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Decarbonizing EU's Public Transport Sector
Bridging Stakeholder Objectives and Emerging Technologies

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Front Matter

Abstract

Diese Masterarbeit untersucht strategische Pfade zur Dekarbonisierung des öffentlichen Busverkehrs in der Europäischen Union. Aufbauend auf der Design-Science-Research-Methodologie wird ein analytischer Rahmen entwickelt, der technologische Optionen mit den Zielkonflikten und Handlungslogiken zentraler Akteursgruppen – EU-Politik, öffentliche Verkehrsbetreiber und Fahrzeughersteller – systematisch verknüpft.

Kapitel 5 analysiert die divergierenden Interessenlagen der Stakeholder und bildet die Grundlage für die anschließende techno-ökonomische Bewertung emissionsfreier Antriebstechnologien in Kapitel 6. Die Ergebnisse zeigen, dass batterieelektrische Busse (BEBs) im europäischen Kontext derzeit die höchste Zielkongruenz aufweisen. Sie reduzieren die CO_2-Emissionen über einen Zeitraum von 50 Jahren um über 70 % und erzielen – unter Berücksichtigung realistischer CO_2-Preisverläufe – deutliche ökonomische Vorteile gegenüber Dieselbussen.

Demgegenüber erfüllen wasserstoffbetriebene Busse zentrale Zielkriterien nicht simultan und weisen eine ungünstigere Kosten- und Energieeffizienzstruktur auf. Die modellierte schrittweise Elektrifizierung – etwa durch jährlichen Austausch von 10 % der Flotte – reduziert Investitionsrisiken und erlaubt haushaltskompatible Übergangspfade.

Eine ergänzende Sensitivitätsanalyse untersucht die Auswirkungen unterschiedlicher CO_2-Preisentwicklungen, Diskontierungszinssätze und Elektrifizierungsraten in 27 Szenarien. Sie zeigt, dass die Vorteilhaftigkeit von BEBs auch unter konservativen Annahmen erhalten bleibt – insbesondere bei schneller Elektrifizierung und ambitionierter CO_2-Bepreisung. Darüber hinaus wurde in einem separaten Kapitel eine jährliche Dieselpreiserhöhung von 1 % modelliert. Die Ergebnisse verdeutlichen, dass steigende fossile Brennstoffkosten die Wettbewerbsfähigkeit von BEBs zusätzlich stärken und ihre langfristige ökonomische Resilienz unter realistischen Marktbedingungen untermauern.

Auf dieser Basis formuliert die Arbeit praxisorientierte Handlungsempfehlungen für Politik, Betreiber und Industrie. Sie betont die Bedeutung regulatorischer Klarheit, zielgerichteter CO_2-Bepreisung, technikkompatibler Förderinstrumente und skalierbarer Beschaffungsstrategien. Damit leistet die Studie einen evidenzbasierten Beitrag zur strategischen Ausgestaltung resilienter Dekarbonisierungspfade im öffentlichen Verkehr.

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Symbol	Description	Unit
C_A	Acquisition cost per vehicle	€
C_F	Energy cost per kilometer	$\frac{€}{km}$
C_I	Infrastructure cost per kilometre	$\frac{€}{km}$
C_M	Maintenance cost per kilometre	$\frac{€}{km}$
C_T	Total cost	€
D_a	Annual mileage per bus	km
E_{TTW}	Tank-to-Wheel emissions (direct use-phase emissions)	$\frac{g\ CO_2}{km}$
E_{WTT}	Well-to-Tank emissions (upstream energy production)	$\frac{g\ CO_2}{km}$
E_{WTW}	Well-to-Wheel emissions (total lifecycle emissions)	$\frac{g\ CO_2}{km}$
i	Discount rate	10^{-2}
n	Total number of buses	-
$n_{\mathrm{BEB},0}$	Initial number of battery-electric buses	-
$p(t)$	Share of zero-emission buses in year t	-
$r_{CO_2}(t)$	CO_2 price in year t	$\frac{€}{t\ CO_2}$
R	Residual value of the vehicle	€
t	Time Index	years
TCO	Total Cost of Ownership	€

List of Abbreviations

Abbreviation	Meaning
ACEA	European Automobile Manufacturers' Association
AFIR	Alternative Fuels Infrastructure Regulation
BEB	Battery Electric Bus
CAPEX	Capital Expenditure
CEF	Connecting Europe Facility
CVD	Clean Vehicles Directive
DSR	Demand Side Response
EC	European Commission
EEA	European Environment Agency
EGD	European Green Deal
ETS	Emissions Trading System
EU	European Union
FCEB	Fuel Cell Electric Bus
GHG	Greenhouse Gas
HDV	Heavy-Duty Vehicle
ICCT	International Council on Clean Transportation
IPCC	Intergovernmental Panel on Climate Change
MLP	Multi-Level Perspective
OEM	Original Equipment Manufacturer
OPEX	Operational Expenditure
PTO	Public Transport Operator
SSMS	Sustainable and Smart Mobility Strategy
TCO	Total Cost of Ownership
TIS	Technological Innovation System
TTW	Tank-to-Wheel
WTT	Well-to-Tank
WTW	Well-to-Wheel
ZEB	Zero-Emission Bus

1. Introduction

1.1 Motivation

A long-term strategy for changing the transport system by 2050 has been set out in the European Union's [EU] Sustainable and Smart Mobility Strategy [SSMS]. It establishes three core objectives for the future of mobility: sustainable, smart, and resilient. These guiding principles serve as the strategic foundation for EU transport policy and show that the transition to climate-neutral mobility is not merely a question of technological substitution.

Instead of simply replacing diesel vehicles with electric ones, the strategy highlights the need for a systemic shift that also addresses digital integration, infrastructure, operational flexibility, and long-term crisis preparedness. The complex nature of these goals makes clear that the decarbonization of public transport requires more than a one-dimensional focus on e-mobility - it calls for coordinated action across regulatory frameworks, energy systems, business models, and stakeholder objectives (European Commission [EC], 2020).

Despite ambitious commitments, the EU is currently at risk of missing its climate targets for the transport sector. According to recent assessments, greenhouse gas [GHG] emissions from transport have not shown significant reductions compared to other sectors, which poses a threat to the EU's overarching goal of achieving climate neutrality by 2050. Still, the transport sector remains heavily reliant on fossil fuels (European Environment Agency [EEA], 2023). This persistent dependence underscores the urgent need for comprehensive strategies and investments.

At the same time, the public transport sector faces persistent economic and structural uncertainty. The COVID-19 pandemic triggered a sharp decline in ridership, and subsequent global crises—including energy shocks and geopolitical tensions—have further undermined the financial and operational stability of public transport providers. Siqueira (2023) notes that the post-pandemic era has ushered in a “new normal mobility,” marked by reduced commuter travel, increased operating costs, and unstable funding, all of which hinder long-term planning and sustainable investment.

In addition to these challenges, recent developments in mobility behavior have led to a shift in the modal share - the distribution of transport demand among different modes. Siqueira (2023) highlights a persistent trend towards reduced commuting and increased use of individual and flexible transport options such as cycling, walking, and shared mobility services. This development puts further pressure on traditional public transport systems, which now face the dual task of decarbonizing operations while adapting to changing demand structures and evolving user expectations. Public transport must therefore not only be green, but also more attractive, affordable, and digitally integrated to remain competitive within an increasingly multimodal urban mobility landscape.

Against this background, it becomes clear that emerging technologies alone will not be sufficient to decarbonize EU public transport unless they are embedded in broader systemic change. In order to contribute effectively, such innovations must not only deliver emissions reductions, but also prove resilient under uncertainty, adaptable to different urban and regional contexts, and acceptable to operators, policymakers, and passengers alike. Technological progress must therefore be evaluated not only in terms of

environmental performance, but also in relation to cost-efficiency, scalability, and operational integration.
This thesis sets out to examine how technological innovation can support the decarbonization of public transport in the EU while addressing these broader requirements. Rather than focusing on individual technologies, the analysis considers categories of innovation - such as alternative propulsion systems, intelligent operational technologies, and digital integration mechanisms - with particular attention to certain criteria according to stakeholder needs. The aim is to identify viable pathways that enable a sustainable transformation of public transport, balancing ecological imperatives with economic, technical, and social realities. A detailed problem context will be given in **Chapter 2**.

1.2 Research Questions

The decarbonization of EU's public transport sector represents a multidimensional challenge that spans climate policy, infrastructure development, technological innovation, and business strategy. While the EU has formulated ambitious targets under the European Green Deal [EGD], including a 90% reduction in transport-related GHG emissions by 2050 (EC, 2019), effective implementation requires alignment across multiple actors—particularly public transport operators [PTOs] and vehicle manufacturers.
The SSMS (EC, 2020) operationalizes the transport-related goals of the EGD. However, despite this strategic framework, a gap remains in understanding how EU climate ambitions can be reconciled with the economic, operational, and technological realities of key stakeholders. PTOs face infrastructure and cost constraints, while manufacturers must respond to market pressure and regulatory demands. Existing studies often address these perspectives in isolation, but few provide a structured approach to identifying shared priorities and evaluating technologies capable of meeting them.
To address this gap, the present study investigates how emerging technologies can support the decarbonization of public transport while also aligning with the goals and challenges of PTOs and vehicle manufacturers. Particular attention is given to the economic implications of technology choice under varying conditions. To this end, a dedicated sensitivity analysis was conducted to test the robustness of technology performance across different discount rates, carbon pricing trajectories, and deployment speeds.
The central research question guiding this thesis is:
How can emerging technologies be strategically deployed to decarbonize urban bus fleets in the EU, while balancing environmental effectiveness, economic feasibility, and stakeholder alignment?
To answer this overarching question, the following sub-questions are formulated:

- Which strategic goals and policy instruments define the EU's decarbonisation agenda for urban public transport, and how do they influence fleet procurement and technology adoption across Member States?
- What economic, operational, and regulatory challenges do public transport operators face when transitioning to battery-electric and hydrogen-powered bus fleets, and how do these challenges shape their investment strategies?
- What are the core innovation drivers, economic constraints, and policy interactions shaping vehicle manufacturers' zero-emission product development, and how do these influence technological readiness and market uptake?

- Where do the goals of policymakers, operators, and manufacturers align or conflict, and how can these dynamics inform coordinated technology deployment strategies?
- How do battery-electric and fuel cell bus technologies compare in terms of emissions performance and lifecycle cost under realistic deployment scenarios, and what are the implications for long-term public fleet planning?
- How robust are the cost-benefit outcomes of zero-emission bus technologies under different assumptions regarding discount rates, carbon price trajectories, and fleet transition speeds?

These questions serve as the analytical foundation for the thesis and are addressed through a structured framework based on the Design Science Research [DSR] methodology. The goal is to derive actionable insights that connect technological feasibility with strategic and financial stakeholder needs in the context of EU decarbonization policy. Particular emphasis is placed on the economic implications of technology adoption, investment planning, and operational efficiency—ensuring that the analysis remains grounded in business relevance.

1.3 Objectives of the Thesis

The objective of this thesis is to develop a strategic framework that supports the decarbonisation of public transport in the EU by aligning emerging drivetrain technologies with the concrete goals and constraints of key stakeholders—namely policymakers, PTOs, and OEMs. The research is situated at the intersection of climate policy, business strategy, and technological feasibility, acknowledging that sustainable transitions require coordinated efforts across institutional, operational, and industrial domains.

Unlike existing studies that analyse policy, operations, or technology in isolation, this thesis adopts an integrated perspective. It systematically connects stakeholder objectives with the technical and economic performance of zero-emission bus technologies—especially battery-electric and hydrogen fuel cell systems—under realistic conditions. Central to this approach is a long-term cost-benefit and emission model, which simulates transition scenarios and monetises environmental impacts through EU ETS-based carbon pricing. To ensure robustness, a sensitivity analysis was conducted that tests the model against variations in discount rates, CO_2 price trajectories, and technology deployment speeds.

By explicitly considering lifecycle costs, transition dynamics, and system constraints, the study provides a decision-oriented framework that addresses key implementation challenges such as infrastructure readiness, investment timing, and policy alignment.

The intended contribution is twofold:

First, to support public transport operators and vehicle manufacturers in making economically and operationally robust investment decisions under uncertainty.

Second, to offer policymakers actionable insights that strengthen coordination between regulatory ambition, technological progress, and stakeholder capacity.

Ultimately, the thesis aims to enable more coherent, cost-effective, and resilient decarbonisation pathways by identifying technologies and strategies that fulfil environmental, financial, and operational requirements simultaneously.

1.4 Structure of the Thesis

The structure of this thesis follows the principles of the Design Science Research (DSR) methodology, which supports the development of actionable and context-specific solutions to real-world challenges. DSR enables an iterative and stakeholder-oriented research approach that bridges theoretical insight, policy analysis, and business relevance (Hevner et al., 2004). **Chapter 4** provides a detailed discussion of the DSR framework and its operationalization in this study. The following section offers an overview of the thesis structure and the logical flow of the argument.

Chapter 2 introduces the theoretical and empirical background of the research. It outlines the climate policy context, emission trends in the European transport sector, and structural barriers to the decarbonisation of public transport—highlighting the urgency and complexity of the transition.

Chapter 3 defines the analytical scope and boundaries of the study. It specifies the relevant types of emissions, vehicle technologies, and public transport segments, and introduces the analytical dimensions applied throughout the thesis.

Chapter 4 presents the methodological approach, focusing on the DSR cycle and its integration into the thesis design. It explains how stakeholder perspectives and technical modelling are combined to derive implementation-oriented insights.

Chapter 5 conducts a structured stakeholder analysis. It examines the strategic objectives, constraints, and interactions of three central actor groups—EU policymakers, public transport operators, and vehicle manufacturers—and identifies areas of goal alignment, conflict, and leverage. The chapter closes with a synthesis of cross-stakeholder dynamics to guide subsequent evaluation steps.

Chapter 6 delivers a comprehensive technology and scenario-based analysis. It defines benchmark vehicle profiles, compares alternative drivetrain technologies (battery-electric and fuel cell electric buses), and models their performance over a 50-year horizon in terms of emissions, lifecycle costs, and cost-benefit trade-offs. The chapter operationalises the stakeholder priorities identified earlier and translates them into measurable evaluation criteria. An extended sensitivity analysis and specific fuel cost scenario examine the robustness of these findings under varying parameter assumptions.

Chapter 7 synthesises the findings and formulates stakeholder-specific recommendations. It interprets the results of the comparative analysis, matches stakeholder goals with viable technological pathways, and outlines targeted strategies for policy support, operational planning, and innovation alignment.

Chapter 8 concludes the thesis by summarising the key insights, reflecting on methodological limitations, and offering an outlook on future decarbonisation trends and research avenues. The conclusion integrates the empirical and strategic dimensions of the study and defines priority areas for further investigation and implementation.

2. Theoretical Framework and Problem Context

2.1 Background and Context of Decarbonization in the EU

To understand the relevance of decarbonization efforts in public transport, it is necessary to situate the sector within the broader context of climate policy and emissions trajectories in the EU. This section provides a structured overview of the scientific rationale behind the EU's climate agenda, the role of transport as a persistent emission source, and the specific relevance of public transport within this transition. Rather than treating public transport as a self-contained system, the aim is to frame it as a strategically embedded component of Europe's climate response.

2.1.1 Climate Change: Scientific Basis and Political Urgency

Climate change constitutes one of the most critical and far-reaching challenges of the 21st century. According to the Intergovernmental Panel on Climate Change [IPCC], global warming must be limited to 1.5 °C above pre-industrial levels to minimize the risks of severe and potentially irreversible damage to both natural and human systems. Achieving this objective requires global GHG emissions to decline by approximately 43% from 2019 levels by 2030 and to reach net zero by around 2050 (IPCC, 2023).

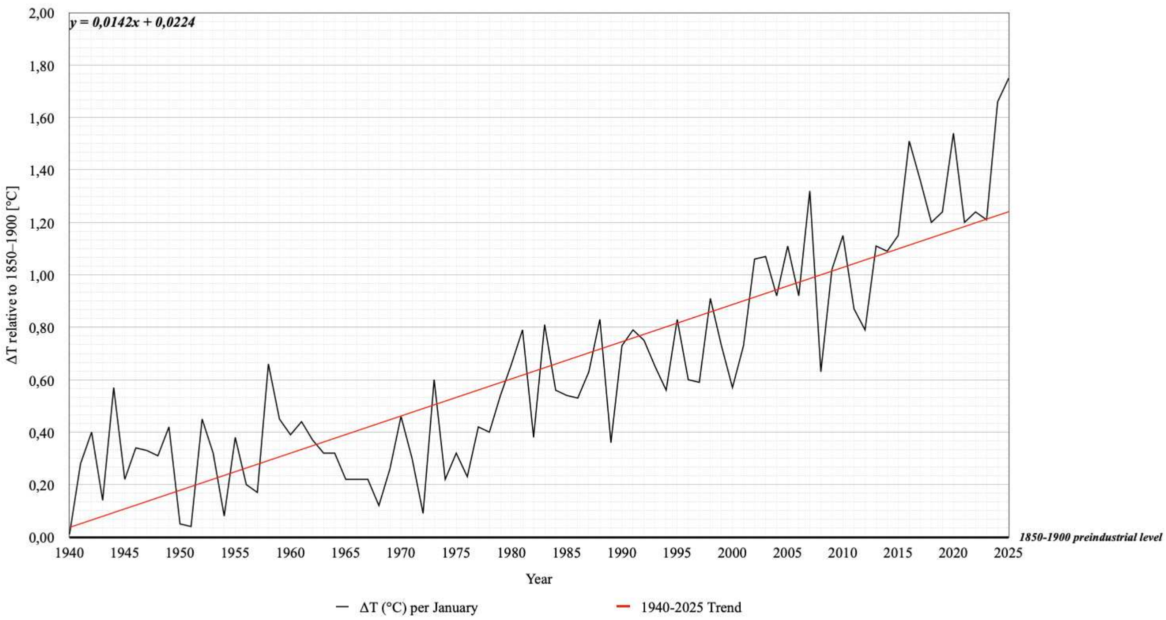

Figure 1
Global Monthly Mean January Surface Temperature Anomalies in °Celsius (ΔT) per year 1940 to 2025, Relative to Pre-Industrial Reference Period (1850-1900)
Note. Adapted from *ERA5 monthly averaged data on single levels from 1940 to present* (Copernicus, 2025)

As shown in **Figure 1**, the long-term development of global mean January surface temperature anomalies can be approximated using a linear regression function. The equation of this function is y = 0.0142x + 0.0224, where *x* denotes the number of years since 1940 and *y* the corresponding temperature anomaly relative to the 1850–1900 baseline. The slope of the function, 0.0142, reflects an average annual increase in January

temperatures of approximately 0.0142 °C. Over the observed period from 1940 to 2025, which corresponds to a time interval of Δx = 85 years, this results in a modelled temperature anomaly of y = 1.2294, or roughly 1.23 °C. This outcome is consistent with empirical records and highlights the persistent and cumulative nature of anthropogenic climate change. The continued rise depicted by the regression function demonstrates that mitigation efforts to date have not been sufficient to stabilize global temperature increases.
Recent observations confirm that global temperatures continue to rise at an alarming rate. January 2025 was recorded as the warmest January on record, with global average temperatures reaching 1.75 °C above pre-industrial levels (Copernicus, 2025).

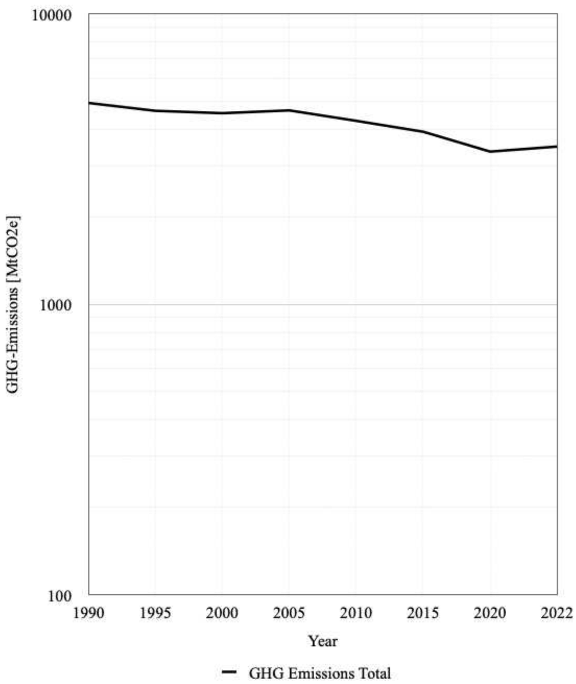

Figure 2.1
EU27 GHG Emissions in Million Tonnes CO2 Equivalent (Excl. int. Maritime and LULUCF)
Note. Adapted from *EU Transport in Figures – Statistical Pocketbook 2024* (EC, 2024). A logarithmic scale is applied to the y-axis to improve comparability across subsectors of differing magnitude.

While global temperatures have steadily increased, GHG emissions in the EU have shown a moderate decline over recent decades. As illustrated in **Figure 2.1**, total GHG emissions across all sectors in the EU27 fell from nearly 5,000 million tonnes of CO_2 equivalent in 1990 to around 3,500 $MtCO_2e$ in 2022. This reduction reflects progress in certain sectors, particularly energy production and industry. However, the decrease is not uniform and remains insufficient to meet the scale and urgency of climate targets. The data underline a critical insight: even as emissions decline gradually, the climate system continues to respond to cumulative historical emissions. This reinforces the importance of both immediate action and long-term systemic change.
In Europe, the frequency and intensity of extreme weather events—including heatwaves, floods, and droughts—have steadily increased, resulting in widespread impacts on ecosystems, public health, infrastructure, and economic stability (EEA, 2023).
The IPCC's Synthesis Report underscores that anthropogenic GHG emissions are unequivocally responsible for observed climate change. It emphasizes that each additional increment of warming increases the likelihood of simultaneous and interrelated hazards, including heavy precipitation, prolonged droughts, tropical cyclones, and cascading extreme events. The report further stresses that climate change poses an escalating threat to human security and planetary integrity. According to the IPCC, the window of opportunity to ensure a livable and sustainable future is rapidly closing. Only deep, rapid, and sustained emission reductions can limit future warming and stabilize atmospheric concentrations within a few years (IPCC, 2023).
In recognition of the escalating climate risks, climate policy has moved to the center of political and economic discourse. International and regional institutions increasingly treat climate change not only as an environmental issue, but as a structural challenge that affects nearly every sector of society. Nevertheless, major implementation gaps remain, and

current global efforts are not yet sufficient to meet the 1.5 °C target (UNEP, 2023). This underlines the urgency of translating scientific warnings into effective and timely action.

2.1.2 Climate Change and Transport Emissions

While the EU has achieved significant reductions in GHG emissions across several major sectors since 1990, the transport sector has proven comparatively resistant to change. Between 1990 and 2022, total EU GHG emissions fell from nearly 5,000 million tonnes of CO_2 equivalent ($MtCO_2e$) to approximately 3,500 $MtCO_2e$, reflecting an overall reduction of around 30% (EC, 2024). Other sources are confirming this trend. According to EEA, total net GHG emissions in the EU-27 declined by approximately 31% between 1990 and 2022 (EEA, 2024a) while Eurostat states 29.2% for the same period (Eurostat, 2024). This achievement is largely attributed to mitigation efforts in energy supply, industry, buildings, and waste management. Specifically, emissions from the energy supply sector decreased by 46% between 1990 and 2022, primarily due to a significant decline in coal usage and the growth of renewable energy sources. Waste management emissions were reduced by 41% over the same period, reflecting advancements in waste treatment and recycling practices (Eurostat, 2024). The buildings sector achieved a 34% reduction in emissions from 2005 to 2022, attributed to improved energy efficiency standards and the decarbonization of heating systems (EEA, 2024b).

In contrast, emissions from the transport sector have remained relatively stable or even increased slightly over the same period. As illustrated in **Figure 2.2**, transport-related emissions fluctuated around 1,000 $MtCO_2e$ from 1990 to 2022. Short-term reductions, such as those observed during the COVID-19 pandemic in 2020 and 2021, were temporary and quickly reversed. Data from the *EU Transport in Figures – Statistical Pocketbook 2024* indicates that transport was the largest emitting sector in the EU in 2022, accounting for 30.1% of total emissions, ahead of energy production (26.4%) and industry (21.7%) (EC, 2024). These figures may vary slightly in other datasets, depending on how international transport and indirect energy use are classified. Nonetheless, the trend is consistent: transport remains one of the most emission-intensive sectors in Europe.

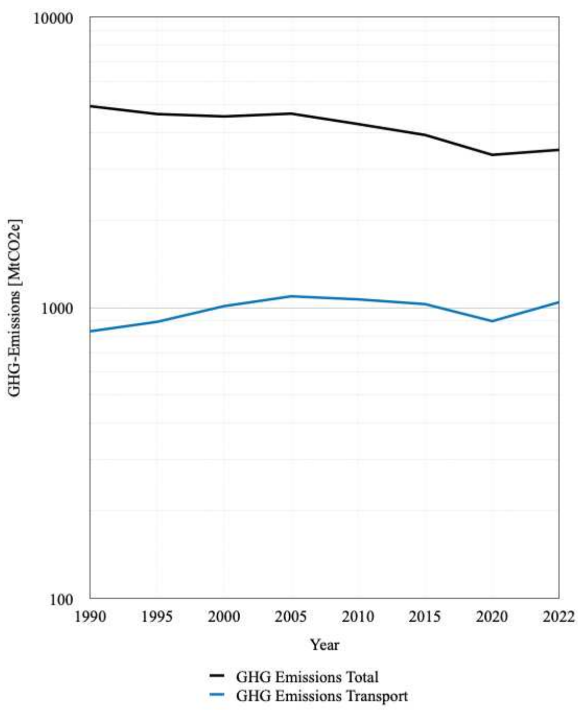

Figure 2.2
EU27 GHG Emissions Total and from Transport in Million Tonnes CO2 Equivalent (Excl. int. Maritime and LULUCF)
Note. Adapted from *EU Transport in Figures – Statistical Pocketbook 2024* (EC, 2024). A logarithmic scale is applied to the y-axis to improve comparability across subsectors of differing magnitude.

Several systemic factors contribute to the slow progress in transport decarbonization. These include the dominance of road-based systems, growing demand for freight and personal mobility, the slow market penetration of zero-emission vehicles, and continued reliance on fossil fuels. However, the complexity and fragmentation of the transport system - marked by millions of vehicles and thousands of operators - means that progress has been slow, and the sector remains one of the most difficult to decarbonize in the EU climate framework.

2.1.3 The Role of Public Transport in Climate Transition

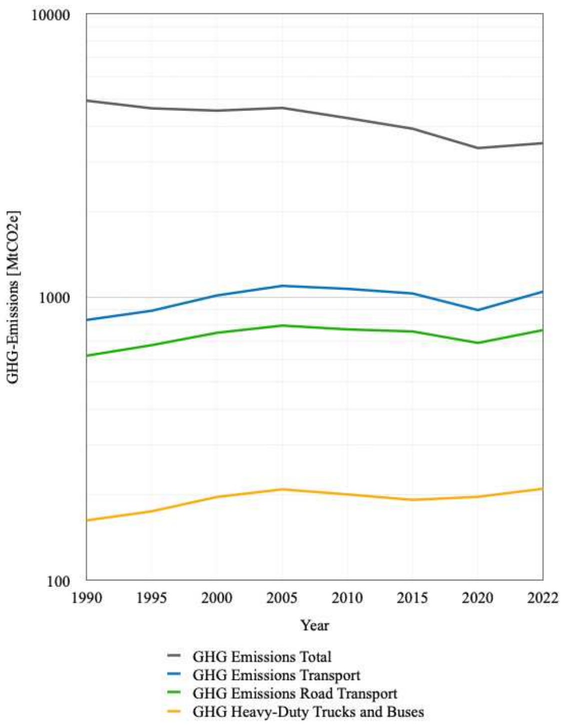

Figure 2.3
EU27 GHG Emissions Total and by Sector in Million Tonnes CO2 Equivalent (Excl. int. Maritime and LULUCF)
Note. Adapted from *EU Transport in Figures – Statistical Pocketbook 2024* (EC, 2024). A logarithmic scale is applied to the y-axis to improve comparability across subsectors of differing magnitude.

Public transport represents a central component in the EU's strategy to decarbonize the transport sector. While its direct share in GHG is lower compared to individual motorized transport, its structural role and untapped mitigation potential make it a key area for targeted climate policy.
Figure 2.3 shows that emissions from road transport in the EU have increased slightly over the past three decades, rising from just under 900 $MtCO_2e$ in 1990 to approximately 1,000 $MtCO_2e$ in 2022. This upward trend contrasts with other sectors where significant reductions have occurred and illustrates that road-based systems continue to drive emissions, despite technological advances and policy interventions (EC, 2024).
This trend is especially relevant for public transport decarbonization, as most public transport vehicles—especially buses—operate within the road transport system. The overall increase in road transport emissions signals that climate policies targeting this sector have not yet achieved meaningful structural change. Moreover, it highlights that public transport, while often perceived as a sustainable alternative, still operates within a largely fossil-fuel-dependent environment. Without focused decarbonization efforts, expanding public transport alone may not reduce emissions effectively. **Figure 2.3** builds upon this insight by also illustrating the development of emissions from heavy-duty vehicles [HDVs], which include public buses. The graph shows a similar upward trend to overall road transport, confirming that this sub-sector contributes consistently to the broader emission profile. In 2022, HDVs emitted over 300 $MtCO_2e$, accounting for around 30% of road transport emissions. While public transport buses represent only a subset of HDVs, they are part of this emission pattern and cannot be viewed in isolation (EC, 2024).
Given their frequent use and high mileage—especially in densely populated areas—buses have a disproportionately high impact on the sector's climate footprint. Therefore, transitioning public bus fleets to low-emission or zero-emission propulsion technologies is essential. This is not only a question of climate mitigation, but also of policy credibility: if

public transport is to serve as a pillar of climate strategy, its operational foundation must be climate-compatible.

At the same time, modal share data confirms that there is considerable potential for expanding public transport use across Europe. In 2022, private passenger cars accounted for 82.4% of inland passenger kilometers in the EU, whereas buses and coaches made up 8.2% (EC, 2024).

However, these EU-wide averages conceal significant national differences. In Austria, for example, private passenger cars represented only 72.1%, while buses and coaches accounted for 7.8%. This reflects a comparatively balanced modal split, supported by strong public transport infrastructure. In Hungary, the share of passenger kilometers travelled by bus and coach was among the highest in the EU at 15.3%, while the car share was comparatively low at 74.4%. At the other end of the spectrum, the Netherlands recorded one of the lowest shares for buses and coaches at just 2.8%, with 85.0% of passenger kilometers attributed to private cars.

In addition to these cross-country differences, recent EU-level trends highlight the increasing importance of the bus and coach segment in the climate transition. While the overall modal share of buses and coaches has declined over the last two decades—from 10.4% in 1995 to 7.2% in 2022—the absolute transport volume has remained robust and is rising again. Following a drop in 2020 due to the COVID-19 pandemic, bus and coach transport in the EU-27 declined from 421.8 billion pkm in 2019 to 330.8 billion pkm in 2021. However, in 2022 it rebounded to 406.2 billion pkm, marking a remarkable year-on-year increase of 22.8% (EC, 2024, p. 48).

This strong recovery suggests that the mitigation potential of public bus systems is not only substantial but growing. In fact, the overall passenger transport volume in the EU increased by 14.4% from 2021 to 2022, but the growth for bus and coach transport outpaced that average. In comparison, private car use rose by only 6.0% in the same period (EC, 2024).

These figures indicate that an increasing number of journeys are once again being made by bus - particularly in urban contexts, where public transport alternatives are more viable. As demand for buses recovers, the climate relevance of this mode grows accordingly. Every additional passenger-kilometre shifted away from private cars and towards buses contributes to lowering average transport emissions - **but only if** these services are delivered with clean propulsion systems. This pronounced variation between car-dominated and bus-oriented systems thus reveals a substantial reservoir of untapped mitigation potential. If even a moderate share of car users shifted to public transport - particularly in cities - the resulting emissions reductions would be significant. However, expanding public transport without greening its fleets risks offsetting these benefits. The key challenge for EU climate policy is therefore to ensure that rising public transport demand is matched by a rapid transition to low- and zero-emission technologies.

2.2 Frameworks for Sustainable Mobility Transitions

The decarbonization of the public transport sector is not a purely technological challenge but a complex, multi-dimensional transition involving innovations, institutions, policies, and societal change. To capture the systemic nature of this transition, various conceptual frameworks have been developed. This chapter introduces three influential approaches that help analyze and structure the dynamics of sustainable mobility transitions: the Multi-

Level Perspective [MLP], Technological Innovation Systems [TIS], and the Sustainable Mobility Paradigm.

2.2.1 Multi-Level Perspective [MLP]

The MLP, developed by Geels (2002), conceptualizes socio-technical transitions as the interaction of processes at three different analytical levels:

- **Niche innovations (micro-level)**: Protected spaces where radical innovations emerge, such as pilot projects for electric or hydrogen buses in urban transport systems.

- **Socio-technical regimes (meso-level)**: The dominant configurations of practices, rules, and technologies that stabilize the existing system, like the reliance on diesel buses and established infrastructure in the public transport sector.

- **Socio-technical landscape (macro-level)**: Broader contextual developments such as climate change, urbanization, and societal pressure for sustainability.

Transitions occur when landscape pressures destabilize existing regimes, creating windows of opportunity for niche innovations to break through and reshape the system. In the context of smart mobility, the MLP provides a useful lens to understand how systemic decarbonization requires not only technological advances but also institutional, cultural, and policy shifts (Geels, 2002).

2.2.2 Technological Innovation Systems (TIS)

The TIS framework focuses on the development, diffusion, and utilization of specific technologies within an innovation system (Carlsson, et al., 2002). A TIS includes all structural elements (actors, networks, institutions) that influence a particular technology.
Key components of TIS are:

- **Actors**: Firms, universities, research institutions, regulatory agencies, and users that interact to shape technological development.

- **Networks**: Formal and informal relationships that facilitate knowledge exchange, advocacy, and resource mobilization.

- **Institutions**: Norms, rules, and regulations that support or hinder innovation processes.

In the context of public transport decarbonization, TIS analysis can help identify barriers (e.g., missing infrastructure, regulatory uncertainty) and success factors (e.g., subsidy schemes, technological maturity) that influence the adoption of emerging solutions like battery-electric and hydrogen-powered buses.
TIS emphasizes that technology development alone is insufficient; active system-building efforts, including policy support and stakeholder coordination, are necessary to foster sustainable transitions (Carlsson et al., 2002).

2.2.3 Sustainable Mobility Paradigm

Banister's (2008) Sustainable Mobility Paradigm presents a fundamental rethinking of traditional transport policy objectives. Instead of focusing narrowly on travel time reductions and traffic flow optimization, the sustainable mobility approach prioritizes:

- **Reducing the need to travel** through better urban planning and local accessibility.
- **Promoting modal shift** from private cars to public transport, cycling, and walking.
- **Integrating transport and land-use planning** to create compact, mixed-use, and sustainable urban areas.

This paradigm stresses that technical improvements in vehicles and fuels must be complemented by behavioral and structural changes. In the public transport sector, this means not only deploying cleaner technologies but also increasing the attractiveness, affordability, and accessibility of public mobility options (Banister, D. 2008).
The Sustainable Mobility Paradigm is highly relevant for decarbonization strategies, as it links technological innovation with broader goals of environmental protection, social inclusion, and urban livability.

3. System Definition and Scope

Building upon the scientific and political urgency outlined in **Chapter 2**, this study focuses on identifying viable decarbonization pathways for the EU's public transport sector. A clear thematic focus and system delimitation are essential to ensure analytical precision and consistency across the methodological steps. This chapter defines the research scope, the system boundaries, and the rationale for the technologies and emissions considered in the modelling.

3.1 Scope of the Study

3.1.1 Research Focus and Objectives

The central objective of this thesis is to investigate how the decarbonisation of public bus fleets in the EU's can be accelerated through the deployment of commercially mature zero-emission technologies and the alignment of strategic measures with stakeholder needs. The analysis builds on a stakeholder-centred perspective and evaluates technologies based on their environmental effectiveness, financial feasibility, and operational suitability.

The study concentrates on solutions with demonstrable emissions-reduction potential and high deployment readiness. Rather than adopting a broad view on innovation or digitisation, the research focuses on drivetrain-level changes that are expected to dominate EU fleet transitions over the next two decades. Special emphasis is placed on battery-electric buses [BEBs] and hydrogen fuel cell buses [FCEBs], which are evaluated using consistent environmental and economic indicators.

Broader behavioural or societal transformations, while highly relevant to the success of zero-emission transitions, are excluded from systematic modelling due to their context dependency and complexity. However, relevant observations—such as perceived risk aversion or demand-side inertia—are qualitatively integrated where they support strategic interpretation.

The techno-economic analysis is conducted over a 50-year horizon to capture multiple procurement cycles, investment feedback effects, learning curves, and the cumulative effect of rising CO_2 prices. Scenario logic reflects both a theoretical full-fleet baseline and a realistic transition pathway based on the case of Wiener Linien, whose operational and emissions data allow for high analytical transparency.

3.1.2 Focus on EU Policies and Decarbonisation Goals

The research is situated within the institutional and regulatory framework of the EU, drawing from overarching policy packages such as the European Green Deal (EC, 2019), the Sustainable and Smart Mobility Strategy (EC, 2020), and the Fit for 55 Package (EC, 2021a). These policies form the backbone of EU-level emission targets and drive strategic technology funding and regulation across Member States.

The thesis explicitly uses EU-level decarbonisation objectives as its normative benchmark to ensure cross-country comparability. While national initiatives such as Austria's EBIN programme are cited to contextualise implementation challenges, they are not used to derive strategic assumptions. This delineation ensures consistency and avoids skewing the modelling by country-specific incentive structures.

3.1.3 Key Areas of Analysis

The thesis integrates three dimensions of analysis: technological performance, economic viability, and regulatory coherence. The technological evaluation is limited to drivetrain technologies with immediate application potential in EU bus fleets. The economic assessment includes cost trajectories, residual values, and lifecycle emissions abatement cost. The policy dimension considers the alignment between technological readiness, operator incentives, and regulatory requirements.

Solutions are included only if they offer significant GHG mitigation and comply with EU definitions of zero-emission vehicles. Technologies such as plug-in hybrids, biodiesel, compressed natural gas (CNG), or synthetic fuels (e.g., e-diesel) are excluded due to incomplete decarbonisation potential, high tank-to-wheel emissions, or low cost-efficiency. Although such fuels may serve a role in hard-to-abate segments, they are not prioritised in urban bus decarbonisation strategies under current EU regulation.

3.2 System Boundaries

3.2.1 Definition of the System

The geographical scope includes all 27 EU Member States. Public transport is defined as scheduled and regulated passenger services operated by public operators or under public service obligation (PSO) contracts. The analysis excludes purely private or unsubsidised services.

To ensure consistency in fleet characteristics, the analysis focuses exclusively on standard 12-meter solo buses. These represent the most common segment in EU procurement and provide a stable baseline for comparing cost and emissions performance. The case of Wiener Linien is used for empirical parameterisation due to its representative urban fleet, detailed emissions statistics, and relevance for EU benchmarking.

3.2.2 Emission Types Considered

The environmental scope is limited to greenhouse gas (GHG) emissions, specifically CO_2, CH_4, and N_2O, measured in CO_2-equivalents. A well-to-wheel (WTW) approach is used to reflect both upstream energy emissions and operational (tank-to-wheel) emissions. This method supports fair comparison between electricity-based and fuel-based propulsion systems.

Other environmental impacts, such as air pollutants (NO_x, PM), noise, or land use, are acknowledged as important but excluded from the model to retain analytical focus on climate targets.

3.2.3 Public Transport Modes Included

The modal scope is restricted to road-based public transport, specifically bus operations in urban environments. Rail-based transport modes such as metros, trams, or regional trains are excluded due to their high electrification levels and comparatively low marginal GHG abatement potential. Their inclusion would obscure the analysis of drivetrain substitution and distort the cost-emission benchmarking.

3.2.4 Technologies Considered

Only commercially available zero-emission propulsion systems are included. This encompasses BEBs with depot charging and hydrogen FCEBs. Opportunity charging systems, inductive charging, and trolleybus solutions are excluded due to their high infrastructure dependency and limited deployment across the EU. While such systems may be optimal in specific cities, they lack generalisability for EU-wide fleet transition scenarios.

Combustion-based solutions—including natural gas, hybrid drives, and synthetic fuels—are excluded due to their non-zero tank-to-wheel emissions and limited alignment with EU zero-emission definitions. Their lifecycle GHG profiles are also less favourable compared to BEBs under current grid compositions.

Complementary technologies like regenerative braking or digital fleet tools are not modelled individually, as their marginal contributions depend heavily on operational context and are difficult to quantify in comparative lifecycle assessments.

3.2.5 Economic and Business Aspects Considered

The economic model incorporates capital expenditure [CAPEX], operating expenditure [OPEX], infrastructure costs, residual value assumptions, and energy costs. Total cost of ownership [TCO] is used as a unifying metric to compare drivetrain types over multiple lifecycles. Carbon pricing is integrated into the model through a linearly rising ETS price assumption.

A fixed real interest rate of 3% is used to discount future cost and benefit flows. This simplification allows for comparability across technologies and reflects average public-sector investment conditions. Public authorities and funding instruments are considered indirectly via their effect on capital costs, but are not treated as separate actors.

3.2.6 Social and User Perspectives

Social, behavioural, and political aspects - such as public acceptance, operator risk aversion, or voter preferences - are not part of the quantitative modelling but are qualitatively acknowledged in the stakeholder analysis in **Chapter 5**. Their integration into policy design remains crucial, but their effects are not captured in the cost or emissions results. The thesis focuses on designable system levers - such as incentives, regulations, and procurement strategies - that are within the reach of public institutions and fleet operators.

4. Methodology

The methodological framework of this thesis is designed to address the complexity of decarbonizing the EU's public transport sector by systematically evaluating the interplay between policy frameworks, stakeholder objectives, and emerging technologies. While the study is primarily descriptive and analytical in nature, it adopts the principles of Design Science Research [DSR] to guide the development of a conceptual decision-support framework. This framework serves as an "artifact" in the DSR sense - providing structured, evidence-based guidance for aligning stakeholder needs with viable technological pathways. In line with this logic, the study includes both scenario-based lifecycle modelling and a dedicated sensitivity analysis, which tests the robustness of key outcomes against variations in parameter assumptions. The following sections introduce the core principles of DSR, justify its relevance to this research context, and outline how its cycles are applied throughout the thesis to iteratively connect empirical insights with theoretical models and practical recommendations.

4.1 Description of the DSR

This thesis adopts the principles of Design Science Research (DSR) as its methodological foundation. DSR is a research approach aimed at creating and evaluating artifacts—such as models, frameworks, or methods—intended to solve identified problems in complex, real-world environments (Hevner et al., 2004). Unlike purely descriptive or exploratory research methods, DSR combines two essential objectives: ensuring relevance to practical problems and maintaining rigor through the application of scientific theories and validated methods.

The structure of DSR is organized into three interrelated cycles (Hevner, A. R., 2007):

- **The Relevance Cycle** connects the research activities with the application environment, ensuring that the problem addressed is grounded in real-world needs.
- **The Design Cycle** represents the core iterative process where artifacts are developed, tested, and refined.
- **The Rigor Cycle** ensures that the research draws upon and contributes to the existing knowledge base, including theoretical frameworks, design principles, and empirical findings.

Through the interaction of these three cycles, DSR provides a systematic yet flexible framework that enables researchers to bridge the gap between academic theory and practical application. It is particularly suited for addressing wicked problems characterized by high complexity, multiple stakeholders, and evolving objectives—such as the decarbonization of public transport systems.

4.2 Choice of Methodology

DSR was selected as the methodological foundation for this thesis because it offers a structured approach for solving interdisciplinary real-world problems such as the decarbonization of the EU's public transport sector. Such a challenge connects technology development, business strategy, and policy-making. Addressing such complexity requires a methodology that not only analyzes existing structures but also develops actionable artifacts to guide decision-making (Hevner et al., 2004).

DSR is particularly suitable for research contexts where established theories provide important insights but are not sufficient to fully resolve practical challenges. In this study, the goal is to create a strategic framework that links emerging technologies to the needs and expectations of policymakers, PTOs, and manufacturers. This artifact-based focus aligns closely with the core purpose of DSR: to extend knowledge through the design and evaluation of innovative solutions (Hevner et al., 2004).

Also, DSR emphasizes an iterative development process. In the context of this thesis, iteration is achieved by first conducting a stakeholder analysis to identify the strategic and operational requirements of key actors. Based on these findings, technologies are assessed according to how well they meet the derived needs. The iterative nature arises from the continuous alignment between stakeholder goals and technology evaluation, allowing for refinements and prioritizations as new insights emerge. Thus, the research process is not strictly linear but adapts to evolving understandings, which is consistent with the principles of DSR (Hevner, 2007).

Another strength of DSR in this context is its ability to bridge disciplines. By integrating elements from engineering, management science, and policy studies, DSR supports a holistic exploration of decarbonization pathways. This interdisciplinary orientation ensures that both technical feasibility and strategic relevance are considered, making DSR particularly well-suited for addressing the research questions of this thesis.

In summary, DSR offers a methodological framework that accommodates the iterative, interdisciplinary, and solution-oriented nature of the research. It provides the necessary flexibility and rigor to develop a strategic framework that is both theoretically grounded and practically applicable to the challenges of public transport decarbonization in the EU.

4.3 Steps in the DSR Process

Following Hevner's (2007) three-cycle model, this thesis applies the Relevance Cycle, Design Cycle, and Rigor Cycle.

The Relevance Cycle connects the research to the real-world environment, which in this case is the challenge of decarbonizing the EU public transport sector. This cycle is primarily addressed in **Chapters 1** to **3**, where the urgency of climate action is established, the EU climate and mobility frameworks (such as the EGD, SSMS, and Fit for 55 Package) are examined, and the analytical scope of the study is defined. These chapters ground the research in real-world policy priorities and sectoral transformation needs. Importantly, while the stakeholder analysis responds to real-world challenges, it belongs to the Design Cycle and is not part of the Relevance Cycle itself.

The Design Cycle forms the core of the research process. It is reflected in **Chapters 5** to **7**, where stakeholder goals, constraints, and strategic objectives are systematically analyzed. Based on this analysis, a structured evaluation of decarbonization technologies is conducted to assess their alignment with stakeholder needs. This includes a sensitivity analysis that tests how lifecycle cost and emission outcomes vary under different assumptions for key parameters—namely discount rates, carbon price trajectories, and fleet transition speeds. This iterative process supports the development of a conceptual decision-support framework that matches stakeholder priorities with viable technological solutions.

Although no physical prototype is developed, the design artifact takes the form of an evaluative model that enables strategic decision-making. By structuring the research in this way, the Design Cycle ensures that the developed framework remains aligned with both practical challenges and theoretical insights (Hevner et al., 2004; Hevner, 2007).
The Rigor Cycle ensures that the research process and its outcomes are grounded in scientific knowledge and validated approaches. Throughout the thesis, rigor is achieved by integrating recognized theoretical frameworks - such as the MLP, TIS, and the Sustainable Mobility Paradigm - as introduced in **Chapter 2**. Furthermore, the study draws extensively on peer-reviewed literature, official EU policy documents, environmental datasets, and industry reports (e.g. from EEA, Eurostat, UITP). This consistent linkage to established sources ensures that the research is not only practically relevant, but also theoretically sound and academically traceable.

5. Stakeholder Analysis

The successful decarbonisation of the EU public transport sector hinges not only on technological innovation and regulatory ambition, but also on the complex interplay of goals, capabilities, and constraints among the key stakeholder groups involved in its implementation. These include policymakers who shape the regulatory framework, PTOs)who manage daily operations and fleet procurement, and OEMs who develop and supply the required technologies. Each group brings its own perspective, priorities, and limitations to the transition, resulting in both synergies and tensions that must be systematically understood to design effective and feasible decarbonisation strategies.

This chapter analyses the strategic roles and objectives of these three stakeholder categories in detail. It begins with an examination of EU policymakers in **Section 5.1**, focusing on the legal instruments and strategic frameworks they have established to promote clean urban mobility, including the European Green Deal, the Fit for 55 package, and the Clean Vehicles Directive. The section further explores challenges related to multi-level governance and policy implementation, as well as the overarching environmental, economic, and social goals pursued at EU level.

Section 5.2 investigates the demand-side perspective of public transport operators. It provides an overview of their operational context, including modal shares, fleet composition, and deployment trends of zero-emission vehicles. This is followed by a detailed assessment of the economic, infrastructural, and institutional barriers that hinder large-scale electrification. The section also outlines strategic adaptations made by PTOs to comply with regulatory targets and manage technological transitions, concluding with a synthesis of their strategic objectives.

Section 5.3 presents the supply-side perspective of vehicle manufacturers and technology providers. It analyses the structure of the European bus manufacturing market, recent shifts in drivetrain technologies, and the challenges associated with cost, infrastructure, and supply chain risks. The section highlights manufacturers' strategic responses, including product innovation, industrial reorganisation, and vertical integration, before summarising their key objectives in regulatory compliance, operational compatibility, and economic scalability.

Finally, **Section 5.4** brings these perspectives together by comparing stakeholder goals, identifying points of alignment and divergence, and introducing strategic levers to facilitate coordination. A qualitative goal alignment matrix is presented to visualise shared priorities and to guide the technology assessment in **Chapter 6**. This stakeholder analysis thus forms the conceptual and analytical foundation for evaluating decarbonisation technologies in terms of their feasibility, acceptability, and alignment with sectoral objectives.

5.1 Policymakers

5.1.1 Overview and Context

The EU's provides the strategic and regulatory framework for the decarbonization of public transport through a series of major policy initiatives.

European Green Deal (2019)

The European Green Deal, presented by the EC in December 2019, sets the overarching framework for the EU's transition towards climate neutrality by 2050 (EC, 2019). It defines climate action not only as an environmental necessity but also as a catalyst for economic growth and social transformation. Transport is explicitly identified as a critical sector, responsible for approximately 25% of the EU's total GHG emissions, and as an area requiring urgent action due to its current trajectory as outlined in **Chapter 2.1.2**.

Within the Green Deal, the decarbonization of transport is addressed through several key directions. First, the document emphasizes the need for a shift to more sustainable modes of transport, notably public transport, rail, and active mobility such as walking or cycling. Public transport is envisioned as the backbone of urban mobility, supported by investment in cleaner technologies and digitalization (EC, 2019). Second, the Green Deal highlights the necessity of boosting the market for zero- and low-emission vehicles, including the introduction of stricter CO_2 emission standards. In parallel, it calls for the deployment of one million public charging and refueling stations for alternative fuel vehicles by 2025. Third, sustainable mobility is explicitly linked to broader objectives such as improved air quality, public health, and industrial innovation.

While the Green Deal does not impose direct legal obligations, it lays down strategic orientations that have led to subsequent legislative initiatives, including the Sustainable and Smart Mobility Strategy and the Fit for 55 package.

Fit for 55 Package (2021)

The Fit for 55 package, presented by the EC in July 2021, translates the ambitions of the European Green Deal into a comprehensive set of legislative proposals with binding legal effect (EC, 2021a). While the Green Deal outlines the strategic vision of achieving climate neutrality by 2050, Fit for 55 provides the concrete regulatory framework necessary to meet the interim target of a 55% reduction in net GHG emissions by 2030 compared to 1990 levels. The package spans a wide range of sectors, including energy, industry, and transport, and aims to align existing legislation with the new climate objectives. In the transport sector, Fit for 55 introduces three core initiatives relevant to the decarbonization of public transport, which are detailed in the following sections.

Alternative Fuels Infrastructure Regulation (2023)

The Alternative Fuels Infrastructure Regulation (AFIR), adopted as part of the Fit for 55 package, aims to overcome one of the key barriers to the decarbonization of transport: the lack of sufficient infrastructure for alternative fuels (EU, 2023a). It replaces the previous directive and introduces binding requirements for Member States to deploy charging and refueling stations at defined intervals along major transport networks. By 2025, electric recharging stations for light-duty vehicles must be available at least every 60 kilometers along the core TEN-T network. For heavy-duty vehicles such as buses and trucks, high-power recharging points must be installed at intervals of at least every 120 kilometers. Additionally, by 2030, hydrogen refueling stations must be available at least every 200 kilometers.

Although AFIR does not regulate vehicles directly, it has substantial impact on the feasibility and pace of public transport decarbonization. For operators, the availability of reliable infrastructure is a precondition for fleet transition. For manufacturers, it reduces market uncertainty by ensuring synchronized infrastructure deployment.

Extension of the Emissions Trading System (2023)

Another initiative within the Fit for 55 package is the extension of the Emissions Trading System (ETS) to road transport and buildings. This expansion, commonly referred to as ETS2, was established by Directive (EU) 2023/959 (EU, 2023b). Under the revised framework, emissions from road transport and buildings will be covered by a separate cap-and-trade system starting in 2027. Fuel suppliers are responsible for purchasing and surrendering emission allowances for the fuels they distribute. The total emissions cap will decline annually by 5.10% from 2027 onwards. A monitoring and reporting system for emissions will be established starting in 2025, while compliance obligations will begin in 2027. The revenues generated from the auctioning of allowances will be partially allocated to the Social Climate Fund, designed to support vulnerable groups and small businesses. ETS2 introduces a market-based mechanism to control GHG emissions from transport fuel consumption through economic instruments, without imposing direct technological or operational mandates on PTOs.

Revised CO_2 Emission Standards for Heavy-Duty Vehicles (2024)

As part of the EU's broader climate agenda, the European Parliament and the Council adopted a revision of the CO_2 emission standards for HDVs in July 2024 (EU, 2024a). This regulation aligns with the EU's 2030 and 2050 climate goals and represents a core element of the Fit for 55 package. It strengthens Regulation (EU) 2019/1242 by introducing stricter emission reduction targets: manufacturers must reduce average fleet emissions by 45% by 2030, 65% by 2035, and 90% by 2040, compared to 2019 levels. The scope of the regulation is also expanded to include urban buses, coaches, and trailers. All newly registered urban buses must be zero-emission vehicles by 2030. The revised regulation introduces binding obligations that directly affect both vehicle manufacturers and public fleet procurement strategies.

Net-Zero Industry Act (2024)

The Net-Zero Industry Act, formally adopted in April 2024 as Regulation (EU) 2024/1252, establishes a legal framework to strengthen the EU's manufacturing capacity for strategic net-zero technologies. It sets a benchmark that at least 40% of the EU's annual demand for technologies such as batteries, fuel cells, electrolysers, grid technologies, and heat pumps should be met by domestic production by 2030 (EU, 2024b). To support this, the regulation introduces fast-track permitting for "Net-Zero Strategic Projects", incentives for industrial clustering in so-called "Net-Zero Valleys", and training initiatives to address skill shortages. While not specific to transport, the act reinforces the industrial foundation for clean mobility technologies and complements demand-side regulations under the Fit for 55 package.

Sustainable and Smart Mobility Strategy (2020)

The Sustainable and Smart Mobility Strategy (SSMS), adopted by the EC in December 2020, provides a sector-specific roadmap that supports the strategic objectives of the European Green Deal (EC, 2020). It outlines the vision for achieving a 90% reduction in transport-related GHG emissions by 2050 and includes interim milestones for 2030. The strategy emphasizes the role of public transport in urban decarbonization and promotes a shift toward more sustainable modes. It also highlights the need to accelerate the market uptake of low- and zero-emission vehicles and to expand alternative fuels infrastructure. In addition, the SSMS supports the deployment of connected and automated mobility solutions and digital innovations to improve operational efficiency and the attractiveness of public transport services.

The strategy calls for an inclusive transition to ensure mobility remains accessible and affordable. Although it is non-binding, the SSMS helps shape stakeholder expectations and provides direction for legislative measures under the Fit for 55 package.

Clean Vehicles Directive [CVD] (2019)

The CVD (Directive (EU) 2019/1161), adopted in June 2019, sets binding procurement targets for clean and zero-emission vehicles in the public sector (EU, 2019a). It amends Directive 2009/33/EC and plays a critical role in stimulating demand for environmentally friendly transport technologies. The directive defines minimum national targets for the share of clean vehicles in total public procurement, distinguishing between light-duty and heavy-duty vehicles. It places particular emphasis on promoting the uptake of zero-emission buses in public transport.

In contrast to the EGD and SSMS, the Clean Vehicles Directive creates legally binding obligations that Member States must transpose into national law. It has a direct impact on procurement practices, operational planning, and fleet renewal strategies within the public transport sector.

Policy/Strategy	Year	Type	Legal Status	Main Objective(s)	Stakeholder Relevance
EGD	2019	Strategic Framework	Non-binding	Climate neutrality by 2050 Modal shift to sustainable mobility	High-level orientation for legislation and long-term planning
Fit for 55	2021	Legislative Package	Partly binding	-55% GHG by 2030, implementation of the EGD	Core framework for sectoral decarbonization policies
AFIR	2023	Regulation	Binding	Infrastructure targets for charging and refueling	Planning certainty for PTOs and manufacturers
ETS	2023	Directive	Binding	Carbon pricing in road transport and buildings	Financial incentive for emission reduction
CO_2 Standards	2023	Legislative Proposal	Pending adoption	Emission reduction targets for manufacturers (45%/65%/90%)	Regulatory pressure on OEMs, fleet transition trigger for PTOs
NZIA	2024	Regulation	Binding	Strengthen EU manufacturing of clean tech 40% domestic capacity by 2030	Supports scaling of vehicle technologies Industrial clarity for manufacturers
SSMS	2020	Sectoral Strategy	Non-binding	-90% GHG in transport by 2050, promote public transport and digitalization	Priority setting for policymakers and PTOs
CVD	2019	Directive	Binding	Minimum public procurement targets for clean vehicles	Direct impact on procurement and fleet planning

Table 1
Overview of Key EU Policies and Strategies Relevant to Public Transport Decarbonization
Note. Own compilation based on official EU policy documents (EC, 2019, 2020, 2021; EU, 2019, 2023a, 2023b).

Table 1 provides a structured overview of the main EU strategies and legislative instruments relevant to the decarbonization of public transport, summarizing their legal nature, core objectives, and stakeholder relevance.

5.1.2 Challenges and Barriers

While the EU's has introduced a wide range of policy instruments to support the decarbonization of transport, including legally binding regulations and directives, their implementation and effectiveness are constrained by several structural and procedural factors.

First, the Clean Vehicles Directive (Directive (EU) 2019/1161) imposes binding procurement targets for clean and zero-emission vehicles in the public sector. These targets are defined for two periods (2021–2025 and 2026–2030) and vary by Member State and vehicle category. However, the directive explicitly delegates responsibility for transposition and implementation to the national level, stating that "Member States shall bring into force the laws, regulations and administrative provisions necessary to comply with this Directive by 2 August 2021" (EU, 2019a). This reliance on Member State-level execution introduces variability in how and when these targets are operationalized.

Second, the rollout of alternative fuels infrastructure as mandated by the AFIR (Regulation (EU) 2023/1804) requires coordinated investments in both electric charging and hydrogen refueling facilities across the TEN-T core network. The regulation establishes mandatory minimum deployment targets, such as one high-power charging station for heavy-duty vehicles every 120 km by 2025 and hydrogen refueling stations every 200 km by 2030 (EU, 2023a). However, the Regulation acknowledges that infrastructure deployment depends on Member States' planning, reporting, and financing commitments, as formalized in national policy frameworks and subject to Commission review.

Third, the revised ETS, which extends carbon pricing to road transport and buildings, introduces a phased implementation timeline. According to Directive (EU) 2023/959, a monitoring and reporting system will be operational from 2025, while compliance obligations - namely the purchase and surrender of emission allowances by fuel suppliers- will begin in 2027 (EU, 2023b). This delayed rollout reflects the complexity of integrating transport into emissions trading and the need for preparatory measures at the national level.

Finally, some challenges stem not from legal gaps but from the nature of non-binding strategies. The SSMS (COM(2020) 789 final) outlines over 80 action points to support a 90% reduction in transport emissions by 2050. While it sets clear objectives—such as boosting zero-emission vehicle deployment, improving multimodality, and digitalizing transport systems—it does not create binding obligations. Rather, it functions as a strategic framework guiding the development and coordination of legislative initiatives (EC, 2020).

Taken together, these policy documents highlight that while the EU has established clear legislative and strategic instruments, the practical realization of decarbonization objectives remains dependent on multi-level coordination, national implementation capacity, and sustained financial commitment.

5.1.3 Strategic Responses and Adaptations

In response to the structural and regulatory challenges outlined above, national and subnational authorities across the EU have adopted a range of strategic approaches to support the decarbonization of public transport. These strategies differ significantly in scope, funding structure, and administrative effectiveness.

At the national level, some Member States have developed dedicated programmes to co-finance the transition to zero-emission bus fleets. One notable example is Austria's EBIN programme, established by the Federal Ministry for Climate Action. The programme provides targeted support for the procurement of battery-electric, hydrogen, and trolley buses as well as the required charging and refueling infrastructure. Funding is allocated based on a competitive selection process and covers up to 80% of the additional costs for vehicles compared to conventional diesel buses, and up to 40% of infrastructure costs. The programme's legal basis is the *Sonderrichtlinie zur Förderung der Umstellung auf emissionsfreie Busflotten im öffentlichen Personenverkehr*, which was published in the context of Austria's national Recovery and Resilience Plan. As of 2024, the EBIN programme aims to support the deployment of up to 682 clean buses by 2026, and explicitly links funding to operational feasibility and long-term climate objectives (FFG, 2025).

Germany has also introduced a national-level funding scheme under the Federal Ministry for Digital and Transport: The *Richtlinie zur Förderung alternativer Antriebe von Bussen im Personenverkehr.* Since 2018, this programme has financed the purchase of more than 1,500 battery-electric buses and includes support for depot charging, planning services, and personnel training. It has been credited with significantly accelerating the market rollout of electric bus fleets, particularly in medium-sized and large cities (BMWK, 2024).

At the municipal level, some cities have developed independent decarbonization strategies. At the municipal level, several European cities have taken proactive steps to integrate climate and transport policies. For example, the City of Vienna has established a dedicated e-mobility strategy that includes investment frameworks, planning targets for the electrification of public transport, and urban infrastructure adaptation. These measures are part of a wider political effort to align municipal transport policy with national and EU decarbonization goals (Wiener Linien, 2022). Cities like Hamburg, Paris, and Oslo have as well issued diesel bus phase-out targets and aligned procurement with national climate strategies.

Although significant EU funding has been directed towards sustainable urban transport, the actual impact on modal shift varies greatly across Member States. This suggests that funding alone is insufficient without coherent planning and implementation at national and local levels.

Furthermore, the EEA reports that the transport sector continues to be a significant contributor to greenhouse gas emissions within the EU. Road transport, in particular, remains a major source of emissions, and the transition to cleaner mobility solutions is progressing slowly. The EEA emphasizes that, despite policy efforts, the overall impact on emission reductions has been limited, underscoring the need for more effective implementation of decarbonisation strategies at both national and municipal levels (EEA, 2021).

These cases illustrate that while the EU provides the overarching regulatory and strategic framework, the actual pace of decarbonization depends heavily on the ability of national and local authorities to translate these goals into concrete, well-financed, and administratively supported strategies. The presence of dedicated co-financing programmes, streamlined procedures, and long-term planning structures has proven essential for enabling PTOs to invest in zero-emission technologies.

5.1.4 Strategic Goals and Objectives

The strategic objectives pursued by EU policymakers in the context of public transport decarbonisation can be grouped into four overarching categories: environmental, economic, social, and institutional. Each category encompasses several distinct but related priorities, as set out in the Green Deal and the legislative instruments presented in **Chapter 5.1.1.**

From an **e**nvironmental perspective, the EU's primary objective is to achieve climate neutrality by 2050, with an interim target of reducing greenhouse gas emissions by at least 55% by 2030, as codified in the European Climate Law and operationalised through the Fit for 55 package (EC, 2021a). Transport, particularly road transport, is explicitly identified as a high-impact sector requiring accelerated decarbonisation. Instruments such as the revised CO_2 emission standards for heavy-duty vehicles and the Clean Vehicles Directive enforce emission targets by mandating zero-emission bus adoption and fleet renewal (EC, 2023; EU 2019a). Public transport is also expected to contribute to air quality improvement, especially in urban areas. These policies position decarbonisation as both a climate and public health measure. Thus, public transport is expected to become increasingly emission-free, climate-aligned, air-quality-enhancing and all of that in a rapid pace.

In terms of economic and industrial goals, the EU aims to ensure that the green transition strengthens rather than undermines European industrial competitiveness. The Net-Zero Industry Act introduces a production benchmark requiring that at least 40% of the EU's annual demand for key clean technologies - such as batteries, hydrogen fuel cells, and grid systems - be met by domestic production by 2030 (EU's, 2024b). This supply-side strategy complements demand-side regulation by providing manufacturers and investors with a more predictable and self-sufficient market environment. Additionally, regulatory tools like the CO_2 standards and CVD incentivise technological innovation by requiring manufacturers to bring viable zero-emission models to market. These efforts are designed to make the sector not only environmentally sustainable but also competitive, innovation-driven, and cost-effective in the long run.

Policymakers also pursue important social goals. The Sustainable and Smart Mobility Strategy frames public transport as a universally accessible service that must remain affordable and reliable, even as it transitions to zero-emission operation (EC, 2020). The extension of the Emissions Trading System to road transport (ETS2) introduces financial incentives for emission reductions but also risks increasing mobility costs. To mitigate this, the Social Climate Fund has been established to support vulnerable households and regions, thereby promoting a just and equitable transition (Directive (EU) 2023/959). These instruments underline the EU's commitment to an inclusive transformation that maintains affordability, social fairness, and accessibility in public transport systems.

Finally, the realisation of these goals depends on a robust institutional and governance framework. The Alternative Fuels Infrastructure Regulation (AFIR) ensures that adequate charging and refuelling networks are in place, thereby removing a major practical barrier to the rollout of zero-emission fleets (EU, 2023a). The NZIA, in turn, streamlines permitting procedures for strategic manufacturing projects and promotes clustering and workforce training, thus strengthening administrative capacity (EU, 2024b). Across all instruments, there is a clear emphasis on improving coordination between governance levels, ensuring enforceability of targets, and securing long-term investment conditions. Policymakers therefore aim to make public transport policy more governable, plannable, and enforceable. While the objectives outlined above are generally aligned, certain internal tensions may arise - for instance, between emission-free and affordable, or between innovation-driven and governable. These will be further explored in **Chapter 5.4**.

5.2 Public Transport Operators (Demand Side)

PTOs form the operational core of urban mobility systems in the EU. They are tasked with providing regular, accessible, and increasingly sustainable bus, tram, and metro services in urban and suburban areas. These services are essential not only for daily commuting but also for broader goals such as social inclusion, congestion mitigation, and environmental protection. PTOs typically operate under municipal ownership or through delegated public service contracts, subject to regulatory oversight and procurement procedures defined at both national and EU levels.

5.2.1 Overview and Context

Modal Split and Passenger Transport Volumes

Although numerous public policy initiatives over the past decades have sought to promote environmentally sustainable mobility, private car usage continues to dominate passenger transport across the EU. According to the EC's *EU Transport in Figures – Statistical Pocketbook 2024*, passenger cars accounted for 72.9% of total inland passenger transport in 2021 (EC, 2024). In comparison, buses and coaches represented just 7.1%, while urban rail systems, including trams and metros, accounted for a mere 1.7% of the total passenger-kilometres travelled.

These figures highlight a clear imbalance in the distribution of transport modes, with a strong emphasis on private motorised transport. However, the situation differs when examining urban contexts in an isolated way. In cities - particularly those lacking comprehensive metro or tram systems - buses play a more significant role. They often serve as the backbone of local public transport, especially in small and medium-sized urban areas where alternative high-capacity rail-based infrastructure is either not present or not economically feasible.

Data published by the European Union Road Federation (2023) show that in several Member States, the modal share of buses in inland passenger transport reaches double-digit percentages. For example, Romania reported a share of 14.75%, followed by Ireland with 12.27%, and Italy at 10.09%. These values contrast sharply with countries where active mobility or rail-based transport modes are dominant. In the Netherlands, the modal share of buses was only 2.08%, while Denmark reported 6.76%, which can be attributed to well-developed cycling infrastructure and regional train services.

These differences illustrate the varying importance of buses across national and urban transport systems in the EU. In many cases, buses are not only a key component of existing mobility patterns but also represent a flexible and cost-efficient option for improving sustainable transport in urban areas - especially in places where the development of rail systems would involve significant financial and technical challenges.

Fleet Size and Composition

With several hundred thousand vehicles in operation across Europe, urban buses represent one of the most widely deployed and accessible modes of public transport. In 2021, the total number of buses in use across the EU-27 was approximately 754,000, a figure that includes both urban and interurban services (EC, 2024). Of this total, it is estimated that roughly 215,000 vehicles are deployed specifically in urban environments (Rabobank, 2023), although exact figures differ by country depending on the classification systems used for fleet reporting.

In addition to their overall scale, bus fleets across the EU exhibit substantial variation in both vehicle age and technological maturity. According to data published by FuelsEurope (2024), the average age of the EU bus fleet was 12.7 years in 2021. However, this figure conceals marked disparities between Member States. For example, Romania operated the oldest fleet in the EU, with an average vehicle age of 20.2 years, while other countries such as Greece, and Poland also reported significantly aged fleets. By contrast, only eight EU Member States maintained a bus fleet with an average age below 10 years, indicating faster fleet renewal cycles and more consistent investment in public transport infrastructure (FuelsEurope, 2024).

The advanced average age of buses in many Member States reflects a slow pace of technological renewal, driven by a combination of financial constraints, long operational lifespans of vehicles, and - in several cases - a lack of dedicated public funding for sustainable fleet modernisation. These older buses are predominantly diesel-powered and often fall short of current standards in emissions and energy efficiency, thereby raising concerns regarding both their environmental performance and their compatibility with national and EU decarbonisation targets. From an operational perspective, ageing fleets also tend to incur higher maintenance costs, lower reliability, and limited compatibility with emerging technologies such as low-noise or digitally connected systems, all of which pose structural challenges for public transport operators across Europe.

The composition of newly registered buses in the EU has undergone a significant shift in recent years, reflecting broader decarbonisation goals and technological developments. While statistics from 2021 still reflected a dominance of conventional drivetrains, more recent figures reveal a major acceleration in the uptake of zero-emission technologies.

According to the ACEA, 68.8% of all new buses registered in the EU in 2021 were powered by diesel engines. Electrically-chargeable buses accounted for 10.6%, non-plug-in hybrid buses made up 10.1%, and buses running on alternative fuels such as CNG/LNG represented 10.5%. In total, 31.2% of new bus registrations in 2021 were powered by alternative drivetrains (ACEA, 2022). These figures refer to all bus categories - including intercity and coach segments - which have historically been slower to adopt low-emission technologies.

However, when focusing specifically on urban public transport, and looking at the most recent data from 2023, a much different picture emerges. According to Transport & Environment (2024), battery-electric Vehicles became the most commonly registered powertrain for new city buses in the EU, making up 36% of new urban bus registrations, while diesel fell to 33%. Zero-emission Buses [ZEB], including both BEBs and Fuel Cell Electric Buses [FCEB], reached a combined market share of 42% - indicating that nearly every second city bus procured in the EU in 2023 was emission-free (Sustainable Bus, 2024).

This transformation is especially pronounced in frontrunner countries. In 2023, the Netherlands, Denmark, Finland, Ireland, and Slovenia each reported ZEB shares exceeding 90% in their newly registered city bus fleets. In contrast, several Member States - particularly in Eastern and Southern Europe - continue to rely heavily on diesel, due to funding constraints, fragmented procurement systems, and limited infrastructure readiness (Transport & Environment 2024).

The contrast between the 2021 ACEA data and the 2023 Transport & Environment findings illustrates both the speed and asymmetry of the transition. While diesel continues to dominate the overall EU bus fleet, especially in the intercity segment, the rapid rise in zero-emission urban bus procurement signals a clear directional shift in public transport policy and investment. For public transport operators, this development implies a growing need to adapt operations, infrastructure, and staff competencies to meet the requirements of electrified fleets.

Urban buses are among the most visible and policy-sensitive segments of public transport. Their high operational frequency, fixed routes, and centralized fleet ownership make them an ideal entry point for the rollout of zero-emission technologies. As such, they are often targeted by EU funding instruments and regulatory mandates (e.g. Clean Vehicles Directive), serving as flagship projects in national decarbonisation strategies.

5.2.2 Challenges and Barriers

The transition to zero-emission bus fleets presents PTOs across the EU with a complex array of challenges that extend far beyond the procurement of vehicles. These barriers span operational, financial, infrastructural, and institutional dimensions and often vary according to local context and technical configurations.

One major challenge concerns the overall cost structure of electrified fleets. A recent simulation-based study by Sistig et al. (2025), which modelled 20 German transit networks under various electrification scenarios, found that BEBs operations lead to an average increase of 12% in TCO compared to conventional diesel systems. This increase is driven primarily by higher vehicle procurement costs and investments in depot-based charging infrastructure. Although reduced energy and maintenance costs partially offset these expenditures, they are not sufficient to close the gap entirely.

Electrification also increases the number of vehicles needed to maintain current service levels. In the same study, the number of buses required rose by 13% on average, mainly due to limited driving range and charging time constraints. Especially for transit systems with high daily mileage and few operational breaks, additional vehicles are necessary to accommodate extended downtimes for charging and to prevent disruptions to timetables (Sistig et al., 2025).

Depot and grid infrastructure present another critical barrier. Most existing bus depots in Europe were not designed to support high-power charging or hydrogen refuelling infrastructure. Retrofitting depots involves complex planning, coordination with utility providers, and—in many cases—cost-intensive grid reinforcement. While the Interreg Europe (2022) report from the eBussed project confirms that these issues are widely observed across multiple European partner cities of the Maltese Public Transport (e.g. Hamburg, Turku, Tartu), it also highlights its own specific case, where the lack of available depot space and grid capacity is particularly pronounced. These structural constraints can significantly delay electrification efforts or limit their scope.

Charging performance and operational flexibility are further affected by technical constraints. Sistig et al. (2025) demonstrate that low-power charging configurations (e.g. 60–120 kW) can result in daily charging times of up to 9.4 hours per vehicle, making them unsuitable for high-frequency routes. Higher-power charging (e.g. 450 kW) reduces dwell times but requires substantial investment in equipment and energy supply. For many PTOs, identifying the optimal charging strategy under financial and infrastructural limitations remains a key bottleneck in implementation.

Vehicle scheduling and driver operations are also impacted. Although the increase in paid driver time observed in electrification scenarios is modest (around 2%), the number of required driver duties grows by 6%, suggesting reduced shift efficiency and increased personnel demand (Sistig et al., 2025). This effect is particularly relevant in the context of an EU-wide shortage of qualified drivers.

Additional barriers relate to climatic and topographic conditions, which influence vehicle energy demand. The eBussed project notes, for instance, that auxiliary loads such as heating and cooling can account for over 30% of total energy consumption, depending on regional climate. While this is mentioned in the context of Malta, similar constraints have been observed in Nordic and Central European partner cities (Interreg Europe, 2022). This variability complicates range planning and battery sizing, especially when „one-size-fits-all“ procurement strategies are applied.

Lastly, institutional fragmentation and short planning horizons impede strategic investment. According to findings from the eBussed network, many PTOs—particularly those in smaller municipalities - lack the administrative resources and long-term contractual security to engage in complex procurement and infrastructure projects. This is further exacerbated where service provision is managed under short public service contracts or via decentralised governance structures, which limits the ability to coordinate infrastructure upgrades, access funding, or launch joint tenders.

These challenges highlight that the deployment of zero-emission bus technologies is not only a question of vehicle selection but is closely linked to practical limitations in cost, infrastructure, and operational feasibility. Addressing these barriers is essential for evaluating the suitability of different technologies in light of public transport operators' objectives.

5.2.3 Strategic Responses and Adaptations

PTOs in the EU are responding to rising regulatory and market pressures with a range of strategic adaptations. The policy environment shaped by instruments such as the European Green Deal, the Fit for 55 Package, and the Clean Vehicles Directive has triggered structural shifts in vehicle procurement, infrastructure investment, and operational planning.

A key driver of this transformation is the Clean Vehicles Directive, which mandates Member States to ensure that 24% to 45% of newly procured public service buses between 2021 and 2025 qualify as "clean vehicles", with higher targets applying from 2026 onwards. This legal framework has prompted operators to accelerate the integration of ZEBs into their fleets and re-evaluate long-term investment strategies (EU, 2019a).

One major response observed in several European networks is the gradual shift toward BEBs. In practice, this transition often involves more than a simple fleet replacement. The adoption of BEBs under realistic scheduling and energy scenarios typically leads to a 13% increase in fleet size and a 12% increase in TCO, due to charging-related downtime and additional vehicle requirements. These findings underline that electrification must be accompanied by broader operational restructuring (Sistig et al., 2025).

To address such implications, many PTOs are adapting their infrastructure and depot configurations. According to the same study, charging power availability is more critical than battery size in determining operational flexibility. Operators increasingly favour high-power depot charging solutions (e.g. 360–450 kW), which can reduce downtime and avoid excessive range oversizing (Sistig et al., 2025).

On the operational side, electrification affects vehicle dispatching and staff scheduling. The study reports a 6% increase in driver duties and a 2% rise in total paid driver time in the analysed networks, indicating the need for dynamic duty planning tools and more flexible crew management systems (Sistig et al., 2025).

Where technical expertise is limited, operators seek external support for fleet simulation, energy planning, or funding applications. Although these activities are not always formalised in strategic partnerships, case-based evidence suggests growing cooperation with local authorities and service providers, particularly regarding depot conversion and energy supply coordination (Interreg Europe, 2022).

In addition, operators are increasingly using phased rollout approaches and pilot-based procurement strategies. Before large-scale electrification, many test different drive technologies under local conditions to assess their suitability. This stepwise approach allows PTOs to make data-driven decisions and mitigate the risks associated with technology selection, climatic variability, or topographic constraints.

Strategic adaptation also includes a broader perspective on cost-efficiency, as many operators move beyond acquisition prices and include life-cycle costs and operational robustness in their technology evaluations. Sistig et al. (2025) highlight that integrating life-cycle cost modelling and energy demand forecasting into decision processes can significantly improve the long-term viability of procurement choices.

Taken together, these strategic responses demonstrate that public transport operators are not merely reacting to policy targets but are actively reconfiguring vehicle procurement, depot infrastructure, and operational systems to support a controlled and context-sensitive transition to zero-emission fleets.

5.2.4 Strategic Goals and Objectives

The strategic objectives pursued by PTOs in the context of fleet decarbonisation can be grouped into five overarching categories: operational, environmental, economic, technological, and user-facing. These goals are shaped both by external policy pressures and by internal performance requirements.

From an operational perspective, PTOs aim to uphold stable service delivery despite the technical constraints associated with zero-emission fleets. Electrification reduces vehicle range and increases the need for charging breaks, which challenges traditional scheduling and depot routines. Operators therefore prioritise keeping services punctual, dependable,

and scalable across different route types. Their operational goals are thus reliable, schedule-compatible, and infrastructure-compatible.
From an environmental perspective, operators contribute to the EU's climate agenda by accelerating fleet decarbonisation and reducing local emissions. This includes compliance with procurement targets under the Clean Vehicles Directive and alignment with national or municipal climate strategies. Their environmental goals are clean, climate-aligned, and future-proof.
From an economic perspective, operators must reconcile rising capital expenditures with limited public budgets and fare revenues. While long-term energy and maintenance savings are expected, the initial investment remains high. To ensure sustainable financing, PTOs aim for procurement and planning processes that are affordable, cost-effective, and financially viable.
From a technological perspective, fleet electrification requires new digital tools for scheduling, charging, diagnostics, and performance management. PTOs increasingly view innovation not as a risk, but as a means to enhance operational efficiency and system flexibility. Their technology-related goals are therefore innovative, data-driven, and integration-ready.
From a user-facing perspective, operators must ensure that public transport remains attractive during the transition. Service quality must be preserved even when vehicles change. Accessibility, frequency, and comfort remain central performance indicators. Accordingly, PTOs pursue goals that are user-oriented, inclusive, and service-stable.
While these objectives are largely complementary, they are not free from tension. For instance, infrastructure-compatible and climate-aligned goals may conflict with affordability, or innovation may challenge reliability. These trade-offs, and their implications for technology choice, will be explored in **Chapter 5.4**.

5.3 Manufacturers and Suppliers (Technology Supply Side)

As pivotal actors in the decarbonisation of public transport, vehicle manufacturers and suppliers operate at the intersection of technological innovation, regulatory pressure, and evolving market dynamics. This chapter provides an overview of the commercial vehicle market and explores the structural, competitive, and strategic dimensions that shape their role in enabling zero-emission mobility solutions.

5.3.1 Overview and Context

The European commercial vehicle sector - particularly in the urban bus segment - plays a pivotal role in the technological transformation towards zero-emission mobility. The industry comprises a concentrated group of original equipment manufacturers [OEM], component suppliers, and technology integrators that develop and deliver the core platforms, propulsion technologies, and system components for public fleets across the EU. This section outlines the structural configuration of the market, key manufacturer profiles, and the current state of technology used in zero-emission public transport vehicles.
The market for public transport buses in the EU is dominated by a small number of established manufacturers. These include Daimler Buses (Mercedes-Benz), the Traton Group - which comprises MAN and Scania -, Volvo Group, Iveco Bus, Solaris, and Van

Hool. In the segment of ZEBs, additional manufacturers have gained relevance in recent years, most notably BYD and Yutong from China, as well as Wrightbus from the UK and VDL Bus & Coach from the Netherlands (Sustainable Bus, 2024).
In 2023, MAN was the leading manufacturer of newly registered electric city buses in the EU, followed closely by Solaris and Yutong. MAN, Solaris, and Karsan each accounted for approximately 12% of the EU's newly registered zero-emission buses, with the remaining market distributed among BYD, Irizar, VDL, Wrightbus, and others (ICCT, 2025). The growing presence of Chinese manufacturers in the EU market, particcularly BYD and Yutong, has been facilitated by vertically integrated supply chains and competitive pricing strategies (Sustainable Bus, 2024).
The electric bus market represents a particularly dynamic and strategically important segment within the public transport sector. While diesel buses continue to dominate in many regions, the share of zero-emission city buses in new registrations across the EU rose from 15% in 2020 to 42% in 2023 (ICCT, 2025). This shift is largely driven by regulatory incentives, national and EU-level funding programmes, and the expanding availability of mature product platforms. In several member states, local governments have published fleet decarbonisation strategies with defined phase-out dates for diesel-powered buses, reinforcing the market momentum for ZEB adoption.
BEBs represent the most mature and widely deployed ZEB solution in the EU public transport sector. Major OEMs including MAN (Lion's City E), Mercedes-Benz (eCitaro), Solaris (Urbino Electric), BYD (eBus series), and CaetanoBus (e.City Gold) offer fully electric platforms with modular battery configurations (MAN Truck & Bus, 2025; Mercedes-Benz Buses, 2025; Solaris, 2025; BYD, 2025; CaetanoBus, 2025). These models are typically designed for 12-meter city bus applications and offer compatibility with both depot and opportunity charging systems. Pantograph charging and high-power plug-in interfaces are increasingly standardised in EU fleets with high daily utilisation.
FCEBs, although still in early commercialisation stages, offer an emerging alternative. Solaris (Urbino Hydrogen) and CaetanoBus (H2.City Gold) are among the leading manufacturers active in this segment (Solaris, 2025; CaetanoBus, 2025). FCEBs enable longer daily operating ranges and faster refuelling compared to BEBs, making them suitable for networks with limited charging infrastructure.
Tier 1 suppliers play a critical role in enabling OEMs to meet performance and energy management requirements. Key suppliers include Siemens (power electronics), Akasol/BorgWarner (battery systems), Bosch (control units and e-drives), and Voith (electric drivetrains). The degree of vertical integration varies significantly across manufacturers: Traton and Daimler internalise large portions of electric drivetrain development, whereas Solaris and Van Hool employ more modular architectures based on third-party components. In contrast, BYD pursues a vertically integrated strategy, developing both battery packs and electric drivetrains in-house (EVboosters, 2025).
Deployment of zero-emission buses in the EU remains geographically uneven. In 2023, Germany accounted for 17% of all newly registered zero-emission buses in the EU, followed by France and the Netherlands (ICCT, 2025). These countries benefit from established industrial capacities, early-stage public procurement policies, and a dense charging infrastructure. In contrast, diesel and CNG buses continue to dominate the fleets in several Central and Eastern European countries. Nonetheless, EU funding programmes and pilot projects have initiated a gradual shift towards ZEBs in these regions as well.

In terms of technology maturity, BEBs are now considered commercially viable for most urban applications, supported by robust charging infrastructure and increasingly modular vehicle designs. Conversely, fuel cell buses are still in the early phases of market scaling and are highly dependent on the availability of hydrogen production and refuelling networks. Ancillary technologies such as intelligent thermal management, predictive energy control, regenerative breaking, and integrated fleet analytics are increasingly embedded in electric bus platforms, although their degree of sophistication and standardisation varies across OEMs.

Overall, the manufacturing landscape for urban public transport vehicles in the EU is shaped by incumbent industrial players, regionally differentiated deployment levels, and a growing divide between technologically integrated OEMs and those relying on modular, supplier-based architectures. The strategic alignment of product platforms, supply chains, and ancillary technologies will critically influence the pace and direction of public fleet decarbonisation across the EU.

5.3.2 Challenges and Barriers

Public transport vehicle manufacturing is characterised by long development cycles, strict regulatory environments, and fluctuating market dynamics. Even before the transition to zero-emission technologies, bus manufacturers faced structural challenges related to global competition, cost pressures, and technological complexity. The industry is dominated by a small number of established players who must continuously adapt to evolving public procurement requirements, safety standards, and expectations for vehicle reliability and lifecycle performance. At the same time, fluctuating raw material prices, variable public tender volumes, and limited standardisation in vehicle configurations across EU countries have long constrained cost efficiency and production scalability. These conditions already posed significant difficulties for OEMs and now provide the foundation on which the additional pressures of the zero-emission transition are building.

The transition to zero-emission vehicle platforms presents manufacturers with a wide range of challenges that go well beyond the development of drivetrains. These challenges include economic, technological, and infrastructural aspects and are made more difficult by market fragmentation, inconsistent policy environments, and the limited flexibility of global supply chains in responding to rapid technological change.

One major challenge concerns the capital intensity of zero-emission bus production. Unlike conventional diesel platforms, battery-electric and fuel cell buses require completely redesigned modular architectures, specialised production equipment, and appropriately trained staff. Recent studies confirm that the production of these platforms remains costly, particularly when economies of scale and stable procurement volumes are lacking. Price ranges for solo BEBs currently lie between €520,000 and €650,000, while hydrogen-powered alternatives exceed €800,000 per unit (NASA, 2024; EMCEL, 2018). These high upfront costs significantly limit the feasibility of large-scale procurement, especially when long-term funding frameworks are missing. Detailed cost comparisons will be presented in **Chapter 6.**

In addition to these cost barriers, OEMs operate within a fragmented and often unpredictable demand environment. Public procurement cycles depend on political decisions, infrastructure readiness, and short-lived funding programmes. According to

BMWK (2024), this situation discourages long-term production planning and increases the risk for manufacturers, delaying both investment decisions and industrial transformation.

Technological and infrastructural bottlenecks further intensify the situation. OEMs remain heavily reliant on Tier 1 suppliers for key components such as power electronics, batteries, and fuel cell systems. In parallel, the increasing presence of highly competitive international bus manufacturers—particularly from China and the Netherlands—has altered the technological and economic dynamics in the EU market. Rabobank (2024) highlights that this shift has intensified pressure on European OEMs to adapt to new innovation cycles, cost structures, and trade conditions in order to remain competitive. The e-mobil BW (2023) study also points to the strategic risks associated with limited access to critical inputs such as lithium and platinum.

Another source of pressure is the growing demand for advanced software systems and integrated thermal and energy management tools. Manufacturers are increasingly expected to provide vehicles that not only function reliably under varying operational conditions but also interface effectively with a range of external systems, including depot infrastructure and fleet management platforms. This creates challenges for ensuring compatibility across different operating environments and often requires technical adjustments to meet diverse specifications. As a result, manufacturers face higher development costs and more complex coordination demands within their supply chains.

OEMs also face practical challenges related to the lack of harmonisation in charging and refuelling infrastructure. Differences in pantograph designs, plug types, and data communication protocols between EU member states make it difficult to offer fully compatible vehicle platforms. This lack of standardisation undermines economies of scale and complicates cross-border vehicle deployment, especially for smaller market players.

Fuel cell buses present additional economic and infrastructural difficulties. Although these vehicles provide longer driving ranges and faster refuelling than battery-electric models, they continue to be affected by high hydrogen prices, complex depot requirements, and time-consuming approval procedures. EMCEL (2024) reports that average unit prices for FCEBs are still significantly high, while e-mobil BW (2024) notes that hydrogen infrastructure for heavy-duty transport - including buses - is still in early-stage deployment, with sparse refuelling locations and regional disparities in network availability.

Finally, the absence of consistent regulations across EU countries leads to considerable planning uncertainty. As highlighted in the NASA (2024) study, the lack of harmonised procurement standards and funding instruments makes it difficult for manufacturers to coordinate production and investment strategies across national markets. This increases administrative complexity, slows platform standardisation, and inhibits broader market development.

These challenges show that the shift toward zero-emission bus manufacturing is not only a technological evolution, but also an institutional and structural transformation of the European automotive industry. Addressing these barriers will require close cooperation between public and private actors, strengthened supply chain resilience, and a stable EU-wide investment framework for OEMs.

5.3.3 Strategic Responses and Adaptations

Vehicle manufacturers have responded to the accelerating decarbonisation agenda in the EU by implementing targeted changes in product strategy, industrial collaboration, and supply chain management. Unlike general statements of intent, these actions reflect concrete adaptations to new regulatory obligations and shifting market expectations resulting from the EGD, Fit for 55, revised CO_2 standards for HDVs, and the CVD.

One of the most visible responses has been the adjustment of product development priorities. In light of the revised CO_2 standards for HDVs, OEMs have announced new model series based exclusively on battery-electric and hydrogen fuel cell drivetrains. Simultaneously, several manufacturers have reduced investments in diesel platforms or announced phase-outs for city buses in this segment (Rabobank, 2024).

In light of binding procurement quotas under the Clean Vehicles Directive, which requires minimum shares of clean vehicles in public transport tenders, manufacturers have increasingly aligned their product portfolios and market offerings with public sector demand (EU, 2019a; BMWK, 2024). The regulatory framework has provided strategic direction that supports long-term investment planning and regional positioning in key EU markets.

Strategic partnerships have become another key element of industry response. OEMs increasingly cooperate with battery suppliers, hydrogen technology firms, and software providers to accelerate development timelines and reduce technological risk. For instance, collaborations now extend to the co-development of thermal management systems, intelligent charging interfaces, and remote diagnostic platforms—all aimed at supporting the operational viability of zero-emission fleets (WRI, 2019).

In parallel, supply chain resilience has become a strategic priority. In response to growing dependencies on imported raw materials such as lithium and platinum (e-mobil BW, 2024), many manufacturers have expanded vertical integration, secured long-term contracts, or engaged in joint ventures to localise component production (Rabobank, 2024). These steps aim to reduce exposure to external shocks and ensure cost stability in the production of zero-emission drivetrains.

Manufacturing operations themselves are undergoing significant change. Several OEMs have introduced dedicated assembly lines for electric buses, upgraded production tooling, and implemented workforce training programmes focused on high-voltage systems and digital components. These internal transformations are indicative of a broader shift from conventional industrial structures to clean technology production ecosystems.

Taken together, these developments demonstrate that European bus manufacturers are not merely reacting passively to regulatory change but actively shaping their role in the zero-emission transition. The regulatory framework has functioned not only as a compliance mechanism but as a catalyst for targeted innovation and structural transformation.

5.3.4 Strategic Goals and Objectives

The strategic objectives pursued by vehicle manufacturers in the context of public transport decarbonisation relate primarily to the development and deployment of advanced vehicle technologies that meet evolving policy requirements and market expectations. These objectives can be grouped into three interrelated categories: regulatory compliance, operational compatibility, and economic scalability. Each category reflects the role of

manufacturers as technology developers within the broader EU decarbonisation framework.
From a regulatory perspective, OEMs aim to develop vehicle technologies that enable compliance with binding CO_2 reduction targets and procurement obligations. Battery-electric and hydrogen fuel cell drivetrains are central to this requirement, as they allow manufacturers to meet zero-emission definitions and avoid penalties. Accordingly, the technologies under development are intended to be regulation-compliant, emission-free in operation, and aligned with applicable fleet standards (EU, 2024a).
In terms of operational performance, manufacturers seek to ensure that zero-emission buses can be integrated into existing public transport systems without compromising service quality. This includes the development of platforms with adequate range, fast-charging capability, thermal resilience, and digital connectivity. In addition, vehicle designs must be compatible with depot infrastructure, scheduling constraints, and varying route profiles. As a result, OEMs pursue technologies that are reliable, interoperable, scalable, and operator-oriented (WRI, 2019).
From an economic standpoint, the focus lies on developing solutions that are cost-effective over the vehicle lifecycle and suitable for large-scale procurement. In addition to being affordable and attractive for public transport operators, zero-emission technologies are also expected to generate adequate margins for manufacturers and contribute to long-term profitability. This includes modular battery systems, energy-efficient drivetrains, and streamlined production architectures. Manufacturers aim to ensure that their zero-emission technologies are affordable, durable, and replicable in different regional contexts (Rabobank, 2024).
These technology-focused objectives are not mutually exclusive but interdependent: achieving regulatory compliance depends on both environmental performance and operational feasibility, while cost control influences both innovation and deployment. Nevertheless, trade-offs can arise—for example, between maximising energy storage and keeping vehicle weight low, or between ensuring compatibility with multiple charging systems and limiting production complexity. Further tensions may occur between offering tailor-made solutions for operators and maintaining standardised, cost-efficient platforms. These tensions will be examined in **Chapter 5.4**.

5.4 Cross-Stakeholder Dynamics and Alignment Potential

This chapter examines the interrelations, overlaps, and divergences among the strategic objectives pursued by key stakeholders in the EU public transport sector. As the decarbonisation of public transport is a multi-actor challenge, successful implementation depends not only on technological progress and regulation, but also on the degree of goal alignment between these actors. The chapter begins by mapping the objectives identified in **Chapters 5.1** to **5.3** into thematic clusters, before analysing potential trade-offs and proposing strategic levers to promote alignment. The analysis will be guided by a stakeholder alignment matrix that highlights the degree to which different objectives can be synchronised, prioritised, or strategically reconciled.

5.4.1 Overview of identified Goals

To establish a basis for analysing stakeholder divergences and alignment potential, **Table 2** provides a structured overview of the strategic objectives identified for each actor group. Drawing on **Chapters 5.1.4, 5.2.4,** and **5.3.4**, these objectives are grouped thematically into four overarching dimensions: environmental-regulatory, economic-financial, technical-operational, and social-user-oriented. While not all objectives are exclusively linked to decarbonisation, they reflect the broader strategic priorities that shape technology decisions, investment frameworks, and implementation timelines in the sector. **Table 2** summarises these objectives in adjectival form to enable subsequent comparison. It does not assess the fulfilment or compatibility of these goals, but provides a descriptive overview to help with the comparison and discussion of stakeholder goals.

Stakeholder	Environmental / Regulatory	Economic / Financial	Technical / Operational	Social / User-oriented
Policymakers	emission-free, climate-aligned, air-quality-enhancing, rapid, governable, plannable, enforceable	competitive, innovation-driven, cost-effective	-	affordable, socially fair, accessible
PTOs	clean, climate-aligned, future-proof	affordable, cost-effective, financially viable	innovative, data-driven, integration-ready, reliable, schedule-compatible, infrastructure-compatible	user-oriented, inclusive, service-stable
OEMs	regulation-compliant, emission-free, standard-aligned	affordable, durable, replicable	reliable, interoperable, scalable, operator-oriented	-

Table 2
Overview of Strategic Objectives by Stakeholder Group and Strategic Dimension
Note. Own compilation based on Chapters 5.1.4, 5.2.4, and 5.3.4.

5.4.2 Stakeholder Divergences and Tensions

Building on the overview of stakeholder goals, this section explores where strategic objectives conflict, overlap, or require negotiated trade-offs. Although many objectives are not inherently conflicting - such as promoting zero-emission transport while maintaining high service quality and operational reliability - they can become difficult to align in practice due to real-world constraints such as limited budgets, infrastructure gaps, or transitional disruptions. For example, aligning ambitious environmental targets with fiscal constraints may create tension between long-term sustainability and short-term affordability, particularly for public transport operators with limited budgets. Similarly, strict regulatory standards can enhance investor certainty but may also limit innovation and limit technological adaptability.

To examine such tensions systematically, this section identifies a set of cross-cutting trade-off dimensions that frequently emerge in the context of public transport decarbonisation. These include:

- Environmental impact vs. cost efficiency
- Regulatory stringency vs. innovation capacity
- Technical compatibility vs. scalability

- Operational reliability vs. investment and transition
- Policy reliability vs. planning flexibility

Each dimension represents a core challenge in aligning divergent stakeholder interests, especially when policy tools and funding mechanisms must accommodate a wide variety of incentives and constraints. Analysing these trade-offs contributes to a more nuanced understanding of which compromises may be necessary, which tensions can be mitigated through design, and which may require new governance frameworks or institutional adjustments.

Rather than attempting to eliminate all conflicts, this section seeks to clarify the structural and strategic nature of the trade-offs involved. In doing so, it identifies areas where alignment may be possible through adaptive policymaking, transparent stakeholder engagement, or well-designed incentive mechanisms. This section lays the groundwork for the next section, which will explore actionable levers that can promote convergence across stakeholder objectives and support a more integrated, resilient path toward decarbonisation.

5.4.3 Strategic Levers for Alignment

In response to the key tensions outlined in the previous section, this section shifts focus to qualitative strategic levers that can help reduce misalignment and reconcile competing priorities. The emphasis here is placed on identifying concrete mechanisms—political, financial, technological, and institutional—that can promote stakeholder coordination and support the practical implementation of decarbonisation strategies. Each lever is directly connected to one or more of the tensions previously identified.

Through policy instruments, Adaptive and technology-neutral regulatory frameworks can help ease tensions between policy reliability and planning flexibility, as well as between regulatory stringency and innovation capacity. For example, instead of prescribing specific technologies, outcome-oriented regulation can set emissions targets while leaving room for local adaptation. Flexible procurement rules or staged mandates allow public transport operators to synchronise vehicle investments with infrastructure readiness, reducing the perceived risk of premature standardisation. Such frameworks enable differentiated implementation while maintaining common targets, thereby enhancing both flexibility and predictability. Adaptive and technology-neutral regulatory frameworks can allow for differentiated implementation while maintaining common targets. This includes flexible procurement rules, staged mandates, and outcome-oriented regulation.

Through financing mechanisms, Targeted subsidies, risk-sharing instruments, and long-term funding commitments are essential to manage the trade-off between environmental impact and cost efficiency and to address operational reliability versus investment and transition risk. Capital expenditure [CAPEX] support for vehicle procurement can lower initial investment barriers, while operational expenditure [OPEX] subsidies for clean energy operations ensure operational continuity during the transition. Instruments such as green bonds or blended finance models also attract private capital while sharing risk between public and private actors. These financial levers can ease financial constraints and reduce perceived investment risk, particularly for public transport operators.

Through cooperation platforms, Trust deficits and timing misalignments often widen the gap between stakeholder goals. Dialogue platforms, cross-sectoral alliances, and multistakeholder partnerships help mitigate policy reliability versus planning flexibility tensions by aligning expectations and enabling iterative policy adjustment. Regional innovation partnerships, for example, can allow vehicle manufacturers, public transport operators, and municipalities to co-develop deployment strategies, thus integrating technological capabilities with local service realities. These mechanisms foster mutual understanding, facilitate communication, and help synchronise timelines across diverse actor groups.

Through technological standardisation, The trade-off between technical compatibility and scalability can be harmonised through common standards for charging systems, digital interfaces, and certification procedures. Interoperable charging systems, shared data protocols, and harmonised certification schemes reduce system complexity and facilitate the integration of new technologies across regions and operators. Standardisation reduces complexity and investment risk for manufacturers and operators alike, allowing them to scale operations across cities and regions without facing incompatible system requirements. Moreover, common standards accelerate market development and improve long-term procurement efficiency.

Through governance innovations, Decentralised planning processes and fragmented decision-making often obstruct coordination across actors. Governance innovations help to resolve the operational reliability versus investment and transition risk tension by improving institutional capacity to manage complexity. Joint planning bodies or inter-agency task forces enhance information flow, reduce redundancies, and align infrastructure and vehicle planning with national and EU-level decarbonisation trajectories. New coordination formats—such as joint planning units, cross-agency task forces, or integrative decision boards—can institutionalise collaboration and streamline implementation across administrative boundaries, providing structure and continuity in complex multi-level governance settings.

These levers are not mutually exclusive and can be combined to form integrated strategies tailored to specific stakeholder constellations and local conditions. Their effectiveness, however, depends on political will, administrative capacity, and the timely availability of supporting infrastructure. The next section will bring these elements together by mapping goal alignments and assessing which stakeholder objectives offer the greatest potential for convergence.

5.4.4 Stakeholder Goal Alignment Matrix

Building on the previous analyses, this section consolidates the identified stakeholder goals into a qualitative matrix to assess alignment potential and identify focal areas for technology evaluation. While the preceding chapters have outlined diverging objectives and potential strategic levers to bridge them, this section turns to the question of which goals are widely shared and therefore offer a strong foundation for coordinated decarbonisation strategies.

The alignment matrix is based on the thematic goal categories introduced in **Chapter 5.4.1** and assesses each dimension with respect to its relevance, stakeholder coverage, and strategic impact. Objectives that appear across multiple stakeholder groups - particularly in areas such as environmental compliance, cost-efficiency, and operational reliability - are considered central points of convergence. These goals are not only more politically feasible but also more actionable in terms of technology procurement, infrastructure planning, and regulatory design.

Conversely, dimensions where alignment is limited - such as innovation speed, specific social goals, or long-term technological sovereignty - are more likely to remain contested and require context-specific negotiation or compensatory policy mechanisms.

The alignment matrix serves three core purposes. First, it visualises areas of strong alignment that can guide joint technology evaluation, particularly with regard to battery-electric and fuel-cell bus systems. Second, it highlights weakly aligned dimensions where further dialogue or policy intervention may be needed. Third, it provides a basis for prioritising objectives that balance feasibility, stakeholder acceptance, and climate impact.

Table 3 summarises these insights in a structured manner. It presents a qualitative assessment of stakeholder alignment across four strategic goal dimensions. Each row reflects one of the thematic categories introduced in **Chapter 5.4.1**, while the columns indicate the degree to which each stakeholder group - policymakers, PTOs, and OEMs - prioritises the respective goal dimension. The rightmost column highlights the overall alignment potential, derived from the level of cross-stakeholder convergence and its applicability to technology evaluation.

As expected, environmental and economic goals show the highest levels of shared prioritisation, making them central anchors for joint decarbonisation strategies. Technical-operational goals also demonstrate moderate to strong alignment, particularly between PTOs and OEMs. Social and user-oriented goals, by contrast, remain less synchronised, especially due to their limited relevance for manufacturers. This qualitative mapping thus offers a foundation for identifying which objectives provide the most robust basis for technology assessment, scenario planning, and cross-stakeholder coordination. Given their high degree of cross-stakeholder alignment and strategic relevance, environmental and economic objectives are selected as the core evaluation criteria in **Chapter 6**. Other dimensions, such as social or technical-operational goals, while important, show lower alignment potential and are therefore considered only qualitatively or in contextual reflection. This ensures the strategic relevance and stakeholder alignment that guide the assessment framework.

6. Technological and Strategic Analysis

Achieving a climate-neutral public transport system requires not only regulatory ambition but also a grounded understanding of the available technological options and their real-world implications. **Chapter 6** provides a structured analysis of zero-emission drivetrain technologies for urban buses, focusing on their market relevance, technical characteristics, and strategic viability for public fleet decarbonization in the EU. The analysis integrates stakeholder priorities, operational parameters, and long-term economic and environmental modelling. To reflect uncertainties in real-world deployment, a dedicated sensitivity analysis tests the robustness of outcomes under varying assumptions—such as carbon pricing trajectories, fleet replacement rates, and discount factors. These elements are critical for informing resilient decarbonisation strategies and investment decisions.

Section 6.1 outlines the current market landscape for zero-emission buses (and emission reducing technologies), including key technological pathways and deployment trends across Member States. It also defines the scope of technologies selected for further analysis based on commercial maturity, policy alignment, and deployment potential.

Section 6.2 introduces the benchmark vehicle—a conventional Euro VI diesel bus—which serves as the reference point for comparisons in terms of cost, emissions, and operational feasibility.

Section 6.3 presents the evaluation framework and criteria used to assess the selected technologies. This includes financial, technical, and environmental indicators grounded in stakeholder objectives and aligned with the WTW perspective adopted in this study. A dedicated subsection (**6.3.4**) conducts a multi-parameter sensitivity analysis to assess how changes in discount rates, CO_2 pricing, and fleet conversion speeds affect the overall cost-effectiveness of battery-electric deployments. The results of all modelling sections provide the empirical foundation for the cost-benefit and policy alignment discussions in subsequent chapters.

6.1 Market Overview and Selection of Technologies

This section provides a structured overview of the technological landscape for decarbonizing urban bus fleets in the EU. It introduces the relevant zero-emission technologies, discusses excluded alternatives, and outlines the rationale for selecting specific drivetrain technologies for further analysis. The chapter concludes with an assessment of current deployment trends across Member States.

6.1.1 Overview of Zero-Emission Bus Technologies

The two primary zero-emission drivetrain technologies increasingly adopted in the EU public transport sector are BEBs and FCEBS. BEBs are powered by electricity supplied via the public grid, which is stored in on-board battery systems and used to drive electric motors. FCEBs, on the other hand, carry hydrogen in pressurized tanks and convert it into electricity using a proton exchange membrane fuel cell, which then powers an electric drivetrain. Both technologies produce no TTW emissions and are therefore classified as Zero-Emission Vehicles under EU regulation (EC, 2023).

Beyond their emission performance, BEBs and FCEBs differ in key operational characteristics. BEBs are particularly well-suited for short and medium-range urban routes with access to depot-based overnight charging infrastructure. First operational experiences with BEBs indicate considerable potential for reducing operating expenses. For instance, the Chicago Transit Authority reports five-figure annual savings per vehicle in operational and maintenance costs (Public Power Association, 2019). The Texas A&M Transportation Institute similarly documents significantly lower maintenance expenditures based on a longitudinal study of electric bus deployments at several US transit agencies (Texas A&M Transportation Institute, 2020). Lower lifecycle costs are also attributed to the simplified drivetrain design of electric buses, which requires less maintenance due to fewer moving parts.

FCEBs, in contrast, offer greater range and faster refueling, making them more suitable for long-distance routes or network configurations where high operational flexibility is required. Nevertheless, their deployment remains constrained by several factors. Recent studies highlight that hydrogen refueling infrastructure is still limited in many regions, restricting scalability (Fuel Cell Buses, 2024). In addition, operators report concerns about high fuel costs and the complex maintenance requirements of fuel cell systems (Barnard, 2025). A European survey conducted by IMI Critical Engineering further found that 93% of public transport decision-makers anticipate challenges related to hydrogen storage capacity and, in the case of BEB-fleets, concerns about grid connection and power availability (IMI Critical Engineering, 2025).

These technologies have progressed beyond the pilot phase and are now increasingly being integrated into public procurement frameworks. EU-level support instruments such as the Connecting Europe Facility [CEF], the Clean Bus Europe Platform, and the Clean Hydrogen Partnership have played a key role in advancing deployment across Member States. The CEF provides co-financing for infrastructure and clean transport projects, including charging and refueling networks for alternative fuels (EC, 2025a). The Clean Bus Europe Platform fosters knowledge exchange and capacity-building for local authorities transitioning to zero-emission fleets. Meanwhile, the Clean Hydrogen Partnership supports the development and early deployment of hydrogen technologies through coordinated public-private funding efforts (EC, 2025b).

6.1.2 Alternative Drivetrains and Excluded Technologies

In addition to battery-electric and hydrogen fuel cell buses, several other drivetrain technologies are also in use within European public transport contexts. These include vehicles powered by synthetic fuels (such as e-diesel or synthetic methane), compressed natural gas (CNG), plug-in hybrid electric systems, and trolleybuses. However, these technologies are excluded from the scope of this analysis for the following reasons.

Synthetic fuels and e-gases may offer potential lifecycle greenhouse gas savings when produced using renewable electricity and carbon capture. However, these fuels are not yet market-ready at scale and currently face significant challenges regarding cost, availability, and production efficiency. Moreover, since they are combusted in internal combustion engines, they still generate TTW emissions and therefore do not qualify as zero-emission technologies under EU regulation (EC, 2023).

CNG and plug-in hybrid buses face the same issue, as they are regarded as transitional solutions. While they may help bridge the gap between conventional diesel fleets and zero-emission operation, they do not meet the criteria for zero-emission vehicles. Nevertheless, their contribution to long-term decarbonisation goals is limited, and their relevance in the European market is declining. The Clean Vehicles Directive and national procurement strategies increasingly prioritise fully zero-emission technologies, reducing the strategic importance of these interim options.
Trolleybuses and opportunity charging systems, while operationally viable in certain urban contexts, rely on extensive fixed infrastructure such as overhead lines or in-route charging stations. This significantly restricts their geographic applicability and makes large-scale deployment across varied operator environments less feasible.
For these reasons, the present study focuses exclusively on battery-electric and hydrogen fuel cell buses as the only zero-emission drivetrain technologies with broad commercial viability and policy alignment in the EU context.

6.1.3 Role of Operational Support Systems (non-drivetrain)

In the context of emission-reducing bus deployment, a range of operational support systems has emerged to enhance efficiency, reduce energy consumption, and facilitate integration into existing transport networks. These systems, while not constituting independent drivetrain technologies, are considered essential for supporting the viability and scalability of emission-reduced bus operations.
Key examples include digital fleet management software, smart depot charging systems, predictive maintenance tools, and traffic signal prioritisation technologies. Smart charging infrastructure allows operators to balance energy demand, optimise charging schedules, and reduce peak loads on the electricity grid. By aligning charging cycles with energy-efficient operating windows and renewable electricity availability, these systems directly

Stakeholder / Goal Dimension	Policymaker	PTO	OEM	Potential
Environmental / Regulatory	+++	++	+++	High
Economic / Financial	++	+++	+++	High
Technical / Operational	+	+++	++	Moderate to High
Social / User-oriented	+	++	-	Low to Moderate

Table 3
Stakeholder Goal Alignment Matrix
Note. Qualitative assessment of shared strategic objectives across EU policymakers, operators, and manufacturers, based on thematic goal categories identified in Chapter 5.4.1. The scale ranges from + (low prioritisation) to +++ (high prioritisation)

contribute to reducing the carbon footprint of depot operations. Digital fleet tools further enable data-driven route planning, real-time vehicle monitoring, and enhanced operational transparency. From an environmental perspective, such tools facilitate the optimisation of driving patterns, minimise unnecessary mileage, and support energy-efficient scheduling, all of which reduce total energy consumption and related emissions.
In addition to these system-level tools, modern buses are increasingly equipped with on-board technologies designed to optimise energy use and vehicle performance. Regenerative braking systems, for instance, recover kinetic energy during deceleration and convert it

into electricity, which is then stored in the vehicle's battery. This process improves overall energy efficiency and reduces the frequency and duration of external charging requirements. Other embedded features include thermal management systems that optimise interior climate control with minimal energy expenditure and vehicle control units that coordinate drivetrain and auxiliary loads in real time.

Moreover, intelligent transport systems (ITS) such as adaptive traffic light management and dynamic passenger information services can contribute indirectly to emission reductions by improving passenger confidence, supporting modal shift from private cars, and increasing overall public transport attractiveness. Adaptive signal control systems can be designed to prioritise buses—especially those operating at high capacity—thus granting right of way to vehicles with the lowest CO_2 emissions per passenger-kilometre. This not only enhances operational efficiency but also maximises the emission-reduction potential of the most climate-friendly modes. While the emissions impact of such systems is difficult to isolate quantitatively, they are widely recognised as essential enablers for a high-efficient and wlow-emission public transport system.

Despite their importance, these operational support systems are excluded from the comparative drivetrain analysis in this study. The assessment in **Chapter 6.2** focuses exclusively on drivetrain technologies and their associated technical and economic characteristics. Nonetheless, the availability and quality of operational support systems remain a key consideration for public transport operators when evaluating the feasibility of zero-emission fleet transitions.

6.1.4 Technology Selection for the Analysis

This section outlines the rationale for focusing the comparative drivetrain assessment on battery-electric and hydrogen fuel cell buses. These technologies were selected because they represent the only propulsion systems currently available that meet two key criteria: full compliance with the EU's regulatory definition of zero-emission vehicles, and demonstrated viability for near- to mid-term deployment (i.e. market-ready) in public transport fleets.

Other drivetrain configurations, such as compressed natural gas (CNG), plug-in hybrids, or synthetic fuels, were excluded for various reasons, as detailed in Section 6.1.2. While such systems may offer partial or moderate emission reductions compared to conventional diesel buses, they still produce TTW emissions or rely on transitional infrastructure. Moreover, their relevance in EU public procurement is declining due to increasingly stringent emission targets and funding eligibility rules prioritising fully zero-emission solutions.

Focusing the analysis on battery-electric and hydrogen fuel cell buses allows for a coherent and policy-aligned evaluation of zero-emission technologies. Both systems are actively promoted under EU strategies such as the Clean Vehicles Directive (EU, 2019a) and receive targeted funding through programmes including the Connecting Europe Facility and the Clean Hydrogen Partnership. Furthermore, BEBs and FCEBs are the only technologies for which sufficient real-world deployment data and total cost of ownership analyses are currently available.

By narrowing the scope to these two drivetrain types, the study ensures that the comparative assessment in **Chapter 6.4** remains focused, practical, and relevant to public transport operators and decision-makers seeking to decarbonise their fleets in line with EU objectives.

6.1.5 Market Uptake and Deployment Trends in the EU

The market uptake of battery-electric and hydrogen fuel cell buses has accelerated significantly in recent years, driven by regulatory pressure, public funding, and declining technology costs. According to the IEA (2024), BEBs accounted for 43% of all new city bus registrations in the EU in 2023. This development marks a clear shift in procurement patterns across Member States and reflects the growing confidence of public transport operators in the operational viability of electric drivetrains.

The deployment of FCEBs, while still at an earlier stage, is also expanding. Fuel cell buses currently account for approximately 1% of all new zero-emission bus registrations in the EU, reflecting a deployment ratio of roughly 1:99 compared to BEBs (ICCT, 2023). FCEBs are increasingly included in regional deployment strategies and pilot programmes, particularly in countries with ambitious hydrogen roadmaps such as Germany, France, and the Netherlands. According to ICCT (2023), nearly all fuel cell bus deployments in 2022 occurred in just four countries: the Netherlands, Germany, Austria, and Poland. EU-level initiatives like the Clean Hydrogen Partnership and the Clean Bus Europe Platform are instrumental in supporting these developments by providing co-funding, knowledge exchange, and technical assistance.

Geographical differences in deployment trends are striking and reflect broader disparities in national policy ambition, funding capacity, and infrastructure maturity. Northern and Western European countries, such as the Netherlands, Denmark, Finland, and Luxembourg, have achieved electric bus shares of over 80% in new city bus registrations. These frontrunners benefit from long-standing climate strategies, reliable electricity grids, advanced depot infrastructure, and clear procurement mandates favouring zero-emission technologies. In addition, their cities often have air quality plans and environmental zones that create demand for clean urban fleets.

In contrast, Member States in Eastern and Southern Europe—such as Bulgaria, Romania, Greece, and Estonia—face a combination of limited access to EU co-financing, fragmented procurement processes, and institutional constraints. Estonia, for example, recorded a natural gas bus share of over 80% in 2022, the highest in the EU (ICCT, 2023). In Romania and Slovakia, a lack of local manufacturing capacity and slower permitting procedures hinder the large-scale rollout of BEBs. Meanwhile, France, Spain, and Italy continue to rely heavily on natural gas technologies, driven in part by earlier infrastructure investments and the Clean Vehicles Directive, which classifies CNG buses as 'clean'.

Furthermore, the pace of transition is also affected by differences in operator structure. In many Western Member States, municipal transport companies manage procurement and benefit from bundled public investment schemes. In contrast, more liberalised or decentralised systems, as found in parts of Southern and Eastern Europe, often lack strategic alignment across local operators, complicating coordinated fleet electrification.

The share of electric buses is also highly dependent on the segment. In 2022, over 3,000 zero-emission city buses were sold in the EU, accounting for nearly 30% of all new city bus registrations (ICCT, 2023). Sales of coaches and interurban buses, by contrast, remain dominated by diesel, with zero-emission shares below 1%. This confirms that city buses are functionally and structurally best suited for early electrification, given their defined routes, overnight depot access, and urban air quality co-benefits.

On the supply side, Chinese manufacturers such as BYD and Yutong continue to expand their presence in the European market, with a combined HDV market share of 17% in 2022 for BYD and Yutong (IEA, 2024). This development reflects both price competitiveness and increased model availability. Among European OEMs, Solaris, MAN, Mercedes-Benz, and Volvo lead the market. Solaris holds a particularly strong position in BEBs, though the company also continues to offer diesel, hybrid, and CNG models as part of its broader portfolio. MAN and Mercedes-Benz have recently expanded their zero-emission bus offerings, while Volvo maintains a robust presence in northern and western European markets.

Overall, the increasing market penetration of BEBs and the emerging deployment of FCEBs indicate a growing momentum toward fleet decarbonisation across the EU. These trends underscore the importance of sustained policy support, harmonised procurement rules, and targeted investment in enabling infrastructure to maintain progress toward the EU's climate and mobility goals. A recent update by the International Council on Clean Transportation [ICCT] highlights that urban buses continue to lead zero-emission uptake across all HDV segments in the EU, accounting for nearly 80% of all zero-emission HDV registrations in 2022 and 2023. This dominant role is attributed to shorter routes, predictable schedules, and depot-based operations, which make urban buses particularly suitable for battery-electric operation. The report further indicates that policy-driven demand and the availability of targeted public funding have accelerated bus fleet transitions more rapidly than in other HDV segments such as trucks or coaches. Urban buses are thus not only pioneering the operational shift toward zero-emission mobility but also serve as a scalable blueprint for electrification strategies in other transport sectors (ICCT, 2023).

6.2 Assessment Vehicle Profiles

This chapter outlines standardized vehicle profiles for three key propulsion technologies in urban public transport: diesel, battery electric, and hydrogen fuel cell. The configurations are based on representative technical and operational characteristics of typical vehicles and serve as a consistent baseline for comparison. The focus is on 12-meter low-floor solo buses, which represent the most common vehicle category in European city fleets.

For each technology, core technical specifications (such as drivetrain power, energy storage, and range), operational parameters (including energy consumption and refueling or charging times), and economic aspects (such as purchase price, maintenance, and infrastructure costs) are presented. Emissions are calculated on a well-to-wheel basis to capture both direct and upstream environmental impacts.

These benchmark vehicles form the foundation for the comparative cost and emission assessment presented later in the chapter. All assumptions follow a consistent methodological approach to ensure realism and comparability across technologies. This provides a transparent and robust framework for systematically evaluating the implications of different propulsion options in the context of public transport decarbonization.

6.2.1 Benchmark Vehicle: Diesel Bus

This vehicle represents a 12-meter standard solo bus with low-floor design and two to three passenger doors, typical for urban public transport. Power is delivered by a 235 kW Euro VI diesel engine with 1200 Nm of torque, representative of common solo diesel buses. Approximately 300 L of diesel are stored onboard, enabling a typical range of 550 km. Refueling is conducted via standard diesel nozzle technology and takes around 10 minutes. The purchase cost is assumed at 250,000 € with a residual value of 20.000€ after 12 years, and infrastructure cost per kilometer is set at 0.04 €/km and includes depot adaptations, its maintenance and fuel storage. The benchmark configuration reflects the prevailing technological standard in European fleets (Kim et al., 2021).
The diesel bus consumes approximately 40 liters of fuel per 100 kilometers, equivalent to 0.40 L/km. With an assumed lower heating value (LHV) of 9.7 kWh per liter for Diesel, the total energy consumption per kilometer is:

$$\text{Energy Consumption} = 0.40\ \frac{\text{L}}{\text{km}} \cdot 9.7\ \frac{\text{kWh}}{\text{L}} \approx 3.88\ \frac{\text{kWh}}{\text{km}}$$

With:

$$LHV_{\text{Diesel}} = 9.7\ \frac{\text{kWh}}{\text{l}}$$

The GHG intensity of fossil diesel is assumed to be 269 g CO_2/kWh for the tank-to-wheel [TTW] phase, representing emissions from fuel combustion, and 74 g CO_2/kWh for the well-to-tank [WTT] phase, representing emissions from fuel production and distribution (Fritz et al., 2023). The sum of both phases is referred to as well-to-wheel [WTW] emissions.

The resulting TTW emissions of the diesel bus are calculated as:

$$E_{D,\text{TTW}} = 3.88\ \frac{\text{kWh}}{\text{km}} \cdot 269\ \frac{\text{g CO}_2}{\text{kWh}} \approx 1043\ \frac{\text{g CO}_2}{\text{km}}$$

The WTT emissions are:

$$E_{D,\text{WTT}} = 3.88\ \frac{\text{kWh}}{\text{km}} \cdot 74\ \frac{\text{g CO}_2}{\text{kWh}} \approx 285\ \frac{\text{g CO}_2}{\text{km}}$$

Thus, the total WTW emissions are:

$$E_{D,\text{WTW}} = E_{D,\text{TTW}} + E_{D,\text{WTT}} = 1043\ \frac{\text{g CO}_2}{\text{km}} + 285\ \frac{\text{g CO}_2}{\text{km}} \approx 1328\ \frac{\text{g CO}_2}{\text{km}}$$

Fuel price is set at 1.60 €/liter, which leads to the following Fuel cost per kilometer:

$$\text{Fuel Cost} = 0.40\ \frac{\text{L}}{\text{km}} \cdot 1.60\ \frac{€}{\text{L}} = 0.64\ \frac{€}{\text{km}}$$

According to Kim et al. (2021), maintenance costs amount to 0.25 €/km. These values were derived here as the underlying methodology accounts for multiple interdependent factors such as vehicle purchase cost, depreciation, infrastructure investment, and financing conditions.

6.2.2 Alternative I: Battery Electric Bus

The BEB examined here is a 12-meter low-floor solo bus with two to three doors and a centrally mounted electric motor. It provides 250 kW of power and 3000 Nm torque, reflecting common specifications of current electric city buses. The battery pack has a capacity of 350 kWh, yielding a real-world range of about 270 km. Charging is assumed to occur via CCS2 or pantograph overnight at depot-based infrastructure, requiring approximately 210 minutes. Vehicle cost is set at 400,000 €, infrastructure cost per kilometer at 0.10 €/km to account for a 12-year cycle for modifictions, renewal or expansion. Vehicle and Battery residual value is set at 90.000€ and Battery replacement at 105,000 €. It is planned to be executed once during the 12 year lifecycle of the vehicle. The configuration corresponds to typical fleet deployment in European cities (Estrada Poggio et al., 2023).

As BEBs have no internal combustion engine, they produce zero tailpipe emissions, resulting in a TTW value of zero.
Energy consumption is based on an average of 137 kWh per 100 km (Estrada Poggio et al., 2023). For standardised format, the specific energy consumption is calculated as:

$$\text{Energy Consumption} = 137\ \frac{\text{kWh}}{100\ \text{km}} = 1.37\ \frac{\text{kWh}}{\text{km}}$$

The upstream GHG intensity of electricity is set to 180 g CO_2/kWh (Fritz et al., 2023), resulting in:

$$E_{E,\text{WTT}} = 1.37\ \frac{\text{kWh}}{\text{km}} \cdot 180\ \frac{\text{g CO}_2}{\text{kWh}} \approx 247\ \frac{\text{g CO}_2}{\text{km}}$$

$$E_{E,\text{TTW}} = 0\ \frac{\text{g CO}_2}{\text{km}}$$

$$E_{E,\text{WTW}} = E_{E,\text{TTW}} + E_{E,\text{WTT}} = 0\ \frac{\text{g CO}_2}{\text{km}} + 247\ \frac{\text{g CO}_2}{\text{km}} \approx 247\ \frac{\text{g CO}_2}{\text{km}}$$

With electricity priced at 0.17 €/kWh, this leads to an energy cost per kilometer of:

$$\text{Energy Cost} = 1.37\ \frac{\text{kWh}}{\text{km}} \cdot 0.17\ \frac{€}{\text{kWh}} \approx 0.23\ \frac{€}{\text{km}}$$

According to Kim et al. (2021), maintenance cost is reported at 0.29 €/km. No further calculations were conducted in this chapter, as the value already reflects vehicle-specific characteristics such as battery wear and electric drivetrain servicing requirements, as well as associated infrastructure considerations.

6.2.3 Alternative II: Fuel Cell Electric Bus

The analyzed FCEB is a 12-meter low-floor solo bus with two to three doors. It combines a fuel cell system and auxiliary battery to provide a rated output of 250 kW. Hydrogen is stored at 350 bar in a 35 kg tank, complemented by a 70 kWh battery system, yielding a usable energy equivalent of about 1150 kWh. Operational range is estimated at 350 km. Refueling takes approximately 20 minutes at a depot-based station. Purchase cost is estimated at 700,000 € with a residual value of 90.000 € after 12 years, infrastructure per kilometer costs are assumed at 0.82 €/km accounting for a 12 year cycle for modification, renewal or expansion. Fuel cell and battery replacement is set at 200,000 € and is planned to be executed once during the 12 year lifecycle of the vehicle. The assumptions are aligned with current market offerings and European deployment scenarios (Estrada Poggio et al., 2023).
Hydrogen consumption is set at 9.3 kg/100 km or 0.093 kg/km (Estrada Poggio et al., 2023). As fuel cell electric buses have no combustion process and emit only water vapor, they produce zero tailpipe emissions, resulting in a tailpipe emission value of zero. With a lower heating value of 33.3 kWh/kg H_2 (Edwards et al., 2020), the energy consumption per kilometer is:

$$\text{Energy Consumption} = 0.093\ \frac{\text{kg}}{\text{km}} \cdot 33.3\ \frac{\text{kWh}}{\text{kg}} \approx 3.10\ \frac{\text{kWh}}{\text{km}}$$

With:

$$LHV_{\text{H}_2} = 33.3\ \frac{\text{kWh}}{\text{kg}}$$

The GHG intensity of hydrogen produced via electrolysis with EU electricity mix is set at 277 g CO_2/kWh (Edwards et al., 2020), resulting in:

$$E_{H_2,\text{WTT}} = 3.10\ \frac{\text{kWh}}{\text{km}} \cdot 277\ \frac{\text{g CO}_2}{\text{kWh}} \approx 859\ \frac{\text{g CO}_2}{\text{km}}$$

$$E_{H_2,\text{TTW}} = 0\ \frac{\text{g CO}_2}{\text{km}}$$

$$E_{H_2,\text{WTW}} = E_{H_2,\text{TTW}} + E_{H_2,\text{WTT}} = 0\ \frac{\text{g CO}_2}{\text{km}} + 859\ \frac{\text{g CO}_2}{\text{km}} \approx 859\ \frac{\text{g CO}_2}{\text{km}}$$

Assuming a hydrogen price of 10 €/kg (Kim et al., 2021), the resulting energy cost is:

$$\text{Fuel Cost} = 0.093\ \frac{\text{kg}}{\text{km}} \cdot 10\ \frac{€}{\text{kg}} = 0.93\ \frac{€}{\text{km}}$$

According to Kim et al. (2021), maintenance costs are estimated at 0.33 €/km. This value was adopted without modification, as the original source accounts for high vehicle and infrastructure costs specific to hydrogen technology.

6.2.4 Vehicle Overview Table

Specification	Diesel Bus	BEB	FCEB
Length (m)	12	12	12
Doors	2-3	2-3	2-3
Low Floor Access	Yes	Yes	Yes
Engine/Motor	Diesel Euro VI Engine	Central Electric Motor	Fuel Cell System + Electric Motor
Fuel / Energy type	Diesel	Battery-electric (NMC)	Hydrogen + Battery (NMC)
Power / Torque	235 kW / 1200 Nm	250 kW / 3000 Nm	250 kW / variable
Onboard Energy Storage	300l	350 kWh	35 kg H_2 + 70 kWh
Range (km)	550	270	350
Refueling / Charging interface	Diesel nozzle	CCS2 / Pantograph	Hydrogen nozzle (350 bar)
Refueling Time (min)	10	210	20
Fuel / Energy consumption (per 100 km)	40 l	137 kWh	9.3 kg
Fuel / Energy consumption (per km)	0,41	1.37 kWh	0.093 kg
Fuel / Energy consumption (kWh/ km)	3.88	1.37 kWh	3.10
Vehicle purchase cost (€)	250,000	400,000	700,000
Infrastructure cost (€/km)	0.04	0.10	0.82
Fuel / Energy cost (€/unit)	1.60 / l	0.17 / kWh	10 / kg
Fuel / Energy cost (€/km)	0.64	0,23	0.93
Battery / Fuel cell replacement cost (€)	-	105,000	200,000
Maintenance cost (€/km)	0.25	0.29	0.33
Residual value after 12 years (€)	40,000	90,000	90,000
GHG Intensity (g CO_2/kWh, WTT)	74	180	277
CO_2 emissions (g/ km, WTT)	285	247	859
GHG Intensity (g CO_2/kWh, TTW)	269	-	-

CO_2 emissions (g/km, TTW)	1043	-	-
CO_2 emissions (g/km, WTW)	1323	247	851

Table 4
Comparative Vehicle Overview and Specifications of Benchmark and Alternative Bus Types
*Note***.** The table provides a comparative overview of key technical, economic, and environmental performance indicators for diesel, battery-electric, and fuel cell electric buses. Instead of using a single vehicle model, representative benchmark profiles were created for each technology to allow for generalized comparison based on aggregated data. Values are based on data from Kim et al. (2021), Estrada Poggio et al. (2023), Fritz et al. (2023), JEC Consortium (2014), Jeffers et al. (2021), Texas A&M Transportation Institute (2020), and DIHK (2021). Calculations underlying the values presented here are explained in detail in Chapters 6.2.1 to 6.2.3.

6.3 Comparative Analysis

This comparative analysis focuses on the BEB as the sole zero-emission alternative. FCEBs are excluded from the cost-benefit analysis due to their overall weaker performance across all key indicators. As Table 5 shows, FCEBs have the highest fuel and infrastructure costs, while offering lower emission reductions per euro invested compared to BEBs. Their energy consumption (3.10 kWh/km) is significantly higher than that of BEBs (1.37 kWh/km), and their abatement cost per ton of CO_2 would exceed typical policy thresholds. Therefore, given the current state of technology, BEBs represent the more economically and environmentally viable option for public bus fleet decarbonization. This exclusion is consistent with the iterative refinement logic of the DSR approach, which emphasizes the progressive narrowing of alternatives toward implementable solutions.

To ensure consistency in lifetime cost calculations and residual value considerations, a typical operational lifetime of 12 years is assumed for all vehicle types. This duration aligns with standard public transport bus procurement and depreciation cycles in Europe and serves as the basis for amortization and replacement modelling. The analysis is conducted over a 50-year period to reflect long-term investment cycles, multiple bus generations, and policy-relevant climate targets. This timeframe enables the modeling of staggered procurement, repeated replacements, long-run savings effects, and the cumulative impact of rising carbon pricing.

To monetize environmental benefits, the EU ETS carbon price is incorporated into the analysis. At year 2024 ($t = 0$), the CO_2 price is set to 64.74 €/t CO_2 (ICAP, 2024). Following current market forecasts, the price is expected to increase to 125–160 €/t CO_2 by 2030 (AP News, 2023). A linear growth assumption of approximately 13 €/t CO_2 per year is applied across the 50-year horizon to estimate annualized monetization of avoided CO_2 emissions. This value reflects the midpoint of the projected 2030 range (142.5 €/t CO_2), assuming steady growth from 2024.

Regarding financing assumptions, the analysis uses a constant real interest rate for discounting future cost components and benefits. While interest rates may fluctuate over time due to economic and monetary policy changes, they are assumed constant here for modeling simplicity and to maintain comparability across drivetrain types. A constant real interest rate of 3% is assumed throughout the calculation.

To frame the analysis, two deployment scenarios are considered:

1. Scenario A in which all buses in the fleet are diesel-powered.
2. Scenario B real-world composition of the Wiener Linien fleet.

As of 2024, Wiener Linien - the public transport operator in Austria's capital city Vienna - operates a total of 486 buses, of which 62 run battery-electric (Wiener Linien, 2024). This corresponds to an electrification share of approximately 12.8%, placing Vienna among the

more advanced public transport networks in Europe. For the theoretical scenario, the same fleet size is used - therefore 486 diesel-powered buses.
To model a full transition, it is assumed that 10% of the remaining diesel buses are replaced annually with zero-emission alternatives, resulting in a complete conversion over 10 years. While fleet transitions in practice often proceed at a slower pace and vary significantly across EU countries, this assumption reflects the pace of transition observed in urban transport modernization strategies and allows for a realistic implementation horizon in the 50-year analysis period.
For the annual mileage per vehicle 45,500 km are assumed, based on the 2024 total bus mileage of Wiener Linien (22.1 million km in own-operation (Eigenbetrieb)) divided by the total fleet size of 486 vehicles (Wiener Linien, 2024). In this context, 'own-operation' refers to bus services directly operated by Wiener Linien, as opposed to subcontracted services run by third-party operators.
For the sake of comparability and analytical simplicity, only 12-meter solo buses are included in the model. These archetypical low-floor city buses represent the dominant vehicle class in European public transport and provide a suitable baseline for technology comparison. Articulated buses and midi buses, which differ considerably in energy demand, operational patterns, and cost structure, are not included in the analysis to avoid the need for multiple differentiated vehicle class models. This approach supports consistent evaluation of drivetrain alternatives within a clearly defined and widely used vehicle category.
The following three sub-sections each examine one key evaluation criterion: emissions performance, economic performance, and integrated cost-benefit outcomes. In section **6.3.1**, well-to-wheel emissions are quantified for all scenarios and used as the foundation for monetizing environmental benefits. **Section 6.3.2** evaluates economic performance by calculating the total cost of ownership, subdivided into capital expenditures [CAPEX] and operating expenditures [OPEX]. CAPEX includes upfront acquisition and battery replacement costs, while OPEX covers fuel or electricity, maintenance, and infrastructure costs per kilometer. Finally, s**ection 6.3.3** integrates both cost and environmental dimensions into a cumulative 50-year perspective, combining TCO and carbon pricing effects to estimate the long-run financial implications of different drivetrain strategies.

6.3.1 Emission Performance

Let the emission parameters be defined as:

- n : Number of vehicles in the fleet, with $n = 486$
- D_a : Annual mileage per vehicle (km), with $D_a = 45{,}500$ km
- $E_{D,\mathrm{WTW}}$: Well-to-wheel emissions for Diesel, with $E_{D,\mathrm{WTW}} = 1328\ \frac{\mathrm{g}}{\mathrm{km}}$
- $E_{E,\mathrm{WTW}}$: Well-to-wheel emissions for BEB, with $E_{E,\mathrm{WTW}} = 247\ \frac{\mathrm{g}}{\mathrm{km}}$

As a reference, total emissions over 50 years without any drivetrain conversion can be calculated as:

$$E_{50} = n \cdot D_a \cdot E_{\text{WTW}}$$

For the Diesel-only scenario throughout a 50 year period, it follows:

$$E_{50}^{D} = 486 \cdot 45{,}500 \text{ km} \cdot 1328 \ \frac{\text{g CO}_2}{\text{km}} \cdot 50 \approx 1.468 \times 10^6 \text{ t CO}_2$$

This value serves as the baseline against which emission reductions from fleet electrification can be evaluated.
For comparison, total emissions over 50 years assuming a fully electrified fleet from the beginning (i.e., all 486 vehicles are BEBs) are calculated as:

$$E_{50}^{E} = 486 \cdot 45{,}500 \text{ km} \cdot 247 \ \frac{\text{g CO}_2}{\text{km}} \cdot 50 \approx 0.2731 \times 10^6 \text{ t CO}_2$$

This means that the BEB-only scenario produces only approximately 18.7% compared to the emissions of the diesel-only case over 50 years. It compares a fully diesel-powered with a fully electrified fleet without accounting for a transition phase.

The more realistic cumulative emissions over a 50-year horizon with a gradual fleet transition, can be modelled as:

$$E_{50} = \sum_{t=0}^{49} \left[n \cdot D_a \cdot \left(E_{D,\text{WTW}} \cdot p(t) + E_{E,\text{WTW}} \cdot (1 - p(t)) \right) \right], \quad t \in \{0,\ldots,49\}$$

With the function p(t) enabling a variable fleet composition at year t=0:

- $n_{\text{BEB},0}$: Number of battery-electric buses in year $t = 0$
- $p(t)$: Share of diesel vehicles in year t, with $p(t) = \dfrac{n - n_{\text{BEB0}} - 0.1 \cdot \left(n - n_{\text{BEB0}}\right) \cdot t}{n}$, with $p(t) \geq 0$

This version of the formula allows for flexible adjustment of the initial electrification level through the input variable $n_{\text{BEB},0}$. When set to 0, the equation models a pure diesel fleet at year 0. When set to 62, it reflects the current Wiener Linien configuration.

Substituting $p(t)$ into the main formula yields:

$$E_{50} = \sum_{t=0}^{49} \left[n \cdot D_a \cdot \left(E_{D,\text{WTW}} \cdot \frac{n - n_{\text{BEB0}} - 0.1 \cdot (n - n_{\text{BEB0}}) \cdot t}{n} + E_{E,\text{WTW}} \cdot \left(1 - \frac{n - n_{\text{BEB0}} - 0.1 \cdot (n - n_{\text{BEB0}}) \cdot t}{n} \right) \right) \right]$$

This expression calculates the total emissions over 50 years while accounting for the dynamic shift in drivetrain composition. It models how the diesel share declines by 10 % of the remaining diesel fleet per year, adjusted for any pre-existing electrification $n_{\text{BEB},0}$. With $n_{\text{BEB},0} = 0$ for Scenario A:

$$E_{50}^{A} \approx \sum_{t=0}^{49} \left[486 \cdot 45{,}500 \cdot \left(1328 \cdot \frac{486 - 0 - 0.1 \cdot (486 - 0) \cdot t}{486} + 247 \cdot \left(1 - \frac{486 - 0 - 0.1 \cdot (486 - 0) \cdot t}{486} \right) \right) \right] \approx 404{,}568 \text{ t } CO_2$$

And $n_{\text{BEB},0} = 62$ for Scenario B:

$$E_{50}^{B} \approx \sum_{t=0}^{49} \left[486 \cdot 45{,}500 \cdot \left(1328 \cdot \frac{486 - 62 - 0.1 \cdot (486 - 62) \cdot t}{486} + 247 \cdot \left(1 - \frac{486 - 62 - 0.1 \cdot (486 - 62) \cdot t}{486} \right) \right) \right] \approx 387{,}796 \text{ t } CO_2$$

Compared to the baseline scenario of 50 years with 100% diesel operation (≈ 1,468,303 t CO_2), Scenario A achieves a total CO_2 reduction of 1,063,735 t (−72.4%), while Scenario B achieves a reduction of 1,080,507 t (−73.6 %). These results underscore the substantial mitigation potential of battery-electric bus deployment, particularly when partial electrification is already present at the outset. The implications of these findings will be further interpreted and contextualized in **Chapter 7**, where the comparative evaluation across environmental and economic dimensions is conducted.

6.3.2 Economic Performance

Let the cost parameters be defined as:

- D_a : Annual mileage per vehicle (km), with $D_a = 45{,}500$ km
- R_D : Residual value of diesel bus, with $R_D = 40{,}000$ €
- R_E : Residual value of BEB, with $R_E = 90{,}000$ €
- $C_{A,D}$: Acquisition cost of diesel bus, with $C_{A,D} = 250{,}000$ €
- $C_{A,E}$: Acquisition cost of BEB, with $C_{A,E} = 400{,}000$ €
- $C_{F,D}$: Fuel cost per km for diesel, with $C_{F,D} = 0.64 \ \frac{€}{\text{km}}$
- $C_{F,E}$: Energy cost per km for BEB, with $C_{F,E} = 0.23 \ \frac{€}{\text{km}}$
- $C_{M,D}$: Maintenance cost per km for diesel, with $C_{M,D} = 0.25 \ \frac{€}{\text{km}}$

- $C_{M,E}$: Maintenance cost per km for BEB, with $C_{M,E} = 0.29\ \frac{€}{\text{km}}$
- $C_{I,D}$: Infrastructure cost per km for diesel, with $C_{I,D} = 0.04\ \frac{€}{\text{km}}$
- $C_{I,E}$: Infrastructure cost per km for BEB, with $C_{I,E} = 0.10\ \frac{€}{\text{km}}$
- C_B : Battery replacement cost for BEB, with $C_B = 105{,}000\ €$

The economic model assumes that each bus is operated for a 12-year period. Infrastructure investments are distributed evenly over the lifetime of the vehicle and expressed on a per-kilometer basis. Battery replacement for BEBs is assumed once during the 12-year lifetime, based on typical degradation intervals. At $t = 0$, all cost parameters, including fuel costs, are set to current price levels. While in reality fuel prices are subject to fluctuations influenced by geopolitical, economic, and technological factors, projecting their evolution over a 50-year period introduces significant uncertainty. Given the wide range of possible scenarios and the absence of a reliable long-term forecast, this chapter assumes constant real fuel prices throughout the analysis period.
This simplification ensures that the model isolates the effects of drivetrain electrification without conflating them with speculative fuel market dynamics. **Chapter 6.3.5** will extend the analysis by incorporating a dynamic fuel price trajectory, such as the one projected by Financial Times *(*2025*),* into the sensitivity analysis to assess their interaction with fleet transition strategies.
While real interest rates can fluctuate over time depending on macroeconomic conditions and monetary policy, a constant rate of 3% is assumed here for analytical simplicity and to ensure comparability across scenarios. This approach aligns with common practices in long-term transport investment assessments and reflects a standard discounting method rather than financing costs or credit interest.
To calculate Total Cost of Ownership per km for each drivetrain type, three approaches are presented:

OPEX Model:
The OPEX model includes only operational expenses such as fuel, infrastructure and maintenance.

$$\text{TCO}_{\text{OP}} = C_F + C_M + C_I$$

$$\text{TCO}_{\text{OP}}^{D} = 0{,}64\ \frac{€}{\text{km}} + 0{,}25\ \frac{€}{\text{km}} + 0{,}04\ \frac{€}{\text{km}} = 0{,}93\ \frac{€}{\text{km}}$$

$$\text{TCO}_{\text{OP}}^{E} = 0{,}23\ \frac{€}{\text{km}} + 0{,}29\ \frac{€}{\text{km}} + 0{,}10\ \frac{€}{\text{km}} = 0{,}62\ \frac{€}{\text{km}}$$

CAPEX Model:
The CAPEX model covers investment-related costs such as acquisition, residual values and battery replacement.

$$\mathrm{TCO}_{\mathrm{CAP}} = \frac{C_A - R + C_B}{12 \cdot D_a}$$

$$\mathrm{TCO}^{D}_{\mathrm{CAP}} = \frac{250{,}000\ € - 40{,}000\ €}{12 \cdot 45{,}500\ \mathrm{km}} \approx 0{,}38\ \frac{€}{\mathrm{km}}$$

$$\mathrm{TCO}^{E}_{\mathrm{CAP}} = \frac{400{,}000\ € - 90{,}000\ € + 105{,}000\ €}{12 \cdot 45{,}500\ \mathrm{km}} \approx 0{,}76\ \frac{€}{\mathrm{km}}$$

TCO (OPEX + CAPEX) Model:
The combined TCO model integrates both components for a full lifecycle perspective.

$$\mathrm{TCO} = \mathrm{TCO}_{\mathrm{OP}} + \mathrm{TCO}_{\mathrm{CAP}} = C_F + C_M + C_I + \frac{C_A - R + C_B}{12 \cdot D_a}$$

$$\mathrm{TCO}^{D} = 0{,}64\ \frac{€}{\mathrm{km}} + 0{,}25\ \frac{€}{\mathrm{km}} + 0{,}04\ \frac{€}{\mathrm{km}} + \frac{250{,}000\ € - 40{,}000\ €}{12 \cdot 45{,}500\ \mathrm{km}} \approx 1{,}30\ \frac{€}{\mathrm{km}}$$

$$\mathrm{TCO}^{E} = 0{,}23\frac{€}{\mathrm{km}} + 0{,}29\frac{€}{\mathrm{km}} + 0{,}10\frac{€}{\mathrm{km}} + \frac{400{,}000€ - 90{,}000€ + 105{,}000€}{12 \cdot 45{,}500\mathrm{km}} \approx 1{,}38\frac{€}{\mathrm{km}}$$

Compared to the OPEX and CAPEX models, the combined TCO model incorporates both ongoing operational expenses and long-term capital cost factors, such as acquisition cost, residual value, and battery replacement. It therefore provides a more comprehensive and realistic estimate of lifecycle costs per kilometer. This makes it particularly suitable for long-term investment comparisons, especially when aligned with the emission analysis timeframe and typical asset renewal cycles in public transport planning.
Compared to diesel, the BEB option is approximately 33.3% cheaper under the OPEX model but 100% more expensive under the CAPEX model. When including all cost components (OPEX + CAPEX), BEBs are 6.2% more expensive per km than diesel buses.
To extend this analysis to a 50-year dual-system perspective, a dynamic cost model is introduced. This reflects staggered vehicle replacements, cost discounting, and fleet transition dynamics. It can be modelled as:

$$C_{50} = \sum_{t=0}^{49} \left[\left(\mathrm{TCO}_{\mathrm{D}} \cdot p(t) + \mathrm{TCO}_{\mathrm{E}} \cdot (1 - p(t)) \right) \cdot n \cdot D_a \cdot \frac{1}{(1+i)^t} \right]$$

With the function p(t) enabling a variable fleet composition at year t:

- $p(t)$: Share of diesel vehicles in year t, with $p(t) = \frac{n - n_{\text{BEB0}} - 0.1 \cdot (n - n_{\text{BEB0}}) \cdot t}{n}$, with $p(t) \geq 0$
- $n_{\text{BEB},0}$: Number of battery-electric buses in year $t = 0$

This function allows for flexible adjustment of the initial electrification level through the input variable $n_{\text{BEB},0}$. When set to 0, the equation models a pure diesel fleet at year 0. When set to 62, it reflects the current Wiener Linien configuration.
Substituting p(t) into the main formula yields:

$$C_{50} = \sum_{t=0}^{49} \left[\left(\text{TCO}_D \cdot \frac{n - n_{\text{BEB0}} - 0.1 \cdot (n - n_{\text{BEB0}}) \cdot t}{n} + \text{TCO}_E \cdot \left(1 - \frac{n - n_{\text{BEB0}} - 0.1 \cdot (n - n_{\text{BEB0}}) \cdot t}{n} \right) \right) \cdot n \cdot D_a \cdot \frac{1}{(1+i)^t} \right]$$

The additional variables are defined as follows:

- n : Number of vehicles in the fleet, with $n = 486$
- D_a : Annual mileage per vehicle (km), with $D_a = 45{,}500$ km
- i : Constant real interest rate, with $i = 0.03$
- TCO_D : Per-km total cost for diesel (OPEX + CAPEX model), with $\text{TCO}_\text{D} = 1{,}30 \ \frac{€}{\text{km}}$
- TCO_E : Per-km total cost for BEB (OPEX + CAPEX model), with $\text{TCO}_\text{E} = 1{,}38 \ \frac{€}{\text{km}}$

As a baseline scenario, the total costs over 50 years without any drivetrain conversion - i.e., a scenario in which all 486 vehicles remain diesel-powered - can be calculated as:

$$C_{50}^{D} = \sum_{t=0}^{49} \left[\frac{1{,}30 \cdot 486 \cdot 45{,}500}{(1+0{,}03)^t} \right] \approx 761{,}840{,}482 \ €$$

Scenario A starts its transition phase from a point without any BEBs implemented yet, so $n_{\text{BEB},0} = 0$:

$$C_{50}^{A} = \sum_{t=0}^{49} \left[\left(1{,}30 \cdot \left(\frac{486 - 0 - 0.1 \cdot (486 - 0) \cdot t}{486} \right) + 1{,}38 \cdot \left(1 - \frac{486 - 0 - 0.1 \cdot (486 - 0) \cdot t}{486} \right) \right) \cdot 486 \cdot 45{,}500 \cdot \frac{1}{(1+0{,}03)^t} \right] \approx 848{,}842{,}708 \ €$$

Scenario B starts its transition phase from a point with 62 BEBs already in operation, so $n_{\text{BEB},0} = 62$:

$$C_{50}^{B} = \sum_{t=0}^{49} \left[\left(1{,}30 \cdot \left(\frac{486 - 62 - 0.1 \cdot (486 - 62) \cdot t}{486} \right) + 1{,}38 \cdot \left(1 - \frac{486 - 62 - 0.1 \cdot (486 - 62) \cdot t}{486} \right) \right) \cdot 486 \cdot 45{,}500 \cdot \frac{1}{(1+0{,}03)^t} \right] \approx 843{,}724{,}552 \ €$$

Compared to the diesel-only scenario, Scenario A results in additional costs of approximately 87 million euros (+11.42%), while Scenario B results in additional costs of around 82 million euros (+10.74%).
These results highlight the substantial economic impact of a full fleet transition to battery-electric buses under current cost assumptions. The interpretation and broader implications of these findings will be discussed further in **Chapter 7**.

6.3.3 Cost-Benefit Perspective

This final subsection combines the economic and environmental results derived in the previous chapters to assess the integrated cost-benefit performance of diesel versus battery-electric drivetrains over a 50-year horizon. To achieve this, the total lifecycle cost and the monetized value of avoided CO_2 emissions are considered jointly.
Let the variables be defined as follows:

- n : Number of vehicles in the fleet, with $n = 486$
- D_a : Annual mileage per vehicle (km), with $D_a = 45{,}500$ km
- i : Constant real interest rate, with $i = 0.03$
- TCO_D : Per-km total cost for diesel (OPEX + CAPEX model), with $\text{TCO}_\text{D} = 1{,}30\ \frac{€}{\text{km}}$
- TCO_E : Per-km total cost for BEB (OPEX + CAPEX model), with $\text{TCO}_\text{E} = 1{,}38\ \frac{€}{\text{km}}$
- $E_{D,\text{WTW}}$: Well-to-wheel emissions for Diesel, with $E_{D,\text{WTW}} = 1328\ \frac{\text{g}}{\text{km}}$
- $E_{E,\text{WTW}}$: Well-to-wheel emissions for BEB, with $E_{E,\text{WTW}} = 247\ \frac{\text{g}}{\text{km}}$

For the diesel-only reference scenario, all vehicles remain diesel-powered throughout the 50-year period:

$$C_{50}^{D} = \sum_{t=0}^{49} \left[\text{TCO}_\text{D} \cdot n \cdot D_a + E_{\text{D,WTW}} \cdot \left(\frac{n \cdot D_a}{1000} \right) \cdot \left(\frac{r_{\text{CO}_2}(t)}{1000} \right) \right] \cdot \frac{1}{(1+i)^t}$$

With reflecting the Emission price development per tCO_2 with a starting value of 64,74 € and an increase of 13 € per year:

- $r_{\text{CO}_2}(t)$: CO_2 price at year t, with $r_{\text{CO}_2}(t) = 64{,}74 + 13 \cdot t\ \left[\frac{€}{\text{tCO}_2} \right]$

this leads to:

$$C_{T50}^{D} = \sum_{t=0}^{49} \left[\mathrm{TCO_D} \cdot n \cdot D_a + E_{\mathrm{WTW,D}} \cdot \left(\frac{n \cdot D_a}{1000} \right) \cdot \left(\frac{64{,}74 + 13 \cdot t}{1000} \right) \right] \cdot \frac{1}{(1+i)^t}$$

The Diesel-only Scenario equals the following:

$$C_{T50}^{\mathrm{D}} = \sum_{t=0}^{49} \left[1{,}30 \cdot 486 \cdot 45{,}500 + \frac{1328 \cdot \left(\frac{486 \cdot 45{,}500}{1000} \right) \cdot (64{,}74 + 13 \cdot t)}{1000} \right] \cdot \frac{1}{(1+0{,}03)^t} \approx 999{,}975{,}149 \text{ €}$$

To modify this approach to transition scenarios, the following full-cost model is used:

$$C_T = \left(C_{\mathrm{economic}} + C_{\mathrm{emissions}} \right) \cdot \frac{1}{(1+i)^t}$$

where

$$C_{\mathrm{economic}} = \left(\mathrm{TCO_D} \cdot p(t) + \mathrm{TCO_E} \cdot (1 - p(t)) \right) \cdot n \cdot D_a$$

and

$$C_{\mathrm{emissions}} = \left(E_{\mathrm{WTW,D}} \cdot p(t) + E_{\mathrm{WTW,E}} \cdot (1 - p(t)) \right) \cdot \left(\frac{n \cdot D_a}{1000} \right) \cdot \left(\frac{r_{\mathrm{CO_2}}(t)}{1000} \right)$$

Substituting the full expressions for $C_{\mathrm{emissions}}$, C_{economic} , $p(t)$, and $r_{\mathrm{CO_2}}(t)$, the formula expands to:

$$\begin{aligned} C_T = \Bigg[& \left(\mathrm{TCO_D} \cdot \left(\frac{n - n_{\mathrm{BEB,0}} - 0.1 \cdot (n - n_{\mathrm{BEB,0}}) \cdot t}{n} \right) + \mathrm{TCO_E} \cdot \left(1 - \frac{n - n_{\mathrm{BEB,0}} - 0.1 \cdot (n - n_{\mathrm{BEB,0}}) \cdot t}{n} \right) \right) \cdot n \cdot D_a \\ & + \left(E_{\mathrm{D,WTW}} \cdot \left(\frac{n - n_{\mathrm{BEB,0}} - 0.1 \cdot (n - n_{\mathrm{BEB,0}}) \cdot t}{n} \right) + E_{\mathrm{E,WTW}} \cdot \left(1 - \frac{n - n_{\mathrm{BEB,0}} - 0.1 \cdot (n - n_{\mathrm{BEB,0}}) \cdot t}{n} \right) \right) \\ & \cdot \left(\frac{n \cdot D_a}{1000} \right) \cdot \left(\frac{64.74 + 13 \cdot t}{1000} \right) \Bigg] \cdot \frac{1}{(1+i)^t} \end{aligned}$$

For Scenario A, starting with 0 BEBs and linear transition:

$$\begin{aligned} C_{T50}^{A} = \sum_{t=0}^{49} \Bigg[& \left(1.30 \cdot \left(\frac{486 - 0 - 0.1 \cdot (486 - 0) \cdot t}{486} \right) + 1.38 \cdot \left(1 - \frac{486 - 0 - 0.1 \cdot (486 - 0) \cdot t}{486} \right) \right) \cdot 486 \cdot 45{,}500 \\ & + \left(1328 \cdot \left(\frac{486 - 0 - 0.1 \cdot (486 - 0) \cdot t}{486} \right) + 247 \cdot \left(1 - \frac{486 - 0 - 0.1 \cdot (486 - 0) \cdot t}{486} \right) \right) \cdot \left(\frac{486 \cdot 45{,}500}{1000} \right) \\ & \cdot \left(\frac{64.74 + 13 \cdot t}{1000} \right) \Bigg] \cdot \frac{1}{(1+0.03)^t} \approx 856{,}329{,}162 \text{ €} \end{aligned}$$

For Scenario B, starting with 62 BEBs:

$$C^{B}_{T50} = \sum_{t=0}^{49} \Bigg[\Bigg(1.30 \cdot \left(\frac{486 - 62 - 0.1 \cdot (486 - 62) \cdot t}{486}\right) + 1.38 \cdot \left(1 - \frac{486 - 62 - 0.1 \cdot (486 - 62) \cdot t}{486}\right)\Bigg) \cdot 486 \cdot 45{,}500$$

$$+ \Bigg(1328 \cdot \left(\frac{486 - 62 - 0.1 \cdot (486 - 62) \cdot t}{486}\right) + 247 \cdot \left(1 - \frac{486 - 62 - 0.1 \cdot (486 - 62) \cdot t}{486}\right)\Bigg) \cdot \left(\frac{486 \cdot 45{,}500}{1000}\right)$$

$$\cdot \left(\frac{64.74 + 13 \cdot t}{1000}\right)\Bigg] \cdot \frac{1}{(1 + 0.03)^{t}} \approx 855{,}906{,}315 \text{ €}$$

In summary, the diesel-only reference scenario leads to total costs of 999,975,149 €, while Scenario A results in savings of approximately 143.65 million € (–14.36%) and Scenario B in savings of 144.07 million € (–14.41%). The implications of these findings will be further interpreted and contextualized in **Chapter 7**, where both cost and emission trends are synthesized and discussed in light of long-term decarbonization strategies and policy targets.

6.3.4 Sensitivity Analysis

To reflect uncertainties in long-term projections and better understand the influence of key model assumptions, a sensitivity analysis was carried out using the total cost equation.
This equation forms the analytical foundation of the cost-benefit assessment, integrating both economic and environmental cost components over a 50-year horizon. It accounts for vehicle-related total cost of ownership, well-to-wheel emissions, and carbon pricing, all adjusted via an annual discount factor. An annotated version of the equation is provided below, in which the three varied input parameters are highlighted in red - the discount rate i, the carbon price function $r_{CO_2}(t)$, and the replacement rate function $p(t)$:

$$C_{T50} = \Bigg[\Bigg(\mathrm{TCO_D} \cdot \left(\frac{n - n_{\mathrm{BEB},0} - p(t) \cdot n \cdot t}{n}\right) + \mathrm{TCO_E} \cdot \left(1 - \frac{n - n_{\mathrm{BEB},0} - p(t) \cdot n \cdot t}{n}\right)\Bigg) \cdot n \cdot D_a$$

$$+ \Bigg(E_{\mathrm{D,WTW}} \cdot \left(\frac{n - n_{\mathrm{BEB},0} - p(t) \cdot n \cdot t}{n}\right) + E_{\mathrm{E,WTW}} \cdot \left(1 - \frac{n - n_{\mathrm{BEB},0} - p(t) \cdot n \cdot t}{n}\right)\Bigg)$$

$$\cdot \left(\frac{n \cdot D_a}{1000}\right) \cdot \left(\frac{r_{CO_2}(t)}{1000}\right)\Bigg] \cdot \frac{1}{(1+i)^{t}}$$

The sensitivity analysis specifically investigates these three parameters because they represent the most influential yet uncertain inputs in long-term decarbonization modelling:
The sensitivity analysis specifically investigates these three parameters because they represent the most influential yet uncertain inputs in long-term decarbonization modelling.
The discount rate i reflects the time value of money and significantly affects the weight assigned to future costs. In line with typical public investment appraisal ranges, values of 1%, 3%, and 5% were tested. A higher discount rate reduces the present value of future expenditures, thereby favoring short-term cost savings over long-term benefits. The carbon

price trajectory $r_{CO_2}(t)$ determines the monetized weight of CO_2 emissions over time. Although all scenarios start from a common empirical baseline of 64.74 €/t in 2024, the rate of increase varies across three assumptions: a low scenario with linear growth of 5 €/t p.a., a base scenario with 13 €/t p.a., and a high scenario with 20 €/t p.a. These reflect varying degrees of climate policy ambition and regulatory stringency. The replacement rate function $p(t)$ models the annual substitution of diesel buses with BEBs. This parameter captures the speed of the fleet transition. A base case assumes a linear substitution of 10% p.a., while a slower transition assumes 5% p.a., representing logistical or financial constraints. Conversely, a fast transition of 15% p.a. reflects accelerated policy support or rapid technological adoption.
Each combination of these variables was tested to generate a set of total cost outcomes , expressed in euros, over the modeled 50-year period assuming buses and an initial BEB share of . The goal of this analysis is to test the robustness of the results and to identify under which conditions battery-electric adoption delivers maximum cost-effectiveness.
The following three compact matrices (**Tables 5-7**) summarize the cumulative total costs for all combinations of parameter values. Each matrix corresponds to one replacement rate scenario and displays how variations in discount rate and carbon price trajectory affect overall system costs. The complete data table is provided in **Appendix A.1**. The interpretation of these results and their policy implications are discussed in greater detail in **Chapter 7**.

Slow BEB Replacement (5% p.a.):

- $p(t) = \dfrac{n - n_{\text{BEB0}} - 0.05 \cdot \left(n - n_{\text{BEB0}}\right) \cdot t}{n}$, with $p(t) \geq 0$
- $n_{\text{BEB,0}} = 0$

$r_{CO_2}(t)$	i = 0.01 (**1%**)	i = 0.03 (**3%**)	i = 0.05 (**5%**)
64.74 + 5t	1,535,498,380 €	1,000,449,867 €	753,965,358 €
64.74 + 13t	1,541,566,469 €	1,013,507,338 €	768,327,942 €
64.74 + 20t	1,546,876,476 €	1,024,804,241 €	781,517,437 €

Table 5
Total cost under slow BEB replacement scenario (5% annual substitution)
Note. All values reflect the cumulative total cost C_T over 50 years, assuming n = 0, $n_{\text{BEB,0}}$ = 0, and varied input parameters for the functions $p(t)$ and $r_{CO_2}(t)$ and the variable i

Medium BEB Replacement (10% p.a.):

- $p(t) = \dfrac{n - n_{\text{BEB0}} - 0.1 \cdot \left(n - n_{\text{BEB0}}\right) \cdot t}{n}$, with $p(t) \geq 0$
- $n_{\text{BEB,0}} = 0$

$r_{CO_2}(t)$	i = 0.01 (**1%**)	i = 0.03 (**3%**)	i = 0.05 (**5%**)

64.74 + 5t	1,710,194,000 €	1,101,401,027 €	768,400,038 €
64.74 + 13t	1,522,833,165 €	1,018,891,383 €	732,109,832 €
64.74 + 20t	1,364,111,615 €	947,975,973 €	700,355,902 €

Table 6
Total cost under medium BEB replacement scenario (10% annual substitution)
Note. All values reflect the cumulative total cost C_T over 50 years, assuming $n = 0$, $n_{\text{BEB},0} = 0$, and varied input parameters for the functions $p(t)$ and $r_{\text{CO}_2}(t)$ and the variable i

Fast BEB Replacement (15% p.a.):

- $p(t) = \dfrac{n - n_{\text{BEB0}} - 0.15 \cdot \left(n - n_{\text{BEB0}}\right) \cdot t}{n}$, with $p(t) \geq 0$
- $n_{\text{BEB},0} = 0$

$r_{\text{CO}_2}(t)$	$i = 0.01$ (**1%**)	$i = 0.03$ (**3%**)	$i = 0.05$ (**5%**)
64.74 + 5t	1,884,896,344 €	1,205,208,734 €	832,810,569 €
64.74 + 13t	1,703,918,734 €	1,024,275,768 €	765,171,823 €
64.74 + 20t	1,538,273,860 €	948,025,523 €	709,110,773 €

Table 7
Total cost under fast BEB replacement scenario (15% annual substitution)
Note. All values reflect the cumulative total cost C_T over 50 years, assuming $n = 0$, $n_{\text{BEB},0} = 0$, and varied input parameters for the functions $p(t)$ and $r_{\text{CO}_2}(t)$ and the variable i

6.3.5 Dynamic Fuel Cost Scenario

In this section, a dynamic fuel cost scenario is introduced to capture the long-term impact of fluctuating fuel prices on the TCO. While TCO_E remains a constant component, TCO_D evolves into the time-dependent function $TCO_D(t)$, incorporating the fuel cost $C_F(t)$.
At the core of the model lies the following decomposition:

$$\text{TCO}_D(t) = C_F(t) + C_M + C_I$$

where

$$C_F(t) = C_F(0) \cdot 1.01^t \quad \left[\frac{€}{\text{km}}\right]$$

and

$$C_F(0) = 0.64 \ \frac{€}{\text{km}}$$

The function $C_F(t)$ represents the dynamic development of fuel costs, which are assumed to increase by **1% annually**. This assumption is based on market outlooks reported by the

Financial Times (2025), highlighting the steady upward trend in global fuel prices. Consequently, the diesel-related share of the TCO is not static, but rises incrementally with each year of the 50-year model horizon.
To operationalize this, the baseline fuel cost of 0.64 €/km is multiplied by an annual growth factor of 1.01. The total cost of diesel buses is then derived by combining this dynamic fuel cost with the constant maintenance and infrastructure components, resulting in the following formulation:

$$\mathrm{TCO}_D(t) = (0.64\ \frac{€}{km} \cdot (1.01)^t) + 0.25\ \frac{€}{km} + 0.93\ \frac{€}{km}$$

Building on this foundation, the model calculates the cumulative cost trajectories under Scenario A with $n_{\mathrm{BEB},0} = 0$. A baseline Scenario without any transition can be expressed through the following:

$$C_{T50}^{D} = \sum_{t=0}^{49} \left[\mathrm{TCO}_D(t) \cdot n \cdot D_a + E_{\mathrm{WTW},D} \cdot \left(\frac{n \cdot D_a}{1000} \right) \cdot \left(\frac{64{,}74 + 13 \cdot t}{1000} \right) \right] \cdot \frac{1}{(1+i)^t}$$

which then results in:

$$C_{T50}^{D} = \sum_{t=0}^{49} \left[\left(0{,}64 \cdot (1{,}01)^t + 0{,}25 + 0{,}93\right) \cdot 486 \cdot 45{,}500 + \frac{1328 \cdot \left(\frac{486 \cdot 45{,}500}{1000} \right) \cdot \left(64{,}74 + 13 \cdot t\right)}{1000} \right] \cdot \frac{1}{(1+0{,}03)^t} \approx 1{,}385{,}068{,}310\ €$$

The Cost-Benefit-Perspective with monetised emissions can be expressed through the following:

$$\begin{aligned} C_{T50} = \sum_{t=0}^{49} \Bigg[& \left(\mathrm{TCO}_D(t) \cdot \frac{n - n_{\mathrm{BEB},0} - 0.1 \cdot (n - n_{\mathrm{BEB},0}) \cdot t}{n} + \mathrm{TCO}_E \cdot \left(1 - \frac{n - n_{\mathrm{BEB},0} - 0.1 \cdot (n - n_{\mathrm{BEB},0}) \cdot t}{n} \right) \right) \cdot n \cdot D_a \\ & + \left(E_{D,\mathrm{WTW}} \cdot \frac{n - n_{\mathrm{BEB},0} - 0.1 \cdot (n - n_{\mathrm{BEB},0}) \cdot t}{n} + E_{E,\mathrm{WTW}} \cdot \left(1 - \frac{n - n_{\mathrm{BEB},0} - 0.1 \cdot (n - n_{\mathrm{BEB},0}) \cdot t}{n} \right) \right) \\ & \cdot \left(\frac{n \cdot D_a}{1000} \right) \cdot \left(\frac{64.74 + 13 \cdot t}{1000} \right) \Bigg] \cdot \frac{1}{(1+i)^t} \end{aligned}$$

which then results in:

$$\begin{aligned} C_{T50}^{A} = \sum_{t=0}^{49} \Bigg[& \left(\mathrm{TCO}_D(t)\, s_D^*(t) + \mathrm{TCO}_E\, s_E^*(t) \right) \cdot n \cdot D_a \\ & + \left(E_{D,WTW}\, s_D^*(t) + E_{E,WTW}\, s_E^*(t) \right) \cdot \left(\frac{n \cdot D_a}{1000} \right) \cdot \left(\frac{64.74 + 13t}{1000} \right) \Bigg] \cdot \frac{1}{(1+i)^t} \approx 916{,}413{,}406\ € \end{aligned}$$

Under the dynamic fuel cost scenario with a 1% annual diesel price increase, Scenario A delivers a substantially lower present-value cost than the diesel-only baseline once monetised emissions are included. Specifically, Scenario A totals €916,413,406, versus €1,385,068,310 for the diesel-only case, yielding absolute savings of €468,654,904. This corresponds to a 33.83% reduction relative to the diesel-only baseline, confirming that a phased transition to BEBs is economically preferable when realistic fuel price growth is considered.These results will be further discussed in **Chapter 7**.

7. Findings

This chapter brings together the key findings of the analysis and evaluates them in light of stakeholder priorities, technological viability, and long-term policy objectives. The assessment is rooted in the DSR methodology, which combines structured problem analysis with iterative refinement of solution options. A key element of this methodology was the integration of a stakeholder analysis (**Chapter 5**), which systematically captured the distinct goals, constraints, and strategic orientations of EU policymakers, public transport operators, and vehicle manufacturers. These perspectives helped to shape the criteria for technology selection and provided an analytical foundation for the comparative assessment conducted in **Chapter 6**. The focus has progressively narrowed from a broad technology landscape to the most feasible decarbonization solution for urban bus fleets: battery-electric buses. This narrowing process was based on empirical performance data, policy relevance, and stakeholder alignment.

While other drivetrain options—such as compressed natural gas (CNG), liquefied natural gas (LNG), or plug-in hybrid systems—were initially considered, they were excluded due to limited emission reduction potential, ongoing reliance on fossil infrastructure, or transitional status. FCEBs remained under consideration until the final stages but were ultimately excluded from the quantitative cost-benefit analysis due to their high energy consumption, infrastructure and fuel costs, and weaker overall performance.

The remaining sections of this chapter translate the findings into actionable insights. **Section 7.1** provides a detailed interpretation of the empirical results from **Chapter 6**, identifying the key factors behind the superior performance of BEBs. **Section 7.2** formulates recommendations for EU policymakers, public transport operators, and vehicle manufacturers, derived from both the performance assessment and stakeholder goal analysis.

7.1 Interpretation of Results

The comparative cost and emission analyses in **Chapter 6** demonstrate that the implementation of BEBs represents the most viable long-term decarbonisation strategy for urban public transport in the EU. They outperform diesel and hydrogen alternatives on environmental grounds when assessed over a 50-year horizon. The decisive factors behind this result are their low operational and maintenance costs, superior energy efficiency, and rapid technological cost decline, particularly in battery modules.

From an economic perspective, BEBs currently remain slightly more expensive than diesel buses when total lifecycle costs are considered. In the simulation, the TCO of BEBs amounts to 1.38 €/km, compared to 1.30 €/km for diesel buses, resulting in a cost disadvantage of 8 ct/km. However, this gap is narrow and expected to diminish as battery prices fall further and fuel cost increase. Moreover, the analysis shows that the integration of CO_2 pricing and the monetization of avoided emissions significantly improve the economic outlook for BEBs: over the 50-year modelling horizon, Scenario A, which starts with no BEBs and introduces them gradually, incurs additional costs of +11.42%, while Scenario B, starting from an initial stock of 62 BEBs, results in slightly lower additional costs of +10.74% compared to the diesel-only-scenario without any transition.

Once CO_2 emissions are monetized, the outcome follows the same trend: Scenario A yields savings of approx. 143.65 million euros (−14.36%), and Scenario B yields savings of approx. 144.83 million euros (−14.48%) relative to the diesel-only reference. This outcome reflects the long-term benefit of avoided emissions when internalized via carbon pricing and supports the conclusion that BEBs can offer net economic benefits under realistic policy conditions.

In addition to the main scenarios, **Chapter 6.3.4** introduced a sensitivity analysis to examine how changes in key model parameters affect total system costs. Specifically, the discount rate , the carbon price trajectory , and the substitution rate were systematically varied. The analysis confirms that even under conservative carbon pricing and slower electrification rates, BEBs remain competitive over the long term. In particular, the results highlight that faster electrification (e.g., 15% replacement per year) and stronger carbon pricing (e.g., 20 €/t annual increase) significantly improve the economic case for BEBs. Conversely, higher discount rates (e.g., 5%) reduce the present value of future benefits and may delay the point of cost parity, especially under weak climate policy signals. These dynamics demonstrate the importance of policy design and timing and underline the value of long-term planning horizons. For instance, in the most conservative scenario—featuring a slow replacement rate of 5% per year, a low carbon price increase of 5 €/t annually, and a high discount rate of 5%—total costs still fall below 754 million euros. In contrast, under the most favorable conditions—15% replacement per year, a carbon price trajectory of 64.74 + 20t, and a low discount rate of 1%—the system incurs total costs of approximately 1.885 billion euros. These extreme cases demonstrate how sensitive the long-term outcome is to climate policy ambition and financial assumptions. The full range of all 27 scenarios is provided in Appendix Table A.1, complementing the summary in Tables 5–7 and offering additional transparency for policy-oriented interpretation.

In addition, a separate simulation assessed the effect of a continuous diesel price increase of 1% per year, reflecting the long-term upward trend in fossil fuel costs reported in international energy markets (Financial Times, 2025). The results indicate that such a fuel cost escalation substantially narrows the cost gap between diesel and BEB operation. Over the 50-year horizon, total system costs in the diesel-only baseline increase markedly, while the BEB scenarios remain largely unaffected due to their higher energy efficiency and insulation from fossil fuel price volatility. This finding further reinforces the conclusion that BEBs offer superior long-term economic resilience, particularly under realistic assumptions of sustained increases in conventional fuel prices.

In terms of emissions performance, BEBs demonstrate a dramatic improvement over diesel buses. With well-to-wheel emissions of 247 g CO_2/km compared to 1328 g CO_2/km for diesel, they reduce specific GHG output by over 81%. Over 50 years, the emission model estimates approximately 1,469,971 t CO_2 for a diesel-only scenario, approximately 404,568 t CO_2 for Scenario A with a gradual BEB transition from 0, and approximately 374,732 t CO_2 for Scenario B starting from 62 BEBs. These values reflect a cumulative reduction of 72.5% and 74.5% respectively, highlighting the environmental superiority of BEBs, particularly when electrification efforts start early. Even a modest initial BEB share significantly amplifies cumulative emission savings.

The stakeholder analysis from **Chapter 5** confirms that BEBs offer the highest goal alignment across all three actor groups. For policymakers, they ensure compliance with fleet decarbonisation targets. For PTOs, they offer long-term cost stability and operational

simplicity. For manufacturers, they present a scalable and regulation-compatible product platform.
Alternative technologies such as FCEBs were ultimately excluded from the quantitative modelling due to their infrastructure intensity, fuel cost volatility, and unfavourable efficiency profile. While FCEBs may remain relevant in niche contexts—e.g. for long-distance, intercity or airport-shuttle applications—the findings suggest they are not the optimal default for urban fleet decarbonisation.
In summary, the simulation results validate the DSR-based technology selection framework. The combination of stakeholder goal alignment, empirical cost and emission performance, and long-term policy compatibility converges on BEBs as the dominant solution archetype for urban public bus fleets in the EU.

7.2 Stakeholder Recommendations

The following recommendations are derived from the cost-benefit analysis, sensitivity tests, and stakeholder alignment results developed throughout **Chapters 5 and 6**. They aim to translate the study's insights into tailored guidance for policymakers, public transport operators, and manufacturers, and are structured along the three key stakeholder groups examined.

7.2.1 Policymakers

To accelerate the decarbonisation of urban bus fleets, EU policymakers should begin by addressing the most impactful strategic levers in the correct sequence. First, they should implement more binding zero-emission procurement mandates. As demonstrated in **Chapter 6.3.1**, even a modest initial BEB share significantly improves long-term emission outcomes. These mandates can provide regulatory certainty and stimulate early investment in infrastructure and fleet conversion.
Second, financial instruments must be better aligned with early transition incentives. Targeted subsidies and reformed co-financing mechanisms should reward early adopters through preferential funding access. This approach ensures that frontrunners are not penalized for taking initiative, while also creating visible benchmarks for other Member States.
Third, a credible CO_2 price trajectory should be communicated well in advance. As shown in **Chapter 6.3.3** and confirmed through sensitivity analysis in **Chapter 6.3.4**, the inclusion of rising carbon prices materially shifts long-run cost competitiveness in favor of BEBs. Clear pricing signals can influence procurement decisions even before diesel operation becomes more expensive in absolute terms, as investors anticipate future cost trends.
Fourth, energy taxation reform is required to remove distortions in fuel pricing. Instead of artificially low diesel tax rates, the framework should be adjusted to reflect environmental externalities. This includes reducing electricity levies for public transport and increasing diesel taxation. Once BEB-TCO falls below the one of diesel – a development supported by battery learning curves – the market can self-regulate without the need for ongoing subsidy.

Fifth, structural disparities across Member States must be addressed. **Chapter 6.1.5** highlights major geographical differences in BEB deployment, reflecting unequal financial and institutional capacity. Funding instruments should therefore prioritise structurally weaker regions through dedicated financial windows, simplified application procedures, and enhanced technical assistance.
Finally, monitoring and coordination mechanisms should be enhanced. Linking funding eligibility to transparent performance reporting can improve accountability, while coordinated EU-level planning for infrastructure interoperability can avoid fragmentation.

7.2.2 Public Transport Operators (Demand Side)

To ensure that the transition to zero-emission buses proceeds in a financially and operationally sustainable way, public transport operators should align their fleet strategies with long-term decarbonisation goals and stakeholder dynamics. The following measures are derived from the overall stakeholder and scenario-based analysis conducted in **Chapters 5** and **6**:
First, operators should adopt strategic fleet electrification plans that are phased and aligned with infrastructure expansion and long-term cost-benefit projections. **Chapter 6.3** showed that gradual transitions – such as 10% conversion per year – yield substantial emissions reductions without overstretching budgets or infrastructure capacity.
Second, total cost of ownership (TCO) models should guide procurement and investment decisions. As demonstrated in **Chapter 6.3.2**, while BEBs entail higher capital expenditures, they offer lower energy and maintenance costs, reducing lifecycle expenses over time.
Third, fleet investment strategies should account for residual value risks and customer-side uncertainties, as identified in Chapter 5. Operators often show risk-averse behavior, which can be linked to uncertainties around asset lifetimes, resale values, and changing regulatory frameworks. While resolving these issues requires coordinated policy support, operators can proactively manage this uncertainty by diversifying procurement portfolios, engaging in second-hand market coordination with regional peers, and fostering internal scenario planning capabilities. This reduces dependency on external guarantees and builds internal resilience over time.
Fourth, the structural disparities identified in **Chapter 6.1.5** should prompt operators in less advanced Member States to proactively build up institutional capabilities and technical know-how—potentially through partnerships with frontrunner cities, knowledge-sharing platforms, or EU-supported capacity-building programs. While funding instruments play a crucial role here, operators themselves can lay the groundwork by seeking collaboration, piloting small-scale deployments, and aligning early with policy frameworks.
Fifth, operators should take advantage of EU and national funding mechanisms that align with long-term climate goals. The frontrunner examples discussed in **Chapter 6.1.5** illustrate how coordinated access to funding, infrastructure, and technical assistance accelerates electrification.
Sixth, operators should explore shared procurement consortia with neighboring cities or regional alliances. Pooling demand across municipalities could help unlock bulk purchase discounts, reduce transaction costs, and increase negotiation leverage with manufacturers —especially relevant in countries with fragmented transport governance.

Seventh, in anticipation of falling battery prices and stricter CO_2 pricing, operators should develop flexible procurement frameworks that allow them to scale up BEB investments rapidly once cost parity is reached. This adaptive approach reduces the risk of lock-in to outdated technologies and supports dynamic alignment with evolving policy and market conditions.
Finally, operators should adopt scenario-based financial planning over a 50-year horizon. The results in **Chapter 6.3.3** and the extended sensitivity analysis in **Chapter 6.3.4** show that long-term thinking reveals cumulative cost advantages and mitigates exposure to fossil fuel price risks. This integrated approach enables operators to implement evidence-based, economically viable, and emission-reducing electrification strategies, tailored to local capabilities and aligned with EU decarbonisation objectives.

7.2.3 Manufacturers and Suppliers (Technology Supply Side)

Manufacturers and technology suppliers play a pivotal role in advancing the public transport decarbonisation agenda. The analysis in **Chapters 5** and **6** highlights specific areas where supply-side actions are essential to support large-scale deployment of BEBs.
First, manufacturers should respond to the finding in **Chapter 6.3.2** that total cost of ownership (TCO) for BEBs remains slightly higher than for diesel buses, primarily due to elevated capital costs. To enable cost parity, suppliers must accelerate reductions in upfront vehicle prices—e.g., through economies of scale, localised production, and streamlined supply chains. A promising but underutilized strategy is the use of standardized modular bus platforms across models and regions, which can reduce development complexity and shorten innovation cycles.
Second, as **Chapter 6.2** highlights substantial differences in infrastructure costs across drivetrain types, manufacturers should proactively support operators with turnkey infrastructure solutions. This includes offering vehicle-infrastructure bundles, providing digital depot management systems, and assisting in energy demand planning. Suppliers could further reduce friction by co-investing in depot upgrades or offering "charging-as-a-service" models to decouple infrastructure ownership from fleet decisions.
Third, **Chapter 5.2.2** reveals that uncertainty around residual values and lifecycle performance limits investment willingness among operators. Manufacturers should therefore improve transparency through real-world performance tracking, establish repurchase programs, and support secondary markets to reduce customer-side risk. Additionally, manufacturers could collaborate with leasing firms to introduce performance-based leasing contracts, tying rates to actual vehicle efficiency and uptime.
Fourth, given the variations in operating conditions identified in **Chapter 6.1.5** - e.g., urban density, climate, topography - manufacturers should develop region-specific vehicle variants. This could include battery size adaptations, modular drivetrain configurations, or thermal management systems optimised for extreme temperatures. Collaborating with operators during the design phase may also yield use-case-driven vehicle specifications, improving both acceptance and operational fit.
Fifth, supply-side actors must adapt to market fragmentation in structurally weaker Member States, as shown in **Chapter 6.1.5**. To unlock demand, manufacturers should offer low-volume procurement solutions, flexible leasing models, and capacity-building support for smaller operators. A particularly high-leverage intervention could be the creation of

shared after-sales service hubs across cities and regions, pooling technical expertise and lowering maintenance costs for individual operators.

These targeted and innovative measures - each rooted in identified barriers - can enhance the commercial viability of BEBs and ensure that technology provision evolves in step with operational realities and EU policy expectations.

8. Conclusion

This final chapter synthesizes the analytical findings of the thesis, critically reflects on methodological limitations, and outlines potential directions for future research and policy development. The aim is to consolidate the implications of the stakeholder-based technology assessment and provide a forward-looking perspective on the decarbonisation of urban bus fleets in the EU.

8.1 Summary of Findings

This thesis examined the technological, economic, and regulatory conditions for decarbonising urban public bus fleets in the EU. Guided by a stakeholder-centred analytical framework and scenario-based modelling, the study evaluated how different drivetrain technologies perform under realistic operating and policy environments.

Chapter 5 provided a detailed analysis of the objectives and constraints of three key stakeholder groups - EU policymakers, public transport operators, and vehicle manufacturers. It identified a broad alignment in decarbonisation ambition but also revealed fundamental differences in priorities: policymakers emphasise regulatory consistency and climate targets, PTOs focus on cost-efficiency and service reliability, while manufacturers are driven by innovation, risk minimisation, and policy compatibility. These insights formed the foundation for the subsequent technology evaluation in **Chapter 6.**

Chapter 6 responded directly to these findings by assessing which zero-emission drivetrain technologies best address the most salient stakeholder priorities. BEBs emerged as the most balanced solution. From a policy perspective, they deliver substantial emission reductions - over **80%** in well-to-wheel CO_2 compared to diesel—and align with EU definitions of zero-emission vehicles. From the operator perspective, BEBs offer significantly lower operating costs and predictable charging infrastructure models, even though their total cost of ownership remains slightly higher than diesel (**+6.2%**) under current conditions. However, the inclusion of ETS-based CO_2 pricing turns BEBs into the economically superior option over a 50-year horizon, supporting investment planning from both the operator and manufacturer sides. The analysis also showed that a moderate annual diesel price increase of 1% significantly improves the relative competitiveness of BEBs by amplifying the long-term cost disadvantage of diesel operations, thereby strengthening the case for electrification under realistic market dynamics.

In addition, the findings show that early deployment yields substantial cost and emission benefits over time, confirming the importance of strategic timing identified by stakeholders.

Moreover, the dynamic scenario modelling demonstrated that a gradual fleet transition—e.g., replacing 10% of diesel buses annually—significantly mitigates investment intensity and risk. This flexibility supports more manageable capital planning, especially for operators with constrained procurement budgets.

The analysis also highlighted the critical role of CO_2 pricing as a structural enabler for cost parity. Only through the internalisation of environmental externalities do BEBs achieve full lifecycle cost advantages over diesel. This finding underscores the importance of stable and rising carbon price trajectories to align market signals with long-term climate goals.

Hydrogen fuel cell buses, by contrast, failed to meet key stakeholder goals simultaneously. Their higher energy consumption and fuel costs exceed the willingness-to-pay thresholds of PTOs. Moreover, limited infrastructure availability and low CO_2 price leverage weaken their policy relevance in the current EU context. Nonetheless, they may remain useful in specific long-range or topographically challenging applications.
Other drivetrain alternatives—such as plug-in hybrids, CNG buses, and synthetic fuels—were deliberately excluded from the analysis due to their inability to meet the EU's regulatory definition of zero-emission vehicles and their limited long-term viability. Their continued dependence on combustion processes, limited competitiveness and transitional infrastructures makes them less suitable for full fleet decarbonisation.
In sum, the combination of stakeholder-centred analysis and long-term technology modelling provided a robust framework for identifying implementation-ready solutions. It demonstrated that BEBs not only represent a feasible path for fleet decarbonisation but also offer the greatest convergence across regulatory, operational, and technological goals.
The complementary sensitivity analysis in **Chapter 6.3.4** further validated the robustness of these findings. By systematically varying three key parameters - carbon price trajectory, discount rate, and technology replacement rate - the model tested 27 distinct scenario combinations. The results confirmed that BEBs remain economically and environmentally advantageous even under conservative assumptions. In particular, faster electrification and higher carbon price growth produced the most substantial cost reductions, while high discount rates diminished the present value of long-term savings. These insights reinforce the case for early and ambitious deployment strategies and are summarized in Appendix Table A.I.

8.2 Limitations of the Research

While this thesis offers a comprehensive assessment of technological and stakeholder-based decarbonisation strategies, several limitations must be acknowledged. The analysis focuses exclusively on 12-meter solo city buses. Articulated, midi, or coach buses were excluded due to data limitations and substantial variation in use patterns, energy demand, and infrastructure requirements. As such, the results cannot be extrapolated without caution to other vehicle segments.
The economic model relies on several simplifying assumptions, including fixed residual values, and average energy and fuel prices. Although these inputs are based on literature benchmarks and realistic projections, they are not immune to future market volatility, regional price divergences, or changes in procurement frameworks. In addition, specific cost factors such as battery replacement, infrastructure expenditure, and carbon price trajectories were modelled using static or linear estimates. These simplifications, while necessary for tractability, may affect the accuracy of long-term scenario projections.
Moreover, several input values - such as maintenance costs, electricity and hydrogen prices, and total cost of ownership components - are derived from secondary data and expert-based estimates. Their applicability may vary across different national contexts and operator settings, which limits the precision of cross-country comparability. The use of the Wiener Linien fleet as the primary case study further restricts generalisability to cities with different topographies, procurement traditions, or regulatory setups.

In addition, non-monetised dimensions - such as social acceptance, political feasibility, or co-benefits from air quality improvements - were not included in the quantitative modelling framework. Although they are relevant to real-world decision-making, they were beyond the methodological scope of this study.

Finally, the stakeholder analysis was based solely on secondary sources and did not include empirical interviews or surveys. This limited the granularity of insight into local governance processes, operator strategies, and manufacturer positioning in specific markets.

These limitations underscore the need for complementary research approaches that incorporate empirical fieldwork, localised datasets, and multi-criteria evaluation methods to support more context-sensitive decarbonisation strategies.

8.3 Further Research

While this study provides a structured and comparative evaluation of battery-electric and hydrogen fuel cell buses, as well as cross-stakeholder dynamics, several avenues remain open for future research - particularly for advancing the precision, scope, and practical implementation of the findings.

First, the assumptions around carbon pricing were based on a linear growth forecast. A more sophisticated modelling framework could incorporate **non-linear price trajectories**, price shocks, or political risk scenarios using stochastic approaches or agent-based simulations. This would help assess the robustness of BEB cost advantages under volatile or regionally differentiated policy environments.

Second, the current analysis assumes **uniform fleet characteristics and usage profiles**, which simplifies comparison but underrepresents the diversity of real-world operations. Future work could integrate **granular, high-frequency operational data** (e.g. GPS driving profiles, route elevation, temperature) to better model energy demand and operating costs. This would allow for route-specific optimization of technology choice.

Third, researchers should explore **integrated system-level models** that include not only bus performance but also upstream electricity and hydrogen supply dynamics—such as marginal grid emissions, seasonal storage cycles, and renewable availability. This would enable more holistic lifecycle assessments and identify infrastructure constraints.

Fourth, residual value assumptions in this study were static. Future work could introduce **dynamic depreciation curves**using empirical market data and investigate the economic effects of second-life applications (e.g. stationary battery reuse, inter-municipal transfers).

Fifth, adding **mixed-fleet modelling** could more accurately reflect transition strategies, assessing how diesel, BEB, FCEB, and other configurations (e.g. trolleybuses, plug-in hybrids) could coexist. Such modelling would need to account for regional differences in energy prices, depot capacity, and infrastructure maturity.

Sixth, future research could disaggregate results by **vehicle segment**, including articulated, midi, double-decker buses, and alternative electric configurations such as **trolleybuses, opportunity charging systems**, and **inductive charging platforms**. These technologies differ significantly in cost structure, range, infrastructure dependency, and operational viability, especially in topographically or climatically challenging areas. Segment- and technology-specific analysis would improve decision-making relevance.

Eighth, **modularizing core formulas** would enable regional customization. Variables such as taxation regimes, grid emissions, labour costs, and subsidy frameworks could be integrated as inputs, making the model more adaptable for comparative policy assessments. Where appropriate, **country-specific formula variants** could be designed to reflect distinct national market conditions, enabling policy stress-testing across EU regions.

Finally, **alternative financing models**, such as cooperative ownership, performance contracting, or leasing schemes, should be evaluated for their impact on lifecycle cost dynamics. Simulating these models under varying **CAPEX** assumptions could support more viable financing pathways.

Together, these extensions would build on and refine the outcomes of this thesis while addressing modelling simplifications. They also highlight the need for interdisciplinary, flexible tools in designing effective decarbonisation strategies for EU urban transport.

8.4 Outlook

While this thesis has focused on the current state of zero-emission drivetrain technologies and their techno-economic implications, several ongoing developments **are gaining momentum** and could further accelerate the decarbonisation of public transport in the EU.

First, the expansion of the **Trans-European Transport Network (TEN-T)** offers strategic opportunities for integrated deployment of clean bus technologies, particularly in urban nodes and along key multimodal corridors. TEN-T funding mechanisms are increasingly aligned with the EU's climate objectives and could facilitate investments in shared charging and hydrogen refuelling infrastructure (EC, 2024c).

Second, the emergence of **platooning concepts** and **connected vehicle technologies** holds promise for improving energy efficiency in bus operations, especially for Bus Rapid Transit (BRT) systems or **BRT-like configurations**. These refer to high-capacity bus corridors that mimic the performance of light rail by combining features like dedicated lanes, signal prioritisation, and platform-level boarding. Such systems are increasingly integrated into urban planning strategies and can benefit substantially from connected driving modes. Consistent speeds, reduced aerodynamic drag, and optimised traffic prioritisation lead to tangible operational emission savings. In the context of urban decarbonisation, BRT configurations offer a scalable and relatively low-cost alternative to rail-based transit, while still enabling full electrification of fleets.

In addition, the diversification of electric bus architectures—such as **trolleybuses**, **opportunity charging** systems, and **inductive charging**—may allow cities with specific infrastructural legacies or operational constraints to find viable electrification pathways. These solutions can be particularly useful in dense corridors or high-frequency routes where conventional BEB charging models face capacity limits or depot space constraints.

Third, **automated and autonomous public transport systems** are being trialled in several European cities. While currently limited to pilot phases, such systems could improve scheduling efficiency and reduce idle times. Their integration with zero-emission drivetrains could significantly boost overall system sustainability.

Fourth, further integration of **renewable electricity and smart grid interaction** is critical for maximising the environmental benefits of BEBs. Smart depot charging, vehicle-to-grid (V2G) capabilities, and dynamic pricing integration allow for better alignment between fleet energy demand and grid supply, minimising marginal emissions and operational costs.

Fifth, the future of **hydrogen in heavy-duty mobility** remains contingent on achieving sufficient scale and cost reduction. While FCEBs currently underperform in cost-benefit terms, ongoing investments under **EU Hydrogen Strategies** and the **Clean Hydrogen Partnership** may alter this trajectory in selected segments, particularly for long-distance or topographically demanding routes (EC, 2025b).
Moreover, the revision of the **EU Energy Taxation Directive** (ETD) aims to eliminate tax advantages for fossil fuels and introduce CO_2-based minimum rates. As of 2025, this proposal remains under negotiation, but its eventual adoption could significantly shift fiscal incentives by reducing current distortions between diesel and electricity. If complemented by a gradually rising CO_2 price signal, as outlined in the EU ETS roadmap, these fiscal instruments could strongly influence investment behavior - encouraging early adoption of BEBs by increasing the long-term opportunity cost of diesel dependency (EC, 2021b).
These and other trends underscore the importance of maintaining a technology-open, adaptive policy environment. Continued innovation in digitalisation, automation, infrastructure integration, and fiscal frameworks will play a decisive role in shaping the next phase of decarbonisation strategies for Europe's public transport networks.

Back Matter

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Annex

A.I: Total Cost Results (C_t) Across Discount Rate i, CO_2 Price Development, and Replacement Scenarios

Replacement Rate ∈ p(t) (% p.a.)	rCO_2 (t)	Discount Rate i	C_t
0.05	64.74 + 5t	0.01	1,535,498,380 €
0.05	64.74 + 5t	0.03	1,000,449,867 €
0.05	64.74 + 5t	0.05	753,965,358 €
0.05	64.74 + 13t	0.01	1,541,566,469 €
0.05	64.74 + 13t	0.03	1,013,507,338 €
0.05	64.74 + 13t	0.05	768,327,942 €
0.05	64.74 + 20t	0.01	1,546,876,476 €
0.05	64.74 + 20t	0.03	1,024,804,241 €
0.05	64.74 + 20t	0.05	781,517,437 €
0.10	64.74 + 5t	0.01	1,710,194,000 €
0.10	64.74 + 5t	0.03	1,101,401,027 €
0.10	64.74 + 5t	0.05	768,400,038 €
0.10	64.74 + 13t	0.01	1,522,833,165 €
0.10	64.74 + 13t	0.03	1,018,891,383 €
0.10	64.74 + 13t	0.05	732,109,832 €
0.10	64.74 + 20t	0.01	1,364,111,615 €
0.10	64.74 + 20t	0.03	947,975,973 €
0.10	64.74 + 20t	0.05	700,355,902 €
0.15	64.74 + 5t	0.01	1,884,896,344 €
0.15	64.74 + 5t	0.03	1,205,208,734 €
0.15	64.74 + 5t	0.05	832,810,569 €
0.15	64.74 + 13t	0.01	1,703,918,734 €
0.15	64.74 + 13t	0.03	1,024,275,768 €
0.15	64.74 + 13t	0.05	765,171,823 €
0.15	64.74 + 20t	0.01	1,538,273,860 €
0.15	64.74 + 20t	0.03	948,025,523 €
0.15	64.74 + 20t	0.05	709,110,773 €

Declaration of AI Use

In the preparation of this thesis, generative AI tools such as ChatGPT (OpenAI, GPT-4 Plus) were used to support technical and editorial tasks. Specifically, assistance was limited to:

- Structuring LaTeX syntax for mathematical expressions and tables
- English text formatting and grammar suggestions
- Citation management and standardisation of abbreviations

No AI-generated content was used in the development of scientific arguments, analytical reasoning, or original writing. All content and conclusions were conceived, written, and critically reviewed by the author. The AI served exclusively as a technical and linguistic aid.