental and economic feasibility of adopting electric buses over conventional systems. The Shoonya Campaign of India is an ambitious exercise aimed at achieving net zero emissions by 2070. The campaign is based on the Sanskrit term, Shoonya (meaning zero) and highlights the point that the transport sector should be revolutionized, as it is the most important task in achieving the goal. The intended transformation implies a drastic and swift move to zero-emission cars, which essentially brings an end to emission-laden transportation networks. One of the first and most popular definitions of sustainable development originated from the World Commission on Environment and Development. It defines sustainable development as a type of development that meets the needs of the current generation without sacrificing the ability of future generations to meet their own needs. WCED, 1987, Report of the World Commission on Environment and Development [43], Our Common Future, Cities remain the primary victims of the adverse effects of transport infrastructure that depends heavily on fossil fuels. The emissions have a significant effect on the environment of a city, disrupting the ecological balance. Sustainable transportation is an essential part of

the sustainable city development process in line with modern trends of encouraging a green corridor model. The trend in planning and design in today's urban landscape is moving towards smart growth, new urbanism, and sustainable transportation policy as a possible substitution for traditional city urban transportation applications [1].

1.2 Global Transportation Sustainability and Current Scenario in India.

The large increase in the global deployment of renewable energy efforts over the last decade has seen the total deployed renewable energy capacity exceed 4448 GW by the end of 2024 [43]. Solar energy, alongside other renewable sources, is the predominant capacity component in the global capacity mix, with almost half of the total installed capacity being dominated by solar energy because of the steep reductions in cost, shorter installation periods, and robust policy support in both developed and developing economies. Solar energy witnessed a growth of 32.2% in 2024, followed by wind power, with its share at approximately 30%, backed by onshore and offshore large wind turbines [40]. Hydropower is another reliable and considerable source of renewable power worldwide. Statistically, it has also been shown that renewable energy additions have always been greater in recent years than the expansion of fossil fuel capacity. In the future, solar power is expected to contribute close to 80% of all renewable capacities added by 2030 owing to the development of photovoltaic technology, economies of scale, and conducive regulatory conditions. Meanwhile, the global wind power industry is set to recover from the recent economic downturn and supply chain issues, and the installed wind power capacity is forecasted to increase by almost twofold before 2030. The improvement of turbine efficiency through more investments and offshore wind

developing markets is expected to support this recovery. All of these trends point to a rapid shift to clean energy systems, which are expected to achieve greenhouse gas abatement, increase energy security, and allow all economies in the world to achieve sustainable development. India is increasingly focusing on renewable energy sources, with solar energy power generation accounting for 36% of the total estimated renewable energy, touching to 748990 MV i.e., 748.99GW) [45].

As of March 2022, approximately 10,50,497 electric vehicles (EVs) in India had been registered, which is almost 0.36% of the total vehicle population registered. Thus, the adoption of EVs is still in its infancy compared to traditional vehicles with internal combustion engines (ICEs). On the one hand, the annual EV sales data show a slow yet steady increase, and the driving force of the changes were positive government policies, financial incentives, and programs, such as FAME, along with the rising awareness about the importance of environmental sustainability. Out of all the EVs that have been introduced, it can be said that about 9% of the EVs are three-wheelers, which have experienced massive adoption following suitability in the short route transport segment in cities and commercial usage. Second are two-wheelers, with their share of EV being approximately 17%, facilitated by the low cost of acquisition and charging facilities. Conversely, four-wheelers contribute a relatively small portion of the total EV registrations of approximately 3%, mainly because of the costlier initial investments and insufficient charging infrastructure. Notwithstanding this growth, ICE vehicles still prevail in the Indian automobile industry, and EVs constitute a small portion of vehicles sold each year. Realizing such a gap, the Government of India has set a target of reaching 30% EV penetration by 2030 [46]. The goal is to harmonize electric mobility with the

power sector, establish a common and interoperable charging ecosystem, and increase the production of EVs and batteries in the USA. The realization of these targets is likely to dramatically decrease reliance on fossil energy, decrease automotive exhaust, and improve energy security in the long run.

The policies on EVs adopted by the international community reflect a holistic strategy with financial incentives, regulatory support, infrastructure development, and long-term climate commitments. Such policies do not only foster the use of electric vehicles, as well as the decline in carbon emissions, enhancement of air quality, and energy security. Across the world, several nations and states have adopted progressive policies to speed up the uptake of electric vehicles (EVs) as a component of their overall climate change solution and environmentally sustainable transport system. These foreign policies are mainly aimed at delivering carbon neutrality, Vehicular emissions reduction, and enhancing the use of renewable energy in the transport sector. Asia, Australia, and Europe are excellent examples of electric mobility transitions prompted by policies.

Asia has introduced long-term decarbonization targets in countries such as Japan, China, and Thailand. Japan and China are determined to become net carbon-neutral by 2050, and Thailand aims to become a large EV producer by 2025. To reinforce these goals, Asian countries have presented supportive policy measures, such as the development of new credit policies up to 2025, road tax exemption, and fixed capital investment incentives for EV charger installations. In addition, special electricity charges at EV charging facilities, loans waived to buy EVs, and special parking places for EV owners were introduced. All of these will help make electric mobility more affordable and easily charged as an alternative to the expensive nature of upfront costs, enhance consumer

demand, and encourage the industrial revolution in electric mobility. Australia has been proactive and has made efforts to facilitate EV adoption in its climate agenda. The nation has established a goal of net-zero carbon emissions by 2030, with CO₂ emissions in the transport sector being greatly curtailed. The actions taken in the form of policy include removing all importation tariffs on electric vehicles, no registration and road taxes, and an aim of having 10% of the registered EVs on the roads by 2022. Moreover, Australia has invested heavily in financial resources, such as USD 151 million, to develop charging infrastructure and provide incentives of up to USD 4,500 to EV charging stations, especially fast charging stations (FCS). These programs aim to reinforce charging networks, enhance the affordability of EVs, and promote their adoption nationwide.

1.3 National and State Level Policies for Sustainable Transportation

Several initiatives aimed at promoting sustainable transportation are being implemented in India. A broad range of policies and strategic frameworks have been developed to support and achieve transportation sustainability. In this regard, some important policies, missions, and initiatives introduced in India include the following to meet India's ambitious low-emission development strategy, declared at ITF 2025 [47]. The United Nations Framework Convention on Climate Change (UNFCCC) was adopted in 1992 at the Earth Summit to address the global issue of climate change [35]. The main objective of the convention is to stabilize greenhouse gas concentrations in the atmosphere and prevent dangerous human interference with climate systems. It encourages countries to cooperate in reducing emissions and adapt to climate impacts. The Convention also provides a framework for international climate agreements, such

as the Paris Agreement. Through regular meetings and reports, member countries work together to promote sustainable development and environmental protection.

India's transition towards electric mobility is strongly supported by proactive state-level policies that complement national missions, such as the National Electric Mobility Mission Plan (NEMMP) and the FAME scheme. States such as Andhra Pradesh and Karnataka have emerged as key contributors by formulating targeted strategies to accelerate electric vehicle (EV) adoption, strengthen manufacturing ecosystems, and reduce carbon emissions from the transport sector. The Study adopts an ambitious and structured roadmap to promote electric mobility across multiple vehicle segments. A major objective of the state policy is to convert Andhra Pradesh into a clean transportation hub, demonstrating leadership in clean transportation. Additionally, the state aims to deploy EVs across various categories, including two- and three-wheelers, passenger cars, and commercial vehicles. Recognizing the critical role of public transportation in reducing emissions, Andhra Pradesh has set a long-term goal of electrifying its entire public bus fleet by 2029. This initiative is expected to significantly reduce urban air pollution, reduce dependence on fossil fuels, and contribute to long-term operational cost savings for state transport undertakings. The policy also encourages private sector participation through incentives for EV manufacturing, charging infrastructure development, and skill enhancement.

In contrast, Karnataka has adopted a technology- and innovation-driven approach to EV adoption. The state focuses on creating a cutting-edge research and development ecosystem to position itself as a leading hub for electric vehicle and battery manufacturing in the coming years. Karnataka emphasizes the development of

advanced EV technologies, battery systems, power electronics, and software integration by supporting startups, research institutions, and global manufacturers in the state. To create a favorable investment climate, the state government offers financial incentives for charging infrastructure, exemptions or reductions in road tax and registration fees, and policy support for EV manufacturing. These measures not only encourage EV adoption but also promote local value addition, job creation and export-oriented growth. Overall, the policies of Andhra Pradesh and Karnataka highlight two complementary pathways towards sustainable mobility: large-scale deployment and public transport electrification on one hand, and innovation-led manufacturing and R&D on the other. Together, these state initiatives play a crucial role in advancing India's broader objective of achieving environmentally sustainable transportation, reducing greenhouse gas emissions, and building a resilient electric mobility ecosystem.

1.3.1 National Urban Transport Policy India (2006-2014)

The National Urban Transport Policy (MORT,2006,2014) [48,49] was introduced by the Government of India in 2006 to promote safe, efficient, and sustainable urban transportation systems. The main objective of the policy is to focus on moving people rather than vehicles in urban areas. It encourages the development and improvement of public transport systems, such as buses, metro rail, and other mass transit systems. The policy also promotes non-motorized transport (NMT), such as walking and cycling, to reduce congestion and pollution. Furthermore, it emphasizes the need for integrated land-use and transport planning to improve accessibility and mobility in urban areas.

1.3.2 National Policy on Biofuels (India) (2009, Revised 2018)

The National Policy on Biofuels was first introduced by the Government of India Ministry of Petroleum and Natural Gas in 2009 and later revised in 2018 [50] to promote the use of biofuels as an alternative to fossil fuels. The policy encourages ethanol blending with petrol and biodiesel blending with diesel to reduce dependence on imported crude oil and fossil fuels. This supports the use of agricultural residues, waste materials, and non-food crops for biofuel production. The policy also aims to enhance energy security, support rural development, and reduce the greenhouse gas emissions. Additionally, it promotes research and investment in advanced biofuel technology.

1.3.3 Development of Solar Cities Program (2008)

The Development of Solar Cities Program was launched in 2008 by the Ministry of New and Renewable Energy to promote renewable energy use in urban areas. The program aims to develop cities that rely more on solar energy and other renewable energy sources while reducing their dependence on conventional fuels. Under this initiative, selected cities prepare a comprehensive energy master plan to reduce fossil fuel consumption through solar power and energy efficiency. The program encourages the installation of solar lighting, solar water heating systems and rooftop solar panels. It also raises public awareness of renewable energy and supports sustainable urban development. This initiative aligns with India's efforts to achieve net-zero emissions by 2027.

1.3.4 Gujarat Solar Policy (2009,2015,2021,2025)

The Gujarat Solar Policy was introduced by the Government of Gujarat in 2009 [51] to promote solar power generation in the state. This policy encourages the development of large-scale solar parks and rooftop solar installations. It provides incentives and regulatory support to attract investments in solar energy projects. Through this policy, Gujarat aims to become a leader in solar energy production in India. The policy also contributes to reducing greenhouse gas emissions and supporting sustainable energy development, fulfilling the “Panchamrit” commitment at COP26.

1.3.5 Jawaharlal Nehru National Solar Mission (2010)

The Jawaharlal Nehru National Solar Mission was launched in 2010 under the National Action Plan on Climate Change (India) by the Government of India [52], The mission aims to promote the large-scale adoption of solar energy across the country. It focuses on increasing the capacity for solar power generation and encouraging rooftop solar installations. This initiative helps reduce dependence on fossil fuels and contributes to lowering carbon emissions. It also promotes the research, development, and manufacturing of solar technologies in India, thereby strengthening the renewable energy sector.

1.3.6 Smart Cities Mission (India) (2015)

The Smart Cities Mission was launched in 2015 by the Government of India to develop modern, sustainable citizen-friendly cities. The mission focuses on improving urban infrastructure, such as transportation, water supply, sanitation, housing, and digital connectivity. It promotes the use of smart technologies and energy-efficient systems to enhance the quality of urban living. This initiative also encourages sustainable mobility,

renewable energy, waste management, and green spaces. The mission aims to improve the quality of life and promote economic growth in urban areas.

1.3.7 National Electric Mobility Mission Plan (NEMMP) 2020

The National Electric Mobility Mission Plan (NEMMP) 2020, implemented in 2013, outlines India's long-term vision and strategic framework for adopting and integrating electric mobility within the country's transportation system. The mission was formulated to address key challenges, such as rising crude oil imports, increasing vehicular emissions, and the need for sustainable and energy-efficient transport Solutions [37]. The NEMMP serves as the foundational policy guiding India's transition to electric vehicles (EVs) while simultaneously promoting energy security and environmental sustainability. The NEMMP focuses on creating a comprehensive ecosystem for electric mobility by combining policy support, financial incentives and industrial development. It encompasses several subsidy mechanisms aimed at accelerating the adoption of electric vehicles across the country. These subsidies are structured into four major areas. The first area targets consumer demand stimulation by reducing the high upfront cost of electric vehicles through direct financial incentives. The second area supports the scaling up of EV manufacturing, encouraging domestic production to achieve economies of scale and reduce the costs of vehicles. The third area emphasizes the development of a robust charging infrastructure network, which is essential for addressing range anxiety and ensuring the operational feasibility of EVs. The fourth area focuses on research and development (R&D) investments to advance battery technology, improve vehicle performance, and enhance the overall system efficiency.

A key component of the NEMMP is its strong emphasis on localization and value addition to the EV supply chain. The mission defines clear targets for value addition at various stages of localization, covering critical components such as batteries, electric motors, power electronics, and charging equipment, among others. This approach is aligned with the Make in India initiative and aims to build domestic manufacturing capabilities, reduce dependence on imports, and create employment opportunities. By outlining a structured localization roadmap, the NEMMP seeks to develop a self-reliant electric mobility ecosystem while fostering technological innovation and industrial growth for India's transition to clean and sustainable transportation.

1.3.7.1. Faster Adoption and Manufacturing of Electric Vehicles in India, FAME-I (2015–2019)

FAME Phase I was launched in 2015 as part of the National Electric Mobility Mission Plan (NEMMP) 2020. The primary objective of this phase was to stimulate the early adoption of electric and hybrid vehicles in the Indian market. Financial incentives were provided to buyers of electric two-wheelers, three-wheelers, passenger cars, LCVs, and buses to offset the high initial costs. In addition, FAME-I supported Summary This phase played a crucial role in creating market awareness, encouraging consumer confidence, and laying the foundation for electric mobility in India.

1.3.7.2. Faster Adoption and Manufacturing of Electric Vehicles in India, FAME-II (2019–2022)

FAME Phase II was introduced with a substantially increased budget compared to that of FAME-I. This phase focused on achieving electric vehicles, particularly electric buses, three-, and two-wheelers, as these segments offer higher environmental benefits owing to greater daily usage [2]. FAME-II also emphasized the expansion of the

summary, localization of EV components, and reduction in battery costs. By promoting domestic manufacturing and mass adoption, FAME-II aims to significantly reduce urban air pollution and greenhouse gas emissions while strengthening India’s electric mobility ecosystem [3]. The global experience highlights the importance of coordinated policy frameworks, which can serve as valuable references for strengthening electric mobility initiatives in developing economies, such as India. Overall, the FAME Scheme has been instrumental in accelerating India’s transition towards clean, efficient, and sustainable transportation. The production target of EV-buses is 7090 by 2024[41]. The Government of Gujarat took the initiative and, by 2021, ordered EV buses for Ahmedabad, Surat, and Rajkot Urban Local Body (ULB), as shown in Figure 1.1.

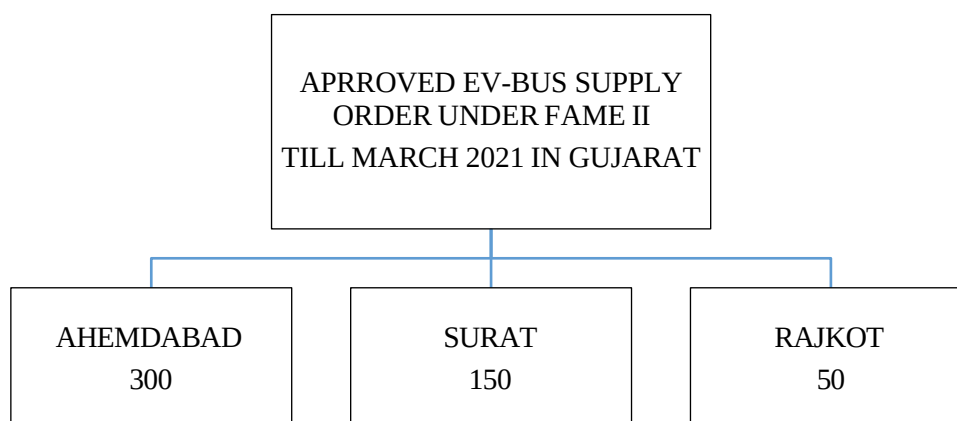


Figure 1.1: Approved EV-Bus Supply Order Under Fame

Currently, GSRTC operates EV-buses on the Ahmedabad-Vadodara and Ahmedabad-GIFT city/Gandhinagar routes.

1.3.8 National Mission on Transformative Mobility and Battery Storage (NMTMBS), 2019

It emphasizes the development of a robust battery value chain, from raw materials to recycling, in alignment with the Make in India initiative. The NMTMES supports

research, innovation, and skill development to enhance indigenous technological capabilities. It also focuses on the large-scale deployment of energy storage systems to support renewable energy integration and grid stability. By encouraging public–private partnerships, the mission seeks to attract investments and create employment opportunities. The NMTMES complements demand-side schemes such as FAME by addressing supply side challenges and enabling a sustainable, self-reliant EV ecosystem in India. While FAME focused mainly on demand support and charging infrastructure, NMTMES aimed to develop a summary covering advanced battery manufacturing, energy storage, and domestic value chains. The mission emphasizes summary in the mobility and storage sectors. It also aligns EV growth with the Summary for India.

1.3.9 Gujarat State Electric Vehicle Policy 2021

Gujarat is enriching its EV-buses fleets in ULBs, such as Surat, Ahmedabad, and Rajkot. In addition, EV buses were introduced by GSRTC charging stations, and EV manufacturing was subsidized. Regional passenger transport requires the inclusion of EV buses on an optimized basis. The Gujarat Energy Research and Management Institute (GERMI) provides specialized training programs for capacity enhancement in the areas of EV, charging stations, and green hydrogen.

1.4 Definition of the Problem

The transportation sector is facing increasing challenges related to energy consumption, environmental impacts, rising passenger demand, and dependence on imported fossil fuels. The transition towards clean energy and renewable-energy-based electric mobility provides an opportunity to address these challenges while improving the sustainability and competitiveness of public transportation. In this context, the following aspects define

the need for and relevance of fleet electrification.

1.4.1 Clean Energy Development

Clean energy solutions are essential for reducing the environmental impact of transportation. Electric vehicles powered by renewable energy can significantly reduce emissions, while investment in public transport, such as electric buses and rail, reduces car usage. Smart traffic systems, urban planning for walking and cycling, and innovations such as sustainable aviation fuels and hydrogen transport further support low-emission mobility.

1.4.2 Increasing Rate of Passenger Transport

Rapid population growth is driving increased demand in the transportation sector, leading to higher vehicle emissions, air and noise pollution, and traffic congestion. This growth contributes to climate change, health risks and productivity loss. Expanding transport infrastructure often causes habitat loss and deepens fossil fuel dependence, whereas safety concerns and unequal access worsen social and economic disparities.

1.4.3 India's Future Trend: Market Competitiveness

India's electric vehicle (EV) sector is rapidly growing, driven by government support, rising consumer demand, and increased investment from major automakers and startups. Incentives and expanding charging infrastructure are accelerating the shift towards sustainable mobility, reducing fossil fuel dependence, and supporting environmental objectives.

1.4.4 Reducing Energy Dependence Import by Adopting Renewable Energy

By 2050, global dependence on fossil fuels is expected to drop from 80% to 50%, driven by the growing adoption of renewable energy [38]. This shift is fueled by technological

advances, lower renewable energy costs, environmental concerns, supportive policies, and increasing public demand for sustainable energy. The increasing regional passenger demand leads to an increase in bus operations. Buses using ICE can be converted to EV with appropriate charging facilities, reducing energy dependence and greenhouse gas emissions. This requires research for an optimized solution for EV-bus conversion by stages, charging station location, renewable solar energy harvesting, and financial viability.

1.5 Study Objectives

The transportation segment globally plays a meaningful role in worsening air quality and negatively impacting the health of living beings. Some key factors to be considered have been identified: conserving energy, enhancing energy security by reducing dependence on conventional fuels, minimizing the carbon footprint by curtailing greenhouse gas emissions, and enhancing air quality by reducing other pollutants. To address these issues, this study was framed to work on the Gujarat State Road Transport Corporation Regional Bus Transit operation in the Kutch Region. The following objectives were identified:

- To assess the fuel consumption dependency and air quality impact of the existing bus transit fleet of GSRTC, Kutch.
- To explore Fleet Electrification feasibility.
- To evaluate the optimum probability of replacing existing fuel with an environmentally friendly sustainable energy source.
- To analyze environmental and economic benefits with respect to the proposed fleet electrification.

1.6 Scope of Work

This study focuses on the electrification of bus fleets of the Gujarat State Road Transport Corporation in the Kutch region of India. It includes the analysis of existing routes, estimation of energy requirements, and assessment of suitable electric buses and charging infrastructure, with energy consumption considered to be supplied from renewable sources such as solar energy. This study also covers optimal fleet replacement strategies, charging station scheduling, environmental impact assessment in terms of emission reduction, financial feasibility, and estimation of External Cost of Pollutant potential.

The study is limited to 8 major depot of Kutch region and focuses on the fleet electrification assessment of intercity buses operating between towns and cities within the region. The analysis considers only bus routes and operations serving destinations within Kutch, while routes extending beyond other than 8 major depot of Kutch region are not considered in the study.

1.7 Original Contribution by Thesis

While alternative fuel technologies are crucial for sustainable bus transportation, a significant gap remains in comprehensively examining their localized economic, environmental, and social implications, especially within specific regional contexts like Kutch. This thesis addresses this gap by conducting an integrated assessment of these implications tailored to the Kutch region, employing a combination of life cycle cost analysis, social benefit–cost evaluation, and environmental impact quantification to provide actionable insights for policymakers. Among the various evaluation methods, social benefit–cost analysis plays a vital role by simultaneously considering economic,

environmental, and social impacts. This study applies this framework specifically to the Kutch context, incorporating region-specific data and stakeholder perspectives to improve the valuation of non-monetary factors such as pollution reduction and social welfare, which are traditionally challenging to quantify.



Figure 1.2 Sustainable Development Goals (SDGs)

Source: NITI Aayog. (2024). SDG India Index & Dashboard 2023-24: Towards Sustainable Tomorrow. Government of India

High costs often prevent individual cities or developing nations from independently implementing environmentally friendly transport systems. International cooperation and global partnerships play crucial roles. Several international and national institutions provide financial assistance via grants, soft loans, and funding programs to promote sustainable transportation and renewable energy projects. Organizations such as the Indian Renewable Energy Development Agency, World Bank, Asian Development Bank, and Japan International Cooperation Agency significantly support these initiatives. This study contributes to five specific SDGs, including SDG 11 (Sustainable Cities and Communities) and SDG 13 (Climate Action), by quantifying emission reductions, evaluating sustainable energy integration, and assessing social benefits

related to electric bus adoption in Kutch.

The Sustainable Development Goals (SDGs) were adopted in 2015 by the United Nations as part of the 2030 Agenda for Sustainable Development [32]. The SDGs consist of 17 global goals and 169 targets designed to address major global challenges, such as poverty, inequality, climate change, environmental degradation, peace, and justice [33]. These goals aim to achieve a balanced approach to development by integrating economic growth, social inclusion and environmental protection. The SDGs encourage cooperation among governments, organizations, and communities worldwide to promote sustainable development [34]. All countries are expected to work collectively towards achieving these goals by 2030, ensuring a better and more sustainable future for present and future generations. This study acknowledges the inherent complexity in monetizing all environmental and social benefits, which may limit the precision of some valuations. Data availability constraints specific to the Kutch region and assumptions made in modeling scenarios are recognized as potential limitations. These factors and their implications for the study's findings will be discussed in detail in Chapter 6.

1.8 Research contribution

The study develops a region-specific, systematic guideline for assessing the feasibility of transitioning conventional diesel buses to electric buses for intercity operations in the Kutch region of Gujarat. The methodology can also be applied to other regions or bus fleets with similar operational conditions, environmental and economic benefits, and electrification criteria, thereby reducing the need for further study.

❖ **Integration of operational data with bus electrification planning.**

The study uses actual operational characteristics such as route distance, daily operation, bus utilization, energy consumption and route-wise performance to identify buses/routes suitable for electrification. This provides a more practical approach than relying solely on assumed average operating conditions.

❖ **Comparative economic assessment of diesel and electric buses.**

The study develops a comparative Life Cycle Cost Assessment & Total Cost of Ownership studies considering major components such as capital cost, fuel/electricity cost, maintenance cost, manpower/operating cost and charging infrastructure. The analysis further evaluates the economic viability using NPV and IRR, providing decision-support for fleet replacement.

❖ **Assessment of environmental benefits of fleet electrification.**

The research quantifies the reduction in GHG emissions and major vehicular pollutants resulting from the replacement of diesel buses with EVs. Thus, the study links the economic feasibility of electrification with its environmental benefits.

❖ **Development of an implementation-oriented guidelines for GSRTC/intercity transport**

The final contribution is practical: the study does not stop at comparing diesel and EV costs but translates the findings into a fleet replacement strategy for public transport agencies, indicating how EV adoption can be planned progressively under technical, economic and environmental constraints.

1.9 Thesis Organization

The remainder of this thesis is organized as follows.

Chapter 1 emphasizes sustainable development through the promotion of a “green corridor” model in the Kutch region of Gujarat, India. It highlights the importance of the study while examining both national and global perspectives on transportation sustainability, covering key initiatives such as FAME I, FAME II, and the National Electric Mobility Mission Plan (NEMMP). Based on the identified problem, the research aims and objectives were formulated. The chapter also outlines the need for the study and concludes with a description of the overall organization of this thesis.

Chapter 2 reviews previous studies on sustainable transportation, focusing on electric mobility, energy consumption and emission reduction. It highlights Indian initiatives such as the Shoonya Campaign, NEMMP 2020, and FAME schemes, as well as global research on transport energy models and climate policies. The literature is categorized into areas such as EV routing, charging infrastructure, fleet management, and environmental impacts. Relevant models and methods are discussed, including energy consumption models, optimization techniques, and the life cycle analysis of electric buses. Key findings from various studies emphasize the importance of large-scale EV adoption, efficient infrastructure planning, and policy support for EVs. Based on this review, important inferences were drawn, and research gaps were identified for the present study.

Chapter 3 presents the methodology adopted for this research, detailing the systematic procedures and approaches employed to achieve the stated objectives. It comprehensively explains each stage of the research process conducted in this study.

This chapter also provides essential background information on the Kutch region of Gujarat, India. Furthermore, it elaborates on the selection of the study corridor, along with its justification and relevance to the research objectives of this study.

Chapter 4 focuses on the data requirements for the research, encompassing primary and secondary data sources. This section describes the data collection techniques and methodologies adopted for the study. This chapter also presents the collected data systematically using tables and various graphical representations to facilitate the effective analysis and interpretation of the results. Finally, a concise summary of the analysis is provided to highlight key findings.

Chapter 5 describes the models developed for fleet electrification analysis and planning. The major aspects covered include Fleet Electrification Feasibility, Optimal Replacement Strategy, and Economic Benefits. The feasibility assessment identifies suitable electric-bus models and charging infrastructure, whereas the replacement strategy determines the optimal selection of routes and buses based on operational and energy considerations. This chapter also presents an economic evaluation of the proposed system, including a cost analysis and financial viability. In addition, the model validation techniques adopted in this study are discussed to ensure the reliability and accuracy of the results. Finally, this chapter concludes with a summary of the key findings.

Chapter 6 presents a summary of the key findings of this study. It also outlines the overall conclusions and highlights the contributions of the thesis. Furthermore, this chapter discusses the limitations of the study, provides suggestions for future research, and indicates the practical applications of the research work.

CHAPTER – 2

Literature Review

2.1 General

Several researchers have conducted studies to analyze the impacts of electric vehicle adoption and fleet electrification in public transportation systems. A comprehensive review of the literature highlights the effects of EV integration on energy consumption, greenhouse gas emissions, operational performance, and economic viability, which form the basis for sustainable transport planning. For each topic, Indian studies are discussed separately from international studies so that the existing Indian research context and the wider international evidence can be clearly identified.

2.2 Literature Review

In recent years, a substantial volume of research has been conducted on sustainable energy systems, transportation electrification, and emission reduction strategies. With increasing concerns over climate change, energy security, and environmental degradation, the transition toward low-carbon and energy-efficient transportation systems has become a major area of research. The literature reviewed in this chapter broadly covers renewable energy integration, energy demand and emissions, electric vehicle (EV) technologies, route optimization, charging infrastructure, environmental impacts, and economic feasibility.

2.2.1 Literature review on Emission Problems

A substantial body of research has been examined the environmental impacts of transportation, particularly in terms of greenhouse gas emissions, air pollution, energy consumption, and climate change. Studies from India and other countries have investigated the contribution of road transportation to emissions and have explored various technological and policy measures for reducing its environmental impacts. The major findings from Indian and international studies related to transportation emissions, global warming, and pollution are discussed below.

Indian Research Review

Singh et al. (2021) developed a comprehensive emission inventory for India's road transport sector and assessed the implications of transport policies for emission reduction. The study is relevant to the present research because it establishes the importance of quantifying road-transport emissions in the Indian context. The findings underline that transportation decarbonization requires a combination of cleaner vehicle technologies, efficient public-transport systems and appropriate policy measures. This provides an important environmental basis for examining the replacement of conventional diesel buses with electric buses in the present study. **Napitupulu et al. (2018)** examined the role of public transportation improvements in reducing urban air pollution. Their findings indicated that improvements in public transport systems can contribute significantly to reducing pollution levels. The findings underline that transportation decarbonization requires a combination of cleaner vehicle technologies, efficient public-transport systems and appropriate policy measures. This provides an

important environmental basis for examining the replacement of conventional diesel buses with electric buses in the present study. **Dey and Mehta (2020)** examined emission-control technologies for conventional vehicles and highlighted the importance of catalytic technologies in controlling emissions from conventional transport. The findings underline that transportation decarbonization requires a combination of cleaner vehicle technologies, efficient public-transport systems and appropriate policy measures. This provides an important environmental basis for examining the replacement of conventional diesel buses with electric buses in the present study. **Jing et al. (2022)** investigated the relationship between public transport usage and carbon emissions and reported that greater availability and use of public transport can reduce per-capita emissions. The findings underline that transportation decarbonization requires a combination of cleaner vehicle technologies, efficient public-transport systems and appropriate policy measures. This provides an important environmental basis for examining the replacement of conventional diesel buses with electric buses in the present study. **Brohi et al. (2018)** examined the role of smart transportation systems in reducing traffic-related pollution and emphasized the importance of intelligent transport solutions for sustainable mobility. The findings underline that transportation decarbonization requires a combination of cleaner vehicle technologies, efficient public-transport systems and appropriate policy measures. This provides an important environmental basis for examining the replacement of conventional diesel buses with electric buses in the present study. **Jain and Rankavat (2023)** analysed the driving factors behind CO₂ emissions from India's transportation sector using the Logarithmic Mean Divisia Index approach. Their findings demonstrate the importance of understanding the major factors

responsible for transport-sector carbon emissions in India. The findings underline that transportation decarbonization requires a combination of cleaner vehicle technologies, efficient public-transport systems and appropriate policy measures. This provides an important environmental basis for examining the replacement of conventional diesel buses with electric buses in the present study. **Loo, Li and Namdeo (2023)** examined road-transport emissions in India and China and discussed strategies for reducing transport-related emissions under climate policies. The findings underline that transportation decarbonization requires a combination of cleaner vehicle technologies, efficient public-transport systems and appropriate policy measures. This provides an important environmental basis for examining the replacement of conventional diesel buses with electric buses in the present study. **Raman et al. (2025)** discussed challenges associated with achieving Sustainable Development Goals in India and emphasized policy integration, institutional capacity building and sustainable infrastructure development. The findings underline that transportation decarbonization requires a combination of cleaner vehicle technologies, efficient public-transport systems and appropriate policy measures. This provides an important environmental basis for examining the replacement of conventional diesel buses with electric buses in the present study.

International Research Review

Krajačić et al. (2011) evaluated the feasibility of achieving a fully renewable and energy-independent energy system by integrating renewable energy sources with advanced energy-storage technologies. The study highlighted the importance of storage systems in managing renewable-energy intermittency. The findings underline that

transportation decarbonization requires a combination of cleaner vehicle technologies, efficient public-transport systems and appropriate policy measures. This provides an important environmental basis for examining the replacement of conventional diesel buses with electric buses in the present study. **Mathiesen et al. (2011)** conducted an integrated energy-system analysis covering electricity, heating and transportation. Their findings emphasized sector coupling and smart energy management for improving system flexibility and reducing energy costs. The findings underline that transportation decarbonization requires a combination of cleaner vehicle technologies, efficient public-transport systems and appropriate policy measures. This provides an important environmental basis for examining the replacement of conventional diesel buses with electric buses in the present study. **Blanford et al. (2012)** analysed future energy demand and emissions across major Asian economies using integrated assessment models. The study projected substantial increases in energy consumption and emissions due to urbanization, industrialization and economic growth. The findings underline that transportation decarbonization requires a combination of cleaner vehicle technologies, efficient public-transport systems and appropriate policy measures. This provides an important environmental basis for examining the replacement of conventional diesel buses with electric buses in the present study. **Steckel et al. (2013)** investigated the relationship between economic growth and energy consumption in developing countries and emphasized the need to combine energy access and economic development with cleaner technologies. The findings underline that transportation decarbonization requires a combination of cleaner vehicle technologies, efficient public-transport systems and appropriate policy measures. This provides an important environmental basis for

examining the replacement of conventional diesel buses with electric buses in the present study. **Gracceva and Zeniewski (2014)** developed a framework for evaluating energy security in low-carbon energy systems, considering reliability, affordability, resilience and environmental sustainability. The findings underline that transportation decarbonization requires a combination of cleaner vehicle technologies, efficient public-transport systems and appropriate policy measures. This provides an important environmental basis for examining the replacement of conventional diesel buses with electric buses in the present study. **Nordelöf et al. (2019)** examined the life-cycle environmental impacts of electric buses and demonstrated that the environmental benefits of electric buses depend strongly on the electricity-generation mix. The findings underline that transportation decarbonization requires a combination of cleaner vehicle technologies, efficient public-transport systems and appropriate policy measures. This provides an important environmental basis for examining the replacement of conventional diesel buses with electric buses in the present study. **Holland et al. (2021)** assessed the environmental benefits of bus electrification by incorporating external costs associated with air pollution and climate change. The findings underline that transportation decarbonization requires a combination of cleaner vehicle technologies, efficient public-transport systems and appropriate policy measures. This provides an important environmental basis for examining the replacement of conventional diesel buses with electric buses in the present study. **Matthews et al. (2001)** emphasized the importance of incorporating external environmental costs into transportation planning to account for the wider societal impacts of transport emissions. The findings underline that transportation decarbonization requires a combination of cleaner vehicle technologies,

efficient public-transport systems and appropriate policy measures. This provides an important environmental basis for examining the replacement of conventional diesel buses with electric buses in the present study. **Ferrer and Thomé (2023)** proposed an integrated framework for analysing transport-related carbon emissions and emphasized the importance of considering technological, behavioural and policy-related factors together. The findings underline that transportation decarbonization requires a combination of cleaner vehicle technologies, efficient public-transport systems and appropriate policy measures. This provides an important environmental basis for examining the replacement of conventional diesel buses with electric buses in the present study. **Winkler et al. (2023)** examined sustainable mobility transition policies and their influence on cumulative urban transport emissions and energy demand. The findings underline that transportation decarbonization requires a combination of cleaner vehicle technologies, efficient public-transport systems and appropriate policy measures. This provides an important environmental basis for examining the replacement of conventional diesel buses with electric buses in the present study. **Speizer et al. (2024)** used integrated assessment modelling to investigate pathways toward a zero-emission global transportation sector. The findings underline that transportation decarbonization requires a combination of cleaner vehicle technologies, efficient public-transport systems and appropriate policy measures. This provides an important environmental basis for examining the replacement of conventional diesel buses with electric buses in the present study. **Ling et al. (2024)** reviewed the relationship between carbon emissions and carbon footprints in transportation and proposed a framework for sustainable transportation. The findings underline that transportation decarbonization requires a combination of cleaner

vehicle technologies, efficient public-transport systems and appropriate policy measures. This provides an important environmental basis for examining the replacement of conventional diesel buses with electric buses in the present study. **Horesh and Quinn (2024)** investigated the role of fuel switching in reducing greenhouse-gas emissions from transportation. The findings underline that transportation decarbonization requires a combination of cleaner vehicle technologies, efficient public-transport systems and appropriate policy measures. This provides an important environmental basis for examining the replacement of conventional diesel buses with electric buses in the present study. **Peng et al. (2024)** examined carbon-emissions trading in ground transportation and discussed policy mechanisms for reducing transportation-related carbon emissions. The findings underline that transportation decarbonization requires a combination of cleaner vehicle technologies, efficient public-transport systems and appropriate policy measures. This provides an important environmental basis for examining the replacement of conventional diesel buses with electric buses in the present study. **Slimi et al. (2026)** reviewed the relationship between traffic and global warming and highlighted the contribution of transportation activity to climate change. The findings underline that transportation decarbonization requires a combination of cleaner vehicle technologies, efficient public-transport systems and appropriate policy measures. This provides an important environmental basis for examining the replacement of conventional diesel buses with electric buses in the present study.

2.2.2 Literature review on Fleet Electrification

With increasing concerns regarding transportation-related emissions and fossil-fuel dependence, considerable research has focused on the electrification of public-transport

fleets. Studies conducted in India and abroad have examined electric-bus deployment from different perspectives, including energy consumption, route planning, charging infrastructure, fleet optimization, and operational feasibility. The relevant Indian and international studies on fleet electrification and electric-bus systems are reviewed below.

Indian Research Review

Khandekar et al. (2018) evaluated the feasibility of electrifying urban bus fleets in India. The study considered economic, environmental and operational aspects and concluded that electric buses can provide significant emission reductions and long-term cost benefits. The study also indicates that successful electrification depends on matching vehicle technology with actual operating conditions, route characteristics and charging requirements. These considerations are particularly relevant when identifying buses or routes that can be prioritized for phased electrification. **Deb et al. (2019)** conducted a GIS-based analysis for optimal EV charging-station placement, considering factors such as traffic density, land use and population distribution. The study demonstrated the importance of strategic charging-infrastructure planning. The study also indicates that successful electrification depends on matching vehicle technology with actual operating conditions, route characteristics and charging requirements. These considerations are particularly relevant when identifying buses or routes that can be prioritized for phased electrification. **Gairola and Nezamuddin (2023)** developed a battery-electric-bus system considering operational constraints and waiting times. The study is relevant to the planning and operation of electric public-transport systems. The study also indicates that successful electrification depends on matching vehicle technology with actual operating conditions, route characteristics and charging requirements. These considerations are

particularly relevant when identifying buses or routes that can be prioritized for phased electrification. **Singh et al. (2024)** investigated electric-bus deployment and procurement considerations for 9-m and 12-m buses in India. The study also indicates that successful electrification depends on matching vehicle technology with actual operating conditions, route characteristics and charging requirements. These considerations are particularly relevant when identifying buses or routes that can be prioritized for phased electrification. **Varghese and Pradhan (2025)** developed a roadmap for transitioning privately owned bus fleets in India toward electric fleets. The study provides useful insights into the challenges and strategies associated with large-scale fleet electrification. The study also indicates that successful electrification depends on matching vehicle technology with actual operating conditions, route characteristics and charging requirements. These considerations are particularly relevant when identifying buses or routes that can be prioritized for phased electrification. **Kumar and Upadhyay (2026)** examined electrification of public-transport buses in Ahmedabad and proposed a policy framework and strategy for adoption. The study is particularly relevant to the Gujarat context. The study also indicates that successful electrification depends on matching vehicle technology with actual operating conditions, route characteristics and charging requirements. These considerations are particularly relevant when identifying buses or routes that can be prioritized for phased electrification.

International Research Review

Mehar et al. (2013) developed energy-aware EV route-planning algorithms considering battery constraints, road conditions and charging-station locations. The study demonstrated that conventional shortest-path methods are inadequate for electric

vehicles. The study also indicates that successful electrification depends on matching vehicle technology with actual operating conditions, route characteristics and charging requirements. These considerations are particularly relevant when identifying buses or routes that can be prioritized for phased electrification. **Zhang et al. (2018)** integrated EV route planning with charging decisions and considered nonlinear battery-charging behaviour. Their results showed that optimized charging can improve travel efficiency. The study also indicates that successful electrification depends on matching vehicle technology with actual operating conditions, route characteristics and charging requirements. These considerations are particularly relevant when identifying buses or routes that can be prioritized for phased electrification. **Zhou and Wang (2019)** developed dynamic routing models incorporating real-time traffic information and demonstrated the potential for adaptive routing to reduce energy consumption. The study also indicates that successful electrification depends on matching vehicle technology with actual operating conditions, route characteristics and charging requirements. These considerations are particularly relevant when identifying buses or routes that can be prioritized for phased electrification. **Perger and Auer (2020)** incorporated topography and battery degradation into EV route-planning models and demonstrated the importance of elevation and battery health in route selection. The study also indicates that successful electrification depends on matching vehicle technology with actual operating conditions, route characteristics and charging requirements. These considerations are particularly relevant when identifying buses or routes that can be prioritized for phased electrification. **Hecht et al. (2021)** investigated EV route planning using real-world charging-infrastructure data and emphasized the importance of charging-station location,

power rating and availability. The study also indicates that successful electrification depends on matching vehicle technology with actual operating conditions, route characteristics and charging requirements. These considerations are particularly relevant when identifying buses or routes that can be prioritized for phased electrification. **Manzoli et al. (2022)** reviewed developments in electric-bus technologies, battery systems, charging strategies and fleet-optimization approaches and identified challenges associated with real-world implementation. The study also indicates that successful electrification depends on matching vehicle technology with actual operating conditions, route characteristics and charging requirements. These considerations are particularly relevant when identifying buses or routes that can be prioritized for phased electrification. **Ji et al. (2022)** developed a data-driven model for estimating electric-bus energy consumption at the trip level. The study identified vehicle speed, road gradient, passenger load and traffic conditions as important factors influencing energy consumption. The study also indicates that successful electrification depends on matching vehicle technology with actual operating conditions, route characteristics and charging requirements. These considerations are particularly relevant when identifying buses or routes that can be prioritized for phased electrification. **Zhou, Ong and Meng (2023)** examined alternative strategies for replacing conventional buses with electric buses and evaluated fleet-replacement decisions. The study also indicates that successful electrification depends on matching vehicle technology with actual operating conditions, route characteristics and charging requirements. These considerations are particularly relevant when identifying buses or routes that can be prioritized for phased electrification. **Hendriks and Sturmberg (2024)** developed an integrated model for

electric-bus energy consumption and optimized depot charging. The study also indicates that successful electrification depends on matching vehicle technology with actual operating conditions, route characteristics and charging requirements. These considerations are particularly relevant when identifying buses or routes that can be prioritized for phased electrification. **Ye et al. (2024)** proposed an assessment approach for electric-bus fleet transition considering both economic and environmental impacts. The study also indicates that successful electrification depends on matching vehicle technology with actual operating conditions, route characteristics and charging requirements. These considerations are particularly relevant when identifying buses or routes that can be prioritized for phased electrification. **Othman, Shalaby and Abdulhai (2025)** developed route-selection guidelines and prioritization tools for efficient bus-fleet electrification. The study also indicates that successful electrification depends on matching vehicle technology with actual operating conditions, route characteristics and charging requirements. These considerations are particularly relevant when identifying buses or routes that can be prioritized for phased electrification. **Naeimian et al. (2025)** investigated public-transport fleet electrification together with charger scheduling and optimization. The study also indicates that successful electrification depends on matching vehicle technology with actual operating conditions, route characteristics and charging requirements. These considerations are particularly relevant when identifying buses or routes that can be prioritized for phased electrification. **Callegari et al. (2025)** examined battery-electric buses in emerging markets and developing economies and discussed their role in a just energy transition. The study also indicates that successful electrification depends on matching vehicle technology with actual operating conditions, route

characteristics and charging requirements. These considerations are particularly relevant when identifying buses or routes that can be prioritized for phased electrification. **Varghese and Pradhan (2025)** also provided a comprehensive review of electric-bus adoption, transition and procurement in public transportation. The study also indicates that successful electrification depends on matching vehicle technology with actual operating conditions, route characteristics and charging requirements. These considerations are particularly relevant when identifying buses or routes that can be prioritized for phased electrification. **Gowande (2025)** examined the electrification of India's bus sector with particular emphasis on public deployment and private intercity bus operators. The report considered vehicle economics, charging infrastructure, operational requirements and policy support for the transition to zero-emission buses. Its focus on intercity bus operations makes it particularly relevant to the present research on intercity public transport in Kutch. The study also strengthens the Indian literature by providing recent evidence on the practical requirements and challenges of bus electrification.

2.2.3 Literature Review on LCCA, TCO and Economic Feasibility

The economic feasibility of fleet electrification is an important consideration because electric buses generally involve higher initial investment while offering the potential for lower energy, maintenance, and operating costs. Consequently, researchers in India and abroad have applied different economic assessment approaches, including life-cycle cost analysis (LCCA), total cost of ownership (TCO), net present value (NPV), social cost–benefit analysis, and break-even analysis. The major studies addressing the economic feasibility of electric and conventional bus systems are discussed below.

Indian Research Review

Adheesh et al. (2016) examined the feasibility of electric buses compared with conventional diesel buses in Bangalore, India. The study found that electric buses require higher initial investment but can provide economic and environmental benefits over their operating life. The findings therefore support the use of a life-cycle perspective rather than comparing only the initial purchase price of alternative bus technologies. Such an approach is relevant to the present study, where capital, energy, maintenance, manpower and infrastructure costs are considered over the project life. **Sheth and Sarkar (2021)** conducted a social cost–benefit and life-cycle cost analysis of electric and diesel buses in India. The study considered vehicle costs, energy costs, operation and maintenance, infrastructure and environmental externalities. The study is particularly relevant to the present research because it applied total cost of ownership and net present value approaches to compare bus technologies. The findings therefore support the use of a life-cycle perspective rather than comparing only the initial purchase price of alternative bus technologies. Such an approach is relevant to the present study, where capital, energy, maintenance, manpower and infrastructure costs are considered over the project life. **Fabianová and Janekova (2021, 2022)** conducted life-cycle cost analyses comparing electric, diesel and CNG buses and demonstrated that higher initial investment in electric buses can be offset by lower operating costs. The findings therefore support the use of a life-cycle perspective rather than comparing only the initial purchase price of alternative bus technologies. Such an approach is relevant to the present study, where capital, energy, maintenance, manpower and infrastructure costs are considered over the project life. **Singh et al. (2024)** evaluated the total cost of ownership and break-even

considerations for electric buses in India. The findings therefore support the use of a life-cycle perspective rather than comparing only the initial purchase price of alternative bus technologies. Such an approach is relevant to the present study, where capital, energy, maintenance, manpower and infrastructure costs are considered over the project life. **Tripathi et al. (2025)** evaluated the life-cycle environmental and cost impacts of different bus powertrains using real driving cycles, providing useful evidence for integrating operational, environmental and economic assessment. The findings therefore support the use of a life-cycle perspective rather than comparing only the initial purchase price of alternative bus technologies. Such an approach is relevant to the present study, where capital, energy, maintenance, manpower and infrastructure costs are considered over the project life. **Varghese and Pradhan (2025)** examined economic considerations associated with the transition of privately owned bus fleets to electric fleets in India. The findings therefore support the use of a life-cycle perspective rather than comparing only the initial purchase price of alternative bus technologies. Such an approach is relevant to the present study, where capital, energy, maintenance, manpower and infrastructure costs are considered over the project life.

International Research Review

Johnson et al. (2020) developed a financial model for evaluating the viability of electric-bus fleets and identified capital cost, energy prices and subsidies as important factors affecting economic feasibility. The findings therefore support the use of a life-cycle perspective rather than comparing only the initial purchase price of alternative bus technologies. Such an approach is relevant to the present study, where capital, energy, maintenance, manpower and infrastructure costs are considered over the project life.

Grauers, Borén and Enerbäck (2020) developed a total-cost-of-ownership model for electric-bus systems and identified major cost parameters affecting the design and economic performance of electric bus fleets. The findings therefore support the use of a life-cycle perspective rather than comparing only the initial purchase price of alternative bus technologies. Such an approach is relevant to the present study, where capital, energy, maintenance, manpower and infrastructure costs are considered over the project life. **Say et al. (2023)** investigated the economics of public-transport electrification using a case study from Victoria, Australia, providing important evidence regarding the economic feasibility of bus electrification. The findings therefore support the use of a life-cycle perspective rather than comparing only the initial purchase price of alternative bus technologies. Such an approach is relevant to the present study, where capital, energy, maintenance, manpower and infrastructure costs are considered over the project life. **Abdelouahed, Berrada and El Mrabet (2024)** conducted a techno-economic assessment of electric buses for sustainable urban and interurban transportation. The findings therefore support the use of a life-cycle perspective rather than comparing only the initial purchase price of alternative bus technologies. Such an approach is relevant to the present study, where capital, energy, maintenance, manpower and infrastructure costs are considered over the project life. **Pei et al. (2024)** analysed the economic and environmental effects of electric-bus transit systems from a life-cycle perspective. The findings therefore support the use of a life-cycle perspective rather than comparing only the initial purchase price of alternative bus technologies. Such an approach is relevant to the present study, where capital, energy, maintenance, manpower and infrastructure costs are considered over the project life. **Razy-Yanuv and Meron (2024)** evaluated the

benefits, costs and policy implications of transitioning to cleaner bus fleets using a life-cycle perspective. The findings therefore support the use of a life-cycle perspective rather than comparing only the initial purchase price of alternative bus technologies. Such an approach is relevant to the present study, where capital, energy, maintenance, manpower and infrastructure costs are considered over the project life. **Sistig et al. (2025)** evaluated the costs and operational implications of public-bus fleet electrification, including vehicle, energy, maintenance, charging and operational requirements. The findings therefore support the use of a life-cycle perspective rather than comparing only the initial purchase price of alternative bus technologies. Such an approach is relevant to the present study, where capital, energy, maintenance, manpower and infrastructure costs are considered over the project life. **McCluskey, Larkin and Druitt (2025)** examined how bus availability affects the economics of fleet electrification. The findings therefore support the use of a life-cycle perspective rather than comparing only the initial purchase price of alternative bus technologies. Such an approach is relevant to the present study, where capital, energy, maintenance, manpower and infrastructure costs are considered over the project life. **Ghotge, van Rooij and van Breukelen (2025)** evaluated the total cost of ownership of electric buses in Europe. The findings therefore support the use of a life-cycle perspective rather than comparing only the initial purchase price of alternative bus technologies. Such an approach is relevant to the present study, where capital, energy, maintenance, manpower and infrastructure costs are considered over the project life. **Chong and Hanafiah (2026)** assessed life-cycle externalities and abatement costs associated with public-transport electrification using battery-electric and fuel-cell buses. The findings therefore support the use of a life-cycle perspective rather than comparing only the initial purchase price of alternative bus technologies. Such an

approach is relevant to the present study, where capital, energy, maintenance, manpower and infrastructure costs are considered over the project life.

2.3 EV Charging Standards in India

In India, electric vehicle (EV) charging standards are primarily governed by guidelines issued by the Bureau of Indian Standards and the Department of Heavy Industry. These standards aim to ensure safety, interoperability, and uniformity in the development of EV charging infrastructure across the country [53].

2.3.1 Low Voltage EV Charging Standards (<120V)

Electric vehicle charging standards for low-voltage applications in India are governed by IS 17017 [54], which outlines the requirements for conductive charging systems to ensure safety and compatibility. Under this framework, the Department of Heavy Industry (DHI) has approved Bharat charger specifications, namely Bharat EV Charger AC-001 and DC-001, primarily aimed at supporting early-stage EV adoption. The AC-001 charger is designed for slow charging with an output of about 3.3 kW using a single-phase 230 V supply and is commonly used for two-wheelers, three-wheelers, and small passenger vehicles. It typically provides multiple charging points, making it suitable for public and semi-public charging stations. The DC-001 IS-17017 Part-23 [55], charger enables faster charging with a power output of up to 15 kW and operates at lower voltage levels, making it appropriate for small commercial vehicles and fleet operations. Communication in DC-001 chargers is generally based on CAN protocol. Onboard chargers in such vehicles usually range from 2.5 kW to 3 kW, limiting the charging speed but ensuring compatibility with standard electrical infrastructure.

2.3.2 High-voltage EV Charging Standards (>120 V)

India currently relies on globally accepted standards for high-voltage charging systems owing to the absence of a fully developed indigenous technology. The Combined Charging System (CCS2) is the most widely adopted standard for fast DC charging in India, supporting power levels from approximately 30 to 350 kW, and is commonly used in modern electric cars. CCS2 integrates both AC and DC charging capabilities into a single connector, enhancing flexibility and user convenience. CHAdeMO, a Japanese DC fast-charging standard, is also present but has limited adoption in the Indian market. Additionally, Type-2 connectors based on IEC 62196 standards are widely used for AC charging, with power capacities ranging from 3.3 to 22 kW, making them suitable for residential, workplace, and public charging stations. In high-voltage systems, DC fast charging bypasses the onboard charger and directly supplies power to the battery, significantly reducing the charging time.

2.4 Regulatory Framework and Government Initiatives

The EV charging ecosystem in India is supported by a strong regulatory framework involving multiple agencies, such as the Department of Heavy Industry (DHI), Bureau of Indian Standards (BIS), Central Electricity Authority (CEA), and Ministry of Power (MoP). Government initiatives such as Faster Adoption and Manufacturing of Electric Vehicles (FAME) I and II have played a crucial role in promoting EV adoption and establishing charging infrastructure across the country. The Ministry of Power has issued guidelines for the installation and operation of public charging stations, specifying technical standards, safety requirements, and tariff policies for EV charging stations. The BIS standards (IS 17017 series) are largely aligned with the international IEC standards, ensuring global compatibility. These policies also encourage private sector participation, pilot projects, and the development of charging networks in urban

and highway corridors.

2.5 Setup Requirements for Public EV Charging Stations

The establishment of public electric vehicle (EV) charging stations requires adequate infrastructure and technical provisions to ensure safe, efficient, and reliable operations. [56]. A dedicated electrical setup is essential, including an exclusive transformer and all associated substation equipment, to maintain a stable power supply and load management. In addition, proper connectivity through 33/11 kV cables, along with the necessary equipment for line termination and metering, must be provided to ensure accurate energy measurement and efficient power distribution. From a structural perspective, high-quality civil work is required to support the installation of charging equipment and related facilities. The site must also have sufficient space to accommodate not only the charging units but also to allow smooth entry, maneuvering, and exit of vehicles, thereby ensuring user convenience and operational efficiency. Furthermore, appropriate fire protection systems and safety facilities must be installed in compliance with regulatory standards to mitigate risks associated with electrical hazards and ensure the safety of users and equipment

2.5.1 Charger Specifications

The charging station must have electricity with the installation of the following charger models.

Table 2.1: Charger Specifications

Charger Type	Sr.No.	Charger Connectors	Rated Output Voltage(V)	No. of No. of Connector guns (CG)	Charging vehicle type (W=wheeler)
Fast	1	Combined Charging System (CCS) (Min 50 kW)	200-750or higher	1 CG	4W
	2	Charged Move (CHAdemo) (Min 50 kW)	200-500or higher	1 CG	4W
	3	Type-2 AC (Min 22 kW)	380- 415	1 CG	4W, 3W, 2W
Slow / Moderate	1	Bharat DC-001 (15 kW)	48	1 CG	4W, 3W, 2W
	2	Bharat DC-001 (15 kW)	72 or higher	1 CG	4W
	3	Bharat DC-001 (10 kW)	230	3 CG of 3.3 kW each	4W, 3W, 2W

Source: Institute of Electronics & Information Technology

2.5.2 Operational Requirements for Public EV Charging Stations

Public EV charging stations must be integrated with at least one recognized online Network Service Provider (NSP) to facilitate advanced and remote booking of charging slots, thereby enhancing user convenience and efficient utilization of infrastructure, as per the EV Handbook [56]. Additionally, charging station operators are required to share operational and usage data with the respective State Nodal Agency (SNA) and comply

with the protocols and guidelines prescribed by the Central Nodal Agency (CAN), namely, the Bureau of Energy Efficiency (BEE), to ensure standardization and effective monitoring. Furthermore, prior to commissioning, the charging station must undergo proper inspection and obtain the necessary clearances from authorized electrical personnel designated by the local electricity distribution company. This ensures compliance with safety standards, technical regulations, and the reliable operation of the charging infrastructure.

2.6 Challenges and Future Scope

Despite notable progress, several challenges persist in developing EV charging infrastructure in India. These include the lack of a unified indigenous high-voltage charging standard, interoperability issues among different charging systems, limited availability of fast-charging stations in rural and semi-urban areas, and high **costs** associated with installation and grid upgrades. Moreover, issues related to charging time, battery performance, and user awareness continue to influence EV adoption. However, the future outlook remains promising, with ongoing advancements in ultrafast charging technologies (150 kW and above), smart charging systems, and vehicle-to-grid (V2G) integration. The increasing use of renewable energy sources for charging, along with government support and technological innovation, is expected to significantly enhance the efficiency, accessibility, and sustainability of India's EV-charging ecosystem.

2.7 Summary of Literature Review

The reviewed literature indicates that sustainable transportation systems require an integrated approach involving renewable energy integration, electric mobility, infrastructure planning and policy support. Electric buses have emerged as a promising solution for reducing emissions and improving energy efficiency in the transportation sector. However, challenges related to infrastructure, economic feasibility, and technological limitations must be addressed in the future. Insights from previous studies provide a strong foundation for the present research on fleet electrification, route optimization, and sustainable transport planning.

2.8 Research Gap

A comprehensive review of the literature revealed that significant research has been conducted in the areas of sustainable energy systems, electric vehicle technologies, route optimization, charging infrastructure, and environmental impact assessment. However, several gaps still exist, particularly in developing regions such as India. Most previous studies have focused on either energy systems or transportation independently, with limited integration between transport electrification and region-specific operational conditions. Although various models have been developed for electric vehicle routing and energy consumption, many are based on generalized assumptions and do not adequately incorporate real-world factors such as local route characteristics, traffic conditions, and regional variability. Various research gaps were identified from the review of existing literature, and these gaps are systematically summarized and presented in Table 2.2.

Table 2.2: Key Research Gaps in Existing Literature

Sr. No.	Research gap identified from literature	Addressing the Research Gap in the Present Study
1	Existing studies on electric bus implementation in India have predominantly focused on urban and metropolitan transport systems, with comparatively limited attention to intercity bus operations under regional conditions.	The present study evaluates intercity bus fleet electrification in the Kutch region of Gujarat, considering the operational characteristics of the existing bus fleet.
2	Limited studies have addressed bus-level identification and prioritization for electrification based on actual operational energy requirements.	The present study assesses bus-wise energy consumption and prioritizes buses for replacement based on their energy performance.
3	Limited research has simultaneously considered different fleet electrification levels and charging infrastructure requirements for implementation.	The study evaluates 10%, 20% and 30% fleet replacement scenarios and determines the associated charging infrastructure requirements and investment.
4	Existing economic studies often evaluate EV buses at the vehicle level, while limited attention is given to the economic implications of fleet-level implementation under specific regional operating conditions.	The present study performs a comparative economic assessment of diesel and electric buses considering capital cost, fuel/electricity cost, maintenance cost, manpower cost and charging infrastructure cost, using TCO, NPV and IRR.
5	There is limited integration of economic assessment and vehicular air pollutant assessment for intercity electric bus implementation.	The present study combines economic assessment with evaluation of vehicular air pollutant emission reductions resulting from diesel-to-electric bus replacement.
6	Limited studies provide implementation-oriented recommendations for phased electrification of intercity public transport fleets in regional areas.	Based on operational, economic and environmental findings, the study proposes an implementation strategy for phased electrification of the intercity bus fleet in Kutch.

CHAPTER – 3

Methodology and Study Area profile

3.1 General

The methodology is a crucial component for understanding the systematic approach adopted in this study. It provides a structured and theoretical guidelines for the procedures employed to achieve the study objectives. This chapter outlines the methodology used to evaluate the electrification of the bus fleet in the Kutch region, including data collection, route analysis, energy estimation, and modeling. It also describes the various techniques applied throughout the research, along with the relevant details of the study area.

3.2 Methodology

This study presents a systematic and structured approach to evaluate the electrification of the bus fleet in the Kutch region. It provides a comprehensive description of the methods, tools, and procedures used to achieve the research objectives of this study. The methodology outlines the overall guidelines, including data collection (both primary and secondary), route analysis, and energy consumption estimation for electric buses. It also incorporates the use of Geographic Information System (GIS) techniques for the spatial mapping of various bus routes. Furthermore, the methodology describes the approach used to assess fleet electrification feasibility, identify suitable electric bus models, and plan the required charging infrastructure along with scheduling strategies. An optimal replacement model was developed based on operational constraints, such as route length and state of charge. In addition, the methodology includes an

environmental impact assessment and economic evaluation using financial indicators. Overall, this section establishes a clear and logical guidelines for conducting the research and addressing the study objectives. The methodology is presented in the form of a flow diagram in Figure 3.1.

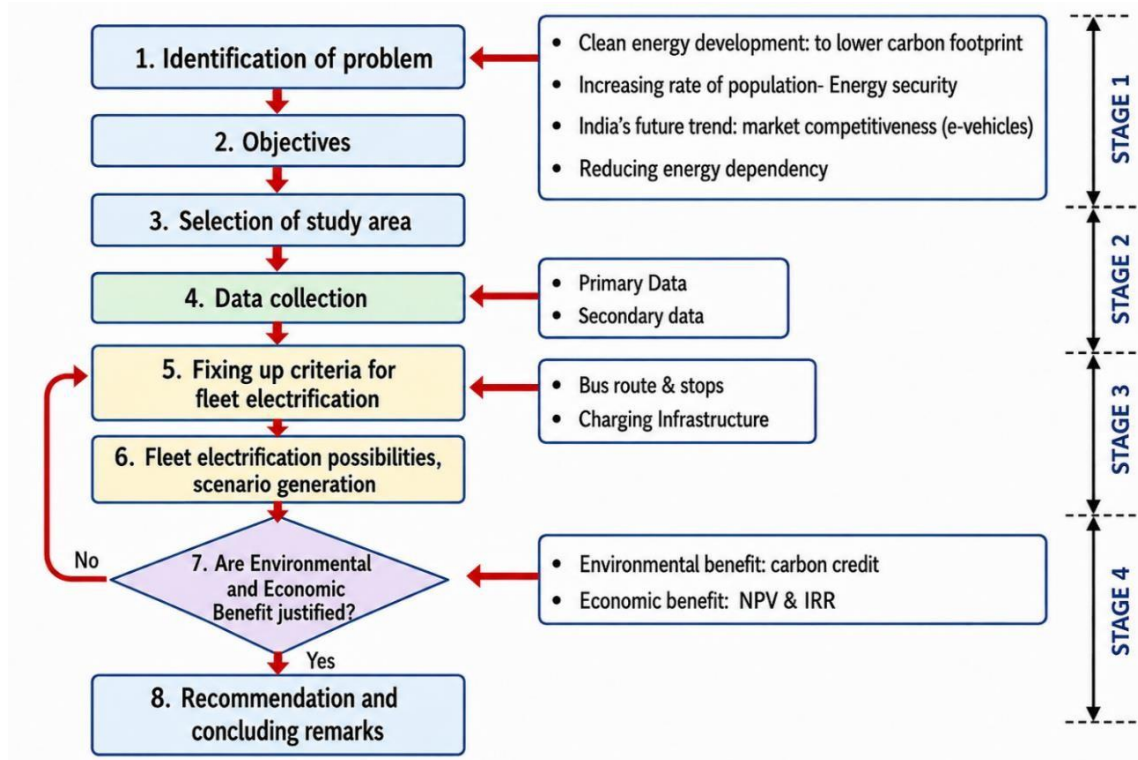


Figure 3.1 Research Methodology

3.3 The Methodological Innovations Introduced in this Study are Summarized as follows:

- Use of actual operational data collected from the GSRTC Bhuj Division instead of relying solely on secondary data or assumed operating conditions.
- Route-wise energy consumption assessment for electric buses under actual intercity operating conditions.
- Prioritization of buses for electrification based on operational suitability and energy requirements rather than replacing the entire fleet simultaneously.

- Development and comparison of three phased fleet replacement scenarios (10%, 20%, and 30%) to support practical implementation.
 - Integration of technical, economic, and environmental analyses, including Total Cost of Ownership (TCO), charging infrastructure requirements, battery replacement, greenhouse gas emission reduction, and life-cycle financial evaluation.
 - External Cost of Pollutant value is incorporated as a monetary benefit of CO₂ emission reduction, allowing the environmental benefit of electric-bus adoption to be quantified economically. Its unique contribution is linking emission savings with a tradable carbon-credit value, which can be incorporated into the overall NPV/IRR and social benefit–cost assessment. Here in study External Cost of Pollutant value are not taken into account.
- Overall, the present research establishes a practical and replicable methodology for evaluating phased electric bus fleet electrification in intercity public transport systems by integrating operational data, energy assessment, economic analysis, charging infrastructure planning, and environmental impact assessment within a unified guideline. The present study focuses on the operational life-cycle economic assessment of diesel and electric buses. The analysis includes vehicle acquisition cost, energy consumption, maintenance cost, battery replacement, charging infrastructure investment, salvage value, and financial feasibility over the project life. A comprehensive cradle-to-grave environmental life cycle assessment, including vehicle manufacturing, battery production, recycling, and disposal, is beyond the scope of the present study and is identified as an area for future research. This phased approach enhances the practical applicability of the study by providing transport planners and policy makers with flexible implementation options for achieving sustainable public transport electrification while ensuring operational continuity and financial feasibility.

3.4 Study Area Delineation and Data Collection

Kutch is the largest district in Gujarat, India, covering an area of 45,674 km², as shown in Figure 3.2. The Kutch district, located in the state of Gujarat, had a total population of approximately 2.09 million (20.92 lakhs) according to the Census 2011. The population is predominantly rural, with approximately 65% residing in rural areas and 35% in urban areas. The literacy rate of the region is approximately 70.59%, and the sex ratio is approximately 908 females per 1000 males. Overall, Kutch is characterized by a low population density (approximately 46 persons/km²) due to its large geographical area, making it one of the least densely populated districts in India, yet showing steady population growth over time.

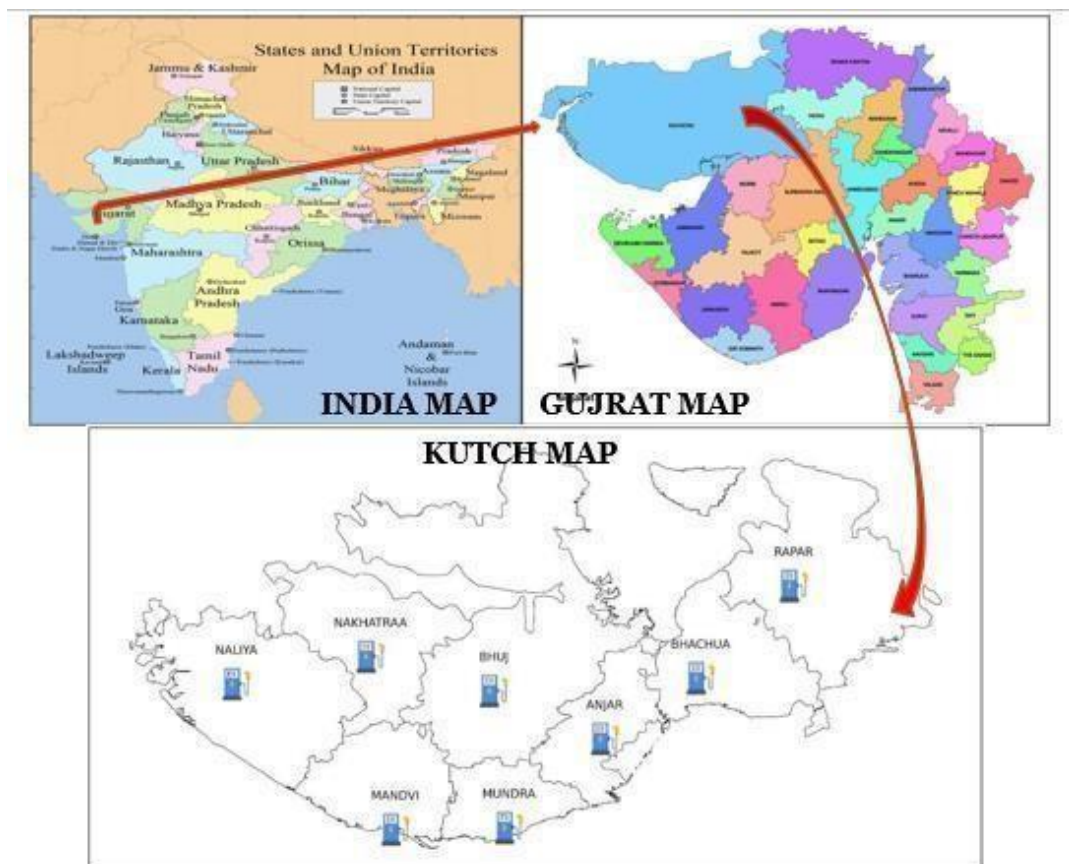


Figure 3.2: Location Map of Study Area

Source: Maps of India, “Political Map of India” (www.mapsofindia.com)

The Kutch-Bhuj Gujarat State Road Transport Corporation (GSRTC) Division is divided into eight main bus depots: Bhuj, Bhachau, Mandvi, Rapar, Mundra, Naliya, Anjar, and Nakhatrana. There are 203 major routes in the Kutch-Bhuj division. Data on different types of buses operated by the GSRTC in the Kutch district, including bus type, distance traveled in kilometers, departure and arrival times, and fuel cost (diesel), were obtained from the Bhuj divisional office. The main bus terminal run by the GSRTC in Bhuj city acts as the main hub for public transportation in Gujarat's Kutch district and is at the heart of the Kutch–Bhuj GSRTC study area. Bhuj has a high daily passenger volume because it is the district headquarters and a significant administrative, commercial, and tourist hub.

Numerous intra- and inter-district bus services connect Bhuj with major cities such as Ahmedabad, Gandhidham, Rajkot, and neighboring taluka towns via the GSRTC bus stand. Because of this function, bus terminals attract a sizable amount of supporting traffic in addition to buses, including taxis, private vehicles, auto rickshaws, two-wheelers, and service vehicles. Commercial stores, small hotels, restaurants, offices, and unofficial street activities are among the mixed land uses surrounding the Kutch–Bhuj GSRTC bus stop.

3.5 The Main Depots Considered for Study purpose

The variation in the population distribution across Kutch is divided into eight main depots. Other minor stops also play an important role in influencing travel demand, transport planning, and the feasibility of deploying electric bus fleets in the Kutch region. The division operates from bus depots located at taluka headquarters in the Kutch district. In Figures 3.3 to 3.10, the red line represents the boundary of the study area for each depot, and the blue lines indicate the road network and bus routes within

the region. The marked point symbol indicates the location of the main bus station, which serves as a central hub for route connectivity and operations.

3.5.1 Rapar Depot

Rapar caters to remote and rural regions, with routes characterized by longer distances and lower passenger densities. Operational challenges include limited infrastructure and extended travel requirements. Careful planning is required for EV deployment owing to charging constraints. Rapar depot, with a population of approximately 2.17 lakhs, is primarily rural but strategically important because of its connectivity with neighboring districts. Transport demand is driven by agricultural activities and regional mobility needs.

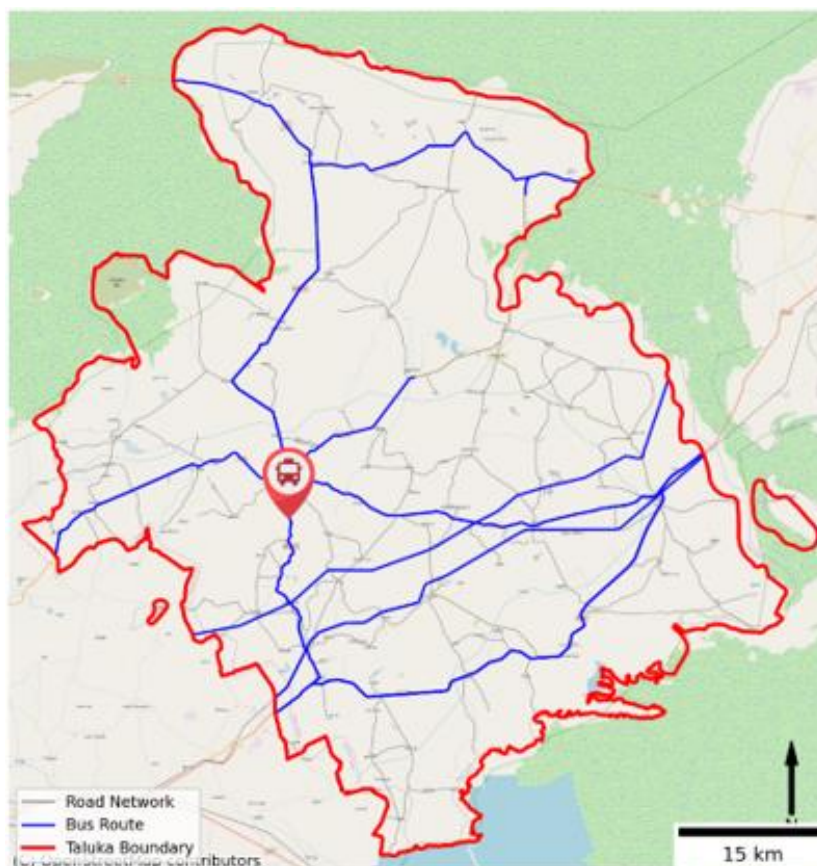


Figure 3.3 Rapar Map

The Rapar depot handles long-route operations, and its inclusion in electrification planning requires careful consideration of route length and energy requirements.

3.5.2 Mandvi Depot

Mandvi primarily serves coastal and tourism-oriented routes and experiences seasonal variations in passenger demand. The routes are relatively short and suitable for electric bus operations. It offers good potential for the integration of sustainable transport in tourist areas. Mandvi, with a population of approximately 2.03 lakhs, is a coastal town known for tourism, traditional industries, and port-related activities. Seasonal variations in travel demand due to tourism significantly influence transportation operations.



Figure 3.4 Mandvi Map

The Mandvi depot serves both local and tourist traffic, making it suitable for the introduction of electric buses to reduce emissions in environmentally sensitive coastal areas.

3.5.3 Nakhatrana Depot

Nakhatrana serves the interior and rural areas with relatively low traffic density. The routes are shorter but spread across less developed regions. It is suitable for selective electrification with proper planning of the charging infrastructure and route scheduling. Nakhatrana, with a population of approximately 1.46 lakhs, is largely rural, with dispersed settlements and moderate transport demand.

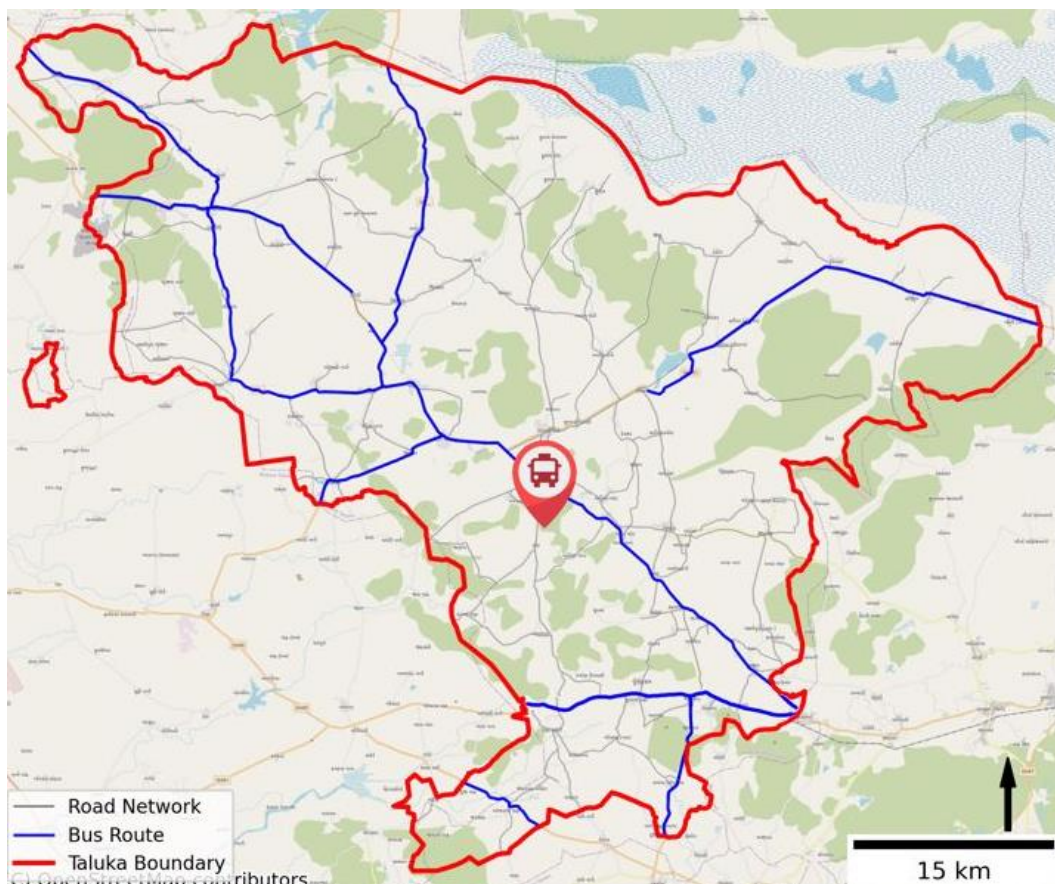


Figure 3.5 Nakhatrana Map

This region is characterized by agricultural activities and limited urbanization. The depot serves as an important link for rural connectivity, and electrification feasibility depends on route optimization and efficient charging strategies owing to the lower passenger density.

3.5.4 Mundra Depot

Mundra is strategically important due to its proximity to industrial zones and port activities. It experiences consistent passenger and worker movements, making it suitable for regular and predictable route operations. Electrification can significantly reduce industrial transport emissions. Mundra is an economically significant region with a population of around 1.53 lakh, primarily due to the presence of major port infrastructure and industrial development.

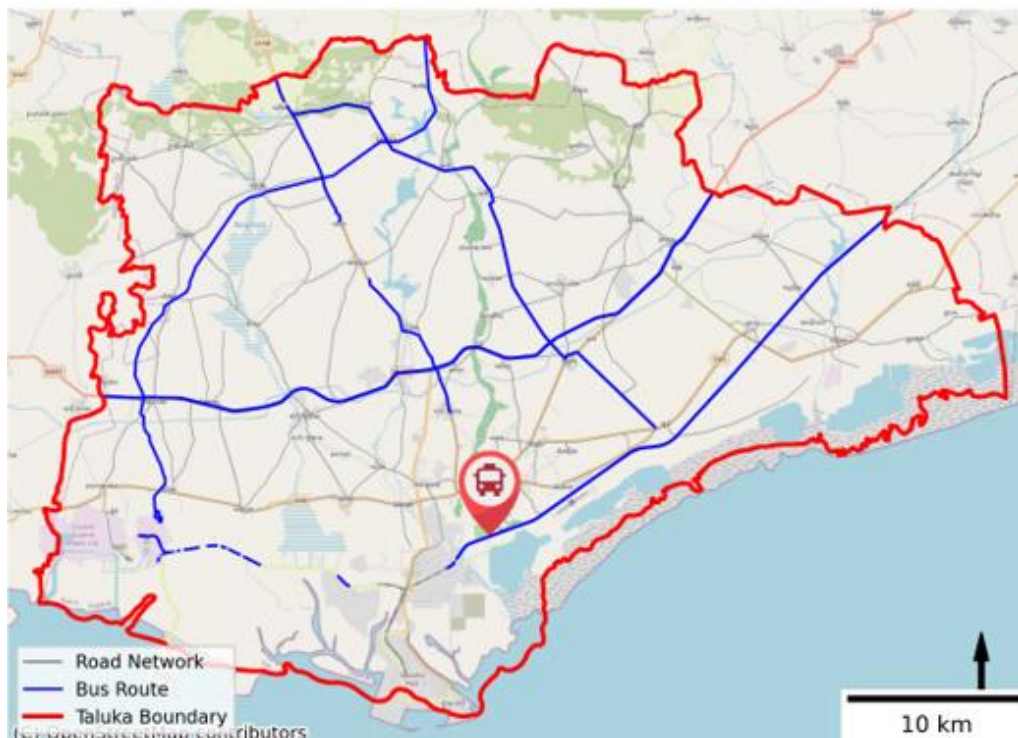


Figure 3.6 Mundra Map

This area experiences substantial freight and passenger movement linked to port activities. Mundra depot has high potential for electrification, particularly for short- to medium-distance routes supported by stable infrastructure and growing energy demand.

3.5.5 Anjar Depot

Anjar supports both urban and industrial connectivity, linking key economic zones within the region. It handles steady passenger flow and moderate route lengths. The depot has good potential for phased EV adoption due to balanced operational conditions. Anjar division, with a population of about 2.35 lakh, is one of the prominent industrial and commercial centers in Kutch. Anjar supports both urban and industrial.



Figure 3.7 Anjar Map

connectivity by linking key economic zones within the region. It handles steady passenger flows and moderate route lengths. The depot has good potential for phased EV adoption because of its balanced operational conditions. Anjar division, with a population of approximately 2.35 lakhs, is one of the prominent industrial and

commercial centers in Kutch. The region benefits from its proximity to industrial zones and ports, resulting in consistent travel demand. The Anjar depot supports both urban and industrial transport needs, making it a suitable candidate for electric bus operations with relatively stable route patterns and high passenger volumes.

3.5.6 Bhachau Depot

Bhachau plays an important role in connecting the eastern parts of Kutch with the major transit corridors. It handles moderate traffic with a mix of intercity and regional routes. Its strategic location makes it suitable for electrification on medium-distance routes.



Figure 3.8 Bhachau Map

The Bhachau division, with a population of approximately 1.86 lakh, is an important transit point because of its strategic location connecting Kutch with other parts of Gujarat. The region has experienced infrastructural growth since the 2001 earthquake, leading to improved connectivity and moderate transport demand. The Bhachau depot plays a key role in interregional bus operations and provides opportunities for integrating electric mobility solutions along long-distance routes.

3.5.7 Bhuj Depot

Bhuj serves as the central and most significant operational hub in the Kutch region, handling a high volume of routes and passenger demands. It connects major urban and semi-urban areas, making it crucial for regional mobility in Gujarat. Owing to its extensive network, it is a key candidate for early EV fleet deployment and charging infrastructure development. Bhuj is the administrative headquarters of the Kutch district in Gujarat and represents the most significant urban center in the region, with a population of approximately 4.43 lakh (Census 2011). It functions as a major hub for commercial, educational, and governmental activities, resulting in high passenger demand and traffic.



Figure 3.9 Bhuj Map

3.5.8 Naliya Depot

Naliya is a small but strategically important town in the westernmost part of the Kutch district. It is known for its extreme climatic conditions and is one of the driest and hottest regions in Gujarat.



Figure 3.10 Naliya Map

Despite its remote location, Naliya holds national significance because of the presence of an Indian Air Force base. The town is connected through road transport and plays an important role in regional connectivity, particularly in supporting public bus services across the Kutch Region.

3.6 Summary

This chapter presents the research methodology and an overview of the study area. It describes the systematic approach adopted, including problem identification, objective formulation, and data collection from primary and secondary sources. The methodology also includes the evaluation of fleet electrification, charging infrastructure, and economic and environmental analyses. The study area profile highlights the geographical and transport characteristics of the selected region along with the existing bus operations. This chapter forms the basis for further analysis and results of this study.

CHAPTER – 4

Data Collection and Data Analysis

4.1 General

Data for this study were systematically collected from both primary and secondary sources. Primary data were gathered through field visits to the Bhuj divisional office and various bus depots across the Kutch region, obtaining detailed information on routes, schedules, fleet composition, and operational characteristics. Interactions with depot officials and technical staff supported the data collection process. Secondary data were compiled from official reports, government publications, and relevant literature to ensure accuracy and comprehensiveness.

4.2 Data Collection

The Kutch-Bhuj Division consists of 8 main depots housing a combined fleet of 381 buses, serving around 530 stops. On average, these buses transport about 1,50,000 passengers each day. This study focuses on planning fleet electrification for 183 bus routes running 82916 km per day that are connected to 8 main depots. Bus route connecting subsidiary depot are not considered in this study. Study focuses on replacing traditional diesel buses with electric vehicles (EVs) for the Gujarat State Road Transport Corporation (GSRTC) regional bus transit. However, in present study focuses only on buses either originating or ending in 8 main depots (Bhuj, Bhachau, Mandvi, Rapar, Mundra, Naliya, Anjar, and Nakhatrana), trips originating or ending in subsidiary depots are not considered in study as charging facilities availability is only plan for 8 main depots.

The required data on time, speed, distance, and grade were obtained from the National Marine Electronics Association (NMEA) tool based on bus travel conditions. The type and number of buses, bus arrival and departure times, and kilometers travelled were obtained from the timetable of the various depot and Form No. 4 of Bhuj-GSRTC

4.2.1 Fuel Consumptions by GSRTC Fleet

Fuel consumption of diesel buses is a key factor affecting operational costs and environmental impact. It depends on route conditions, traffic, vehicle load, and driving patterns, typically ranging between 4.5 and 5.8 km per liter. Higher fuel consumption leads to increased emissions and costs, making it a critical parameter in comparing diesel and electric buses.

Table 4.1: Fuel Consumption of Diesel Operated Buses

Sr. No	Division	No of bus	Buses travel distance (km/day)	Mileage	Fuel Consumption By bus (Liters/day), $(E = C/D)$
	A	B	C	D	E
1	BHUJ	44	20198	5.80	3482.414
2	NALIYA	22	9838	5.80	1696.207
3	NAKHATRANA	21	9651	5.80	1663.966
4	ANJAR	22	9695	5.80	1671.552
5	MANDVI	26	12374	5.80	2133.448
6	MUNDRA	17	7385	5.80	1273.276
7	BHACHUA	15	6388	5.80	1101.379
8	RAPAR	16	6667	5.80	1149.483
Total Fuel Consumption Dependency		183	82,196	-	14,172

Source: Data Collected from Bhuj Division depot, Form No 4

Table 4.1 summarizes fuel consumption across divisions, showing total daily kilometers, fuel usage, fuel efficiency (km per liter), The total fuel consumption is 14,172 liters per day.

4.2.2 Collection of Data Pertaining to Emission Factors

Emission factors were sourced from the Automotive Research Association of India (ARAI) for Methane (CH₄), Hydrocarbons (HC), Oxides of Nitrogen (NO_x), Particulate Matter (PM), Sulfur Dioxide (SO₂), Carbon Monoxide (CO), using standardized values for emission estimation. In accordance with ARAI certification guidelines [57] and international emissions standards (Euro/Bharat Stage), exhaust emissions are quantified solely as Particulate Matter (PM). SPM is a broader ambient air quality metric that includes non-tailpipe and fugitive dust, making it unapplicable as a direct vehicle exhaust parameter. Hence in calculation shown below SPM is excluded.

Table 4.2: Emission Factors for BS-IV and BS-VI Diesel Buses

EMISSION FACTOR	BS-VI (gm/km)	BS-IV (gm/km)
CH ₄	-	0.0024
HC	0.35	1.23
NO _x	1.07	9.38
PM	0.027	0.054
SO ₂	-	0.0038
CO	4.02	4.02

Source: Automotive Research Association of India (ARAI)

4.2.3 Collection of Data Pertaining External Cost of Pollutant

External cost of pollutants refers to the monetary value of the environmental and social damages caused by emissions from transportation activities. In this study, the external costs associated with major pollutants such as CO, HC, NO_x, PM, CH₄ and SO₂ are considered for comparing diesel and electric buses. The emission quantity of each pollutant is multiplied by its corresponding external cost per unit of emission to estimate the total environmental cost. Diesel buses generally have higher external

costs due to their direct tailpipe emissions, whereas electric buses have no tailpipe emissions during operation, resulting in significantly lower local pollutant external costs. Therefore, incorporating external costs into the economic evaluation provides a more comprehensive assessment of the environmental benefits of fleet electrification. Table 4.3 lists external costs of pollutants in INR per ton for 2001 and 2020, reflecting increasing carbon market rates. These values support estimating economic benefits from emission reductions through electric bus adoption. The pollutant specific external cost values for the base year 2001 were adopted from Sheth and Sarkar (2019), who derived these values from Matthews et al. (2001). Since corresponding external cost estimates for 2001 and 2020 values were estimated in the present study using the World Bank India GDP Deflator. The adjustment was performed using the ratio of the GDP Deflator of the target year to that of the base year (2001), thereby expressing the damage costs at the economic price levels of 2020 while maintaining the relative damage costs among pollutants.

Table 4.3 External Cost of Pollutant in INR Per Ton

Pollutant	External Cost of Pollutant in INR Per Ton (2001)	External Cost of Pollutant in INR Per Ton (2020)
CO	33,800	96,752
HC	104,000	297,699
NO _x	182,000	520,973
PM	279,500	800,065
SO ₂	130,000	372,123
CH ₄	17,745	50,799
source	(Sheth & Sarkar, 2021) [19]	www.carbonpricingdashboard.worldbank.org [37,19]

Note: A brief explanation has been added describing the methodology in Appendix A.

This approach provides a transparent and reproducible methodology for estimating pollutant-specific external costs in the absence of updated published values. A brief explanation has been added describing the methodology adopted for deriving the pollutant-specific external cost values from the cited literature in Appendix A.

The variation in external cost values across pollutants reflects differences in their environmental persistence, toxicity, and associated impacts on human health, ecosystems, agriculture, materials, and climate. Consequently, pollutants such as particulate matter (PM) and nitrogen oxides (NO_x) have higher external cost values due to their significant adverse health and environmental effects, whereas carbon dioxide (CO₂) has a comparatively lower external cost per ton because its damages are primarily associated with long-term climate change.

4.3 Data Collected to Explore Fleet Electrification Possibilities

Fleet electrification involves replacing traditional vehicles with EVs, requiring careful planning to balance technological, operational, and strategic factors. This study evaluates bus and charger types, focusing on total cost of ownership (TCO), route energy consumption, charging infrastructure, and economic feasibility.

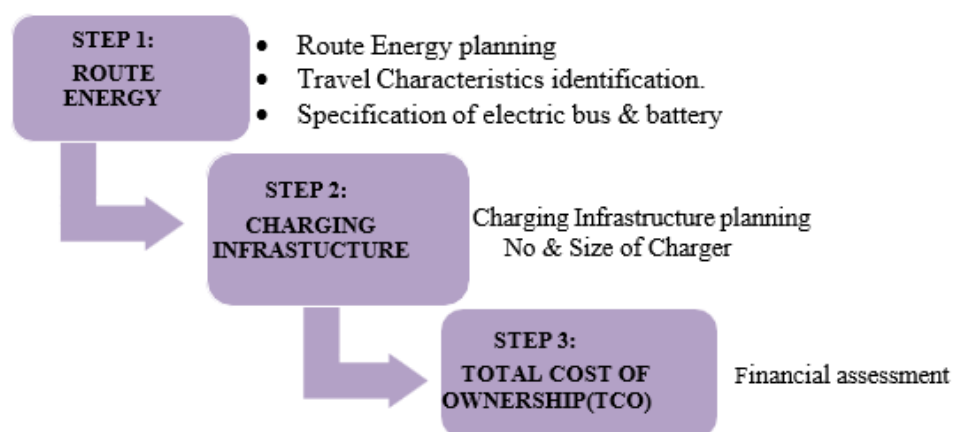


Figure 4.1 Flowchart for Electrification Planning

4.3.1 Route Energy

Route energy is the total energy an EV requires to operate on a specific route, considering distance, speed, terrain, passenger load, and driving conditions. It informs battery sizing, charging schedules, and route electrification feasibility [12].

- **Route Energy planning**

Route details such as route number, stops, and distance were collected for route energy planning (see Appendix B). Annual cost comparisons between diesel and electric buses were conducted. Factors influencing route energy include average travel speed, payload weight, weather conditions, and vehicle condition are discussed in Table 4.4.

Table 4.4: Factors Associated with Route Energy

Factor associated with route energy planning	Description
Average Speed of travel	Buses with less travel speed and frequent breaking benefit from regenerative braking systems.
Payload Weight	Heavier loads demand more energy, requiring adjustments in route
Weather conditions	Cold temperatures reduce battery range, necessitating careful consideration in winter months. Intense heat or humidity may reduce batteries life and necessitate adjustments.
Vehicle Condition	Old vehicles consume more power compared to new vehicles.

Source: NITI Aayog & WRI India, Handbook of Electric Vehicle Charging Infrastructure Implementation, 2021

Travel Characteristics

Key travel characteristics such as route type, distance, terrain, and traffic patterns were analyzed to optimize EV operations, maximize range, and minimize costs. Continuous monitoring and stakeholder collaboration are essential for smooth integration of EV buses.

Table 4.5: Travel Characteristics Identification

Factor Associated with Travel Characteristics Identification	Description
Route Type	High-speed highways may require higher battery capacity than urban streets.
Total Distance	Long highway stretches require different planning compared to short deliveries within cities.
Terrain	Hilly and mountainous regions demand more energy than flat plains.
Traffic Pattern	Congestion and travel delay significantly impact energy consumption.

Source: NITI Aayog & WRI India, Handbook of Electric Vehicle Charging Infrastructure Implementation, 2021

• Specifications of Electric Bus and Battery

Several commercially available electric bus models were reviewed before selecting a representative vehicle for the present study. Table 4.6 compares the technical specifications of three widely available 9-m electric buses manufactured by Tata Motors, Ashok Leyland, and BYD. The comparison indicates that all three buses possess comparable dimensional characteristics and passenger carrying capacities suitable for intercity public transport operations.

Among the available alternatives, the Bus-1 electric bus was selected for its higher passenger capacity (38 seats) compared to competitors. Furthermore, company has an established manufacturing and service network in India, ensuring better availability of technical specifications and operational data required for the present analysis. The methodology developed in this research is not restricted to a specific manufacturer or vehicle model. The proposed guidelines are based on generic operational, technical, economic, and environmental parameters and can readily be applied to other electric bus models by replacing the vehicle-specific input data, such as battery capacity, energy

consumption, vehicle dimensions, passenger capacity, and acquisition cost. Therefore, the outcomes of this study should be interpreted as demonstrating the applicability of the proposed assessment guidelines rather than promoting any particular manufacturer or product.

Table 4.6: Comparison of Selected Electric Bus Models

Company	Kerb weight (kg)	Vehicle width (m)	Vehicle height (m)	Vehicle length (m)	Vehicle capacity (Nos of passenger)	Reference
Bus-1	15225	2.58	3.8	9	38	www.buses.tataultra-ev-busspecification
Bus-2	14500	2.5	3.4	9	35	www.ashokleyland.com/in/alternativefuel/ev/specification
Bus-3	14400	2.5	3.4	9	35	www.byd-k/series/specification

Lithium-ion batteries were chosen for their low maintenance, absence of memory effect, and low self-discharge. A medium-capacity battery (320 kWh) balances cost and charging frequency was considered (Table 4.7). Bus batteries typically have a lifespan of about 10 years or 3,500 charge cycles. Battery technology is pivotal in influencing the performance, reliability, operating range, charging characteristics, and overall cost of electric buses. Various lithium-ion battery chemistries are utilized in commercial electric buses, each providing specific benefits regarding energy density, safety, cycle life, charging capability, and cost.

Table 4.7: Specifications of E-Bus-Battery

Attributes associated with selection of electric battery	Description
Battery useful life cycles	Generally, bus batteries are designed for 10 years, i.e., approximately 3,500 charging cycles.
Size of battery	Big battery: 400–450 kWh, small battery: 150–250 kWh
Battery DOD (Depth of Discharge)	Electric buses with larger battery capacities and longer ranges may require less frequent charging.

Source: NITI Aayog & WRI India, Handbook of Electric Vehicle Charging Infrastructure Implementation, 2021

Table 4.8 offers a comparison of the primary battery technologies employed in electric buses, detailing their approximate market cost, leading manufacturers, and key characteristics. Additionally, the representative market range adopted in this study is highlighted, reflecting the battery technologies commonly used in contemporary electric bus applications.

Table 4.8: Technical Specifications and Cost of Battery for Electric Buses

Battery Type	Common Chemistry	Approximate Cost for 300 kWh Pack (₹ lakh)	Common Manufacturers	Remarks
Lithium Iron Phosphate (LFP)	LiFePO ₄	30.0–37.5	BYD, CATL, Tata, AutoComp, Exide Energy	High safety, long cycle life, and the most widely used battery chemistry in Indian electric buses.
Nickel Manganese Cobalt (NMC)	LiNiMnCoO ₂	37.5–45.0	LG Energy Solution, Samsung SDI, Panasonic	Higher energy density with relatively higher cost and greater thermal management requirements.
Lithium Titanate (LTO)	Li ₄ Ti ₅ O ₁₂	45.0–75.0	Toshiba (SCiB), Microvast	Supports ultra-fast charging and very long cycle life but has a higher initial cost.

Source: NITI Aayog & WRI India, Handbook of Electric Vehicle Charging Infrastructure Implementation, 2021

Generally, EV buses operated by GSRTC have battery capacities ranging from approximately 180 to 320 kWh. In the present study buses operate over relatively higher fleet kilometers, so medium capacity 320-kWh battery pack has been considered. Different type of battery available in the market are shown below in Table 4.8 with their approximate cost. The Figure 4.2 outlines key factors such as distance, acceleration-

deceleration, gradient, passenger loading, and operating schedule that influence battery selection based on energy requirements and total travel distance.

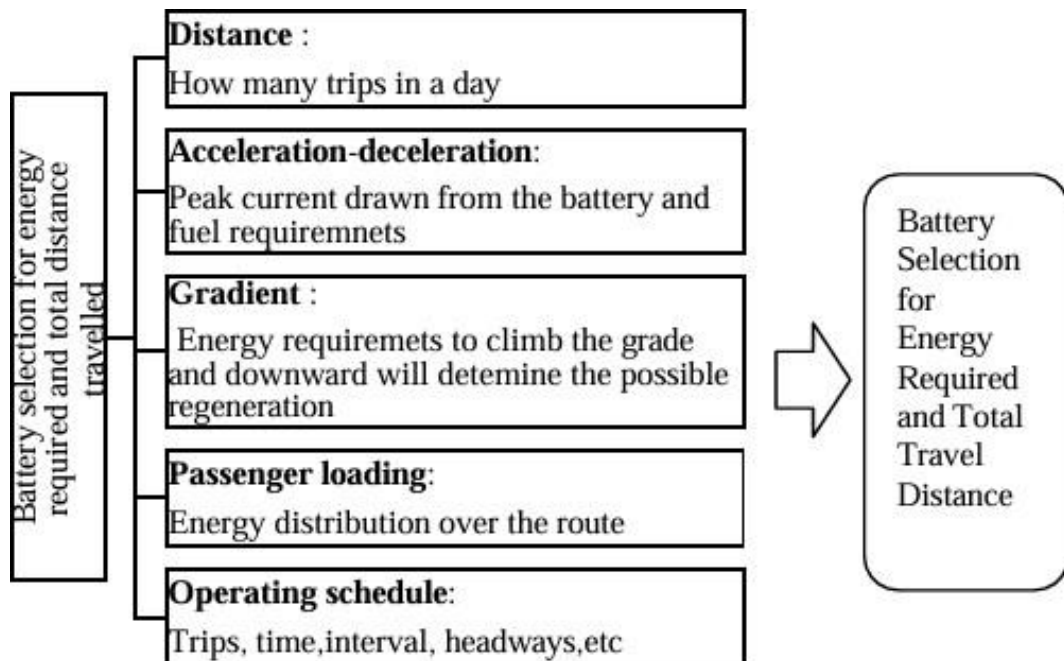


Figure 4.2: Battery Selection Criteria Consideration

4.3.2 Charging Infrastructure: Number and Size of Charger

Electric vehicle chargers are broadly classified based on charging speed and power supply. AC chargers (Level 1 and Level 2) are commonly used for home and workplace charging and provide slow to moderate charging speeds. AC Chargers are the most commonly used chargers and rely on the vehicle's onboard charger to convert AC power to DC.

- **Level 1 (Slow Charging)**



Figure 4.3: AC Chargers L= 1 Slow

Source: NITI Aayog & WRI India, Handbook of Electric Vehicle Charging Infrastructure Implementation, 2021

Level 1 (Slow Charging) typically operates at low power and is mainly suited for residential use. It is ideal for vehicles with small battery capacities, such as electric two-wheelers and private passenger cars, where long charging durations are acceptable. Due to low installation and operating costs, Level 1 charging is economical but impractical for commercial or high-usage vehicles. The charger L1-slow shown in Figure 4.3.

- **Level 2 (Fast Charging)**

Level 2 chargers operate at higher voltage and power levels, significantly reducing charging time compared to Level 1. These chargers are widely deployed in workplaces, shopping complexes, parking facilities, and institutional campuses. Level 2 charging provides a reliable and cost-effective solution for daily commuting needs and is increasingly preferred for public and semi-public charging infrastructure. The different level 2 fast charger is shown in Figure 4.4.



Figure 4.4 Level 2 Fast Charger

Source: NITI Aayog & WRI India, Handbook of Electric Vehicle Charging Infrastructure Implementation, 2021

Ultra-fast chargers further reduce charging time and are suitable for commercial fleets and long-distance travel. Wireless and battery-swapping systems are emerging technologies aimed at improving charging convenience and efficiency. Electric Vehicle (EV) chargers are classified according to the speed with which they recharge an EV's battery. DC fast chargers supply high power directly to the battery, enabling rapid charging and are mainly installed at public charging stations and highways.

- **Level 3 or DC Fast Chargers (Rapid Charging)**

DC Chargers, classified as Level 3 or DC Fast Chargers supply direct current straight to the battery, eliminating reliance on the onboard charger. This allows much higher power transfer and substantially shorter charging times. DC fast chargers are critical for electric buses, commercial fleets, and highway corridor charging, enabling quick turnaround and long-distance travel. However, they involve higher capital costs, require grid upgrades, and demand advanced thermal and safety management systems. Collectively, these charger types enable a flexible and scalable EV charging ecosystem. Various level 3 DC fast chargers are given in Figure 4.5.



Figure 4.5: Level 3 or DC Fast Charging

Source: NITI Aayog & WRI India, Handbook of Electric Vehicle Charging Infrastructure Implementation, 2021

Charging infrastructure planning considers fleet size, battery capacity, and route requirements. Table 4.9 summarizes charging infrastructure attributes, including location, charging speed, cost, and number of charging nodes.

Table 4.9: Charging Infrastructure Attributes

Attributes associated with Charging Infrastructure	Description
Location and Accessibility	Depot charging, mobile chargers or partnerships with existing infrastructure should be considered. Mapping of existing charging stations and planning of routes accordingly
Charging speed	Prioritizing routes with fast-charging stations for long journeys is beneficial. There are typically three levels of charging for electric buses: slow, fast, and rapid.
Cost for utilizing charging infrastructure	Charger Cost- 7.5Lakh (Fast Charger), 1.5Lakh (Slow Charger), Transformer + Connection + Beaker etc.=8L, Software maintenance =0.5Lakh / Year, Technician/ Labour =2.5Lakh / year, Maintenance =1.8Lakh / Year. Total Charging infrastructure= capital cost + Total operational & maintenance cost.
Number of nodes available for charging	A larger fleet will require more chargers to ensure that all buses can be charged as needed. As per India government norms 3-fast and 3-slow chargers are to be installed for larger fleet and as per requirement for small fleet.

Source: NITI Aayog & WRI India, Handbook of Electric Vehicle Charging Infrastructure Implementation, 2021

4.3.3 Total Cost of Ownership (TCO)

TCO represents the total cost incurred over the ownership period of a bus, including the initial purchase cost, energy/fuel, crew cost, maintenance, and other operating costs. It provides a common basis for comparing the economic performance of diesel and electric buses, generally expressed as cost per kilometer (₹/km). Maintenance cost represents the variable cost associated with maintaining the buses in operational condition and includes Tyre replacement, spare-parts consumption, routine servicing and repairs, and miscellaneous maintenance expenses. The Total Cost of Ownership (TCO) and provides a realistic basis for comparing the long-term economic performance of conventional diesel buses and electric buses under different scenarios.

A Life Cycle Cost Assessment (LCCA) compares diesel and electric buses, including initial, operational, and maintenance costs (Table 4.10). Key cost components include bus price, battery cost (after subsidy), fuel/electricity tariffs, manpower, and charging infrastructure costs.

Table 4.10: Parameter for Life Cycle Cost Assessment

Parameter		Cost
Fixed / Capital Cost	Diesel bus purchase cost	₹40 lakh/bus
	Electric bus purchase cost	₹82 lakh/bus (with subsidy)
	Charger Cost	₹7.5Lakh /Fast Charger 1.5Lakh/ Slow Charger
	Charging Infrastructure	Transformer + Connection + Beaker etc.=8L
	Registration cost	₹1380/bus
	Salvage cost	10% of bus purchase cost
Variable Operating Cost	Diesel fuel cost	₹84/L
	Electricity cost	₹4.50/kWh
	Crew cost	₹8.30/km
	Diesel bus maintenance cost (Tyre cost, spare parts, routine servicing/repairs, miscellaneous maintenance)	₹5.78/km
	EV maintenance cost (Tyre cost, spare parts, routine servicing/repairs, miscellaneous maintenance)	₹4.5/km
Technical Parameters	Daily distance	220 km/day
	Diesel mileage	5.8 km/L
	EV mileage	1.5 km/kWh
	Bus life	10 years
	Operating days	days/year
	Discount rate	8%

Source: For diesel operate buses: GSRTC Bhuj Office, For E-bus: Source: NITI Aayog & WRI India, Handbook of Electric Vehicle Charging Infrastructure Implementation, 2021

4.4 Data Analysis

In the present research the entire collected data was analyzed and modeled to assess fleet electrification possibilities considering various optimization parameters. The bus transit in Kutch is operated by GRTC as policy frame work. This study aims to integrate electric mobility with bus transportation systems in Kutch region of Gujarat, India. To conduct a comparative analysis and calculate life cycle costs, the study considers 183 buses serviceable unit of a single bus operating 220 km for 10 years of useful life.

4.5 Criteria Consideration for Replacement of ICE bus by Ev-bus

After data collection, the Vehicle-on-Route Energy for electric vehicles was calculated to analyze energy consumption on specific routes. The NMEA smartphone app was used to gather time, speed, distance, and gradient data. This data was used as input into the route energy worksheet to determine the energy required to compute each trip where vehicle specification parameters are already entered. Cost of fuel taken from Bhuj depot (84Rs/liter). Phase-wise fleet electrification planning is considered by progressively increasing the electrification percentage (e.g., 10%, 20%, 30%, and so on). The final percentage will be determined based on the number of buses that fulfil the predefined criteria, including State of Charge (SoC), charging scheduling, and area availability for charging infrastructure. For finding optimum probability of replacing existing fuel to environment friendly sustainable energy source below given criteria are considered.

4.5.1 First Criteria for Replacement: State of Charge (SoC)

First and most important criteria for fleet electrification is State of Charge (SoC). It is a vital indicator in EV-Buses that shows the remaining battery level as a percentage. It helps to estimate driving range and is managed by the Battery Management System

(BMS) for safe and efficient operation. Accurate SoC prevents battery damage from overcharging or deep discharging and aids in smart charging and route planning for EV fleets.

Time-speed data					Vehicle-specification		
Time	Speed	Distance	Grade	Passengers	Parameter	Unit	Value
[s]	[kph]	[m]	[%]	[-]	Vehicle		
0	0	0.000	0.000	25	Kerb Weight (If unknown, use ICE kerb weight + battery weight below)	[kg]	16425
1	0.2	0.000	-1.801	25	Payload (Enter 0 or expected luggage load for bus)	[kg]	150
2	0.25	0.050	-1.801	25	Vehicle Overall Width	[m]	2.58
3	0.31	0.250	-1.801	25	Vehicle Overall Height	[m]	3.8
4	0.27	0.700	-1.511	25	Coefficient of Rolling Resistance (CRR)	[N/kg]	0.075
5	1.5	1.500	-1.244	25	Coefficient of Aerodynamic Drag (CD)		0.64
6	2.8	2.750	-0.994	25	Driveline Efficiency (losses not accounted for in CRR)		81.0%
7	1.2	4.500	-0.756	25	Motor		
8	1.9	6.750	-0.527	25	Maximum power	[kW]	245.0
9	0.27	9.500	-0.305	25	Average Efficiency		80.0%
10	1.5	12.750	-0.090	25	Battery		
11	2.8	16.500	0.121	25	Select Battery Chemistry		Lithium Nickel Manganese Cobalt Oxide (LiNiMnCoO ₂) - NMC
12	1.2	20.750	0.331	25	Battery efficiency		95.0%
13	1.9	25.500	0.248	25	Useful Battery Capacity (Spec x Depth of Discharge x Age Fade)	[kWh]	252
14	1.1	30.750	0.188	25	Battery Mass	[kg]	2291
15	0.38	36.500	0.143	25	Unit Cell Nominal Voltage	[V]	3.7
					Battery Voltage (If unsure, use Nominal Voltage x [V])		400
					Maximum Charging C-rate	[/hr]	1
					Battery Charge Capacity	[Ah]	630.0
					Accessories		
					Air Conditioning Power with 40 passage	[kW]	12
					Air Conditioning Power with no passage	[kW]	2.5
					Other Accessories Average Power Consum	[kW]	2.67

Figure 4.6: Data to Input in Excel Sheet for Route Energy Calculation

In this study, SoC was evaluated for each bus trip across the eight divisions of Kutch—Rapar, Mundra, Mandvi, Naliya, Bhachau, Bhuj, Nakhatrana, and Anjar. Priority was assigned to buses that required minimal opportunity charging or no intermediate charging during their routes, ensuring operational feasibility with existing charging infrastructure. After finding SoC for each bus trip, priority was given to buses who required minimum opportunity charging or no charging in between route. Out of a total fleet of 183 buses, 119 buses were initially shortlisted during the screening process based on SoC suitability.

Table 4.11: Criteria 1: SOC (state of charge: < than 25%) for 8 Division of Kutch

Depot	Number of buses in Depots	Number of buses available for replacement
RAPAR	16	8
MUNDRA	17	16
MANDVI	26	20
NALIYA	22	9
BHACHAU	15	10
BHUJ	44	28
NAKHATRANA	21	13
ANJAR	22	15
Total	183	119

4.5.2 Second Criteria for Replacement: Charging Scheduling

In this study, after applying the first screening criterion based on State of Charge (SoC), 119 buses were shortlisted for further evaluation. These buses were then assessed under charging scheduling scenarios, including both opportunity charging (charging during short layovers) and overnight depot charging. Charging scheduling details is provided in Appendix-C. Further screening was conducted based on the minimum requirement of opportunity charging. Under the 0.5C charger scenario, 42 buses were found suitable for replacement, whereas under the 2C charger scenario, 66 buses met the operational feasibility criteria. The 2C fast-charging option significantly increased the number of feasible buses due to reduced charging time and improved route compatibility. Thus, based on minimum opportunity charging duration and operational viability, 66 buses were shortlisted for detailed techno-economic analysis in the next stage of the study. Charging scheduling for EV buses is a crucial aspect of efficient fleet management. It

involves planning of timing and duration of charging to ensure that buses are adequately powered. Proper scheduling helps avoid peak-hour charging, reduces downtime, and extends battery life. Charging scheduling for one bus has shown in Figure no 4.9.

The old fleet → entirely diesel operated

The EV buses → proposed

	Activity	Start of Activity		Duration hh:mm	Energy Exchange in kWh (+ve consumption / -ve charging)
		Time hh:mm	SoC %		
0	Idle for start of schedule	0:00	100.0%	5:30	
1	ASHAPURA - MANDVI	5:30	100.0%	1:55	90
2	MANDVI - BIDDA - MANDVI	7:25	67.3%	1:00	50
3	LAYOVER	8:25	49.2%	0:20	-60
4	MANDVI - MUNDRA	8:45	71.0%	1:20	69
5	LAYOVER	10:05	45.9%	0:20	-60
6	MUDRA - MANDVI	10:25	67.7%	1:20	69
7	LAYOVER	11:45	42.6%	1:15	-320
8	MANDVI - KOTDI - GADH	13:00	100.0%	2:20	106
9	LAYOVER	15:20	61.5%	0:20	-60
10	GADHASHISHA - KOTDA - GADH	15:40	83.3%	0:50	41
11	LAYOVER	16:30	68.4%	0:30	-120
12	GADHASHISHA - BHUJ	17:00	100.0%	1:10	64
13	LAYOVER	18:10	76.8%	0:10	0
14	BHUJ - ASHAPURA	18:20	76.8%	2:10	103
15	Idle for REST of schedule	20:30	39.4%	0:00	-324

Figure 4.7: Charging Scheduling

This approach supports both operational efficiency and sustainable energy use. In this scenario buses are screen based on minimum period of opportunity charging and overnight charging in which 66 buses fulfil the predefined criteria of Charging Scheduling. For route optimization, a combination of slow and fast charging infrastructure is proposed. Slow chargers have a lower initial investment and are therefore suitable for overnight depot charging, while fast chargers are deployed for opportunity-charging demand is high. This combination enables efficient charging while ensuring maximum bus availability for route operations and optimization.

Table 4.12: Criteria 2: Capacity of Charger

Depot	Total bus	Number of buses available for replacement (By 0.5C charger)	Number of buses available for replacement (By 2C charger)
RAPAR	16	2	5
MUNDRA	17	6	9
MANDVI	26	5	8
NALIYA	22	7	8
BHACHAU	15	5	5
BHUJ	44	8	13
NAKHATRANA	21	5	7
ANJAR	22	4	11
Total	183	42	66

4.5.3 Third Criteria for Replacement: Area Availability for Charging Infrastructure

The third most important criterion for fleet electrification was the availability of area for charging infrastructure. The charging infrastructure is estimated to require approximately 10% additional area or unused area of depo with the existing depot area, mainly to accommodate charging equipment, transformer facilities, vehicle circulation, and associated electrical infrastructure. The assessment of depot land availability indicates that all the studied depots have sufficient additional area to accommodate the proposed charging infrastructure. Therefore, no major land acquisition or depot expansion is anticipated for the proposed electrification plan. The available space at each depot can be utilized for charger installation while

maintaining necessary operational and safety clearances. This availability of area is a key factor in determining the possibility of adopting EV-buses in existing depot. As per thumb rule 10% more area is utilized by charging infrastructure to charge the bus. All the depot has requisite area requirement to fulfill these criteria shown in Table 4.13.

Table 4.13: Criteria 3: Charging Infrastructure Area Availability

Station	Area utilized by existing infrastructure (sq.mt)	Area required for Charging Infrastructure 10% (sq.mt)	Free Area Available for Charging Infrastructure (sq.mt)
MUNDRA	512	51.2	224
RAPAR	251	25.1	122
MANDVI	753	75.3	502
NALIYA	1,097	109.7	560
BHACHAU	1,744	1,74.4	849
BHUJ	5,830	583.0	282
NAKHATRANA	554	55.4	897
ANJAR	1,298	129.8	605
TOTAL	12,039	120.39	416

After screening the buses based on the predefined criteria—State of Charge (SoC), charging scheduling, and area availability for charging infrastructure—a maximum of 66 buses were found to fulfil the criteria. Therefore, a maximum fleet replacement scenario of 30% is considered for the study i.e., 57 buses considered for study. In 30% replacement scenario only, those buses are considered which origin or end from 8 main depot with proper handling time. As a maximum of 66 buses fulfil the predefined criteria, fleet replacement beyond 30% cannot be considered feasible under the present conditions, as a 40% replacement scenario would require 75 buses.

The detailed economic calculations and analysis for phase wise scenario are presented in Section 4.10. Based on the assessment, a 10% to 30% (19 to 56 buses) fleet replacement range can be adopted for phased fleet electrification planning.

4.6 Air Quality Impact Assessment (AQIA)

AQIA evaluates how projects affect air quality by collecting baseline data, estimating emissions, and modeling pollutant dispersion. The study measured emissions from diesel buses (NO_x, SO₂, PM, CO, HC, CH₄) to assess local pollution contributions. Vehicular emissions were calculated by multiplying emission factors (Tables 4.2) with fuel consumption (Table 4.1).

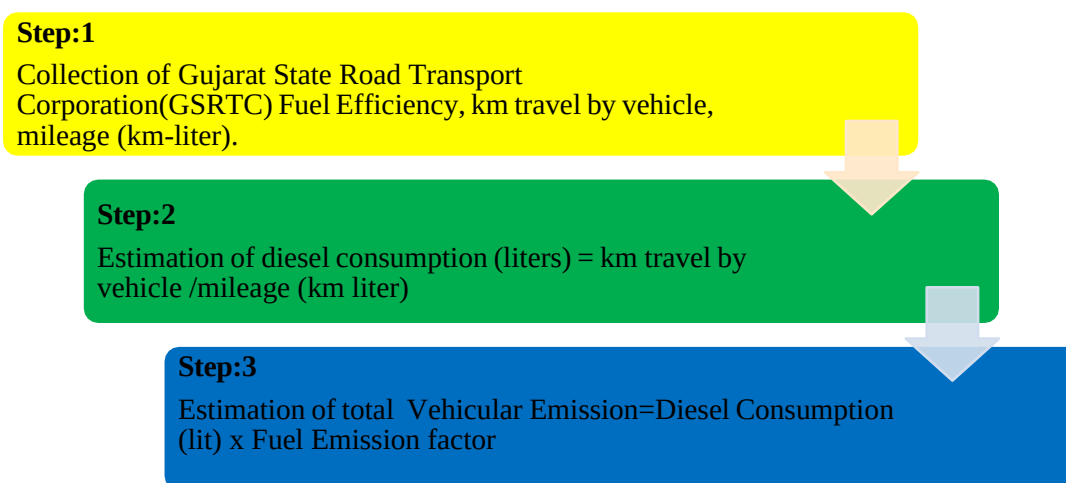


Figure 4.8: Flowchart: Steps for Estimation of Vehicular Emission

The variation in emissions among depots, such as Bhuj and Bhachau, is primarily attributed to differences in fleet size (Bhuj bus fleet size is 44 and Bhachau is 15), daily vehicle kilometers travelled, route characteristics, and diesel consumption. Since the emission factors for each pollutant remain constant for a given Bharat Stage (BS) emission standard, the total emissions are directly proportional to the operational activity and fuel consumption of the bus fleet. Consequently, the Bhuj depot records higher emissions because it operates a larger fleet over longer travel

distances, resulting in greater diesel consumption. In contrast, the Bhachau depot operates fewer buses with lower daily vehicle kilometers travelled, leading to comparatively lower emissions. Thus, the observed variation reflects the scale of transport operations and indicates that larger depots offer greater potential for emission reduction through fleet electrification.

Table 4.14: Vehicular Emissions Estimation for BS-IV Diesel-Operated Bus

Vehicular Emissions calculation of BS-IV existing diesel-operated public transit bus services for Kutch region						
Division Of Kutch	Km travels (Per day)	CH ₄ (g/km)	HC (g/km)	NO _x (g/km)	PM (g/km)	SO ₂ (g/km)
BHUJ	20198	48.4752	24904.1	189457.24	1090.692	76.7524
NALIYA	9838	23.6112	12130.3	92280.44	531.252	37.3844
NAKHATRANA	9651	23.1624	11899.7	90526.38	521.154	36.6738
ANJAR	9695	23.268	11953.9	90939.1	523.53	36.841
MANDVI	12374	29.6976	15257.1	116068.12	668.196	47.0212
MUNDRA	7385	17.724	9105.71	69271.3	398.79	28.063
BHACHUA	6388	15.3312	7876.4	59919.44	344.952	24.2744
RAPAR	6667	16.0008	8220.41	62536.46	360.018	25.3346
TOTAL	82196	-				

Tables 4.14 and 4.15 present the estimated emissions from BS-IV and BS-VI compliant diesel-operated public transit buses, respectively. The assessment includes methane (CH₄), which is a greenhouse gas (GHG), along with regulated air pollutants, namely hydrocarbons (HC), nitrogen oxides (NO_x), particulate matter (PM), and Sulphur dioxide (SO₂). A similar emission pattern is observed across all depots under both BS-IV and BS-VI emission standards because the operational characteristics of the depots remain comparable, while the emission factors are uniformly defined for each vehicle

emission standard. Although the absolute emission quantities vary depending on fleet size, route length, and vehicle kilometers travelled, depots with higher operational activity consistently generate higher emissions than those with lower operational activity.

Table 4.15: Vehicular Emissions Estimation for BS-VI Diesel-Operated Bus

Vehicular Emissions calculation of BS-VI existing diesel-operated public transit bus services for Kutch region						
Division` Of Kutch	Km travels (Per day)	CH ₄ (g/km)	HC (g/km)	NO _x (g/km)	PM (g/km)	SO ₂ (g/km)
BHUJ	20198	0	7069.3	21611.86	561.5044	0
NALIYA	9838	0	3443.3	10526.66	273.4964	0
NAKHATRANA	9651	0	3377.85	10326.57	268.2978	0
ANJAR	9695	0	3393.25	10373.65	269.521	0
MANDVI	12374	0	4330.9	13240.18	343.9972	0
MUNDRA	7385	0	2584.75	7901.95	205.303	0
BHACHUA	6388	0	2235.8	6835.16	177.5864	0
RAPAR	6667	0	2333.45	7133.69	185.3426	0

In phase I, first target is to replace Diesel Bus-BS IV. Table 4.16 presents the Vehicular Emissions for major pollutants from diesel buses under BS-IV and BS-VI standards, along with EVs.

Table 4.16: Vehicular Emissions

Pollutants	Emission from Diesel Bus (BS-IV) Tonne	Emission from Diesel Bus (BS-VI) Tonne	Emission from Ev Tonne
CH ₄	0.00020	0.00000	0
SO ₂	0.00031	0.00000	0
HC	0.10135	0.02877	0
NO _x	0.77100	0.08795	0
PM	0.00444	0.00229	0

The results show that EVs have zero tailpipe emissions, while BS-VI buses exhibit substantially lower emissions than BS-IV buses for most pollutants.

4.7 Economic Assessment for Diesel Operated and EV-Bus

Economic Assessment compares diesel and electric buses based on capital cost, operating and maintenance expenses, energy consumption that is also called as Life-Cycle Cost Analysis (LCCA) helps determine the long-term financial viability and sustainability of transitioning from diesel to electric bus fleets. While electric buses have higher initial procurement costs, they offer significantly lower energy and maintenance costs over their operational life. Diesel buses incur recurring fuel expenses and higher emissions-related external costs, whereas electric buses benefit from energy efficiency and potential incentives.

According to IRC: SP:30, the Road User Cost (RUC) comprises three major components: (i) Cost of construction of the facility, (ii) Periodic cost of maintaining the facility over its design life, and (iii) Road user cost. In the present study, the assessment focuses specifically on the replacement of conventional diesel buses with electric buses. Therefore, the road infrastructure remains unchanged under both the diesel and electric bus scenarios. Within the Road User Cost, the Vehicle Operating Cost (VOC) is considered in the present economic analysis, as it directly varies between diesel and electric buses due to differences in fuel/energy consumption, maintenance, and other operating expenses. Accordingly, the calculated VOC values for both diesel and electric buses are incorporated into the economic assessment. On the other side, travel time cost and accident cost are considered to remain the same for both scenarios and are therefore not included separately in the comparative economic analysis. Moreover, accident costs are influenced by several factors, such as road condition, carriageway width, geometric characteristics, traffic composition, and operating conditions, which are outside the scope of the present study. Hence, these components are excluded, while the Vehicle

Operating Cost is retained as a relevant cost component because it directly reflects the operational differences resulting from the transition from diesel to electric. RUCS and IRC: SP:30-2019 provide established benchmarks for bus operating costs in India. Table 4.17 reviews major Indian studies on bus operations and fleet electrification, covering key cost and environmental parameters relevant to the present study.

Table 4.17: Existing Studies Conducted in India

Research source	Variable considered	Bus operating considered	Environmental cost
IRC: SP:30, the Road User Cost (RUC) [92]	Fuel, tyres, engine oil, lubricants/grease, spare parts, maintenance, depreciation, passenger time	Vehicle operating cost (VOC), road roughness, traffic and passenger time	Environmental cost not directly included in RUC tables
Sheth A & Sarkar D. [09]	Bus procurement, electricity/diesel, O&M, bus replacement, battery replacement, charging station	Energy/electricity, O&M, financing, charging and replacement costs	CO ₂ , CO, PM, HC, NO _x , SO _x and external pollution costs
Majumder et al. [90]	E-bus CAPEX, battery/supercapacitor, solar PV, grid electricity, charging/storage	Energy consumption, electricity, renewable energy, system operation	Emission reduction and renewable-energy contribution
Adheesh, et al. [98]	Bus purchase/operation, electricity/diesel consumption, maintenance, energy efficiency, operating economics	BMTC urban bus; diesel vs. electric bus; real 3-month electric-bus trial	CO ₂ and local air pollution considered; study specifically evaluates environmental implications and pollution reduction
Khandekar et al. [14]	Bus CAPEX, battery cost, electricity, diesel fuel, battery-price reduction, solar electricity, TCO, subsidies	Urban/intracity buses in Indian cities	Air-quality benefits and emissions considered; environmental benefits incorporated into the economic case

Hodge et al. [99]	Bus CAPEX, charging infrastructure, fuel/electricity, maintenance, daily travel, availability, bus life, battery size	Surat BRTS; 8 routes and 4 depots; 9 m and 12 m diesel/BEBs	Not monetized in TCO; emissions reduction discussed, but the report explicitly excludes reduced-emission benefits from TCO
Vijaykumar et al. [100]	Bus CAPEX, battery capacity, fuel/electricity, maintenance, utilization, charging infrastructure, financing, holding period, subsidy	12 m AC e-bus vs. diesel/CNG city buses; approximately 200 km/day	Environmental benefits discussed, but environmental cost is not directly monetized in the TCO model
Jaywant & Kanitkar [101]	CAPEX, battery replacement, electricity, fuel, maintenance, staff, charging infrastructure, TCO, electricity generation mix	PMPML urban fleet; 12 m and 9 m electric buses compared with diesel, CNG and hybrid buses	CO ₂ , CO, HC, NO _x and PM emissions quantified; societal costs include carbon and noise-related health costs
Gadepalli, Gumireddy & Bansal [102]	Number of buses, bus length, contract duration, minimum assured km, additional km, daily operating hours, performance guarantee, penalties, bid period, quoted ₹/km	E-bus contracts across 33 Indian cities / 36 contracts	Environmental cost not included; study focuses on procurement and contract cost drivers
Sheth A et al. [103]	Capital cost, operating cost, infrastructure investment, social benefits, environmental benefits, present worth, social B/C ratio	Proposed electric BRTS in Ahmedabad	Environmental dimension directly included and monetized along with economic and social benefits
UITP India (2022), [104]	Bus and battery CAPEX, charging infrastructure, financing, energy/fuel, crew, maintenance, replacement, utilization, business model	Karnataka regional/rural/intercity buses; KSRTC/RTC operations; diesel vs. e-bus	Environmental benefit acknowledged, but the main TCO/financial model does not monetize environmental externalities
Khanna et al. [105]	Bus CAPEX, battery, financing/interest,	Private 9 m and 12 m e-buses on	Emission reduction is discussed as a

	energy tariff, maintenance, insurance, tyre cost, route length, occupancy, utilization, battery replacement, charging	22 intercity/mofussil routes across four Indian states	policy benefit, but environmental cost is not directly monetized in the TCO
Elango et al. [106]	CAPEX, subsidy, taxes/fees, fuel/electricity, annual mileage, financing, resale/salvage, maintenance, insurance, battery replacement	12 m buses: diesel, CNG, LNG, electric and hydrogen technologies; state-wise Indian TCO	Environmental externality cost is not directly included in TCO; study is primarily financial/ownership-cost based

4.7.1 Net Present Value (NPV)

Net Present Value (NPV) is a widely used financial evaluation tool that helps determine the economic feasibility of a project by comparing the present value of expected benefits with the present value of associated costs over its entire life cycle. It is based on the principle that money has a time value, meaning that cash flows occurring in the future are worth less than those occurring in the present. In the context of transportation projects, such as the adoption of electric buses, NPV provides a comprehensive measure to assess long-term financial viability. NPV considers all major cost components, including initial investment, operation and maintenance expenses, energy or fuel costs, and replacement costs, along with the expected benefits such as fuel savings, reduced maintenance, and potential environmental incentives. By discounting future cash flows to their present value, NPV enables a realistic comparison between conventional diesel buses and electric buses, which typically involve higher upfront costs but lower operating expenses. A positive NPV indicates that the total benefits outweigh the costs, suggesting that the investment is economically viable, while a negative NPV implies

the opposite. This method is particularly useful for long-term infrastructure and public transport projects, as it captures the overall financial impact over the project life. In this study project life considered is for 10years, NPV serves as a key indicator for evaluating the feasibility of fleet electrification and supports informed decision-making for sustainable transportation planning.

$$NPV = \sum_{t=1}^n \frac{C_t}{(1 + R)^t} - C_0$$

(Source: IRC: SP:30-2019)

$$FV = PV(1+r)^n$$

$$FV = 82,00,000 \times (1 + 0.08)^{10}$$

$$FV = 82,00,000 \times 2.1589$$

$$FV = ₹1,77,03,185$$

NPV = Net Present Value

C_t = Net cash inflow during the period t

R = Discount rate (rate of return)

Time period (in years) = 10 years

C₀ = Initial investment

Where:

FV = Future Value (₹)

PV = Present Value (₹)

r = Discount rate (in decimal)

n = Number of years

It considers the time value of money, meaning that cash received today is worth more than the same amount received in the future. For the three different scenarios—1) diesel-operated bus, 2) at depot where nearby charging facilities are available so in this scenario charging facilities cost are not taken into consideration (electric bus excluding charging station facilities), and 3) whereas at some depot charging facilities are not available therefore new infrastructure facilities are to be developed so in this scenario charging infrastructure cost are taken into consideration (electric bus including charging station facilities). Net Annual Cash Inflow (C_t) is the yearly profit a project generates after subtracting all operating, manpower, and maintenance costs from the total revenue.

Maintenance cost are treated as composite maintenance costs; therefore, the individual components such as Tyre, spare-parts and miscellaneous costs are not added separately to avoid double counting in the present study, manpower cost represents the expenditure associated with the personnel required for bus operation for 10-year project life. Therefore, the annual Maintenance cost is calculated using the total annual distance travelled by the bus. Maintenance cost for diesel bus is ₹5.78/km and for Ev-Bus is ₹4.5/km for daily distance 220km.

$$\text{Annual Maintenance Cost} = \left\{ \begin{array}{l} \bullet \text{ Daily Distance} \times \text{Operating Days per Year} \times \text{Maintenance Cost per days/year} \end{array} \right.$$

In the present study, revenue represents the annual income generated from passenger services. It is estimated based on the number of trips per day, passenger capacity per trip, fare per passenger, and operating days per year. On an average bus travels 200-250km/day so in present study 220km distance is considered. considering 4 trips/day, 38 passengers/trip for diesel operated and 38 passengers/trip for EV-bus, a fare of ₹75/passenger, and 365 operating days/year.

$$\text{Annual Revenue} = \left\{ \begin{array}{l} \bullet \text{ Trips/day} \times \text{Passengers/trip} \times \text{Fare/passenger} \times \text{Operating days/year} \end{array} \right.$$

Charging Infrastructure Revenue from the charging infrastructure was estimated by considering the electricity supplied to electric buses through the installed charging facilities. A charging fee of ₹10 per kWh was considered for estimating the revenue generated from the charging service.

For the financial analysis, it was assumed that the installed charging infrastructure would not operate at its full capacity throughout the year. Therefore, a 50% utilization factor was considered to account for variations in bus schedules, charging demand, operational

interruptions and periods of non-utilization. The annual charging revenue 50% of energy i.e., 350kwh/charger energy from fast charger installed was estimated using the following equation.

$$\text{Annual Charging Revenue} = \left\{ \begin{array}{l} \bullet \text{ Total Installed Fast Charger} \times \text{Operating Hours} \times \\ 365 \times \text{Utilization Factor} \times \text{Charging Fee} \end{array} \right.$$

The economic analysis for all fleet replacement scenarios was carried out on an annual operational basis. The annual operating costs, revenues, energy consumption, maintenance costs, and other recurring expenditures were estimated based on the annual vehicle distance travelled (80,300 km per bus per year). Table 4.18 shows the Total Initial Investment for the subsequent Net Present Value (NPV) and Internal Rate of Return (IRR) analyses. The comparison provides a comprehensive understanding of their long-term financial feasibility.

Table 4.18: Total Initial Investment for Scenario's

Fleet Electrification	Diesel Bus (Nos) @40 Lakh/Bu	EV Buses (Nos) @82 Lakh/Bus	Slow Chargers (Nos) @1.5Lakh/charger	Fast Chargers (Nos) @7.5Lakh/charger	Bus Investment (₹ Lakh)	Slow charger Investment (Lakh)	Fast charger Investment (Lakh)	Charging Infrastructure O&M (Transformer, connection, beaker, etc.)
10%	19	19	16	-	1,558.00	24.00	-	64.00
20%	38	38	16	4	3,116.00	24.00	30.00	64.00
30%	56	56	16	8	4,592.00	24.00	60.00	64.00

Table 4.19 presents the annual cash flow components considered for the financial evaluation of diesel and electric buses. The analysis incorporates annual revenue along with major operating expenses, including energy or fuel cost, maintenance cost, and

driver/staff cost, to estimate the net annual cash flow. These annual cash flows were subsequently used over the 10-year project life for the NPV and IRR analysis.

Table 4.19: Annual Cash Flow for NPV and IRR Analysis

Particular	Diesel Bus	Electric Bus	Calculation / Basis
Annual distance	80,300 km	80,300 km	365×220
Annual revenue/bus	₹40.15 L	₹40.15 L	$365 \times ₹75 \times 38 \text{ passengers} \times 4 \text{ (4trip/day)}$
Fuel/Energy cost	₹84/liter	₹4.50/kWh	-
Vehicle efficiency	5.8 km/liter	1.5 km/kWh	-
Annual fuel/energy consumption	13,845 liters	53,533 kWh	Distance ÷ mileage
Annual fuel/energy cost	₹11.63 L	₹2.41 L	Consumption × Rate
Maintenance cost	₹5.78/km	₹4.50/km	-
Annual maintenance cost	₹4.64 L	₹3.61 L	$80,300 \times \text{cost/km}$
Crew/driver cost	₹6.66 L/year	₹6.66 L/year	8.3₹/km
Total operating cost	₹22.93 L	₹12.68 L	Fuel cost+ Maintenance cost + Crew cost
Net operating revenue	₹17.22 L	₹27.47 L	Revenue – Operating cost

The Net Present Value (NPV) analysis was carried out to assess the long-term economic feasibility of diesel and electric bus deployment under different fleet electrification scenarios. The analysis considers the initial investment and the projected annual cash flows over the project life, discounted to their present value using the selected discount rate. The comparison of different replacement scenarios further demonstrates the economic impact of increasing the level of fleet electrification and the integration of charging infrastructure. Net Present Value for 3 different scenario 1) diesel-operated bus, 2) EV-bus excluding charging station facilities, 3) EV-bus including charging station facilities are shown in Table 4.20.

Table 4.20: Net Present Value Scenarios

Scenario	Fleet Replacement	Buses (No's)	Diesel-Bus NPV (Lakh)	EV-Bus with Charging NPV (Lakh)	EV-Bus without Charging (Lakh)
S1	10%	19	1,469	1,927	2,015
S2	20%	38	2,939	4,101	4,030
S3	30%	56	4,331	6,169	5,939

4.7.2 Internal Rate of Return (IRR)

Internal Rate of Return (IRR) is a financial metric used to estimate the profitability of potential investments. It represents the discount rate that makes the Net Present Value (NPV) of all future cash flows from an investment equal to zero. In simpler terms, IRR is the rate at which the investment breaks even where the total present value of benefits equals the total present value of costs. It provides a single percentage value that can be easily compared with the required rate of return or cost of capital to assess the attractiveness of a project. In the context of transportation and infrastructure projects, such as electric bus fleet electrification, IRR is particularly useful in comparing different investment alternatives. It helps decision-makers understand whether the long-term savings from reduced fuel consumption, lower maintenance costs, and environmental benefits justify the higher initial investment associated with electric buses. IRR also facilitates comparison between conventional diesel buses and electric buses under different operational scenarios. Internal Rate of Return for 3 different scenario 1) diesel-operated bus, 2) EV-bus excluding charging station facilities, 3) EV-bus including charging station facilities are shown in Table 4.21.

Table 4.21: Internal Rate of Return Scenarios

Scenario	Fleet Replacement	Buses (No's)	Diesel Bus IRR	EV-Bus with Charging IRR	EV-Bus without Charging IRR
S1	10%	19	41.87%	29.52	31.53%
S2	20%	38	41.87%	31.13%	31.53%
S3	30%	56	41.87%	31.68%	31.53%

4.8 Summary

This chapter presents the methods used for collecting and analyzing data for the study. Data was gathered from both primary sources, including field visits and interactions with depot officials, and secondary sources such as reports and published literature. The collected data was then processed and analyzed using appropriate tools and techniques to evaluate operational, environmental, and economic aspects of diesel and electric buses. The analysis provides a basis for assessing feasibility and supporting the study objectives. However, IRR should be used alongside other economic indicators such as NPV and Total Cost of Ownership (TCO) to ensure a comprehensive evaluation. In this study, IRR is used as a key parameter to assess the financial feasibility and investment potential of the proposed fleet electrification scenarios.

CHAPTER – 5

Results and Discussion

5.1 General

Replacing the GSRTC bus fleet with electric buses proved both environmentally beneficial and financially viable. The key outcomes for each objective are summarized below

5.2 Environmental and Operational Impact

Reducing reliance on diesel significantly decreased emissions and improved air quality.

Table 5.1 presents the reduction in vehicular emissions. When implementing 30% BS VI and E-Buses. Vehicular emissions value is taken from Table 4.14.

Table 5.1: Reduction in Vehicular Emissions by Adopting BS VI And EV

Pollutants	Vehicular Emission Bus-Bs IV (Tonne)	Vehicular Emission Bus-Bs VI (Tonne)	Reduction In Vehicular Emission by adopting 30% Bs VI-Bus (Tonne)	Reduction In Vehicular Emission by adopting E-Buses (Tonne)
CH ₄	0.00020	0.00000	0.00006	0.00006
SO ₂	0.00031	0.00000	0.00009	0.00009
HC	0.10135	0.02877	0.02177	0.03040
NOX	0.77100	0.08795	0.20491	0.23130
PM	0.00444	0.00229	0.00065	0.00133

Source: Computed by Author-Research Scholar

The results in Table 5.1 indicate that BS-IV buses produce the highest emissions for all pollutants, whereas BS-VI buses exhibit substantially lower emission levels due to improved emission control technologies and stricter Bharat Stage VI standards.

Figure 5.1 presents the comparative emission levels of BS-IV, BS-VI, and E-buses for the Kutch region. Electric buses show negligible tailpipe emissions, demonstrating their superior environmental performance during operation. The comparison clearly illustrates that replacing conventional BS-IV diesel buses with BS-VI and electric buses significantly reduces pollutant emissions, with the greatest environmental benefit achieved through complete electrification.

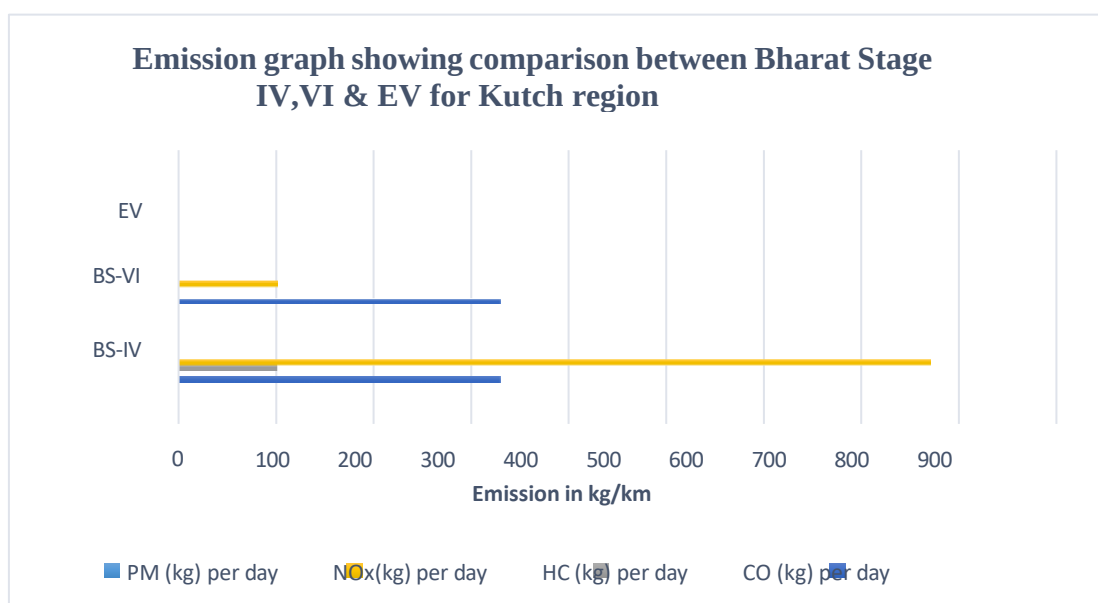


Figure 5.1: Vehicular Emission Difference between BS-VI, BS-IV & EV

The Figure highlights that the reduction is most pronounced for nitrogen oxides (NO_x), followed by hydrocarbons (HC), carbon monoxide (CO), and particulate matter (PM). Although BS-VI technology considerably reduces emissions compared with BS-IV buses, electric buses virtually eliminate tailpipe emissions during vehicle operation. This demonstrates that fleet electrification provides substantially greater environmental benefits than upgrading to cleaner diesel technologies alone, particularly in improving urban air quality and reducing transport-related emissions. Figure 5.2 illustrates the pollutant-wise variation in emissions among BS-IV, BS-VI, and electric buses. For eight

main bus depots, including Bhuj, Bhachau, Mandvi, Rapar, Mundra, Naliya, Anjar, and Nakhatrana of Kutch region the reduction in emission is plotted for each division resulting in good amount of reduction.

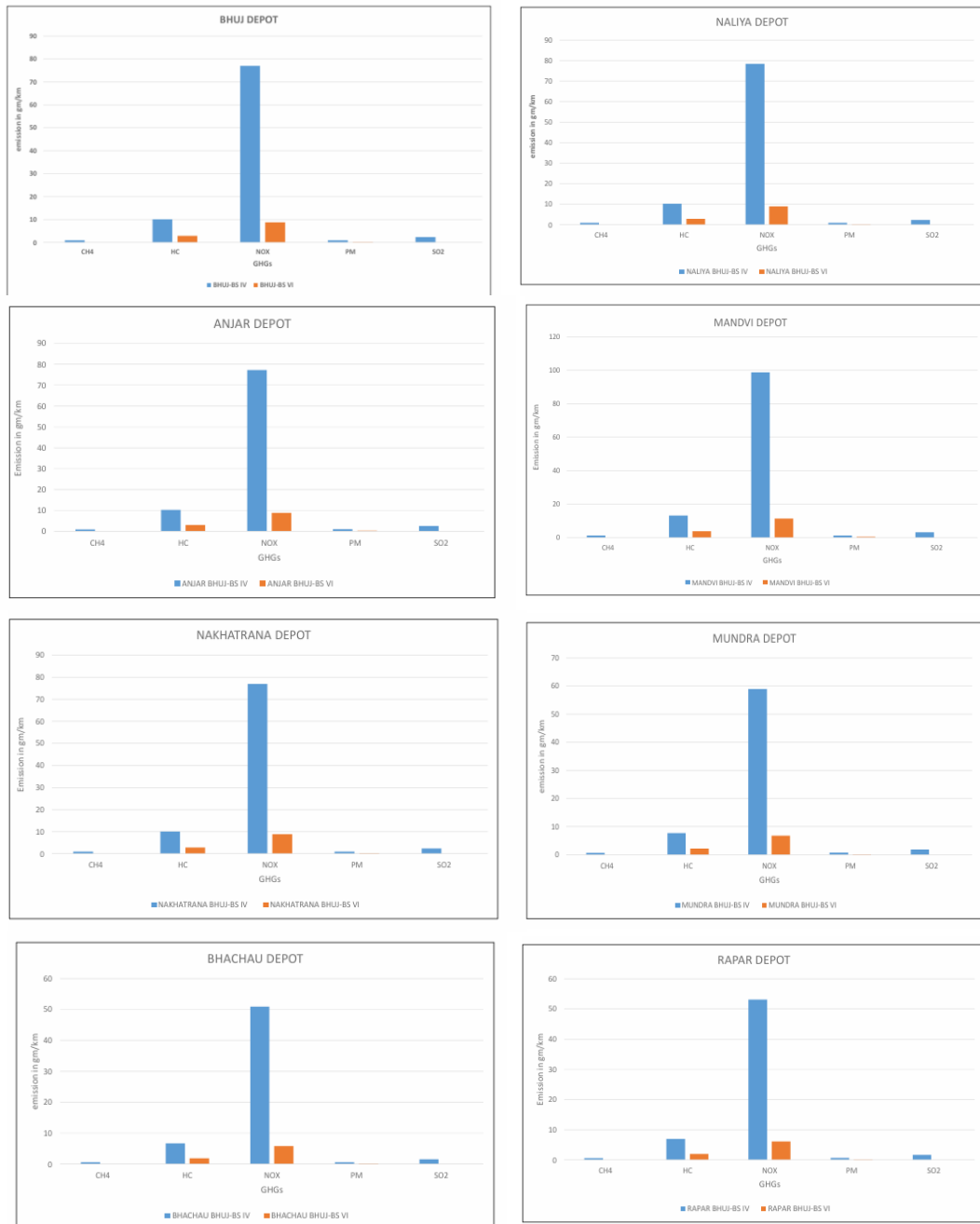


Figure 5.2: Vehicular Emission Comparison between BS IV & BS VI for Bhuj, Naliya, Mandvi, Nakhatrana, Mundra, Bhachau, and Rapar depot

The bus route was digitized in GIS format, enabling precise mapping and spatial analysis. Decreasing in colour shade shows reduction in emissions. For Kutch (GSRTC), by replacing 30% of BS IV buses with EVs leads to a significant reduction in vehicular emission. By this we can earn good amount of External Cost of Pollutant also.

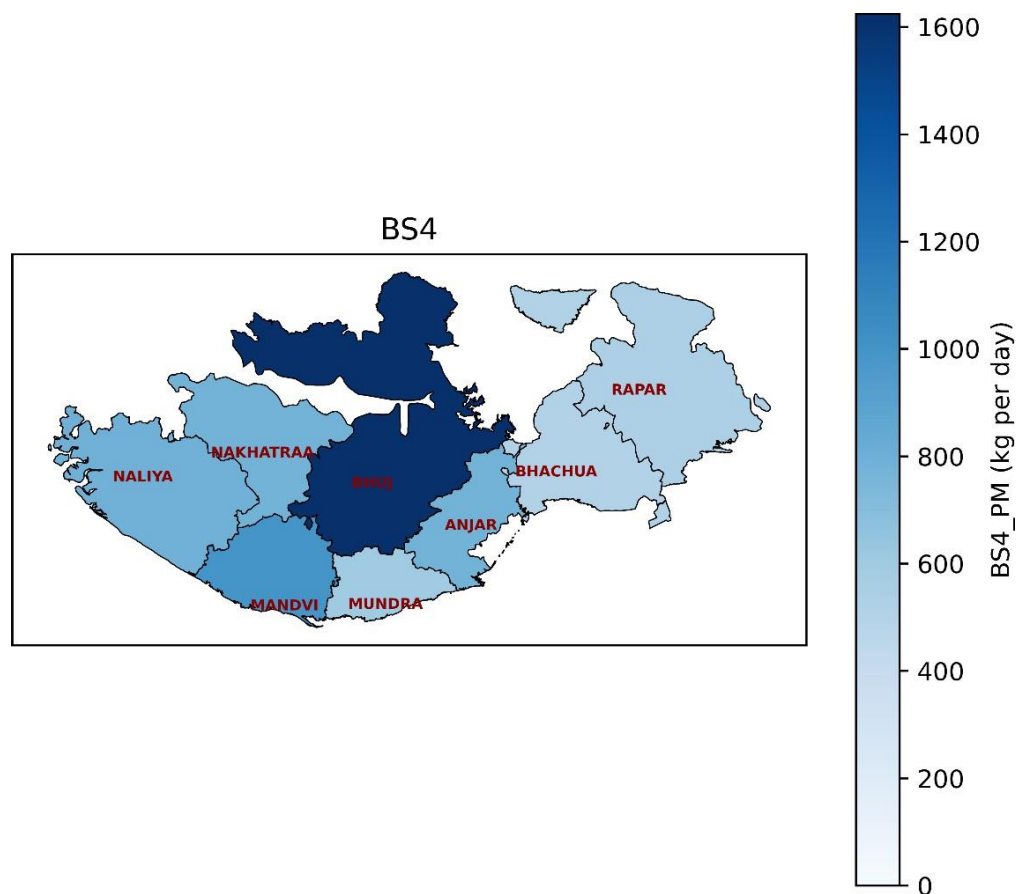


Fig no 5.3: Vehicular Emission for BS-VI

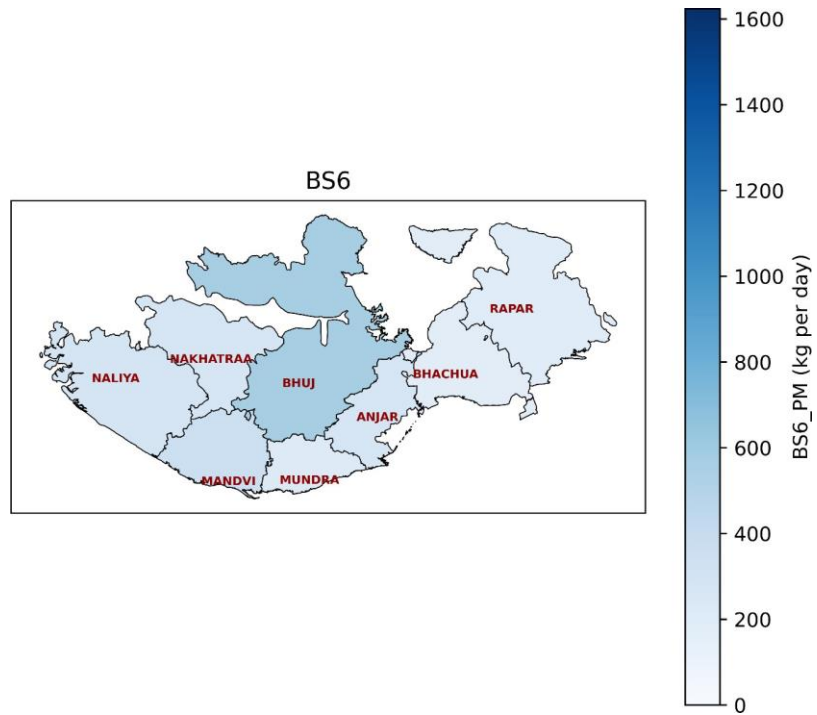


Fig no 5.4: Vehicular Emission for BS-IV

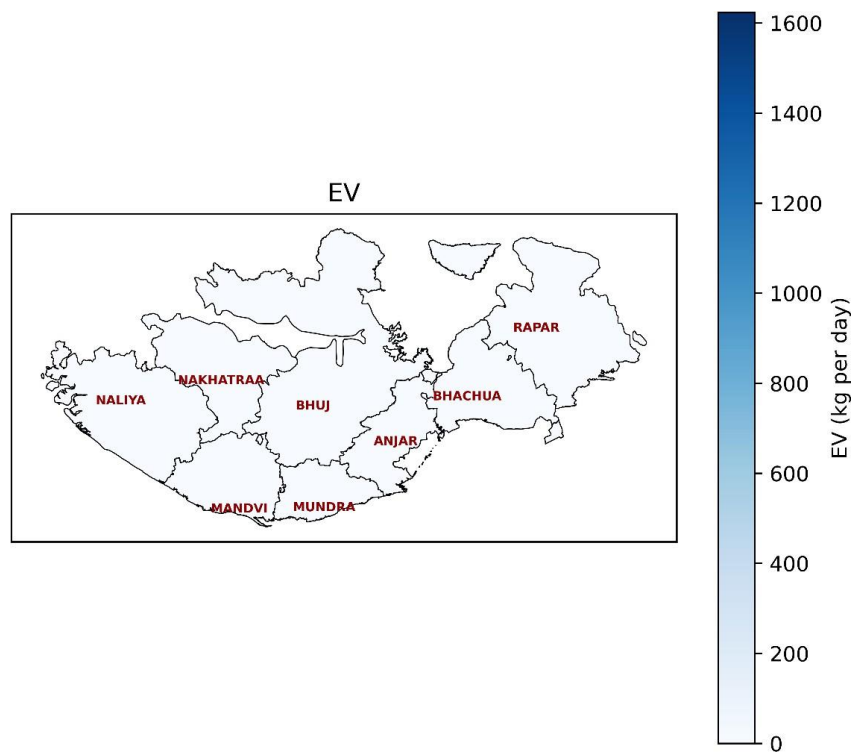


Fig no 5.5: Vehicular Emission for EV

5.3 Fleet Electrification Feasibility

The fleet electrification feasibility analysis was carried out to identify suitable vehicle and charging infrastructure options for future deployment. Based on technical, operational, and economic considerations, the study identified appropriate models that can effectively meet the requirements of the proposed system. The analysis concluded that the 38-seater electric bus is a viable option when compared with 35-seater capacity bus for fleet operations due to its suitability in terms of performance, capacity, and operational efficiency under the given conditions. In addition, the adoption of Bharat EV Charger standards, specifically AC-001 and DC-001, was found to be appropriate for supporting the charging needs of the fleet. These charging systems ensure compatibility, reliability, and ease of implementation within the existing infrastructure. Overall, the findings indicate that the selected combination of electric bus technology and standardized charging solutions provides a practical and sustainable approach toward successful fleet electrification.

5.4 Optimal Replacement Strategy

To successfully replace the fleet, the study established clear criteria for the buses and infrastructure. It was found that 119 buses out of 183 met the necessary state of charge (SoC) criteria in first screening, while in second screening 66 buses could be serviced by the required 30% (57 buses) based on a charging schedule. In QGIS software least energy required routes for EV-buses options highlighted in Kutch region.

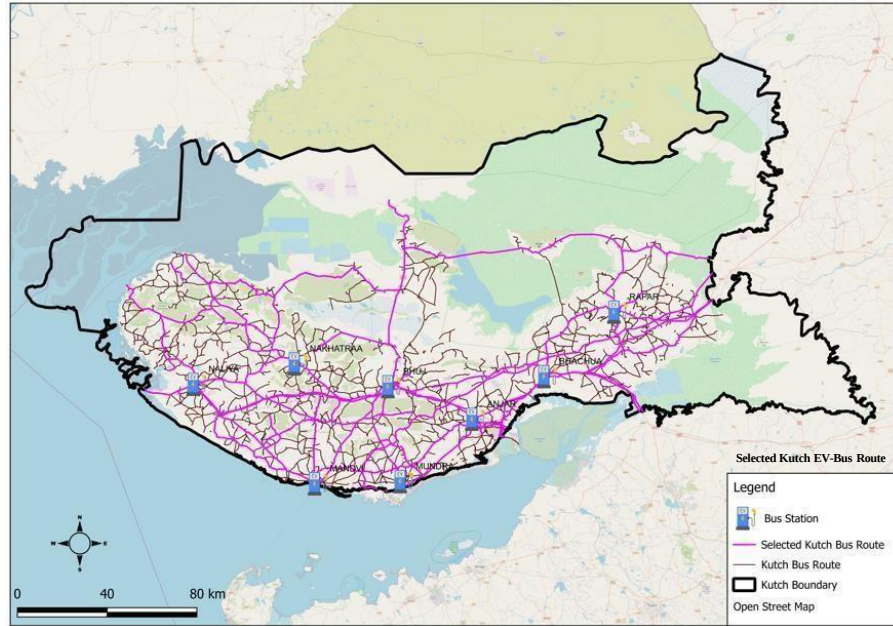


Figure 5.6: Selected 57 EV Bus Route Highlighted of Kutch Region

5.5 Economic Benefits

The Economic analysis revealed a stark contrast between the capital and operational expenditure profiles of diesel and electric bus fleets. The initial capital outlay for a conventional diesel bus was estimated at ₹40 lakhs. Applying an 08% discount rate over the projected 10-year service life, the Present Worth of Annual (PWA) expenses was calculated, with fuel and Operations & Maintenance (O&M) constituting the predominant cost drivers. The results demonstrate a clear increase in total life-cycle cost with increasing levels of fleet electrification, primarily due to the EV-with-charging scenario achieves NPV of EVs with charging infrastructure increases from ₹1,927 lakh to ₹6,169 lakh across the 10%–30% electrification scenarios. The corresponding IRRs are 29.52%, 31.13%, and 31.68%, compared with 41.87% for diesel buses and 31.53% for EVs without charging infrastructure. The NPV of diesel buses increases from ₹1,469 lakh to ₹4,331 lakh, while EVs without charging infrastructure increase from ₹2,015

lakh to ₹5,939 lakh across the respective scenarios. The capitalization cost represents the equivalent annual cost of the initial vehicle investment over its economic service life by considering the time value of money. In the present study, the annual capitalization cost was estimated using the Capital Recovery Factor (CRF) method, which converts the one-time capital investment into an equivalent uniform annual cost. This approach enables a fair comparison of vehicles with different initial purchase costs by expressing the capital investment on an annual basis.

The capitalization cost was determined using Equation below.

$$\begin{aligned}
 \text{Capitalization Cost} &= C \times \frac{i(1+i)^n}{(1+i)^n - 1} \\
 &= 82,00,000 \times \frac{0.08(1+0.08)^{10}}{(1+0.08)^{10} - 1} \\
 &= 82,00,000 \times \frac{0.08 \times (1.08)^{10}}{(1.08)^{10} - 1} \\
 &= 82,00,000 \times 0.14903 \\
 &= 12,21,246.26 \\
 \text{Capitalization Cost} &\approx \text{₹12,21,246/year}
 \end{aligned}$$

Where:

C = Initial Purchase Cost of the Vehicle (₹)

i = Discount Rate (decimal)

n = Life of the Vehicle (years)

source:

Panneerselvam, R. (2014).

Engineering Economics (2nd ed.).

Overall, the findings indicate that the integration of charging infrastructure enhances the financial attractiveness of fleet electrification. However, the cost structure diverges significantly. For diesel buses, the TCO is 32.01 Rs/km that is overwhelmingly dominated by recurrent variable costs, fuel, and maintenance financial exposure, which is projected to intensify with the volatile and rising price of diesel in the Indian market. In contrast, the TCO for electric buses is 31.00 Rs/km characterized by a high initial capital investment, which is subsequently offset by significantly lower operational and energy expenses over the vehicle's lifespan, illustrating a classic capital-for-operations expenditure trade-off that defines the adoption of new technology.

Table 5.2: Total Cost of Ownership

Description	Units	ICE Diesel Bus	e-Bus (Without Subsidy)	e-Bus (State Subsidy 50,00,000)
Bus size	meter	9	9	
Bus cost	Rs	40,00,000	60,00,000	
Battery cost	Rs	-	72,00,00	
Bus cost with Battery	Rs	-	1,32,00,000	82,00,000
Avg. kms run per day	kms/day	220	220	
Operational days per year	days/year	365	365	
Fuel consumption	liter/year	10,037.5	-	
	kWh/year	-	53,533	
Bus Capitalization Cost	Rs/year	5,96,120	19,67,196	12,21,246
Fuel cost	Rs/year	8,43,150 @ 84Rs/liter	2,40,900 @ 4.5 Rs/kWh	
Crew cost	Rs/year	6,66,490 @ 8.3 Rs/km	6,66,490 @ 8.3 Rs/km	
Bus maintenance cost	Rs/year	4,64,134 @ 5.78 Rs/km	3,61,350 @ 4.5 Rs/km	
Total Cost	Rs/year	25,69,894	32,35,936	24,89,986
Total Cost of Ownership	Rs/km	32.01	40.30	31.00

External Cost of Pollutant are calculated through projects that reduce or remove emissions. These projects include renewable energy installations (solar, wind, hydro), energy efficiency improvements, methane capture from landfills, reforestation and afforestation programs, and carbon capture and storage technologies. Each project must be verified by authorized agencies to ensure that the emission reductions are real, measurable, permanent. The benefits of External Cost of Pollutant include encouraging investment in clean energy, promoting sustainable development, creating green jobs, and providing financial support to developing countries for climate mitigation projects. However, challenges exist, such as

difficulties in accurate measurement, risk of double counting, concerns about transparency, and criticism that some companies use credits to avoid making real emission reductions. After summarizing External Cost of Pollutant value, for three decades External Cost of Pollutant is quantified and tabulated in table below. From Table 5.1 Vehicular Emission reduction values are multiplied with the external Cost tabulated in Table 4.3 to find 2001 and 2020 External Cost of Pollutant savings.

Table 5.3: External Cost Savings from Vehicular Emission

Pollutants	Reduction In Vehicular Emission by adopting 30% EV -Bus (Tonne)	External Cost Saving (2001) INR perTonne	External Cost Saving (2020) INR per Tonne
CH4	0.00006	1.050	3.006
SO2	0.00009	12.181	34.869
HC	0.03040	3162.047	9051.330
NOX	0.23130	42096.517	120500.817
PM	0.00133	372.175	1065.347
Total External Cost Savings		45,644	1,30,655

The variation in external cost estimates presented in Table 5.2 is attributable to the adoption of different reference years (2001 and 2020) for economic valuation rather than differences in pollutant emissions. The emission inventory was derived using a consistent methodology, incorporating identical operational data and pollutant-specific emission factors; consequently, the estimated emission quantities remain unchanged. The base-year values reported in the literature were subsequently updated to the respective reference years using recognized economic adjustment factors derived from official macroeconomic indicators. Therefore, the variation in total external costs reflects temporal changes in the economic valuation of environmental damages, while

the underlying pollutant emissions remain constant.

5.6 Summary

This chapter presents analysis results and discusses their implications for fleet electrification. Key parameters include cost, emissions, and feasibility indicators. The findings support the practicality of fleet electrification and provide valuable insights for sustainable public transportation decision-making.

CHAPTER – 6

Summary and Conclusion

6.1 General

This research on replacing the Gujarat State Road Transport Corporation (GSRTC) bus fleet with electric vehicles (EVs) across eight major depots in the Kutch region demonstrates that the transition is both environmentally sustainable and economically viable.

6.2 Conclusions

This study evaluates the feasibility of electrifying GSRTC's intercity bus operations in the Kutch region through route energy analysis, charging infrastructure planning, and economic assessment. The results provide a practical framework for optimizing EV fleet replacement, charging requirements, and overall sustainability of public bus transportation. Replacing 30% of GSRTC's BS-IV diesel buses with EVs leads to significant vehicular emission reductions and improved regional air quality, as confirmed by GIS-based spatial analysis. The 38-seater electric bus and Bharat EV Chargers (AC001 and DC001) were identified as optimal for fleet electrification, based on clear selection criteria. Operational analysis showed that 57 buses could function effectively under the 30% replacement strategy, optimizing energy use and scheduling as a maximum of 66 buses fulfil the predefined criteria, fleet replacement beyond 30% cannot be considered feasible under the present conditions, as a 40% replacement scenario would require 75 buses. The findings confirm that electrifying the GSRTC fleet is feasible, sustainable, and economically sound, aligning with Gujarat's green mobility and carbon reduction goals. Overall, the results indicate that electric buses offer better financial performance

than diesel buses despite their higher initial investment. The EV-with-charging scenario achieves IRRs of 29.52%, 31.13%, and 31.68% for 10%, 20%, and 30% electrification, respectively, compared with 41.84% for diesel buses and 31.53% for EVs without charging facilities. Thus, integrating charging infrastructure improves the financial attractiveness of fleet electrification. These findings indicate that the financial benefits of fleet electrification increase with higher levels of electric bus deployment, and that integrating charging infrastructure further improves project viability through additional revenue generation. Investing in electric buses with appropriate charging infrastructure ensures higher financial returns and long-term environmental and economic sustainability. Capital and operational expenditure profiles differ significantly. External Cost of Pollutant saving, for **2001** and **2020** the values are **45,644** and **1,30,655** respectively.

6.3 Recommendation

Based on the technical, economic and vehicular air pollutant emission assessment carried out in this study, the following recommendations are proposed for the electrification of intercity bus operations in the Kutch region.

❖ Priority-Based Fleet Replacement

Electric bus replacement should be carried out based on operational suitability and energy consumption rather than uniform replacement of the entire fleet. The study identified 119 buses meeting the initial SoC criterion, 66 buses shortlisted after further assessment, and 57 buses finally identified based on charging feasibility. Therefore, priority should be given to these identified buses/routes during the initial stage of electrification.

❖ Charging Infrastructure Development

Charging infrastructure should be developed according to the operational requirements

of the selected electric buses and depot characteristics. The required fast and slow charging facilities should be installed in accordance with applicable Bharat EV Charger standards, with adequate provision for reliable and timely charging. Charging infrastructure planning should be undertaken simultaneously with bus replacement to ensure uninterrupted operations.

❖ **Phased Fleet Electrification**

Fleet electrification should be implemented in a phased manner, beginning with buses identified as technically and operationally suitable. The evaluated 10%, 20% and 30% electrification scenarios provide alternative implementation levels for the transport agency. As a maximum of 66 buses fulfil the predefined criteria, fleet replacement beyond 30% cannot be considered feasible under the present conditions, as a 40% replacement scenario would require 75 buses.

❖ **Economic Planning for EV Adoption**

The economic results indicate that electric bus implementation is financially feasible under the evaluated conditions. Therefore, transport authorities should consider both the higher initial capital investment and the lower operating costs of electric buses when planning fleet replacement. The cost of charging infrastructure should also be incorporated into the overall financial planning for electrification. The EV-with-charging scenario achieves NPV of EVs with charging infrastructure increases from **₹1,927 lakh to ₹6,169 lakh** across the 10%–30% electrification scenarios. The corresponding IRRs are **29.52%, 31.13%, and 31.68%**, compared with **41.87% for diesel buses** and **31.53% for EVs without charging infrastructure**. The NPV of diesel buses increases from **₹1,469 lakh to ₹4,331 lakh**, while EVs without charging infrastructure increase from **₹2,015 lakh to ₹5,939 lakh** across the respective scenarios.

❖ **Consideration of Environmental Benefits**

The reduction in vehicular air pollutant emissions resulting from diesel-to-electric bus replacement should be considered along with economic performance when making fleet replacement decisions. Thus, the selection of buses for electrification should consider technical suitability, economic feasibility and potential emission reduction benefits rather than relying solely on the initial procurement cost. The proposed model can be applied to different cities in India for planning and evaluating electric bus deployment. It can be adapted to local transport conditions, fleet requirements, and charging infrastructure needs. Summarizing External Cost of Pollutant saving, for 2001 and 2020 the values are 45,644 and 1,30,655 respectively.

6.4 Applications of the Present Study

The findings of the present study provide practical guidance for the planning and implementation of bus fleet electrification in public transport systems. The developed guidelines integrate operational, economic, and environmental analyses, enabling transport authorities to make informed decisions regarding fleet replacement strategies based on local operational conditions. The phased fleet replacement approach (10%, 20%, and 30%) enables organizations to gradually transition towards electric mobility while considering financial constraints and infrastructure requirements. The Total Cost of Ownership (TCO) analysis developed in this study provides a practical tool for comparing diesel and electric buses over their operational life cycle assessment. Similarly, the financial evaluation using Net Present Value (NPV) and Internal Rate of Return (IRR) assists decision-makers in assessing the economic viability of electric bus investments under different replacement scenarios as presented in Table 4.20 and 4.21. The environmental assessment developed in this research can be used by transport

agencies and policy makers to estimate reductions in greenhouse gas emissions and air pollutant emissions resulting from fleet electrification as shown in Table 5.1. Such information is useful for preparing sustainable urban mobility plans, climate action strategies, and carbon emission reduction policies. Since the proposed methodology is based on operational data rather than region-specific assumptions, it can be adapted to other State Transport Undertakings (STUs) and public transport organizations across India by incorporating their respective operational characteristics. Therefore, the study provides a practical decision-support guidelines that an assist transport planner, government agencies, and policy makers in developing sustainable, economically viable, and environmentally responsible public transport systems.

6.5 Future Scope of Research

Future research may also investigate emerging battery technologies, vehicle-to-grid (V2G) integration, battery recycling strategies, and real-world battery degradation under Indian operating conditions to further improve the sustainability of electric public transport systems. Research could explore advanced optimization techniques and AI-based models for dynamic route planning, fleet management, and smart charging under variable demand. Developing battery performance models considering degradation and lifecycle analysis would offer deeper insights into long-term efficiency and costs. Expanding the study to multi-city or regional scales would enable comparative assessments under diverse geographical and traffic conditions. Additionally, evaluating policy frameworks, incentives, and carbon credit mechanisms can guide large-scale electric bus system implementation.

By increasing charging infrastructure at subsidiary depots, the percentage of fleet replacement can be progressively increased. The feasibility and impact of higher fleet

electrification levels through enhanced charging infrastructure may be further evaluated in future study.

References

- [1] Global Green Growth Institute and Center for Study of Science, Technology and Policy, "Electric Buses in India: Technology, Policy and Benefits," GGGI, Seoul, Republic of Korea, Tech. Rep., 2015.
- [2] E-Mobilizing India: Accelerating Sustainable Electric Mobility in Indian cities. ELECTRIC BUSES IN INDIA.; 2022.
- [3] Promoting Clean Energy Usage Through Accelerated Localization of E-Mobility Value Chain. 2022.
- [4] Krajačić, G., Duić, N., Zmijarević, Z., Mathiesen, B.V., Vučinić, A.A. and da Graça. Carvalho, M., 2011. Planning for a 100% independent energy system based on smart energy storage for integration of renewables and CO2 emissions reduction. *Applied thermal engineering*, 31(13), pp.2073-2083.
- [5] Blanford, G.J., Rose, S.K. and Tavoni, M., 2012. Baseline projections of energy and emissions in Asia. *Energy Economics*, 34, pp. S284-S292.
- [6] Steckel JC, Brecha RJ, Jakob M, Strefler J, Luderer G. Development without energy? Assessing future scenarios of energy consumption in developing countries. *Ecological Economics*. 2013; 90:53-67.
- [7] Gracceva F, Zeniewski P. A systemic approach to assessing energy security in a low-carbon EU energy system. *Appl Energy*. 2014;123.
- [8] Ji J, Bie Y, Zeng Z, Wang L. Trip energy consumption estimation for electric buses. *Communications in Transportation Research*. 2022; 2:100069.
- [9] Mehar S, Senouci SM, Remy G. EV planning: Electric vehicle itinerary planning. In: 2013 International Conference on Smart Communications in Network Technologies (saconet). IEEE; 2013:1-5.
- [10] Hecht C, Victor K, Zurmühlen S, Sauer DU. Electric vehicle route planning using

- real world charging infrastructure in Germany. *E-Transportation*. 2021; 10:100143.
- [11] Zhang Y, Ma Q, Zhang X, et al. Integrated Route and Charging Planning for Electric Vehicles Considering Nonlinear Charging Functions. In: *Proceedings of the 2018 IEEE 22nd International Conference on Computer Supported Cooperative Work in Design, CSCWD 2018*. Institute of Electrical and Electronics Engineers Inc.; 2018:207-212.
- [12] Zhou W, Wang L. The Energy-Efficient Dynamic Route Planning for Electric Vehicles. *J Adv Transp*. 2019; 2019:1-16.
- [13] Perger T, Auer H. Energy efficient route planning for electric vehicles with special consideration of the topography and battery lifetime. *Energy Efficient*. 2020;13(8):1705 1726.
- [14] Khandekar A, Rajagopal D, Abhyankar N, Deorah S, Phadke A, Berkeley L. The Case for All New City Buses in India to Be Electric Energy Technologies Area.; 2018.
- [15] Deb S, Tammi K, Kalita K, Mahanta P. Charging Station Placement for Electric Vehicles: A Case Study of Guwahati City, India. *IEEE Access*. 2019; 7:100270-100282.
- [16] Mathiesen BV, Lund H, Karlsson K. 100% Renewable energy systems, climate 30.
- [17] mitigation and economic growth. *Appl Energy*. 2011; 88 (2): 488-501. doi:10.1016/j. apenergy.2010.03.001.
- [18] Singh N, Mishra T, Banerjee R. Emission's inventory for road transport in India in 2020: Framework and post facto policy impact assessment. Published online 2021. doi:10.21203/rs.3.rs- 297185/v1.
- [19] Sheth A, Sarkar D. Social Benefit Cost Analysis of Electric Bus Transit for Ahmadabad. *Transportation in Developing Economies*. 2021;7(1). Doi:10.1007/s40890-021-00116-5.

- [20] Napitupulu, B., Ismiyati, I., & Handajani, M. (2018). Analysis of air pollution caused by mass transportation design changes. *MATEC Web of Conferences*, 195, 04021. doi.org/10.1051/matecconf/201819504021.
- [21] Ferrer, A. L. C., & Thomé, A. M. T. (2023). Carbon emissions in transportation: A synthesis framework. *Sustainability*, 15(11), 8475. doi.org/10.3390/su15118475.
- [22] Jing, Q.-L., Liu, H.-Z., Yu, W.-Q., & He, X. (2022). The impact of public transportation on carbon emissions—From the perspective of energy consumption. *Sustainability*, 14(10), 6248. doi.org/10.3390/su14106248.
- [23] Brohi, S. N., Pillai, T. R., Asirvatham, D., Ludlow, D., & Bushell, J. (2018). Towards smart cities development: A study of public transport system and traffic-related air pollutants in Malaysia. *IOP Conference Series: Earth and Environmental Science*, 167, 012015. doi.org/10.1088/1755- 1315/167/1/012015.
- [24] Dey, S., & Mehta, N. S. (2020). Automobile pollution control using catalysis. *Resources, Environment and Sustainability*, 2, 100006. doi. Org/ 10.1016/j.resenv.2020.100006.
- [25] Singh, N., Mishra, T., & Banerjee, R. (2021). Emissions inventory for road transport in India in 2020: Framework and post facto policy impact assessment. Preprint. doi.org/10.21203/rs.3.rs- 297185/v1.
- [26] Manzolli, J. A., Trovão, J. P., & Antunes, C. H. (2022). A review of electric bus vehicles research topics – Methods and trends. *Renewable and Sustainable Energy Reviews*, 159, 112211. doi.org/10.1016/j.rser.2022.112211.
- [27] Fabianová, J., & Janekova, J. (2021). Assessment of investment in electric buses: A case study of a public transport company. *Open Engineering*, 11(1), 907–914. doi.org/10.1515/eng-2021-0089
- [28] Fabianová, J., & Janekova, J. (2022). Economic assessment of investment in electric buses and CNG buses – A case study of a public transport company. *Advances in Science and Technology Research Journal*, 16(4), 96–105.

doi.org/10.12913/22998624/151801.

- [29] Johnson, C., Nobler, E., Eudy, L., & Jeffers, M. (2020). Financial analysis of battery electric transit buses. National Renewable Energy Laboratory.
- [30] Nordelöf, A., Romare, M., & Tivander, J. (2019). Life cycle assessment of city buses powered by electricity, hydrogenated vegetable oil or diesel. *Transportation Research Part D: Transport and Environment*, 75, 211–222. doi.org/10.1016/j.trd.2019.08.019.
- [31] Holland, S. P., Mansur, E. T., Muller, N. Z., & Yates, A. J. (2021). The environmental benefits of transportation electrification: Urban buses. *Energy Policy*, 148, 111921. doi.org/10.1016/j.enpol.2020.111921.
- [32] Matthews, B.H.S., Hendrickson, C. Horvath, A., 2001. External Costs of Air Emissions from Transportation. *Journal of Infrastructure Systems*, Volume 7(1), pp. 13–17.
- [33] Mohandas, P. (2018). Sustainable development goals (SDGs) — Challenges for India. *Indian Journal of Public Health Research & Development*, 9(3), 1.
- [34] Raman, R., Nair, V. K., Lathabai, H. H., & Nedungadi, P. (2025). Research on sustainable development in India: Growth, key themes and challenges. *Social Sciences & Humanities Open*, 11, 101637.
- [35] Green Growth and Sustainable Development in India Towards the 2030, Development Agenda Global green growth institute and center for study of science, technology and policy 2015.
- [36] Ministry of Environment, Forest, and Climate Change (MoEFCC). (2015). First Biennial Update Report to the UNFCCC. Government of India.
- [37] World Bank. (2020). Carbon Pricing Dashboard: Global Carbon Pricing Trends. www.carbonpricingdashboard.worldbank.org
- [38] Commission for Air Quality Management (CAQM). (2020). Indian Air Pollution

- Control Policies. Government of India. www.caqm.nic.in
- [39] International Energy Agency (IEA). (2020). Air Quality and Emission Regulations in India. www.iea.org
- [40] The Energy and Resources Institute (TERI). (2020). Industrial Emission Norms & Carbon Market Mechanisms in India. www.teriin.org
- [41] www.irena.org//media/Files/IRENA/Agency/Publication/2024/Mar/IRENA_RE_Capacity_Statistics_2024.pdf
- [42] International Energy Agency. (2024). Global EV Outlook 2024. IEA. <https://www.iea.org/reports/global-ev-outlook-2024>.
- [43] WCED 1987, report of the world commission on environment and development: our common future, http://www.un-document.net/our_common_future.pdf accessed on 18-04-2026
- [44] **Gowande, B. (2025).** *Electrifying India's buses: Insights from public deployment and case study of private intercity operators*. International Council on Clean Transportation (ICCT).
- [45] IRENA 2025 Renewable capacity highlights, www.irena.org
- [46] MOSPI 2025 Energy statistics India 2025_27031015.pdf
- [47] NITI AAYOG 2025 Unlocking a \$200 billion opportunity: electric vehicles in India www.nitiayog.in/Electric-vehicle-
- [48] ITF 2025 Life cycle assessment of passenger transport – an Indian case study – world bank
- [49] MORTH 2006 National urban transport policy
- [50] MOUD 2014 National urban transport policy
- [51] MOPNG 2018 National policy of biofuel 2018 www.mopng.in

- [52] EPD (2009, 2021, 2025) Gujarat integral renewable energy policy
- [53] SECI 2010 solar energy corporation of India
- [54] 1517017 Part-1 :2018 Electric vehicle conductive charging system, Bureau of Indian standards, new Delhi- 110002
- [55] 1517017 Part-23 :2021 Electric vehicle conductive charging system part 23, dc electric vehicle supply, Bureau of Indian standards, New Delhi- 110002
- [56] NITI AAYOG-2023 Handbook of electric vehicle charging infrastructure implementation_version-1, http://www.gov.in/sites/default/sites/2023-02/EV_Handbook_find_14oct.pdf
- [57] Automotive Research Association of India (ARAI). Vehicle Testing, Certification and Standardisation. Pune, India.
- [58] Ministry of Power, Government of India, Guidelines for Installation and Operation of Electric Vehicle Charging Infrastructure–2024, New Delhi, 2024.
- [59] Jain, S., & Rankavat, S. (2023). Analysing driving factors of India's transportation sector CO₂ emissions: Based on LMDI decomposition method. *Heliyon*, 9(9), e19871. <https://doi.org/10.1016/j.heliyon.2023.e19871>.
- [60] Loo, B. P. Y., Li, L., & Namdeo, A. (2023). Reducing road transport emissions for climate policy in China and India. *Transportation Research Part D: Transport and Environment*, 122, 103895. <https://doi.org/10.1016/j.trd.2023.103895>.
- [61] Winkler, L., Pearce, D., Nelson, J., & Babacan, O. (2023). The effect of sustainable mobility transition policies on cumulative urban transport emissions and energy demand. *Nature Communications*, 14, 2357. <https://doi.org/10.1038/s41467-023-37728-x>.

- [62] Speizer, S., Fuhrman, J., Aldrete Lopez, L., George, M., Kyle, P., Monteith, S., & McJeon, H. (2024). Integrated assessment modeling of a zero-emissions global transportation sector. *Nature Communications*, 15, 4439. <https://doi.org/10.1038/s41467-024-48424-9>.
- [63] Zhang, W., Li, Y., Li, H., Liu, S., Zhang, J., & Kong, Y. (2024). Systematic review of life cycle assessments on carbon emissions in the transportation system. *Environmental Impact Assessment Review*, 109, 107618. <https://doi.org/10.1016/j.eiar.2024.107618>. (National Assembly Library)
- [64] Ling, C., Tang, J., Zhao, P., Xu, L., Lu, Q., Yang, L., Huang, F., Lyu, W., & Yang, J. (2024). Unraveling the relation between carbon emission and carbon footprint: A literature review and framework for sustainable transportation. *npj Sustainable Mobility and Transport*, 1, 13. <https://doi.org/10.1038/s44333-024-00013-5>.
- [65] Horeh, N., & Quinn, J. C. (2024). Fuel shifts reduce most of the greenhouse gas emissions from transportation in the United States. *Communications Earth & Environment*, 5, 781. <https://doi.org/10.1038/s43247-024-01924-4>.
- [66] Peng, H., Sun, Y., Hao, J., An, C., & Lyu, L. (2024). Carbon emissions trading in ground transportation: Status quo, policy analysis, and outlook. *Transportation Research Part D: Transport and Environment*, 131, 104225. <https://doi.org/10.1016/j.trd.2024.104225>.
- [67] Martinez, S. S., & Samaras, C. (2024). Electrification of transit buses in the United States reduces greenhouse gas emissions. *Environmental Science & Technology*, 58(9), 4137–4144. <https://doi.org/10.1021/acs.est.2c07296>.

- [68] Slimi, K., Chrouda, A., & Öztop, H. F. (2026). Traffic effects on global warming: A review. *Renewable and Sustainable Energy Reviews*, 226, 116248. <https://doi.org/10.1016/j.rser.2025.116248>.
- [69] Gairola, P., & Nezamuddin, N. (2023). Design of battery electric bus system considering waiting time limitations. *Transportation Research Record*, 2677(2), 1415–1430. <https://doi.org/10.1177/03611981221113321>.
- [70] Zhou, Y., Ong, G. P., & Meng, Q. (2023). The road to electrification: Bus fleet replacement strategies. *Applied Energy*, 337, 120903. <https://doi.org/10.1016/j.apenergy.2023.120903>.
- [71] Hendriks, J. N., & Sturmberg, B. C. P. (2024). An integrated model of electric bus energy consumption and optimised depot charging. *npj Sustainable Mobility and Transport*, 1, 10. <https://doi.org/10.1038/s44333-024-00008-2>.
- [72] Ye, Z., Huang, Z., Yang, S., Du, Y., & Zhao, H. (2024). Electric bus fleet transition: Assessment approach considering economic and environmental impacts, and its application. *Smart Construction and Sustainable Cities*, 2, 17. <https://doi.org/10.1007/s44268-024-00040-8>.
- [73] Varghese, A. M., & Pradhan, R. P. (2025). Roadmap for transitioning India's privately owned bus fleets to electric fleets. *Transportation Research Part D: Transport and Environment*, 140, 104623. <https://doi.org/10.1016/j.trd.2025.104623>.
- [74] Varghese, A. M., & Pradhan, R. P. (2025). A comprehensive review and research agenda on the adoption, transition, and procurement of electric bus technologies into public transportation. *Sustainable Energy Technologies and Assessments*, 75, 104218. <https://doi.org/10.1016/j.seta.2025.104218>.

- [75] Othman, K., Shalaby, A., & Abdulhai, B. (2025). Route selection guidelines and prioritization tools for efficient electrification of bus fleets. *npj Sustainable Mobility and Transport*, 2, 30. <https://doi.org/10.1038/s44333-025-00048-2>.
- [76] Naeimian, B., Mohseni, G., Barzegari, V., Nourinejad, M., & Park, P. Y. (2025). Public transportation fleet electrification and charger schedule optimization using a decomposition heuristic. *Energy*, 333, 137135. <https://doi.org/10.1016/j.energy.2025.137135>.
- [77] Callegari, C., Oliveira, R., Cunha, B. S. L., Cruz, T., Fiorini, A. C., Schaeffer, R., & Szklo, A. (2025). Battery electric buses in emerging markets and developing economies: A pathway for a just energy transition. *Energy for Sustainable Development*, 85, 101678. <https://doi.org/10.1016/j.esd.2025.101678>.
- [78] Kumar, U., & Upadhyay, R. K. (2026). Electrification of public transport buses in the city of Ahmedabad: Policy framework and strategy for adoption. *Sustainability*, 18(2), 1057. <https://doi.org/10.3390/su18021057>. (MDPI)
- [79] Grauers, A., Borén, S., & Enerbäck, O. (2020). Total cost of ownership model and significant cost parameters for the design of electric bus systems. *Energies*, 13(12), 3262. <https://doi.org/10.3390/en13123262>.
- [80] Say, K., Csereklyei, Z., Brown, F. G., & Wang, C. (2023). The economics of public transport electrification: A case study from Victoria, Australia. *Energy Economics*, 120, 106599. <https://doi.org/10.1016/j.eneco.2023.106599>.
- [81] Abdelouahed, A., Berrada, A., & El Mrabet, R. (2024). Techno-economic study for the implementation of electric buses for sustainable urban and interurban

- transportation. *Environmental Progress & Sustainable Energy*, 43(1), e14278.
<https://doi.org/10.1002/ep.14278>. (DOI)
- [82] Pei, M., Hu, Y., Han, W., Qu, X., & Zou, C. (2024). Life-cycle analysis of economic and environmental effects for electric bus transit systems. *Transportation Research Part D: Transport and Environment*, 131, 104205.
<https://doi.org/10.1016/j.trd.2024.104205>. (ScienceDirect)
- [83] Razy-Yanuv, M., & Meron, N. (2024). Early transition to cleaner bus fleets: Benefits, costs, and policy evaluation of alternatives from a life cycle perspective. *Cleaner Environmental Systems*, 12, 100172.
<https://doi.org/10.1016/j.cesys.2024.100172>.
- [84] Sistig, H. M., Sinhuber, P., Rogge, M., & Sauer, D. U. (2025). Evaluating costs and operations of public bus fleet electrification. *npj Sustainable Mobility and Transport*, 2, 15. <https://doi.org/10.1038/s44333-025-00030-y>. (Nature)
- [85] McCluskey, J., Larkin, C., & Druitt, T. (2025). Charging forward: How bus availability drives the economics of fleet electrification. *Case Studies on Transport Policy*, 22, 101616. <https://doi.org/10.1016/j.cstp.2025.101616>.
- [86] Ghotge, R., van Rooij, D., & van Breukelen, S. (2025). Total cost of ownership of electric buses in Europe. *World Electric Vehicle Journal*, 16(8), 464.
<https://doi.org/10.3390/wevj16080464>.
- [87] Tripathi, S., Gorbatenko, I., Garcia, A., & Sarathy, S. M. (2025). Life cycle environmental and cost impacts of bus transit networks: A real drive cycle evaluation of different powertrains. *Energy Conversion and Management*, 326, 119459. <https://doi.org/10.1016/j.enconman.2024.119459>. (ScienceDirect)

- [88] Chong, J. W., & Hanafiah, M. M. (2026). Life cycle externalities and abatement costs of public transport electrification using fuel cell and battery electric buses in Putrajaya city. *Scientific Reports*, 16, 15312. <https://doi.org/10.1038/s41598-026-46665-w>.
- [89] Sheth, A., & Sarkar, D. (2019). Life cycle cost analysis for electric vs. diesel bus transit in an Indian scenario. *International Journal of Technology*, 10(1), 105–115. <https://doi.org/10.14716/ijtech.v10i1.1958>
- [90] Majumder, S., De, K., Kumar, P., Sengupta, B., & Biswas, P. K. (2021). Techno-commercial analysis of sustainable E-bus-based public transit systems: An Indian case study. *Renewable and Sustainable Energy Reviews*, 144, 111033. <https://doi.org/10.1016/j.rser.2021.111033>
- [91] World Bank. (2026). *World Development Indicators: GDP deflator: linked series (base year varies by country)*. World Bank. Retrieved August 19, 2026.
- [92] IRC:SP:30-2019, *Manual on Economic Evaluation of Highway Projects in India*, Third Revision, Indian Roads Congress, New Delhi.
- [93] Sheth A, Sarkar D. Life Cycle Cost Analysis for Electric vs. Diesel Bus Transit in an Indian Scenario. *International Journal of Technology*. 2019;10(1):105–115. doi:10.14716/ijtech.v10i1.1958.
- [94] **Times of India. (2024, September 14).** How MG Windsor’s EV battery subscription works: BaaS explained. *The Times of India*. <https://timesofindia.indiatimes.com/auto/cars/how-mg-windsors-ev-battery-subscription-works-baas-explained/articleshow/113346020>

- [95] **Ministry of Road Transport and Highways. (2025).** *Annual report 2024–25.* Government of India. <https://morth.nic.in/sites/default/files/Annual-Report-English-with-Cover.pdf>
- [96] **Ministry of Heavy Industries. (2024, August 9).** Production of e-buses. *Press Information Bureau, Government of India.* <https://www.pib.gov.in/Pressreleaseshare.aspx?PRID=2043645>
- [97] **Economic Times. (2024, January 13).** Indians travelled an impressive 4.1 crore km daily, as redBus report unveils travel metrics. *The Economic Times.* <https://travel.economictimes.indiatimes.com/news/research-and-statistics/figures/indians-travelled-an-impressive-4-1-crore-km-daily-as-redbus-report-unveils-travel-metrics/106815324>

List of Publications

- 1) Prajapati, M. L., Gundaliya, P. J., & Sheth, A. (2020). Case study: Solar electric vehicles in India. IOP Conference Series: Materials Science and Engineering, 937(1), 012033. IOP Publishing. <https://doi.org/10.1088/1757-899X/937/1/012033>
- 2) Prajapati, M. L., Maheshwari, K., & Tanwar, G. (2022). Fleet electrification planning for Anjar city. Civil Engineering Department, Tolani F. G. Polytechnic, India.
- 3) Prajapati, M. L., & Desai, N. A. (2024). Exploring cost effective fleet electrification possibilities for public transit services in Kutch region. Current World Environment, 19(1), 1–15. Enviro Research Publishers. <https://www.cwejournal.or>

Appendix A

External Cost Values Using the GDP Deflator

Methodology

The baseline external cost values for 2001 were adopted from Sheth and Sarkar (2019), based on Matthews et al. (2001). To express these values in 2010 and 2020 price levels, the GDP Deflator (linked series) for India published by the World Bank was used.

Equation:

$$EC_t = EC_{2001} \times \frac{GDPD_t}{GDPD_{2001}}$$

Where:

EC_t = External cost in year t (₹/tonne)

EC_{2001} = Baseline external cost in 2001 (₹/tonne)

$GDPD_t$ = GDP Deflator Index for the target year

$GDPD_{2001}$ = GDP Deflator Index for 2001 GDP Deflator Values (India)

Year	GDP Deflator Index
2001	30.686725
2010	55.285502
2020	87.149956

Worked Example (CO)

2001 external cost = ₹33,800/tonne

2010 = $33,800 \times (55.285502/30.686725) = ₹60,894/\text{tonne}$

2020 = $33,800 \times (87.149956/30.686725) = ₹95,992/\text{tonne}$

Final External Cost Table

Pollutant	2001	2010	2020
CO	33,800	60,894	95,992
HC	104,000	187,367	295,359
NO _x	182,000	327,893	516,878
CO ₂	845	1,522	2,400
PM	279,500	503,550	793,777
SO ₂	130,000	234,209	369,199

Source: Sheth & Sarkar (2019) based on Matthews et al. (2001); World Bank, World Development Indicators, GDP Deflator: linked series (Indicator NY.GDP.DEFL.ZS.AD), India.

Appendix B

Bus Route Data

FORM NO. 4 LOCAL SERVICE BHUJ DEPOT									
VH. SCH. NO.	CREW NO.	TRIP NO	TRIP NAME	DISTANCE	DEPARTURE TIME	ARRIVAL TIME	SERVICE TYPE		VIA HALT DETAILS
1	2	3	4	4	5	6	7	8	9
34	36	0	DUNGRANIVANDH - BHUJ	252.40	5.25	12.20	LOC	GEN	N
37	2	2	BHUJ - DUNGRANIVANDH	244.00	13.30	20.25	LOC	GEN	
32	38	1	EKALMATA - RAPAR	36.90	5.15	6.15	S.P.LOC	SP	N
		2	RAPAR - BHUJ	150.00	6.20	10.35	LOC	GEN	
		3	BHUJ - MADHAPAR - BHUJ	13.00	10.45	11.10	LOC	SP	
39	4	4	BHUJ - RAPAR	150.00	12.30	16.45	LOC	GEN	
		5	RAPAR - NALITYATIMBO	24.96	17.00	17.40	S.P.LOC	SP	
		6	NALITYA TIMBO - RAPAR	24.96	17.45	18.15	LOC	OPN	
		7	RAPAR - EKALMATA	36.90	18.45	19.45	LOC	OPN	
33	40	1	MAMNUAARA - BHUJ	30.60	6.35	7.25	S.P.LOC	SP	N
		2	BHUJ - MUNORA	59.00	7.30	9.00	LOC	GEN	
		3	MUNORA - BHUJ	59.00	9.05	10.35	LOC	GEN	
		4	BHUJ - H.J.D. - BHUJ	57.90	10.45	12.20	S.P.LOC	SP	
41	5	5	BHUJ - SANOSARA - BHUJ	55.52	13.15	14.50	S.P.LOC	SP	
		6	BHUJ - KHAVIDA	72.60	15.45	17.40	LOC	GEN	
		7	KHAVIDA - BHUJ	72.60	18.00	19.55	LOC	GEN	
		8	BHUJ - MAMNUARA	30.60	20.00	20.50	S.P.LOC	OPN	
34	42	1	LATHEDI - BHUJ	109.12	5.30	8.15	LOC	TPL	N
		2	BHUJ - RAMANIYA - GELADA	50.30	9.15	10.35	LOC	GEN	
		3	GELADA - RAMANIYA - BHUJ	50.30	10.40	12.00	LOC	GEN	

Appendix C

Ev-Bus charging scheduling

TIMING	MUNDRA		MANDVI		NALIYA		NAKHTRANA		RAPAR		ANJAR		BHACHAU		BHUI		
	charger1	charger2	charger1	charger2	charger1	charger2	charger1	charger2	charger1	charger2	charger1	charger2	charger1	charger2	charger1	charger2	charer 3
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Route Energy	1380 kwh	1260 kwh	840 kwh	300 kwh	600 kwh	600 kwh	720 kwh	420 kwh	780 kwh	420 kwh	840 kwh	660 kwh	1500 kwh	1380 kwh	2340 kwh	2100 kwh	1480 kwh

