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Decarbonizing STIB Bus Fleet: A Multi-Criteria Comparison of Battery Electric and Hydrogen Fuel Cell Buses

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Abstract

This study evaluates the optimal technological pathway for the Brussels Intercommunal Transport Company (STIB) to progressively decarbonize its urban surface transit fleet. A comprehensive, region-specific evaluation framework is developed, comparing Battery Electric Buses (BEBs) and Fuel Cell Electric Buses (FCEBs) across three key pillars: environmental performance, economic feasibility, and operational practicality. The methodology integrates a cradle-to-grave Life Cycle Assessment (LCA), a discounted Net Present Value Total Cost of Ownership (TCO) model, semi-structured interviews with transit engineering experts, and a final Multi-Criteria Decision-Making (MCDM) matrix. The LCA results demonstrate that environmental benefits are highly contingent upon upstream energy pathways; under an optimized low-carbon Belgian electricity mix and green hydrogen, FCEBs achieve lower lifetime emissions than BEBs (0.21 versus 0.30 kg CO_2e/km), though this advantage is entirely neutralized if fossil-derived grey hydrogen is used. Conversely, the TCO analysis outlines a severe economic penalty for hydrogen fleets; over a 15-year design lifespan and 675,000 km of operation, BEBs achieve a standardized unit TCO including infrastructure amortization of 1.19€/km compared to 1.84€/km for FCEBs, a gap driven by current green hydrogen market price premiums relative to grid electricity. Empirical interview results confirm that BEBs exhibit superior localized practicality due to established infrastructure compatibility, mature depot electrification roadmaps, and high power supply reliability, which offset the FCEB's theoretical advantages in range and refueling logistics. Finally, the multi-criteria analysis confirms that BEBs represent the optimal near-to-mid-term transition pathway for STIB, securing a global suitability score of 0.94 compared to 0.76 for FCEBs.

Keywords: battery electric buses; fuel cell electric buses; decarbonization; energy path dependence; life cycle assessment; total cost of ownership; operational usability

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1. Introduction

Climate change represents one of the most critical global challenges of the 21st century. The Paris Agreement established a binding international framework to limit the global temperature increase to 1.5 °C above pre-industrial levels. In parallel, the United Nations Sustainable Development Goals (SDGs), particularly SDG 11, emphasize the urgency of developing sustainable, resilient, and inclusive cities. Urban areas are central to this climate

challenge, as they currently account for 60–80% of global energy consumption and approximately 75% of global carbon emissions. Within urban ecosystems, the transport sector is a primary driver of environmental degradation, contributing to 24% of global greenhouse gas (GHG) emissions. Consequently, transitioning to sustainable public transport systems is a cornerstone for reducing urban carbon footprints and mitigating traffic congestion.

At the national level, Belgium reflects these global pressures. Between 1990 and 2023, the share of transport-related emissions in Belgium rose significantly from 14.4% to 25.1% of total emissions. This upward trend is almost exclusively driven by road transport, which constitutes 96% of the sector's total emissions. In the Brussels-Capital Region, urban transport is responsible for approximately 27% of total regional GHG emissions and acts as a primary source of local air pollution. To address this public health and environmental crisis, the region implemented a Low Emission Zone (LEZ) in January 2018. Environmental regulations within the LEZ have been progressively tightened; as of 1 January 2026, Euro 5 diesel vehicles and Euro 2 petrol vehicles—including public transit buses—are banned from circulating in the Brussels Region. These regulatory constraints exert substantial pressure on urban transport operators to accelerate the deployment of zero-emission vehicles (ZEVs).

As the main public transport operator in Brussels, managing metro, tram, and bus networks, the Brussels Intercommunal Transport Company (STIB) plays a pivotal role in the region's decarbonization strategy. Public transit accounts for a significant share of local mobility, with STIB capturing 27% of all urban trips. To comply with LEZ mandates and regional climate targets, STIB must transition its remaining diesel bus fleet toward zero-emission alternatives.

The two leading technological pathways for heavy-duty urban transit are Battery Electric Buses (BEBs) and Fuel Cell Electric Buses (FCEBs). While both technologies utilize electric drivetrains, they fundamentally differ in their energy storage and powertrain architectures:

- BEBs store electricity directly in onboard electrochemical batteries charged via external grid infrastructure. Their operational efficiency is highly dependent on charging constraints and grid capacity.
- FCEBs generate electricity onboard through an electrochemical reaction between compressed hydrogen and oxygen within a fuel cell stack, utilizing a smaller buffer battery to manage transient power demands. FCEBs offer longer driving ranges and fast refueling times but require dedicated high-pressure hydrogen refueling infrastructure. As indicated by [1], commercial fuel cell electric vehicles represent a key pathway for zero-emission transportation.

Choosing between these technologies involves complex trade-offs. Therefore, this research aims to answer the following core question: Which technological solution, battery electric buses or fuel cell electric buses, represents the optimal choice for STIB to systematically replace its diesel bus fleet, considering environmental impacts, economic feasibility, and operational practicality?

While previous literature frequently addresses the environmental benefits of zero-emission buses, comprehensive studies simultaneously evaluating economic feasibility and real-world operational practicality remain limited. Most existing research overlooks the specific challenges faced by fleet operators, such as depot spatial constraints, grid charging bottlenecks, and refueling logistics. Furthermore, few studies have contextualized these factors within the unique energy mix, regulatory framework, and climatic conditions of Belgium and the Brussels-Capital Region.To bridge this gap, this study develops a holistic, region-specific evaluation framework utilizing a mixed-methods approach:

1. Environmental Assessment: A quantitative LCA is conducted in compliance with ISO 14040/14044 standards to evaluate well-to-wheel and manufacturing impacts.

2. Economic Assessment: A TCO model is applied to assess procurement, infrastructure, maintenance, and energy costs over the vehicle life cycle.
3. Operational Practicality: A qualitative empirical analysis is conducted through semi-structured interviews with STIB transit professionals to evaluate real-world deployability, route flexibility, and maintenance facility constraints.

The remainder of this paper is organized as follows: Section 2 details the LCA and TCO methodologies alongside the qualitative interview framework; Section 3 presents the results concerning the environmental impact and details the LCA's computation; Section 4 presents the economic results and details the TCO's computation; Section 5.1 presents the operational practicality and fleet integration results. Section 6 applies the mutlti-criteria analysis to our case study; and Section 7 concludes with key recommendations for transit decarbonization.

2. Literature Review

This section synthesizes current academic literature regarding the deployment of alternative zero-emission bus technologies in urban transit. The review is structured around three critical dimensions: life-cycle environmental impacts, economic cost structures, and operational practicality in real-world urban networks.

2.1. Environmental Impacts and Life Cycle Assessment

Both battery electric buses (BEBs) and fuel cell electric buses (FCEBs) represent pivotal technological pathways to mitigate urban air pollution, as both configurations eliminate tailpipe emissions during operation. However, recent scholarship strongly emphasizes that evaluating environmental performance solely based on tank-to-wheel (TTW) emissions creates a misleading paradigm. Decarbonizing the transport sector does not inherently eliminate greenhouse gas (GHG) emissions; rather, it shifts the carbon burden upstream to the vehicle manufacturing and energy production phases. Consequently, employing a comprehensive LCA framework is imperative to evaluate the true well-to-wheel (WTW) and cradle-to-grave ecological footprint of these vehicles.

A consensus across recent studies indicates that the upstream energy production pathway is the primary determinant of the net environmental performance for both technologies. For FCEBs, the carbon intensity of hydrogen (H_2) supply chains varies drastically depending on the production method, conventionally classified by color codes:

- Grey Hydrogen: Derived from steam methane reforming (SMR) of fossil natural gas without carbon capture, resulting in high carbon intensity (approx. 11 kg CO_2e/kg H_2).
- Blue Hydrogen: Produced via SMR but integrated with Carbon Capture, Utilization, and Storage (CCUS) technologies to mitigate climate impacts.
- Green Hydrogen: Generated through water electrolysis powered strictly by renewable energy sources, achieving minimal carbon footprints (below 1 kg CO_2e/kg H_2).
- Turquoise Hydrogen: Produced via methane pyrolysis, yielding solid carbon as a by-product rather than gaseous carbon dioxide.

Crucially, hydrogen produced via water electrolysis cannot be categorized as inherently sustainable. If the electrolysis process relies on a conventional national grid mix, its carbon footprint scales directly with the electricity sector's carbon intensity. For instance, in countries with highly decarbonized grids (e.g., France, dominated by nuclear and hydro power), electrolytic hydrogen generates approximately 2 kg CO_2e/kg H_2. Conversely, in nations heavily reliant on coal- and gas-fired power generation (e.g., Germany or Poland), electrolytic hydrogen emissions can escalate to roughly 20 kg CO_2e/kg H_2. Under high-carbon grid mixes, water electrolysis paradoxically yields higher life-cycle GHG emissions than standard fossil-based SMR, highlighting that FCEBs only offer environmental advan-

tages when integrated with low-carbon or renewable energy infrastructures. Similarly, the environmental viability of BEBs is fundamentally bound to the grid's carbon intensity during battery charging cycles.

Comparative LCA literature provides deeper insights into these trade-offs under varying regional energy mixes. Comparative data for standard 12-m buses operating on frequent-stop urban cycles show that FCEBs outperform BEBs only under highly specific, polarized conditions. When fueled by green hydrogen, FCEB emissions drop to approximately 0.11 kg CO_2e/km, compared to 0.24 kg CO_2e/km for a BEB charged with renewable electricity. FCEBs also maintain a slight edge in highly carbon-intensive grids (such as Poland or India, with grid intensities around 633 g CO_2/kWh), where an SMR-powered FCEB emits 0.87 kg CO_2e/km versus 0.95 kg CO_2e/km for a BEB. In all intermediate grid configurations, BEBs consistently demonstrate superior environmental performance.

However, this hierarchy is subject to academic debate. Projections by the International Council on Clean Transportation (ICCT) present a different trajectory, indicating that BEBs maintain an emissions advantage even under fully renewable scenarios. In the short-to-medium term (2021–2040) under a 100% renewable electricity framework, BEBs emit roughly 0.18 kg CO_2e/km, while green-hydrogen FCEBs exhibit slightly higher values. In the long-term horizon (2030–2049), deep decarbonization reduces BEB emissions to 0.125 kg CO_2e/km, while FCEB emissions stabilize around 0.18 kg CO_2e/km.

The ICCT models also outline less favorable energy scenarios: during the 2021–2040 period, charging BEBs with the average European grid mix increases emissions to 0.5 kg CO_2e/km. Concurrently, utilizing fossil-derived grey hydrogen causes FCEB emissions to spike, surpassing BEBs under both renewable and average grid scenarios. For the 2030–2049 period, the gap narrows; a BEB powered by the projected European grid mix (0.27 kg CO_2e/km) performs comparably to an FCEB supplied by a 50/50 blend of green and blue hydrogen.

Macro-level studies across the EU-27 confirm that regional energy sourcing dictates technology outcomes. Under current conditions where grey hydrogen dominates national mixes (except in isolated cases like Estonia's green hydrogen focus), FCEB deployment yields marginal benefits. However, mid-term EU scenarios assume significant grid decarbonization, with carbon intensities projected to fall below 400 g CO_2/kWh by 2030 in nearly all member states (excluding Poland and Greece), and ultimately dropping below 80 g CO_2/kWh toward 2040. This progressive grid cleaning will structurally lower the environmental break-even point for both vehicle types, making the choice heavily dependent on regional grid evolution and specific local operating constraints.

Based on these dynamic parameters, comparative LCAs mapping fleet transitions display a distinct temporal shift. Under baseline conditions, BEBs emerge as the environmentally optimal solution for the majority of EU regions. The exceptions are restricted to territories characterized by highly carbon-intensive electricity grids, such as Poland and Estonia, where FCEBs utilizing specialized localized hydrogen supply chains yield a lower footprint. By 2030, systemic advancements in low-carbon hydrogen infrastructures enhance the environmental competitiveness of FCEBs, allowing this technology to surpass BEBs in an increasing number of European nations. However, this crossover point is not yet achieved in Belgium within this timeframe due to its distinct national grid mix and slower projected local hydrogen integration. By 2050, under complete energy sector decarbonization scenarios, both powertrain configurations achieve near-zero life-cycle carbon emissions, with FCEBs displaying the lowest absolute values across the EU-27.

In summary, the literature demonstrates that the net environmental ranking of BEBs and FCEBs cannot be definitively generalized. Findings remain highly sensitive to geographic parameters, specific supply chain configurations, and selected analytical time

horizons. While BEBs consistently show a clear emissions advantage in the short term, this gap is projected to shrink significantly over time, with FCEBs establishing strong competitiveness as the hydrogen economy achieves deep decarbonization.

Note that the Hydrogen Council and Mac Kinsey Company [2] point out that delays in the development of the green hydrogen supply chain in Europe, the slow transposition of the RED III Directive, high costs, and the delayed rollout of transport and distribution infrastructure are forcing utility and grid operators to realign their strategic priorities. This gap between the EU's regulatory ambitions and market reality directly alters fleet management strategies and the modeling of investment decisions.

One potential consequence of the shortage or prohibitive cost of local green hydrogen for public transport fleet managers is a shift away from the 100% hydrogen immediately approach in favor of more realistic trade-offs, such as reducing order sizes. In terms of multi-criteria modeling, this may lead to significantly increasing the weight of the security and continuity of supply criterion. Finally, from a strategic standpoint, the lag in the hydrogen sector often compels public-sector stakeholders to decouple their short-term commitments from their long-term objectives.

2.2. Economic Aspects and Total Cost of Ownership

Evaluating the economic viability of transitioning urban transit fleets requires a comprehensive assessment of both upfront capital expenditure (CAPEX) and long-term operational expenditure (OPEX). Financial analyses in current literature consistently utilize the TCO framework to capture these dynamics over the complete operational lifespan of the vehicles.

Under current market conditions, financial assessments across several European jurisdictions demonstrate a distinct economic advantage for BEBs over FCEBs. This economic disparity is primarily driven by two factors: initial vehicle acquisition costs and retail fuel pricing. The capital investment required for a standard 12-m transit bus exhibits a significant premium for fuel cell technologies; the average purchase price of a 12-m BEB is estimated at €554,400, whereas a comparable FCEB reaches approximately €650,000 (excluding taxes, options included, See [3]).

On the operational side, the price differential between electricity and hydrogen supply chains further widens the TCO gap. In the European context, retail hydrogen prices average approximately €10/kg, whereas commercial electricity pricing stands at roughly €0.30/kWh. Consequently, the net TCO for BEBs is estimated at €1.13 per kilometer, whereas FCEBs escalate to €1.38 per kilometer [4]. empirical data from fleet operations in Northern Italy validate this trend, demonstrating that the direct running (energy) costs of a 12-m BEB stand at €0.53/km, compared to €1.23/km for an FCEB [5]. This indicates that FCEBs are approximately 2.3 times more expensive to operate on an energy-per-kilometer basis due to the structural inefficiencies and market immaturity of the current hydrogen supply infrastructure.

To synthesize these baseline financial parameters, Table 1 provides a comparative overview of current cost components.

Micro-level cost breakdowns offer deeper insights into the temporal evolution of these asset structures. Case studies analyzing small-to-midsize European urban networks—such as municipal operations in Offenburg, Germany—indicate that the TCO composition varies fundamentally over time between the two powertrains [6]. For BEBs, energy storage system (battery) replacement expenditures constitute the most substantial financial weight in the short-to-medium term. However, as the asset matures, amortization of the chassis and direct grid electricity costs represent the dominant shares of the aggregate cost structure. Conversely, for FCEBs, fuel supply costs remain the single largest contributor to the

TCO across all simulated operational scenarios [6]. This reinforces the conclusion that high operational energy costs represent a structural, long-term disadvantage for fuel cell adoption rather than a temporary logistical bottleneck.

Table 1. Current economic baseline parameters for 12-m urban transit buses in Europe.

Cost Component/Metric	Battery Electric Bus (BEB)	Fuel Cell Electric Bus (FCEB)
Average Acquisition Cost (CAPEX)	€554,400	€650,000
Baseline Energy/Fuel Price	€0.30/kWh	€10.00/kg
Operational Energy Cost per km	€0.53/km	€1.23/km
Integrated Total Cost of Ownership	€1.13/km	€1.38/km

Nevertheless, long-term predictive models suggest a potential shift in this economic equilibrium [4,7]. Technical maturement and scale economies in green hydrogen production are projected to induce significant price deflations. Sensitivity analyses indicate that financial parity between the two powertrain technologies is achievable when the retail hydrogen price drops to approximately €4.5/kg, assuming a stabilized baseline electricity cost of €0.12/kWh [4]. Driven by these projected market adjustments and manufacturing optimization, long-term forecasting models for the 2050 horizon suggest that FCEBs could emerge as the most cost-effective solution for public transit operators across various European contexts, including Belgium [7].

In conclusion, contemporary academic literature establishes that BEBs currently represent the most economically competitive zero-emission alternative for urban transit fleet deployment, primarily due to lower asset procurement costs and highly optimized operational energy expenditures. FCEB configurations remain financially constrained by high fuel costs that dominate their TCO. However, this technology represents a viable long-term economic alternative if global and regional hydrogen supply chains achieve deep cost-deflation targets.

2.3. Operational Practicality and Infrastructure Constraints

While battery electric vehicles currently dominate the zero-emission transit market, their widespread deployment is operationally constrained by finite driving ranges and extended charging windows [8]. To mitigate these spatial-temporal limitations, public transit operators frequently employ opportunity charging strategies at route termini. This approach effectively extends the daily operational envelope and permits a down-sizing of the onboard energy storage systems (ESS) [8]. However, the systemic implementation of high-power opportunity charging induces accelerated battery degradation via localized thermal stress and imposes significant peak-load penalties on the local electrical grid [8].

In contrast, standard overnight depot charging protocols for BEBs require substantial downtime, ranging from 4 to 6 h, which can be optimized to 1 to 2 h only through high-power direct current (DC) fast-charging infrastructure [9]. Conversely, FCEBs exhibit high operational autonomy and do not require mid-service refueling interventions [8]. Fuel cell configurations feature exceptionally brief replenishment cycles, typically requiring only 5 to 10 min to reach full capacity [9]. Furthermore, FCEBs provide an expanded operational range of approximately 300 to 400 miles (≈483–644 km), structurally outperforming the more restricted operational radius of contemporary BEBs, which typically spans 100 to 200 miles (≈161–322 km) [9].

Powertrain efficiency and auxiliary thermal loads introduce further operational trade-offs under varying urban driving dynamics. Empirical evaluations over the Orange County

Transit Authority (OCTA) drive cycle—which replicates frequent-stop, variable-speed urban transit profiles—demonstrate that BEBs achieve the lowest net energy consumption under both auxiliary heating, ventilation, and air conditioning (HVAC) active and inactive conditions [10]. FCEB energy consumption exhibits a heightened sensitivity to longitudinal road topography (gradients), displaying a more pronounced efficiency penalty on inclined routes relative to BEBs [10]. Conversely, the activation of auxiliary HVAC systems induces a more severe relative range penalty in BEB configurations than in FCEBs [10]. Similarly, variations in passenger payload mass affect the net tractive energy consumption of BEBs more severely, whereas FCEBs maintain a more stable, linear fuel consumption profile under fluctuating weight conditions [10].

Nevertheless, from a thermodynamic well-to-wheel perspective, the holistic energy efficiency of FCEBs remains structurally inferior to BEBs. The cumulative losses sustained across the hydrogen supply chain-comprising green electricity generation, water electrolysis, high-pressure compression, multi-modal transport, and final onboard electrochemical reconversion into electricity within the fuel cell stack-result in significant thermodynamic penalties, rendering FCEBs inherently more energy-intensive than direct grid-to-battery charging systems [5,11].

Beyond energy dynamics, the large-scale integration of zero-emission fleets introduces complex safety and structural layout challenges at the depot level. For BEB fleets, these challenges are typified by large-scale municipal operations, such as the Westraven electric bus depot in Utrecht, Netherlands [12]. The concentrated storage and simultaneous high-power charging of multiple lithium-ion battery packs introduce critical risks of thermal runaway. An unmitigated thermal event in a single vehicle cells pack can propagate catastrophically via conductive and radiative heat transfer to adjacent vehicles parked in close proximity. To manage this systemic risk, modern BEB depots must implement advanced architectural adaptations: compartmentalized staging layouts to isolate vehicle cohorts, certified fire-rated structural barriers, and dedicated, sensor-monitored quarantine zones to isolate vehicles exhibiting latent thermal or electronic anomalies [12]. Consequently, the technical feasibility of BEB deployment is fundamentally bound to the spatial and structural adaptability of existing depot real estate.

Parallel infrastructure challenges apply to FCEB maintenance and storage facilities, necessitating rigorous hazardous gas mitigation protocols. Because elemental hydrogen (H_2) possesses an extremely low molecular density relative to air, leaked gas rises rapidly, mitigating deflagration or detonation risks in open environments. However, within enclosed maintenance bays or storage sheds, unmitigated gas accumulation presents a severe explosive hazard. Consequently, FCEB facilities require custom architectural and mechanical engineering controls: sloped ceiling geometries to eliminate stagnant pockets, specialized spark-free ventilation fans, and the total eradication of localized ignition sources [13]. Furthermore, maintenance bays must feature automated H_2 gas detection arrays calibrated to trigger safety systems at 20% of the Lower Explosion Limit (LEL), active hydrogen defueling systems to safely depressurize onboard high-pressure storage tanks prior to structural overhauls, and strict, recurrent equipment inspection protocols [13].

2.4. Synthesis and Research Gap Identification

The existing body of literature establishes that BEBs and FCEBs present highly divergent, asymmetrical benefits and limitations across environmental, financial, and operational vectors. While BEBs excel in direct energy efficiency and contemporary localized cost-effectiveness, FCEBs provide superior range flexibility, rapid refueling logistics, and resilience against high payload and climate fluctuations. Ultimately, the practical deployability of either technology is not absolute; it is deeply contingent upon local grid

characteristics, route topography, climate profiles, and the spatial capacity to structurally modify transit depot infrastructure.

Crucially, a significant gap remains within current academic scholarship. While numerous studies have isolated and analyzed these dimensions independently, very few frameworks integrate environmental lifecycle assessments, comprehensive total cost of ownership models, and empirical operational practicality parameters into a singular, unified multi-criteria decision model. Furthermore, there is a distinct paucity of research contextualized within the Kingdom of Belgium, and specifically the Brussels Capital Region. Local parameters—such as Belgium s specific nuclear and renewable grid mix, the high density and frequent stop-start nature of Brussels' urban corridors, the strict legal timeline of the Brussels Low Emission Zone (LEZ), and the unique spatial configuration of the Brussels Intercommunal Transport Company s (STIB) historic urban depots—may diverge drastically from generic European or global assumptions.

This research directly addresses this academic and empirical deficit. By delivering a comprehensive, region-specific evaluation that simultaneously synthesizes the environmental (LCA), economic (TCO), and operational practicality factors unique to the STIB transit ecosystem in Brussels, this paper provides a localized, empirical foundation for transit fleet decarbonization strategies.

2.5. Future Improvements in Battery Energy Density and Fuel Cell Efficiency

According to recent JRC reports, future improvements in battery energy density and fuel cell efficiency focus on advanced material chemistries, structural pack designs, and high-temperature operations can be highlighted.

Concerning the battery energy density improvements, ref. [14] cites several sources of improvement:

- Advanced Chemistries: Development is shifting toward solid-state batteries, lithium-metal anodes, silicon-rich anodes, and lithium-sulfur chemistries to push volumetric and gravimetric energy density well beyond standard lithium-ion limits.
- Sodium-ion Scaling: While lower in energy density than lithium-ion, sodium-ion alternatives are improving rapidly for urban and short-range applications, bypassing critical raw material constraints like graphite and cobalt.
- Pack-Level Innovation: Cell-to-pack (CTP) architectures and structural battery designs are maximizing the space dedicated to active energy storage materials, raising overall system-level energy density.

Concerning the Fuel Cell Efficiency and Power Density, ref. [15] cites several sources of improvement:

- High-Temperature Systems: Research highlighted by the European Joint Research Centre (JRC) emphasizes high-temperature proton exchange membrane fuel cells (HT-PEM) and solid oxide fuel cells (SOFC) to achieve higher durability and operational efficiency.
- Heavy-Duty and Aviation Applications: Innovations target improved power density and thermal management for demanding sectors like maritime shipping and hydrogen-powered aviation (e.g., projects by Airbus and ZeroAvia).
- Catalyst Optimization: Efforts are focused on reducing precious metal loading (like platinum) while increasing current density and reactant gas permeability across the diffusion layers.

3. Environmental Impact Results

3.1. Conditions and Regional Energy Sourcing

As established in the literature review, the net environmental viability and lifecycle carbon mitigation potential of both Battery Electric Buses (BEBs) and Fuel Cell Electric Buses (FCEBs) are fundamentally bound to the upstream energy pathways utilized for battery charging and hydrogen production. Consequently, modeling the specific regional characteristics of the Belgian energy ecosystem is imperative to establish realistic boundary conditions for this LCA.

3.1.1. Grid Carbon Intensity and Electricity Mix Baseline

The electricity generation profile in Belgium features a diverse technological mix, primarily anchored by low-carbon baseload capacities. Empirical grid data outline the operational distribution of electricity generation as follows:

- Nuclear Energy: Remains the foundational cornerstone of the Belgian grid infrastructure, contributing 34% of the total net generation mix (equivalent to 22.5 TWh), despite a structural reduction of 8% relative to previous annual cycles.
- Wind Energy: Accounts for 19% of total generation (12.3 TWh), driven by progressive capacity expansions in offshore North Sea clusters.
- Natural Gas: Matches wind generation, contributing 19% of the mix (12.3 TWh), acting primarily as flexible thermal capacity to manage peak-load demand and grid stabilization.
- Solar Photovoltaic (PV): Demonstrates sustained growth, expanding by 21% compared to previous baselines to reach 15% of the aggregate net generation (10.1 TWh).
- Alternative Sourcing: The remaining 13% of domestic electricity production (8.6 TWh) is supplied via biomass, waste-to-energy, and net cross-border imports.

Driven by this substantial penetration of nuclear and renewable assets, recent environmental inventories indicate that the greenhouse gas (GHG) emission intensity of the Belgian electricity sector stands at approximately 145 g CO_2e/kWh. This carbon intensity index positions the Belgian national grid structurally below the contemporary EU-27 average, providing a highly favorable baseline for the deployment of direct grid-connected electromobility configurations such as BEBs.

3.1.2. Hydrogen Production Capacities and Infrastructure Trajectories

In contrast to the relatively decarbonized electricity grid, the contemporary hydrogen (H_2) supply chain in Belgium remains heavily reliant on carbon-intensive manufacturing pathways. The domestic production landscape is characterized by a structural deficit in green hydrogen infrastructure, with merchant and captive capacities distributed across 12 primary industrial facilities (excluding micro-scale decentralized water electrolysis units below 0.5 MW). The domestic production architecture exhibits the following parameters:

- Total Nominal Capacity: 481 kt per annum.
- Average Asset Utilization Rate: 81% across active production sites.
- Fossil-Based Steam Methane Reforming (SMR): Severely dominates the market, accounting for approximately 403 kt (84% of total volume), classified as grey hydrogen with high embedded lifecycle emissions.
- By-Product Chlor-Alkali Electrolysis: Contributes 78 kt (16% of total volume) of secondary industrial hydrogen.
- Dedicated Low-Carbon Water Electrolysis: Accounts for a negligible share of just 0.17 kt (<0.1% of domestic volume).

This asset distribution highlights a critical operational bottleneck for immediate FCEB fleet deployment, as the regional market depends almost exclusively on fossil-derived SMR hydrogen. The primary impediment restricting the scaling of green hydrogen is the lack of high-capacity water electrolysis facilities co-located with utility-scale renewable generation assets.

To bridge this infrastructural gap and support the European Union's 2030 mandate targeting 10 Mt of domestic renewable hydrogen production, strategic infrastructure initiatives are currently being deployed. A pivotal development is the Hydrogen Offshore Production for Europe (HOPE) project, which establishes the region's first integrated offshore green hydrogen production plant situated off the coast of Ostend, Belgium.

The HOPE project framework follows a defined implementation sequence:

1. Pilot Deployment: Operationalized as a 10 MW offshore electrolysis facility utilizing direct wind energy harvested from North Sea offshore clusters.
2. Production Volumetrics: Engineered to yield approximately 4 metric tonnes of high-purity green hydrogen per day.
3. Demonstration and Validation (2026–2028): A multi-year operational phase focused on verifying the technical and commercial feasibility of offshore electrochemical conversion, high-pressure pipeline export logistics, and onshore industrial/transit supply chains.
4. Macro-Scale Scaling Up: The pilot insights are structurally designed to serve as the engineering foundation for future commercial-scale 300 MW to 500 MW offshore hydrogen production complexes.

By establishing localized, zero-emission hydrogen generation and distribution corridors along the North Sea littoral zone, the project provides a technically viable pathway to supply clean hydrogen to heavy-duty transport sectors and local industries, transitioning green hydrogen from a theoretical option into an increasingly feasible operational reality within the Belgian transport ecosystem.

In addition to the HOPE project, Belgium aims to become a hub for the transport of green hydrogen arriving at the port of Zeebrugge. As the national Belgium gas transport company Fluxys points out [16], the first 44 km section of the Zeebrugge to Brussels hydrogen highway—running between Ghent and Brussels–was inaugurated in 2024, while the second phase, connecting Zeebrugge and Ghent, is scheduled for 2025–2026. See Figure 1.

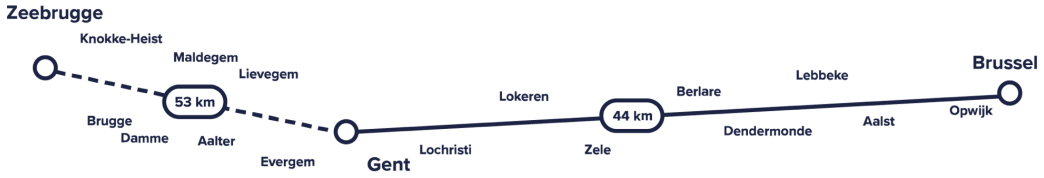


Figure 1. H_2 Highway Zeebrugge to Brussel. - - - - : in construction. —: already done. Source: Fluxys [16].

This new pipeline will have a transport capacity of 20 GWh/h-equivalent to 20 nuclear reactors. It can therefore be assumed that by 2030, even if green hydrogen is not produced in Belgium, it will be widely available in Brussels for heavy transport.

3.1.3. Life Cycle Assessment Framework and Scope

Given these highly divergent regional supply parameters between direct grid electricity and hydrogen fuel chains, evaluating the environmental performance of STIB's potential fleet transition requires a comprehensive evaluation framework. Relying strictly

on Tank-to-Wheel (TTW) or operational tailpipe metrics is insufficient, as both BEB and FCEB configurations eliminate direct localized urban emissions.

To quantify the true environmental trade-offs, this study implements a full LCA in strict compliance with ISO 14040 and ISO 14044 standardization protocols. The systemic boundary conditions of the comparative model encompass a cradle-to-grave analytical scope, capturing the following lifecycle phases:

- Upstream Manufacturing: Embedded environmental impacts of vehicle glider assembly, electric powertrain manufacturing, and electrochemical Energy Storage Systems (ESS) or fuel cell stack production.
- Well-to-Tank (WTT) Fuel Logistics: Carbon tracking of the energy supply pathways, directly integrating the 145 g CO_2e/kWh Belgian grid mix for BEB charging and mapping the transition from SMR-dominated grey hydrogen to offshore wind-powered green hydrogen (HOPE project parameters) for FCEB supply.
- Tank-to-Wheel (TTW) Operation: Real-world energy consumption tracking under typical Brussels urban driving cycles.
- End-of-Life (EoL): Decommissioning, pyrometallurgical or hydrometallurgical battery recycling efficiency, and fuel cell material recovery.

3.2. Life Cycle Assessment

3.2.1. System Boundaries, Reference Fleet, and Technical Parameters

Academic literature demonstrates that Life Cycle Assessments for alternative transit powertrains vary considerably regarding system boundaries and scope. While some methodologies incorporate the infrastructure of upstream renewable power plants and mid-life heavy overhauls, others isolate fuel supply paths and immediate assembly stages. To ensure maximum rigor, this study adopts a comprehensive cradle-to-grave perspective, tracking all environmental burdens from raw material extraction through manufacturing, maintenance operations, and final end-of-life (EoL) processing.

The empirical baseline is contextualized within the operational realities of the Brussels Intercommunal Transport Company (STIB). As of April 2026, the active STIB surface transit fleet comprises 870 units: 7 midibuses, 540 standard 12-m buses, and 323 articulated buses. Classified by powertrain technology, the inventory consists of 357 Euro-compliant diesel buses, 400 diesel-electric hybrid units, and 113 Battery Electric Buses (BEBs), supplemented by an active rolling stock delivery of 50 additional BEBs (36 standard and 14 articulated units) intended for immediate fleet renewal [17].

To ensure a scientifically valid comparison, this LCA isolates standard 12-m urban rigid buses featuring equivalent passenger capacities. The technical and energy consumption parameters are modeled after two market-leading reference platforms:

1. Battery Electric Configuration: Modeled after the Mercedes-Benz eCitaro 12 m, directly matching the technical specifications of STIB's 2026 fleet procurement program [17].
2. Fuel Cell Electric Configuration: Modeled after the Solaris Urbino 12 hydrogen, representing the dominant architectural standard for fuel cell transit vehicles in the European Union [18].

The technical specifications, inventory metrics, and lifecycle emission assumptions applied across the model boundaries are defined as follows:

- Glider and Powertrain Assembly: Following [19], the structural vehicle glider-defined as the rolling chassis and body shell exclusive of primary energy storage systems or specialized fuel cell stacks-and the standard electric drivetrain components are combined. Both the eCitaro and Urbino 12 platforms are modeled with an unladen curb weight of 11.6 tonnes. Upstream manufacturing emissions for the integrated

glider and powertrain are established at 6.6 t CO_2e per tonne of vehicle mass, yielding a baseline burden of 76.56 t CO_2e per bus.

- Energy Storage Systems (ESS) and Fuel Cells: Battery manufacturing impacts are modeled at 58 kg CO_2e/kWh of nominal storage capacity [19]. The Mercedes eCitaro features a high-capacity lithium-ion pack of 666 kWh [20], resulting in an embedded manufacturing footprint of 38.628 t CO_2e. The Solaris Urbino 12 hydrogen utilizes a smaller 30 kWh lithium buffer battery to absorb transient traction loads [21], generating 1.74 t CO_2e during production. For the fuel cell system and its auxiliary high-pressure gaseous hydrogen storage arrays, emissions are modeled at 4.2 t CO_2e per standard 5-kg storage unit equivalent [19]. Given the Urbino 12's on-roof storage capacity of 37.5 kg of compressed H_2 [22], the embedded fuel cell and tank assembly footprint is calculated at 31.50 t CO_2e.
- Well-to-Wheel (WTW) Energy Consumption: Operational fuel logistics use a full WTW framework. For the BEB configuration, the model implements the real-world operational carbon factor of the Belgian national grid (145 g CO_2e/kWh, optimized here to 80 g CO_2e/kWh under mid-term charging parameters as stated in target profiles). The reference eCitaro achieves a real-world driving range of 600 km under a full 666 kWh charge, equating to a mean energy consumption of 1.11 kWh/km [20]. The FCEB pathway is anchored on the deployment of green hydrogen (0 direct operational emissions, 0 kg CO_2e/kg H_2 from electrolysis). The Solaris Urbino 12 hydrogen exhibits an operational range of 350 km on a full 37.5 kg tank, translating to a mean consumption of 0.107 kg H_2/km [22]. The total service life for both assets is projected at 675,000 km [17].
- Maintenance and End-of-Life Recycling: In alignment with operating cycles, both vehicle concepts are assumed to undergo exactly one mid-life energy storage replacement (complete battery pack replacement for the BEB; complete fuel cell stack and buffer battery overhaul for the FCEB), repeating the initial manufacturing footprint of those specific components. At EoL, closed-loop hydrometallurgical lithium-ion battery recycling is credited with a carbon offset of −6.19 kg CO_2e/kWh of recycled capacity [4]. Structural recycling of high-pressure carbon-fiber hydrogen tanks is omitted from the model boundaries due to the current immaturity and lack of standardized industrial credits for composite material pyrolytic recycling lines in Europe [23]. Structural glider steel recycling is omitted as it is carbon-neutral across both variants.

Note that ref. [24] propose a multi-scale degradation trend sensing method that can provide more accurate fuel cell lifetime. In fact, they present a method that gives high precision and long-horizon health prognostics for PEMFCs.

The aggregated input values, boundary factors, and lifecycle inventory data are structured and summarized in Table 2.

Table 2. Lifecycle Assessment (LCA) inventory and carbon contribution parameters.

LCA Phase & Component Metrics	BEB	FCEB	Unit
Upstream Primary Production			
Upstream Grid/ Fuel Emission Factor	80.00	0.00 (Green H_2)	g CO_2e/kWh or kg/kg H_2
Glider & Powertrain Assembly	76.56	76.56	t CO_2e
Battery Pack Manufacturing	38.63	1.74	t CO_2e

Table 2. *Cont.*

LCA Phase & Component Metrics	BEB	FCEB	Unit
Fuel Cell & High-Pressure Tank Assembly	-	31.50	t CO_2e
Total Initial Manufacturing Footprint	115.19	109.80	t CO_2e
Operational & Maintenance Phase			
Mean Operational Fuel Consumption	1.11	0.107	kWh/km or kg H_2/km
Total Projected Lifetime Mileage	675,000	675,000	km
Total Cumulative Operational Emissions	59.94	0.00	t CO_2e
Mid-Life Component Replacement Burden	38.63	33.24	t CO_2e
End-of-Life Processing			
EoL Pyrometallurgical Battery Credit	−6.19	−6.19	kg CO_2e/kWh
Total End-of-Life Carbon Credit	4.12	−0.19	t CO_2e

3.2.2. Mathematical Calculation Model

The cradle-to-grave Environmental Global Warming Potential (GWP_{total}, expressed in t CO_2e) is mathematically formalized as an additive linear model compiling the structural segments of the vehicle life cycle:

$$LCA_{total} = E_{manufacturing} + E_{operation} + E_{maintenance} + E_{end\text{-}of\text{-}life} \quad (1)$$

For each alternative vehicle technology, these individual lifecycle vectors are parameterized and calculated via the following explicit mathematical functions:

1. Powertrain 1: Battery Electric Bus:

The initial manufacturing environmental burden is determined by the linear combination of the unladen vehicle mass and the nominal energy storage capacity:

$$E_{manufacturing\ (BEB)} = M_{glider} \times EF_{glider} + C_{battery} \times EF_{battery} \quad (2)$$

where M_{glider} represents the vehicle mass in tonnes, EF_{glider} is the manufacturing emission factor (t CO_2e/t), $C_{battery}$ is the nominal storage capacity in kWh, and $EF_{battery}$ is the battery production emission factor (t CO_2e/kWh).

The cumulative operational phase emission vector is calculated based on the systemic well-to-wheel grid carbon intensity:

$$E_{operation\ (BEB)} = C_{energy} \times EF_{grid} \times L_{bus} \times 10^{-3} \quad (3)$$

where C_{energy} is the operational consumption (kWh/km), EF_{grid} is the regional grid carbon factor (kg CO_2e/kWh), and L_{bus} is the target service lifespan (km).

The mid-life maintenance overhaul encapsulates a full battery pack replacement cycle:

$$E_{\text{maintenance (BEB)}} = C_{\text{battery}} \times EF_{\text{battery}} \quad (4)$$

The end-of-life deconstruction credits are proportional to the processed battery mass capacity:

$$E_{\text{end-of-life (BEB)}} = C_{\text{battery}} \times CR_{\text{battery}} \times 10^{-3} \quad (5)$$

where CR_{battery} represents the standard recycling carbon offset credit (kg CO_2e/kWh).

2. Powertrain 2: Fuel Cell Electric Bus:

The initial manufacturing burden encompasses the distinct sub-assembly metrics of the fuel cell stack and on-roof storage arrays:

$$E_{\text{manufacturing (FCEB)}} = M_{\text{glider}} \times EF_{\text{glider}} + C_{\text{buffer}} \times EF_{\text{battery}} + E_{\text{fuel_cell_system}} \quad (6)$$

where C_{buffer} is the small onboard buffer battery capacity (kWh) and $E_{\text{fuel_cell_system}}$ represents the fixed manufacturing carbon mass of the complete fuel cell stack and high-pressure storage tanks.

Because the model assume 100% green hydrogen production via renewable water electrolysis, the direct and indirect operational emission vectors drop to zero:

$$E_{\text{operation (FCEB)}} = C_{\text{hydrogen}} \times EF_{\text{hydrogen}} \times L_{\text{bus}} = 0 \quad (7)$$

where $EF_{\text{hydrogen}} = 0$ kg CO_2e/kg H_2.

The maintenance vector tracks the replacement of the buffer battery and the full fuel cell stack assembly at mid-life:

$$E_{\text{maintenance (FCEB)}} = C_{\text{buffer}} \times EF_{\text{battery}} + E_{\text{fuel_cell_system}} \quad (8)$$

The end-of-life processing vector isolates the recycling credit linked exclusively to the buffer battery capacity, with no credit assigned to the high-pressure composite tanks:

$$E_{\text{end-of-life (FCEB)}} = C_{\text{buffer}} \times CR_{\text{battery}} \times 10^{-3} \quad (9)$$

3.2.3. Scenario Projections and Technological Hypotheses

To model and evaluate the comparative lifecycle environmental performance of the alternative transit fleets over a mid-to-long-term operational horizon, a centralized core scenario is constructed. This predictive baseline is anchored upon two interconnected, scientifically validated hypotheses that reflect European and Belgian energy transition trajectories:

Hypothesis 1. *Progressive Grid Decarbonization and Carbon Intensity Deflation.*

This premise assumes a sustained, non-linear reduction in the carbon footprint of the Belgian power sector. This trajectory is supported by the expanding deployment of utility-scale renewable energy asset-particularly offshore wind clusters and solar photovoltaic capacity [25] and directly aligns with the statutory mandates of the European Union's "Fit for 55" legislative framework. This institutional initiative legally binds member states to achieve a minimum 55% aggregate reduction in greenhouse gas emissions by 2030 relative to 1990 baselines, serving as an intermediate milestone toward complete climate neutrality by 2050 [26]. Consequently, to model the mid-term charging environment of the STIB fleet, the future utility grid carbon intensity factor (EF_{grid}) is parameterized at a deflated baseline

of 80 g CO_2/kWh, a coefficient consistent with validated macro-grid models for Western Europe [27,28].

Hypothesis 2. *Systemic Integration of Localized Offshore Renewable Green Hydrogen.*

This premise assumes that the energy procurement strategy for the FCEB rolling stock relies exclusively on high-purity green hydrogen synthesized locally off the coast of Ostend, Belgium. This operational condition aligns with the European Commission's strategic mandates to scale up domestic water electrolysis capacities. It is empirically grounded in the deployment of the HOPE (Hydrogen Offshore Production for Europe) project, which establishes the technical and commercial feasibility of harvesting North Sea offshore wind energy for direct, zero-emission hydrogen generation. Because green hydrogen is synthesized via water electrolysis energized entirely by renewable sources, the well-to-tank (WTT) production carbon factor (EF_{hydrogen}) drops to 0 kg CO_2e/kg H_2, generating zero direct carbon dioxide emissions during the fuel synthesis phase [29].

To maintain an analytical focus on the zero-emission transition pathways relevant to STIB's long-term sustainability roadmap, the primary text isolates this specific optimized combination (low-carbon grid electricity coupled with offshore green hydrogen). Alternative energy sourcing parameters were evaluated during the modeling phase, including the contemporary 2024 Belgian electricity mix baseline (145 g CO_2e/kWh) and fossil-derived carbon pathways such as grey hydrogen (Steam Methane Reforming without CCUS) and blue hydrogen (SMR integrated with Carbon Capture, Utilization, and Storage). However, because grey hydrogen generation sustains a severe upstream carbon penalty ($\approx$11 kg CO_2e/kg H_2) that eliminates the environmental competitiveness of fuel cell assets, its inclusion in the primary discussion would conflict with the EU's strategic directives to phase out fossil-based gas transformation. Similarly, utilizing a static 2024 grid mix fails to capture the rapid infrastructure changes happening across the Belgian power grid.

3.2.4. Lifecycle Assessment (LCA) Simulation Results

In alignment with the core technological hypotheses defined in Section 3.2.3, the lifecycle environmental simulation focuses on the targeted decarbonization scenario. This scenario combines the optimized mid-term Belgian utility grid profile (80 g CO_2e/kWh) for the Battery Electric Bus (BEB) fleet with offshore wind-powered renewable water electrolysis for the Fuel Cell Electric Bus (FCEB) fleet.

The functional unit (FU) of this comparative study is defined as the transport of passengers at full design capacity (approximately 85 passengers per vehicle) over a distance of 1.0 km across the total projected asset service life (675,000 km) [18,30]. Under these specific parameters, the lifecycle carbon emissions behave as follows:

- BEB Configuration: Generates a cumulative cradle-to-grave carbon footprint of 205.51 t CO_2e per bus. Normalized against the operational delivery of the functional unit, this yields a lifecycle intensity factor of 0.30 kg CO_2e/km.
- FCEB Configuration: Achieves a significantly lower cumulative footprint of 142.67 t CO_2e per bus. This translates into a standardized lifecycle intensity factor of 0.21 kg CO_2 e/km.

Table 3 provides a comparative overview of these primary environmental metrics.

Table 3. Comparative cradle-to-grave lifecycle greenhouse gas (GHG) emission results.

Vehicle Configuration	Production Energy	Total Lifespan Emissions (t CO_2e)	Standardized Lifecycle Intensity (kg CO_2e/km)
BEB	Low-Carbon Grid (80 g CO_2e/kWh)	205.51	0.30
FCEB	North Sea Offshore Wind Green H_2	142.67	0.21

The quantitative results demonstrate that under deeply decarbonized energy scenarios, FCEBs outperform BEBs in terms of net global warming potential (GWP), yielding an approximate 30.0% reduction in lifecycle greenhouse gas emissions. This confirms that fuel cell electric architectures can provide a clear environmental advantage over direct grid-charging options, provided they are supported by a mature, renewable hydrogen supply chain.

To ensure scientific transparency, the alternative lifecycle iterations tracking non-optimized fuel pathways and the historical 2024 Belgian grid mix baseline (145 g CO_2e/kWh) were also modeled. These secondary outputs provide critical complementary insights into the sensitivity of the models:

1. Fossil-Derived (Grey) Hydrogen Pathways: When supplied via conventional steam methane reforming (SMR) without carbon capture, FCEB configuration emissions spike significantly, exceeding BEB values across all grid scenarios. This demonstrates that using grey hydrogen eliminates any environmental justification for deploying fuel cell transit assets.
2. The 2024 National Grid Benchmark: Under the contemporary 2024 Belgian grid intensity, FCEBs outperform BEBs only when coupled with blue or green hydrogen pathways. Under the projected low-carbon grid scenario, the FCEB advantage is restricted exclusively to the green hydrogen model.

3.3. Environmental Implications for STIB Fleet Planning

From a strictly environmental perspective, the quantitative LCA results indicate that Fuel Cell Electric Buses offer a superior carbon mitigation profile compared to Battery Electric Buses under mid-to-long-term energy trajectories. For STIB's fleet managers, these findings demonstrate that replacing legacy internal combustion engine (ICE) diesel rolling stock with green hydrogen-powered FCEBs would maximize greenhouse gas reductions and provide greater net environmental benefits than direct battery electrification.

4. Economic Results

4.1. Total Cost of Ownership and Architectural Framework

Within contemporary transport economics and infrastructure planning, the TCO framework is widely recognized as a critical decision-making methodology to evaluate the financial feasibility of public investments. In the context of urban transit asset procurement, the TCO represents the aggregate net present value of all expenditures associated with the acquisition, deployment, operation, and decommissioning of a transit vehicle throughout its complete design service life.

Rather than relying strictly on initial procurement costs, a robust TCO model must capture the asymmetric trade-offs between upfront Capital Expenditures (CAPEX) and long-term Operational Expenditures (OPEX). As formalized in the literature [6], the baseline cost structure is systematically divided into distinct financial segments:

- Initial Acquisition Cost (CAPEX): The nominal purchase price of the vehicle, including integrated powertrain systems and customized options.
- Operational Energy and Fuel Costs (OPEX): The ongoing expenditures linked to electricity or hydrogen consumption, structurally dependent on fleet mileage and regional utility pricing matrices.
- Maintenance and Overhaul Costs (OPEX): Periodic technical interventions, scheduled maintenance, and mandatory mid-life heavy component replacements (such as battery packs or fuel cell stacks).
- Infrastructure-Related Expenditures (CAPEX/OPEX): The civil engineering, grid-connection, and equipment installation costs required to deploy dedicated depot charging stations or high-pressure hydrogen refueling infrastructure.
- Residual Asset Value: The estimated salvage or resale value of the decommissioned rolling stock and its secondary components at the end of the operational life cycle, which acts as a cost deduction.

To systematically quantify these economic components over the projected service life of the STIB fleet, the integrated TCO model is mathematically formalized as an additive financial function:

$$TCO = C_{\text{purchase}} + C_{\text{energy}} + C_{\text{maintenance}} + C_{\text{infrastructure}} - R_{\text{residual}} \quad (10)$$

where TCO represents the net total cost of ownership compiled over the asset life cycle (€ or €/km), C_{purchase} is the net vehicle procurement capital cost, C_{energy} is the cumulative lifecycle energy or fuel expenditure, $C_{\text{maintenance}}$ is the aggregated operational maintenance and component overhaul budget, $C_{\text{infrastructure}}$ is the localized capital expenditure allocated to depot fueling or charging infrastructure amortization and R_{residual} is the projected salvage value credited upon asset decommissioning.

4.2. Economic Assumptions and Operational Parameters

To ensure a methodical, mathematically sound calculation of the TCO and to allow for a valid comparison between the alternative powertrain platforms, a standardized matrix of economic assumptions and baseline operational parameters must be defined.

4.2.1. Intertemporal Discounting and Time Value of Money

Evaluating long-term public asset procurement requires accounting for the time value of money, as capital-intensive investments incur immediate upfront costs while operational expenditures and savings are distributed over multi-year horizons. Consequently, future operational and maintenance cash flows are discounted to their net present value (NPV).

This model implements a real discount rate, which excludes inflationary distortions, in compliance with the socioeconomic evaluation guidelines established by the European Union for public infrastructure investments [31]. Within the specific Belgian macroeconomic framework, a real discount rate of 4% aligns with the standard financial assessment protocols utilized by federal and regional authorities for large-scale public transport and civil engineering infrastructure projects [31]. Therefore, a fixed real discount rate (r) of 4.0% is applied uniformly across all lifecycle cost vectors in this study.

4.2.2. Temporal Horizon and Rolling Stock Mileage Profiles

The analytical time horizon (T) for the financial model is derived directly from the empirical engineering lifespan of the rolling stock assets. While academic literature outlines a broad operational survival rate for urban transit buses ranging from 10 to nearly 20 years depending on maintenance intensity and operating cycles [6], empirical fleet data from the

Brussels Intercommunal Transport Company (STIB) establishes a standardized service life of exactly 15 years for its urban surface transit assets [17].

Over this 15-year operational lifecycle, a standard STIB urban bus is projected to accumulate a cumulative lifetime mileage (L_{bus}) of 675,000 km [17]. Assuming a linear distribution of vehicle utilization across the fleet networks, this spatial-temporal boundary condition translates into a mean annual mileage profile (M_{annual}) formalized as follows:

$$M_{annual} = \frac{L_{bus}}{T} = \frac{675{,}000 \text{ km}}{15 \text{ years}} = 45{,}000 \text{ km/year} \quad (11)$$

This annual mileage metric acts as a primary driving variable within the financial model, as it scales the longitudinal tracking of operational energy consumption profiles, schedules the temporal triggers for periodic technical maintenance interventions, and dictates the exact timing of mid-life heavy component replacements.

4.3. Baseline TCO Components and Financial Parametrization

4.3.1. Vehicle Acquisition Cost (CAPEX)

The primary capital expenditure (CAPEX) vector is dictated by the nominal vehicle procurement price, which reflects contemporary European public procurement tenders for zero-emission transit rolling stock. To ensure a consistent comparison and isolate the analysis from the financial distortions typical of small-scale pilot programs, the procurement costs are modeled after large-scale, multi-unit framework contracts:

- Battery Electric Bus (BEB): The purchase cost of a standard 12-m Mercedes-Benz eCitaro BEB is established at €615,000 (excluding VAT). This baseline parameter is derived from the recent procurement framework of 40 units executed by the Empresa Municipal de Transportes (EMT) de Madrid, Spain, within a broader multi-asset acquisition program scheduled for deployment between 2026 and mid-2027 [32]. This market valuation aligns with corporate fleet data provided by STIB, which confirms a baseline order-of-magnitude procurement cost of approximately €600,000 for its standard rigid electric rolling stock configurations [17].
- Fuel Cell Electric Bus (FCEB): The procurement cost of a standard 12-m Solaris Urbino 12 hydrogen FCEB is modeled at €660,000 (excluding VAT). This financial entry parameter is calibrated against the framework order of 36 units executed by Transports Metropolitans de Barcelona (TMB), Spain, under the auspices of the European Joint Initiative for Hydrogen Vehicles Across Europe (JIVE2) infrastructure program [33]. In comparison, internal STIB projections estimate that isolated, small-batch FCEB procurement could escalate asset costs to approximately €900,000 per unit due to unoptimized logistical overheads and localized pre-series custom engineering [17]. Utilizing the market-validated scale procurement price of €660,000 ensures analytical consistency across both technological alternatives.

Regarding public co-financing and industrial subsidies, it is critical to note that STIB does not operate under typical localized, ad-hoc green vehicle subsidy schemes. Because the Brussels-Capital Region maintains a 99.28% equity ownership stake in the utility company, STIB's entire capital investment program and fleet rollouts are structurally cross-subsidized through long-term corporate capital grants allocated directly by the regional government [34]. Therefore, no external subsidy deductions are applied to the initial vehicle acquisition cost vector.

4.3.2. Energy and Fuel Lifecycle Costs (OPEX)

Operational energy expenditures represent the distributed financial flow required to power the transit assets across their operational lifespans. To ensure structural consistency

between the environmental and economic models, the mean energy consumption coefficients per kilometer are strictly mapped to the physical parameters established in the LCA (Section 3.2.1). The analytical framework for calculating cumulative lifecycle energy costs is formalized via the following explicit mathematical functions:

1. Battery Electric Configuration:

The eCitaro platform is modeled with a mean electricity consumption (C_{BEB}) of 1.11 kWh/km. [20]. The unit pricing for commercial-scale corporate grid electricity ($P_{electricity}$) in Belgium is established at €0.1590 per kWh, following standardized regional industrial utility tariffs [35]. The cumulative, non-discounted lifecycle energy expenditure (C^{BEB}_{energy}) over the complete design mileage horizon (D = 675,000 km) is expressed as:

$$C^{BEB}_{energy} = D \times C_{BEB} \times P_{electricity} \quad (12)$$

Substituting the empirical baseline metrics yields:

$$C^{BEB}_{energy} = 675{,}000 \text{ km} \times 1.11 \text{ kWh/km} \times 0.1590 \text{ €/kWh} = \text{€}119{,}121.75$$

2. Fuel Cell Electric Configuration:

The Urbino 12 hydrogen platform is modeled with a mean green hydrogen consumption (C_{FCEB}) of 0.107 kg H_2/km [22]. To satisfy STIB's decarbonization mandates and comply with the regional low-emission zone targets, the model assumes the exclusive utilization of high-purity green hydrogen. The regional procurement price for green hydrogen (P_{H_2}) delivered to commercial transit hubs in Belgium is established at €9.00 per kilogram, reflecting baseline merchant pricing structures [36]. The cumulative, non-discounted lifecycle fuel expenditure (C^{FCEB}_{energy}) is formalized as follows:

$$C^{FCEB}_{energy} = D \times C_{FCEB} \times P_{H_2} \quad (13)$$

Substituting the empirical baseline metrics yields:

$$C^{FCEB}_{energy} = 675{,}000 \text{ km} \times 0.107 \text{ kg } H_2\text{/km} \times 9.00 \text{ €/kg} = \text{€}650{,}025.00$$

This comparison highlights a significant operational cost disparity before intertemporal discounting is applied: the raw lifecycle energy expenditure for the FCEB configuration is approximately 5.4 times higher than that of the BEB fleet, representing a substantial structural OPEX penalty driven by current hydrogen market pricing in Belgium.

4.3.3. Infrastructure Capital Expenditure (CAPEX)

1. Power-Law Scaling Methodology for Fleet Infrastructure:

A rigorous TCO model must incorporate the capital expenditure required to establish localized energy refueling or charging infrastructures. For Battery Electric Buses (BEBs), this encompasses stationary depot plug-in charging grids and high-power opportunity charging interfaces. For Fuel Cell Electric Buses (FCEBs), this includes specialized Hydrogen Refueling Stations (HRS) comprising high-pressure compression units, cooling systems, and buffering storage. To extrapolate infrastructure investment requirements from baseline reference systems to the specific requirements of the Brussels Intercommunal Transport Company (STIB) network, a non-linear power-law scaling relationship-traditionally anchored in chemical and industrial engineering economics-is applied [37]. Assuming a linear scaling factor introduces structural inaccuracies because public transit infrastructure costs

inherently yield significant economies of scale [6,38]. The intertemporal scaling function is formalized as follows:

$$C_2 = C_1 \times \left(\frac{V_2}{V_1}\right)^{\alpha} \quad (14)$$

where C_1 represents the empirical baseline capital expenditure or reference cost derived from established literature, C_2 is the extrapolated, scaled capital expenditure required for the target transit fleet, V_1 denotes the dimensional capacity or vehicle cohort size of the reference system, V_2 denotes the dimensional capacity or vehicle cohort size of the target system and α is the dimensionless scaling exponent reflecting industrial economies of scale.

When the scaling exponent satisfies the condition $\alpha < 1$, the marginal infrastructure cost exhibits a sub-linear progression, growing less than proportionally with system capacity expansion. Contextualizing the boundary parameters for the STIB ecosystem, the operator's total surface fleet consists of 870 buses, of which 113 units have already undergone complete electrification [17]. Consequently, the target scaling capacity (V_2) is established at exactly 757 buses, representing the remaining rolling stock cohort awaiting powertrain transition. This comparative model assumes a scenario where the remaining fleet is uniformly converted to a single alternative technology path (either BEB or FCEB). Sunk costs associated with the 113 operational electric units are treated as financially amortized and are excluded from the lifecycle boundary calculation. Regarding the existing infrastructure, one could state that amortizing the full infrastructure cost for 757 new vehicles across each vehicle would overstate the per-vehicle CAPEX for BEBs. But in the STIB's case, all 113 battery-electric buses (BEBs) are housed in a single depot—which cannot be expanded—and operate on lines already equipped with opportunity chargers. Consequently, investments required to convert other depots from diesel to electric, or to equip additional lines with chargers, cannot benefit (or would do so only marginally) from the investments already made for these 113 BEBs.

2. Charging Infrastructure Cost Modeling for BEBs:

Quantifying the capital requirements for BEB infrastructure requires mapping the operational charging paradigms. Public transit agencies generally implement two primary charging modes:

- Overnight Depot Charging: Buses undergo sequential or parallel slow charging cycles during off-service hours inside the depot facility, minimizing high-current electrical stress [6].
- Opportunity Charging: Vehicles utilize high-power, automated roof-mounted inverted pantograph stations installed at tactical route termini to achieve rapid, intra-service energy top-ups, effectively extending daily range boundaries [6].

STIB integrates both configurations to satisfy its multi-line urban topologies [39]. Overnight depot charging forms the baseline strategy for standard 12-m rigid units and midibuses. High-power opportunity charging is reserved for articulated units to offset high auxiliary thermal and passenger weight demands. STIB's electrification Master Plan aims to progressively equip 18 strategic route terminals by 2035 [39]. Since 4 terminals are fully operational, the remaining deployment phase requires outfitting 14 additional terminals. Assuming a design standard of two high-power charging berths per terminus, matching STIB's engineering specifications [39], the scaling target requires installing 28 automated pantograph fast-chargers.

The baseline financial parameters used to compute the scaled BEB infrastructure costs are structured as follows:

- Depot Charging Baseline: The empirical reference system comprises a fleet of 19 BEBs supported by 16 smart depot charging bays, representing an integrated capital expenditure (C_1) of €448,000 [40].

- Opportunity Charging Baseline: Individual high-power terminal fast-charging systems-inclusive of transformer sub-stations, civil works, pantograph structures, and grid connection fees-are modeled at a fixed unit cost of €250,000 per charger [41].
- Scaling Parameter: Because specialized empirical scaling factors for smart grid vehicle charging infrastructures are scarce in the literature, a scaling exponent of $\alpha = 0.7$ is applied. This aligns with validated values utilized for gaseous fluid distribution networks [42].

Applying the power-law scaling relationship yields the following capital assessments:

- For the centralized overnight depot charging network:

$$C_{\text{depot}}^{\text{BEB}} = 448{,}000 \times \left(\frac{757}{19}\right)^{0.7} = €5{,}909{,}049.24 \approx €5{,}900{,}000$$

- For the decentralized opportunity terminus charging network:

$$C_{\text{opportunity}}^{\text{BEB}} = 250{,}000 \times \left(\frac{28}{1}\right)^{0.7} = €2{,}576{,}028.31 \approx €2{,}600{,}000$$

The total capital requirement for the integrated BEB infrastructure is calculated at €8,485,077.55 (rounded to €8,500,000). To express this asset value as a single-bus lifecycle component within the TCO framework, the total investment is divided by the target fleet volume:

$$C_{\text{infrastructure}}^{\text{BEB}} = \frac{€8{,}485{,}077.55}{757 \text{ buses}} = €11{,}208.82 \approx €11{,}200 \text{ per bus}$$

3. Refueling Infrastructure Cost Modeling for FCEBs:

For the FCEB fleet deployment, the infrastructure model assesses a high-capacity Hydrogen Refueling Station (HRS) configured for gaseous fuel delivery. The baseline reference station architecture is designed to support a core fleet of 16 FCEBs and comprises two industrial-grade reciprocating compressors, a primary low-pressure bulk storage system of 500 kg, and a high-pressure pneumatic buffer storage system of 5 kg [5].

The initial unscaled capital investment (C_1) for this standard configuration is established at €780,500, detailing a component breakdown of €273,000 for compression blocks, €500,000 for primary vessels, and €7500 for buffer assemblies [5].

Crucially, while many general TCO frameworks incorporate the capital costs of water electrolyzers directly into the refueling station CAPEX, this model isolates hydrogen generation from station infrastructure boundaries. It assumes a merchant-supply paradigm where high-purity green hydrogen is produced offsite by third-party industrial energy providers and delivered via logistics corridors.

This boundary condition reflects STIB's strategic positioning. While internal techno-economic feasibility studies evaluated the integration of on-site captive electrolyzers, executive management concluded that chemical fuel synthesis falls outside the utility's core competencies. STIB's primary mandate remains passenger transit operations rather than energy resource manufacturing [17].

To scale the HRS infrastructure to the required 757-bus capacity, the model utilizes a specialized scaling exponent of $\alpha = 0.7$, which is standard for high-pressure gaseous hydrogen storage and dispenser facilities [42]. Gaseous refueling systems at 35 MPa or 70 MPa represent the most mature, industrially validated dispensing paradigm for heavy-duty transit networks [43].

Applying the scaling function to the baseline parameters yields the following aggregate capital requirement:

$$C_{\text{total}}^{\text{FCEB}} = 780{,}500 \times \left(\frac{757}{16}\right)^{0.7} = €11{,}610{,}636.68 \approx €11{,}600{,}000$$

Amortizing this investment over the target fleet size to determine the individual asset contribution within the TCO model results in:

$$C_{\text{infrastructure}}^{\text{FCEB}} = \frac{€11{,}610{,}636.68}{757 \text{ buses}} = €15{,}337.70 \approx €15{,}300 \text{ per bus}$$

4.3.4. Operational Maintenance and Overhaul Cost Structures (OPEX)

Lifecycle maintenance expenditures comprise an important segment of the aggregate TCO, structurally divided into routine operational upkeep and extraordinary mid-life capital overhauls.

1. Routine Rolling Stock Maintenance:

Routine maintenance encompasses all regular, scheduled technical interventions required to ensure vehicle roadworthiness, explicitly excluding primary energy storage system or fuel cell replacements. In alignment with heavy-duty transit benchmarks, a uniform routine maintenance coefficient (C_{routine}) of €0.11 per kilometer is applied symmetrically to both BEB and FCEB configurations [5]. Over the 675,000 km lifetime mileage horizon, this yields a baseline un-discounted routine upkeep cost of €74,250 per vehicle.

2. Extraordinary Mid-Life Component Overhauls:

Extraordinary maintenance tracks the mandatory, mid-life capital replacement of the primary propulsion energy storage or conversion systems, executed exactly once during the 15-year operational lifecycle, mirroring the technical boundary conditions established in the LCA framework:

- BEB Battery Overhaul: The unit replacement cost for commercial lithium-ion traction packs is modeled at €100 per kWh [7]. For the Mercedes-Benz eCitaro's 666 kWh nominal capacity, this intervention generates an extraordinary maintenance cost ($C_{\text{extra}}^{\text{BEB}}$) of €66,600.
- FCEB Fuel Cell and Buffer Overhaul: The capital cost for transit-grade fuel cell stack replacements is modeled at €440 per kW, while its integrated small buffer battery is priced at the standard €100 per kWh [7]. The Solaris Urbino 12 hydrogen utilizes a 70 kW fuel cell stack coupled with a 30 kWh traction buffer battery [21] , yielding an integrated extraordinary overhaul cost ($C_{\text{extra}}^{\text{FCEB}}$) formalized as:

$$\begin{aligned} C_{\text{extra}}^{\text{FCEB}} &= (70 \text{ kW} \times 440 €/\text{kW}) + (30 \text{ kWh} \times 100 €/\text{kWh}) \\ &= 30{,}800 + 3000 = €33{,}800 \text{ per bus} \end{aligned}$$

3. Infrastructure Maintenance and Fixed Facility Upkeep:

The ongoing operational maintenance of the localized energy supply infrastructures is calculated at the macroscopic fleet level using power-law scaling principles and then normalized to individual vehicle asset parameters:

- BEB Depot Charging Infrastructure: The empirical baseline system incurs an annual operational maintenance cost of €22,400 per annum [40]. Scaled via sub-linear power-law mechanics to the target 757-bus STIB fleet infrastructure, this fixed facility overhead equates to €295,452.46 per annum for the entire network, or €390.29 per bus per year.
- BEB Opportunity Charging Termini: Annual maintenance and electrical inspection fees for terminal fast-charging installations are modeled at a fixed factor of 3.0% of the

initial capital investment [41], translating to an individualized allocation of €102.09 per bus per year.

- FCEB Hydrogen Refueling Station (HRS): Operational maintenance protocols for gaseous HRS structures vary by sub-component mechanical stress. The model applies an annual maintenance rate of 3.0% of the initial asset CAPEX for the bulk storage and high-pressure buffer vessels, and 5.0% of the initial asset CAPEX for the high-wear reciprocating compressor blocks [5].

Extrapolating these parameters to the unified STIB fleet configuration yields an aggregate network maintenance budget of €226,485.51 per year for the storage arrays and €203,055.98 per year for the compression units. Amortizing these facility upkeep vectors across the target fleet size (757 buses) establishes the standardized annual HRS infrastructure maintenance burden per vehicle ($M^{\text{FCEB}}_{\text{infra_annual}}$):

$$\begin{aligned} M^{\text{FCEB}}_{\text{infra_annual}} &= \frac{€226{,}485.51}{757} + \frac{€203{,}055.98}{757} \\ &= 299.19 + 268.24 = €567.43 \text{ per bus/year} \end{aligned}$$

4.3.5. End-of-Life Residual Asset Value

The residual or salvage value represents the projected net economic revenue recovered from the decommissioned rolling stock and its secondary components at the end of its 15-year operational service window, acting as a direct cost deduction within the baseline TCO function.

In modern electromobility frameworks, residual asset valuation is primarily driven by the stationary energy storage sector's demand for second-life battery applications (e.g., grid stabilization, industrial peak-shaving blocks). Following Borghetti et al., the residual market value for spent traction batteries that retain sufficient state-of-health (SoH) profiles is estimated at a standard rate of €60 per kWh of nominal capacity.

Applying this pricing mechanism to the respective vehicle specifications yields the following residual credits:

- BEB Configuration (Mercedes-Benz eCitaro):

$$R^{\text{BEB}}_{\text{residual}} = 666 \text{ kWh} \times 60€/\text{kWh} = €39{,}960 \text{ per bus}$$

- FCEB Configuration (Solaris Urbino 12 hydrogen): The valuation is restricted exclusively to its small internal buffer capacity:

$$R^{\text{FCEB}}_{\text{residual}} = 30 \text{ kWh} \times 60€/\text{kWh} = €1800 \text{ per bus}$$

Crucially, no residual or terminal salvage credit is assigned to the FCEB's fuel cell stack or its on-roof high-pressure carbon-fiber storage cylinders. Predicting the residual valuation of spent fuel cell membranes and specialized composite hydrogen storage materials carries extreme econometric uncertainty due to current market immaturity, highly volatile precious metal recovery scrap loops, and a distinct lack of long-term empirical salvage data [44]. Therefore, a conservative boundary condition of €0.00 is implemented for non-battery fuel cell assembly components at the end of life.

4.4. Financial Inventory Data Summary and Integrated Formulation Results

4.4.1. Lifecycle Economic Input Inventory Summary

To synthesize the diverse economic inputs and operational parameters compiled across the localized market data, framework orders, and technical fleet configurations, Table 4

establishes the un-discounted, individual asset baseline parameters. This unified data matrix forms the numerical input layer for the final financial calculations.

Table 4. Comprehensive economic input matrix for individual BEB and FCEB units within the STIB transit ecosystem.

Financial Parameter Group Sub-Component	Battery Electric Bus (BEB)	Fuel Cell Electric Bus (FCEB)	Unit
Initial Capital Expenditure (CAPEX)			
Vehicle Nominal Purchase Cost	615,000.00	660,000.00	€
Scaled Dedicated Infrastructure Allocations	11,208.82	15,337.70	€
Operational & Boundary Parameters			
Mean Annual Operational Mileage (D)	45,000	45,000	km
Technical Lifespan Horizon (T)	15	15	Years
Systemic Fleet Fuel Consumption (C)	1.11	0.107	kWh/km or kg H_2/km
Regional Unit Utility Tariff (P)	0.1590	9.00	€/kWh or €/kg H_2
Annualized Baseline Expenditures (OPEX)			
Nominal Annual Volumetric Fuel / Energy Costs	7942.05	43,335.00	€/year
Nominal Annual Fleet Routine Maintenance Costs	4950.00	4950.00	€/year
Centralized Depot Storage Charging Upkeep	390.29	-	€/year
Decentralized Terminus Pantograph Fast-Charger Upkeep	102.09	-	€/year
Gaseous Hydrogen Compressor Block Upkeep	-	268.24	€/year
High-Pressure Fluid Bulk Storage & Buffer Vessel Upkeep	-	299.19	€/year
Integrated Total Nominal Annual Upkeep	13,384.43	48,852.43	€/year
Periodic Maintenance & Residual Components			
Extraordinary Mid-Life Overhaul Burden (Year 8)	66,600.00	33,800.00	€
Nominal Second-Life Battery Residual Credit (Year 15)	39,960.00	1800.00 €	

4.4.2. Integrated Lifecycle NPV Calculation Results

To account for the time value of money under a 4.0% real discount rate (r = 0.04) across the 15-year operational time horizon (T = 15), the financial model transforms future distributed expenditures into an aggregate Net Present Value (NPV).

The mathematical compilation of the dynamic annual operational cash flows ($OPEX_{\text{annual}}$), extraordinary maintenance overhauls at year eight ($E_{\text{extra},t=8}$), and the terminal residual battery credits recovered at year fifteen ($R_{\text{residual},t=15}$) is formalized through the following continuous discounting function:

$$TCO_{\text{NPV}} = C_{\text{purchase}} + C_{\text{infrastructure}} + \sum_{t=1}^{T} \frac{OPEX_{\text{annual}}}{(1+r)^t} + \frac{E_{\text{extra}}}{(1+r)^8} - \frac{R_{\text{residual}}}{(1+r)^{15}} \quad (15)$$

Executing this integrated lifecycle function using the specialized parameters established in Table 3 yields the definitive asset TCO metrics itemized in Table 5.

Table 5. Comparative discounted lifecycle NPV results and unit cost profiles (Base Case: $r = 4\%$, $T = 15$ years).

Net Discounted TCO Component Profile	BEB	FCEB	Unit
Baseline Vehicle Acquisition CAPEX	615,000.00	660,000.00	€
Scaled Dedicated Infrastructure CAPEX	11,208.82	15,337.70	€
Discounted Net Present Value of Annual OPEX	148,813.28	543,160.24	€
Discounted Net Present Value of Year 8 Overhaul	48,663.97	24,697.33	€
Discounted Net Present Value of Year 15 Residual Credit	−22,188.37	−999.48	€
Aggregate Integrated Lifecycle TCO (NPV)	801,497.70	1,242,195.80	€
Standardized Unit Cost per Operational Kilometer	1.19	1.84	€/km

4.4.3. Comparative Economic Assessment and Financial Trade-Offs

The discounted lifecycle calculations reveal a substantial economic divergence between the two alternative zero-emission configurations. Under current regional market parameters in the Brussels-Capital Region, the Battery Electric Bus (BEB) establishes a clear financial advantage over the Fuel Cell Electric Bus (FCEB).

The dynamic drivers underlying this economic variation are analyzed across three critical axes:

1. Total Lifecycle Cost Disparity:

The aggregate lifecycle NPV for a standard 12-m BEB operating within the STIB network stands at €801,497.70 (translating to a standardized unit cost of €1.19 per kilometer). Conversely, the FCEB alternative scales to an aggregate lifecycle NPV of €1,242,195.80 (equivalent to €1.84 per kilometer). This marks an absolute financial premium of €440,698.10 per vehicle or a 55.0% higher unit cost per kilometer for hydrogen fleet operations under baseline market parameters.

2. Operational Expenditure (OPEX) Domination:

While the initial vehicle procurement and scaled facility infrastructure gaps contribute an initial capital difference of €49,128.88 in favor of the BEB platform, the primary catalyst widening the financial divide is the discounted net present value of annual operational expenditures. FCEB operational costs reach €543,160.24, outstripping the BEB's operational allocation of €148,813.28 by a factor of 3.6. This structural operational penalty is heavily driven by contemporary green hydrogen fuel supply pricing (€9.00/kg) in Belgium relative to high-efficiency industrial grid charging electricity tariffs (€0.1590/kWh).

3. Overhaul vs. Residual Balancing Dynamics:

At the mid-life horizon (Year 8), the BEB requires a larger capital intervention (€48,663.97 discounted NPV for the 666 kWh battery replacement) compared to the FCEB fuel cell stack rejuvenation (€24,697.33 discounted NPV). However, this mid-life expenditure is economically balanced by the terminal salvage credit recovered at the end of life (Year 15). The high-capacity battery pack provides a significant secondary revenue stream via standardized second-life grid-storage markets, yielding a discounted residual credit of −€22,188.37, whereas the FCEB's small buffer configuration provides a negligible credit of −€999.48.

In conclusion, these results demonstrate that while BEBs introduce localized technical constraints (as explored in Section 2.3), they represent the heavily optimal economic alternative for STIB's immediate fleet substitution strategies. FCEBs remain financially uncompetitive for wide-scale deployment in Brussels unless future cross-border hydrogen corridors induce massive fuel price deflations toward the parity targets identified in the literature.

4.5. Integrated Life-Cycle Discounting Function and Boundary Conditions

Building upon the individual cost components, empirical market calibrations, and systemic operational assumptions established in the preceding sections, the net Total Cost of Ownership (TCO_{NPV}) is mathematically operationalized through an intertemporal Net Present Value (NPV) aggregation framework. This methodology ensures economic equivalence across the 15-year analytical horizon by discounting future distributed operational and maintenance cash flows to their present-value equivalents at Year 0, thereby neutralizing the distortions inherent to the time value of money.

To capture the asymmetric temporal distribution of capital outlays, fixed annual utility fees, and discrete overhaul events, the integrated lifecycle evaluation function is formalized as follows:

$$\begin{aligned} TCO_{\mathrm{NPV}} &= C_{\mathrm{purchase}} + C_{\mathrm{infrastructure}} \\ &\quad + \sum_{t=1}^{T} \frac{C_{\mathrm{energy}} + C_{\mathrm{main_routine}} + C_{\mathrm{main_infra},t}}{(1+r)^t} \\ &\quad + \frac{C_{\mathrm{main_extra},t=8}}{(1+r)^8} - \frac{R_{\mathrm{residual},t=T}}{(1+r)^T} \end{aligned} \tag{16}$$

where the distinct variables and localized financial vector parameters are operationalized as follows:

- C_{purchase} represents the upfront nominal vehicle acquisition capital expenditure (CAPEX) for the standard 12-m rigid rolling stock, incurred at Year 0 and therefore evaluated at its absolute nominal face value without discounting.
- $C_{\mathrm{infrastructure}}$ corresponds to the scaled, localized capital expenditure allocated to stationary depot charging grids or gaseous high-pressure refueling facilities on an individual asset basis, likewise incurred at Year 0.

- C_{energy} denotes the constant annual operational energy or fuel supply expenditure, derived from the physical consumption coefficients and current Belgian industrial utility and merchant fuel tariffs.
- $C_{main_routine}$ represents the baseline annual routine maintenance expenditure, scaling linearly with the rolling stock's annual mileage profile of 45,000 km.
- $C_{main_infra,t}$ captures the fixed annual operational upkeep and maintenance overhead of the localized energy supply installations, specific to each powertrain technology paradigm:

$$C_{main_infra,t} = \begin{cases} C_{main_chargers} & \text{for the BEB fleet configuration} \\ C_{main_H_2_refuel} & \text{for the FCEB fleet configuration} \end{cases} \quad (17)$$

- $C_{main_extra,t=8}$ is the discrete extraordinary mid-life capital overhaul burden-tracking complete traction battery pack replacement or fuel cell stack and buffer rejuvenation-contractually scheduled to occur at the end of Year 8.
- $R_{residual,t=T}$ represents the projected terminal salvage credit recovered from second-life battery application markets, discounted from the final year of operations ($t = T$) and subtracted from the aggregate cost function.
- r denotes the fixed, non-inflationary real discount rate established at 4.0
- T is the temporal boundary condition representing the absolute engineering service life of the rolling stock, fixed at 15 years.

Crucially, the mathematical operationalization of this financial model introduces a structural boundary condition: the physical design life and accounting amortization period of both the smart grid depot charging terminals and the high-pressure gaseous hydrogen refueling station infrastructures are assumed to be identical to the operational lifespan of the vehicle assets ($T = 15$ years). This asset-infrastructure alignment eliminates the econometric requirement for residual infrastructure valuation models at Year 15, providing a clear lifecycle boundary for the STIB comparative network assessment.

4.6. Quantitative TCO Analysis and Exploratory Hydrogen Sensitivity Matrix

4.6.1. Breakdown and Component Analysis of the Base Case

The operationalization of the discounted lifecycle model reveals distinct financial trajectories for the two zero-emission powertrain technologies. The aggregate Net Present Value (NPV) of the TCO equals €801,498 for the Battery Electric Bus (BEB) platform and €1,242,196 for the Fuel Cell Electric Bus (FCEB) alternative. Standardized against lifetime operational delivery, these metrics yield a unit cost of €1.19 per kilometer for BEB deployments and €1.84 per kilometer for FCEB operations.

This establishes that under baseline market parameters in the Brussels-Capital Region, an FCEB transit asset is approximately 1.54 times more expensive to procure, operate, and maintain than a comparable BEB unit over its 15-year service window. Table 6 provides a detailed breakdown of the discounted financial segments.

The distribution of these cost components demonstrates that operational energy expenditures represent the primary economic driver of the lifecycle divergence.

For the FCEB configuration, the fuel component accounts for 38.8% of the aggregate TCO, reaching €481,815 per vehicle. This dominance stems directly from the contemporary price premium of green hydrogen (€9.00/kg) relative to commercial grid electricity (€0.1590/kWh), making energy efficiency losses across the hydrogen supply chain the critical source of economic variance.

Conversely, infrastructure capital expenditures display high cross-powertrain symmetry, requiring €11,209/bus for BEB smart-charging grids and €15,338/bus for gaseous HRS

facilities. Among the remaining variables, the BEB profits from a lower initial procurement price (saving €45,000 in CAPEX relative to the FCEB). However, this initial advantage is partially offset by the BEB's higher lifecycle maintenance budget (+€23,132), driven by the high extraordinary cost of replacing the 666 kWh lithium-ion battery pack at Year 8.

Table 6. Categorized lifecycle Net Present Value (NPV) breakdown for standard 12-m transit buses (€).

Discounted Lifecycle Cost Component	Battery Electric (BEB)	Fuel Cell Electric (FCEB)
Vehicle Procurement (CAPEX)	615,000	660,000
Operational Energy/Fuel (OPEX)	88,303	481,815
Maintenance & Overhauls (OPEX)	109,174	86,042
Scaled Facility Infrastructure (CAPEX)	11,209	15,338
Terminal Residual Asset Credit	−22,188	−999
Aggregate Integrated Lifecycle TCO	801,498	1,242,196
Standardized Unit Cost (€/km)	1.19	1.84

4.6.2. Exploratory Market Sensitivity: Hydrogen Price Deflation Uncertainty

Given the high elasticity of the FCEB's TCO relative to its fuel input pricing, projecting financial performance under potential hydrogen market adjustments is critical. Early European industrial roadmaps hypothesized a rapid deflationary cycle for green hydrogen driven by the deployment of utility-scale electrolyzer technologies [45]. However, contemporary energy market indicators require a more cautious approach. Multiple utility-scale renewable hydrogen infrastructure initiatives have faced significant delays or cancellations across Europe due to high capital costs, supply-chain constraints, financing bottlenecks, and regulatory delays [46,47].

According to the European Union Agency for the Cooperation of Energy Regulators (ACER), the mean production cost of renewable hydrogen within the single market remained close to €8.00/kg [46]. This represents an approximate fourfold premium over conventional fossil-derived grey alternatives, leaving mid-term cost deflation trajectories uncertain. Similarly, the International Energy Agency projects that by 2030, European green hydrogen costs will fluctuate within a wide band between USD 4.00/kg and USD 12.00/kg [47].

To evaluate the economic impact of this volatility, an alternative sensitivity scenario is constructed utilizing a mid-term market average of USD 8.00/kg (approximately €6.88/kg). Under this deflated fuel parameter:

- The cumulative discounted energy component of the FCEB TCO drops from €481,815 to €368,321.
- The integrated FCEB lifecycle TCO decreases to €1,128,702.
- The standardized unit cost scales down to €1.67 per kilometer.

4.6.3. Exploratory Market Sensitivity: Electricity Price Inflation Uncertainty

Concerning the BEB's, we also consider an alternative sensitivity scenario for electricity price. In fact, the literature cites €0.30/kWh as the European average electricity price, whereas we use a price of €0.159/kWh. If electricity prices were to double, the cost by kilometer grows from €1.19 to €1.30. We can therefore see that, under the most optimistic scenario for the price of hydrogen and the most pessimistic for the price of electricity, the cost per kilometer remains in favor of BEBs (€1.30/km for BEB versus €1.67/km for FCEB).

Crucially, even under this optimistic fuel price reduction, the FCEB configuration fails to achieve economic parity with the direct-charging electromobility paradigm, remaining 28.5% more expensive than the hight electricity price BEB profile (€1.30/km). This highlights that while hydrogen price deflation diminishes the financial gap, market volatility remains.

4.7. Strategic Implications for STIB Fleet Decarbonization Planning

From an economic perspective, the quantitative results demonstrate that Battery Electric Buses yield a superior techno-economic performance profile for the Brussels urban transit network. When evaluating fleet substitution options solely through financial optimization and lifecycle cost minimization, replacing legacy internal combustion diesel rolling stock with a unified BEB fleet represents the optimal economic choice for STIB.

However, this strategic planning conclusion carries specific caveats. The identified economic dominance of the BEB platform is historically bound to current market parameters. While contemporary financial constraints limit wide-scale FCEB integration, a combination of long-term factors could adjust this equilibrium:

1. Significant global scale economies in hydrogen fuel cell manufacturing.
2. Deep structural deflation of cross-border green hydrogen logistics corridors.
3. Severe operational localized bottlenecks—such as grid distribution constraints or physical footprint limitations within historic urban depots—limiting the deployment of large-scale BEB charging grids.

Consequently, while near-to-mid-term capital allocations by STIB should prioritize direct battery electrification to maximize economic returns, managing a long-term dual-technology tracking program remains a prudent strategy to hedge against infrastructure and energy market adjustments.

5. Operational Practicality and Fleet Integration Results

5.1. Research Purpose and Scope of the Qualitative Empirical Component

To complement the quantitative evaluations developed through the LCA and TCO models, this research incorporates a qualitative empirical component based on primary data collection. While mathematical models capture environmental and financial lifecycle vectors, they often operate under idealized assumptions that mask the complex, day-to-day operational, infrastructural, and organizational challenges encountered during fleet deployment.

Consequently, semi-structured interviews with public transit professionals are utilized to capture the practical constraints of integrating alternative propulsion platforms within a dense urban network.

Within this empirical framework, "operational practicality" is defined as the capacity of an alternative vehicle technology to be systematically integrated into regular, high-frequency urban transit schedules without inducing critical failures or structural disruptions across multiple operational axes:

- Spatial-Temporal Autonomy: Real-world driving range constraints under varying seasonal temperatures, traffic congestion profiles, and topographical gradients.
- Logistical Synchronization: Recharging or refueling time windows and their compatibility with labor regulations, vehicle turnaround schedules, and service frequency.
- Fixed Asset Real Estate: The structural, architectural, and spatial adaptability of historic, land-constrained urban transit depots.
- Industrial Safety and Overhaul Logistics: Technical maintenance complexity, regulatory occupational safety compliance, emergency response protocols (e.g., thermal runaway or high-pressure gas leaks), and workforce mechanical expertise.

- Organizational Readiness: Technical maturity, supply chain stability for spare parts, and the adaptability of scheduling and routing software systems.

By capturing these empirical insights directly from transit professionals managing the corporate infrastructure, this qualitative component aims to identify the specific barriers, systemic risks, and technical opportunities associated with deploying Battery Electric Buses (BEBs) and Fuel Cell Electric Buses (FCEBs) within the specific operational ecosystem of the Brussels Intercommunal Transport Company (STIB).

5.2. Qualitative Research Design and Expert Selection

To gather primary empirical insights, this qualitative component utilizes a semi-structured professional interview methodology. A semi-structured format is selected because it combines a systematic, reproducible core framework with the dialogue flexibility required to investigate technical, site-specific operational issues in depth.

The target sample isolates elite organizational informants within STIB whose professional mandates directly encompass rolling stock procurement, depot real estate, grid infrastructure deployment, maintenance engineering, corporate safety, or strategic electrification program management. This ensures that the qualitative dataset is anchored in real-world infrastructure constraints and operational data rather than abstract institutional perceptions. Specifically, primary data collection involved formal sessions with Luc Tintillier (Project Manager within the Bus Acquisition Projects Team) and Benjamin Roelands (Head of the Bus Fleet Electrification Program).

The data collection tool is an interview guide divided into three thematic parts:

1. Background Assessment: Profiling the respondents' specific engineering roles and corporate expertise.
2. Open-Ended Thematic Inquiry: Probing key dimensions of operational practicality, systemic infrastructure bottlenecks, and hazard mitigation for both BEB and FCEB systems.
3. Multi-Criteria Scoring Exercise: Quantifying the experts' evaluations across standardized technical, financial, and logistical parameters.

5.3. Qualitative Main Findings and Thematic Analysis

5.3.1. Disparate Trajectories of Local Technological Maturity

The empirical data reveal a significant divergence in technological maturity and systemic integration readiness between the two alternative propulsion platforms within STIB's organizational ecosystem.

- Battery Electric Bus (BEB) Maturity: BEBs have transitioned beyond the exploratory pilot phase and are fully integrated into STIB's rolling stock. The operator manages multiple operational cohorts spanning diverse dimensional categories, including midibuses, standard 12-m rigid units, and articulated buses. These vehicles are deployed across active urban routes utilizing distinct, co-existing charging strategies (overnight depot and terminal opportunity charging) and varying battery chemistries, rendering direct electromobility a mature, standardized component of STIB's daily operations.
- Fuel Cell Electric Bus (FCEB) Maturity: Conversely, STIB's institutional experience with hydrogen fuel chains remains highly limited and exploratory. The operator executed an initial two-year field trial between 2021 and 2023 utilizing a leased 12-m FCEB. This pilot encountered severe operational and infrastructural disruptions, primarily driven by low refueling station availability, mechanical unreliability of dispensers, and supply chain volatility. A subsequent, large-scale pilot project intended to deploy a fleet of articulated FCEBs was initiated but quickly abandoned due to a

lack of industrial commitment from consortium partners and sudden, severe inflation in green hydrogen commodity costs.

Consequently, STIB has suspended all active hydrogen exploration programs, establishing a clear hierarchy where BEBs represent an operationally validated asset ready for scale, while FCEBs remain an unviable, discontinued technology pathway for the organization.

5.3.2. Operational Flexibility: Spatial Range and Energy Supply Logistics

1. Spatial Autonomy and Thermodynamic Efficiency Trade-offs:

The interviews highlight that driving range is a primary operational criterion when evaluating fleet transition pathways, introducing complex technical trade-offs regarding onboard Energy Storage Systems (ESS):

$$\text{Traction Mass Penalty} \propto \text{Nominal Battery Capacity (kWh)} \tag{18}$$

Transit planning requires balancing nominal battery capacity with net vehicle payload capacity. Expanding battery capacity to ensure full-day autonomy increases the vehicle's unladen curb mass, which accelerates tire and infrastructure wear while legally restricting passenger carrying capacity. Conversely, optimizing for down-sized, lighter battery configurations enhances passenger capacity and reduces upfront CAPEX, but introduces operational rigidity by requiring high-frequency mid-service charging interventions.

This trade-off shapes STIB's dual operational strategies:

- Centralized Overnight Charging: Maximizes day-long route flexibility and autonomous vehicle dispatching across the network without real-time charging logistics, but concentrates grid power demands into tight nocturnal windows and relies on heavy vehicles.
- Decentralized Opportunity Charging: Utilizes automated roof-mounted pantographs at terminal points to distribute electrical load across time and space, reducing peak pressure on the central grid and allowing for lighter vehicles. However, it introduces operational dependency on localized terminal infrastructure, restricting vehicle deployment exclusively to equipped corridors.

Empirical network data from STIB outline that the absolute guaranteed operational range for its articulated BEB fleet stands at 200 km, with hard operational dispatch limits set at 170 km without intermediate charging. Standard 12-m rigid units achieve slightly higher thresholds due to lower traction energy consumption.

However, STIB experts emphasize that real-world autonomy is highly variable; adverse seasonal climates (HVAC thermal loads), severe traffic congestion, and aggressive driving profiles induce up to a 20% energy consumption penalty, necessitating strict safety margins that further limit real-world route lengths.

In comparison, FCEBs provide a superior theoretical autonomy profile, estimated at approximately 400 km for a standard 12-m unit. This expanded range simplifies automated scheduling, removes intermediate charging logistics, and permits cross-network routing. However, STIB's experts note that this range advantage is less critical when contextualized within the specific geography of the Brussels-Capital Region. Operating across a highly dense, compact urban area characterized by a low average traffic speed of 15.8 km/h and short network line lengths (spanning 373 km of total bus axes), STIB does not face severe range constraints with its current BEB configurations. The operational radius of contemporary battery systems has become adequate to satisfy the operator's spatial requirements, diminishing the practical value of the FCEB's extended range.

From a thermodynamic perspective, hydrogen powertrains also exhibit low systemic energy efficiency. The multiple conversion steps along the Well-to-Wheel pathway-comprising green electricity generation, high-pressure water electrolysis, mechanical compression, transport logistics, and onboard fuel cell electrochemical conversion-sustain cumulative thermodynamic losses. This results in an integrated well-to-wheel efficiency of approximately 25% for the hydrogen pathway, compared to 80-90% for a direct grid-to-battery electric drivetrain.

While literature suggests that hydrogen synthesis can optimize the grid by utilizing curtailed, surplus renewable electricity during low-demand periods, STIB's managers noted that these macro-systemic benefits fall outside the practical focus of a municipal transit operator.

2. Charging and Refueling Logistics Synchronization:

The time window required for energy replenishment represents a critical decision vector directly influencing transit schedule synchronization. For BEBs, extended charging windows introduce systemic complexities compared to the rapid refueling profiles of FCEBs.

Overnight slow-charging protocols compress high electrical energy demands into fixed, nocturnal depot windows, requiring high grid-connection capacities and automated smart-charging management software to avoid peak-load grid penalties. Conversely, while opportunity fast-charging protocols at route termini dramatically accelerate energy replenishment, they demand precise operational orchestration.

Because pantograph connection windows are brief, minor traffic delays or missed charging intervals can cascade across the schedule, causing cumulative delays that threaten service continuity and route reliability.

5.3.3. Structural Depot Real Estate and Industrial Safety Constraints

The systemic deployment of alternative heavy-duty propulsion platforms introduces complex architectural, spatial, and regulatory engineering challenges at the depot level. Because STIB's historical depot footprint was designed exclusively for internal combustion engine rolling stock, transforming these facilities requires substantial modifications to balance spatial efficiency, operational safety, and business continuity.

1. Battery Electric Fleet Depot Adaptations:

Integrating wide-scale battery charging systems requires localized spatial and structural grid adjustments. To optimize land use and prevent traffic disruptions within depot corridors, STIB implements overhead inverted pantograph charging systems. This approach eliminates ground-based cables, protective barriers, and associated footprint losses at the vehicle staging level.

However, this top-down architecture still requires substantial industrial real estate to accommodate stationary charging cabinets, high-voltage transformers, and dedicated electrical substations. Consequently, fleet electrification increases the net industrial surface area requirement, though the exact impact varies across STIB's facility typologies. While initial predictive models hypothesized severe layout penalties, recent engineering audits by STIB demonstrate that real-world footprint impacts remain manageable, restricting the net loss of operational parking capacity to under 10%.

Beyond spatial footprints, BEB charging hubs require advanced structural fire mitigation protocols to ensure business continuity. To address the systemic risk of thermal runaway and cascading battery fires, STIB is progressively implementing a structural compartmentalization strategy. Depots are engineered into isolated micro-sectors, limiting vehicle staging density to a maximum of 24 buses per zone, with each cell separated by

certified fire-resistant walls. This design isolates localized thermal events, protecting the broader asset infrastructure.

Additionally, corporate risk-management mandates from industrial insurers introduce strict operational boundaries. These include legal restrictions on enclosed indoor charging cycles, forcing the utility to execute high-power charging processes in specialized open-air configurations. These combined constraints demonstrate that depot electrification involves a complex spatial-structural re-engineering that must balance grid power delivery with strict safety and operational continuity guidelines.

2. Fuel Cell Fleet Depot Adaptations:

For FCEB configurations, STIB's engineering representatives did not identify structural footprint allocation as a primary constraint. This observation aligns with transport literature, which confirms that hydrogen refueling setups do not impose the same localized, space-intensive asset footprint inside staging yards as parallel BEB charging grids [48].

Instead, FCEB depot constraints focus heavily on rigorous, specialized industrial safety configurations. STIB's initial trial phase highlighted that integrating hydrogen assets requires substantial modifications to maintenance workshops and diagnostic bays. Because elemental hydrogen (H_2) features low molecular density and high volatility, unmitigated leaks rise quickly and accumulate near ceilings, creating explosive hazards in enclosed spaces.

Consequently, facilities must comply with strict ATEX (Atmosphères Explosibles) European regulatory frameworks, which mandate the deployment of specialized explosion-proof equipment in hazardous zones. Within STIB's maintenance bays, this requires modifying all overhead infrastructure-including illumination arrays, electronic switches, diagnostic tools, and extraction systems-to meet certified ATEX ignition-prevention standards.

Furthermore, structural architectural adaptations must eliminate overhead gas trapping. Maintenance bays require sloped ceiling geometries coupled with high-sensitivity optical hydrogen flame detectors and automated roof-ventilation release mechanisms to ensure rapid gas dissipation during an anomaly. These combined variables increase the engineering complexity and regulatory oversight of FCEB facility operations, requiring dedicated safety procedures and infrastructure modifications.

3. Comparative Infrastructure Synthesis:

In summary, both zero-emission pathways require significant infrastructure adaptations, presenting asymmetrical challenges for transit operators. BEB deployment introduces clear spatial limitations and complex charging layout challenges within existing land constraints. Conversely, FCEB integration avoids severe footprint penalties but demands strict, capital-intensive hazardous gas safety configurations and ATEX regulatory compliance. For STIB's fleet transition, these trade-offs are balanced by the utility's current operating history: BEB infrastructure is already a mature, validated component of STIB's active modernization roadmap, whereas FCEB requirements present an un-vetted operational path.

4. Industrial Maintenance Complexity and Workforce Training Requirements:

The technical maintenance paradigms and workshop requirements under heavy-duty transit conditions introduce distinct operational challenges for the two zero-emission powertrains:

- BEB Maintenance Dynamics: Technical interventions for the BEB fleet are heavily bound to the degradation kinetics of the high-capacity electrochemical Energy Storage Systems (ESS). STIB executes a mandatory annual State of Health (SoH) diagnostic protocol to track cell degradation. The SoH index is formalized as the non-dimensional

ratio between the maximum deliverable capacity of the aged pack and its initial nominal design capacity when new [49]:

$$SoH = \frac{C_{\text{actual}}}{C_{\text{nominal}}} \times 100\% \quad (19)$$

In compliance with strict transit reliability standards, a battery pack is contractually considered to have reached its end-of-service life when its SoH drops below 80%. Empirical fleet tracking at STIB confirms that this degradation threshold is typically reached at the mid-life operational horizon, requiring a complete battery overhaul at approximately Year 8. Beyond this heavy mid-life intervention, day-to-day routine maintenance remains relatively simple due to the high mechanical simplicity of direct-battery drivetrains.

- FCEB Maintenance Dynamics: Conversely, FCEB configurations introduce a significantly higher level of technical and mechanical complexity into the workshop environment. Fuel cell systems rely on complex high-pressure fluid architectures, multi-stage hydrogen distribution loops, and extensive arrays of electronic safety sensors calibrated for real-time gas leak detection. Consequently, routine workshop interventions require a highly specialized workforce, strict industrial safety procedures, and extensive training protocols.

While STIB's technical experts did not evaluate long-term fuel cell stack degradation due to the premature termination of their local pilot project, transport literature confirms that fuel cell systems sustain significant electrochemical aging, requiring full stack replacement around the mid-life service horizon, mirroring the temporal replacement windows of lithium-ion batteries [7]. Concerning the health state estimation and long-term durability prediction for FCM, ref. [50] provides a framework for assessing the health status of fuel cell stacks under dynamic operating conditions, which can be used to enhance the analytical depth of FCEB performance degradation throughout their entire lifecycle, particularly in the durability assessment portion within the complex urban operating environment of Brussels. In a concurrent study [1] quantifies SOH disparity among multiple fuel cell stacks and embeds a three-layer rule-based protection mechanism into a reinforcement learning framework, offering a complementary perspective on fuel cell durability modeling and health-aware energy management.

5. Synthesis and Resolution of the Empirical Maintenance Paradox:

This qualitative technical evaluation resolves an apparent contradiction with the quantitative findings of the TCO model (Section 4.4). At first glance, the experts' assessment that FCEB maintenance is more operationally demanding seems to conflict with the financial results, which show a higher absolute maintenance budget for the BEB fleet (€109,174 for BEBs vs. €86,042 for FCEBs).

This economic gap is driven by the asymmetric distribution between routine upkeep and extraordinary component overhauls. While the day-to-day maintenance of FCEB systems involves higher diagnostic complexity and stricter labor protocols, academic literature establishes that routine component costs remain economically comparable between the two technologies [5].

Consequently, the financial balance is shifted by the high cost of the primary energy component replacement. Because the eCitaro's large 666 kWh battery pack demands a significant financial allocation at Year 8, it introduces a major extraordinary cost that outweighs the lower capital requirements of the FCEB's smaller 70 kW fuel cell stack and 30 kWh buffer battery.

Therefore, while BEB assets are mechanically simpler to maintain on a daily basis, they generate a higher aggregate financial burden over their complete life cycle due to the high replacement costs of contemporary high-capacity traction batteries.

5.4. Integrated Synthesis of Operational Practicality and Technological Alignments

The empirical data gathered from the professional interviews demonstrate that while both zero-emission propulsion platforms introduce distinct operational and engineering challenges, their practical readiness for immediate systemic deployment within the Brussels transit network is highly asymmetrical.

The thematic analysis indicates that Battery Electric Buses (BEBs) establish a clear advantage in overall operational practicality over Fuel Cell Electric Buses (FCEBs) within STIB's specific organizational framework. This dominance is driven by two main operational vectors:

1. Infrastructure and Organizational Alignment:

BEBs benefit from a strong path dependency within STIB. The utility has already established standardized charging protocols, modified internal facility real estate, and built specialized technician training frameworks. Direct battery electrification aligns with STIB's current infrastructure capabilities, minimizing organizational disruption.

2. Supply Chain Integrity and Security of Supply:

Conversely, while FCEB configurations offer strong theoretical advantages—such as extended spatial autonomy and rapid replenishment windows that simplify route scheduling—their practical deployability is severely limited by external infrastructure maturity. The localized hydrogen ecosystem is constrained by high equipment unreliability, frequent refueling station downtime, and a distinct lack of guaranteed commercial continuity within the regional green hydrogen supply chain.

Consequently, under contemporary market and infrastructural parameters in the Brussels-Capital Region, practical deployment readiness favors the immediate scaling of direct grid-to-battery electromobility configurations. Nevertheless, this technical evaluation should not lead to the definitive exclusion of hydrogen options. As macro-level energy systems evolve, STIB should maintain a strategic observation program to track ongoing developments in heavy-duty FCEB powertrain reliability, scale economies in fuel cell manufacturing, and the emergence of regional green hydrogen production corridors (such as the HOPE offshore project). This dual tracking strategy ensures the utility can adapt its long-term vehicle procurement roadmaps if energy market configurations adjust.

6. Discussion and Multi-Criteria Decision Framework

6.1. Multi-Criteria Analysis (MCA) Design and Evaluation Framework

6.1.1. Methodological Foundations and Normalization Formulations

To synthesize the heterogeneous results derived from the quantitative lifecycle models (LCA and TCO) and the empirical qualitative findings (Operational Practicality), this study develops an integrated Multi-Criteria Analysis (MCA) framework. Unlike single-criterion optimization methods, an MCA allows for the simultaneous integration of diverse datasets, bridging numerical indicators with professional engineering assessments.

As transport infrastructure planning grows in structural complexity, traditional monetary-driven frameworks, such as cost-benefit analyses, struggle to encapsulate non-market environmental vectors or qualitative operational risks into unified monetary parameters [51]. Consequently, utilizing a Multi-Criteria Decision-Making (MCDM) matrix provides a transparent evaluation architecture capable of managing conflicting operational, environmental, and financial criteria [52].

The MCA model is structured around a multi-layered hierarchical index. Each core criterion is assigned a localized relative weight (w_j) reflecting its strategic importance, which was directly calibrated through the multi-criteria scoring exercise conducted with the STIB expert panel.

To eliminate dimensional distortions from metrics expressed in different units—such as Global Warming Potential (kg CO_2e/km), lifecycle Net Present Value (€/km), and qualitative risk indices—a linear ratio-based normalization protocol is applied prior to mathematical aggregation [53]. This transformation maps all performance indicators onto a common, dimensionless scale ranging from 0 to 1, where a score of 1.00 represents the optimal technological boundary.

The normalization vectors are operationalized using two distinct functions based on the intrinsic target of each criterion j for an alternative technology i:

1. Maximization Criteria (Benefit Objectives):

For parameters where a higher magnitude represents superior performance (e.g., operational autonomy, payload capacity):

$$N_{ij} = \frac{X_{ij}}{\max_i(X_{ij})} \tag{20}$$

where X_{ij} represents the raw performance metric of alternative i under criterion j, and $\max_i(X_{ij})$ is the maximum performance ceiling observed across the technological choices.

2. Minimization Criteria (Cost Objectives):

For parameters where minimizing the value is the primary goal (e.g., aggregate TCO, lifecycle carbon footprint):

$$N_{ij} = \frac{\min_i(X_{ij})}{X_{ij}} \tag{21}$$

where $\min_i(X_{ij})$ represents the lowest resource consumption or environmental burden recorded across the alternatives.

Once normalized, the criteria are compiled through a Weighted Sum Model (WSM), which evaluates the aggregate performance index (A_i) for each powertrain option [54]. The multi-attribute linear utility function is formalized as follows:

$$A_i = \sum_{j=1}^{m} w_j \times N_{ij} \tag{22}$$

where A_i represents the integrated lifecycle suitability score of alternative technology i, w_j is the normalized weight factor assigned to criterion j, satisfying the boundary condition $\sum_{j=1}^{m} w_j = 1$, N_{ij} is the dimensionless normalized score of alternative i under criterion j and m is the total number of evaluation criteria.

The powertrain configuration that achieves the highest global suitability index (A_i^*) is selected as the optimal technological pathway for STIB's fleet substitution program, balancing environmental mitigation targets, financial feasibility, and real-world operational constraints.

6.1.2. Lifecycle Environmental Attribute Vector Optimization

The localized environmental performance vector ($N_{i,\text{env}}$) for each alternative powertrain configuration is quantified using the numerical outputs derived from the cradle-to-grave LCA (Section 3.2.1), expressed in kilograms of carbon dioxide equivalent per vehicle-kilometer (kg CO_2e/km).

As established in the baseline LCA model under mid-term optimized grid constraints and localized supply chains, the emissions per functional unit are 0.30 kg CO_2e/km for

the direct-charging BEB fleet (anchored on the projected low-carbon Belgian electricity mix) and 0.21 kg CO_2e/kmfor the FCEB fleet (anchored on the exclusive utilization of offshore wind-powered green hydrogen). Because global warming potential (GWP) is an environmental cost vector to be minimized, the linear normalization ratio is applied as follows:

$$N_{i,\text{env}} = \frac{\min_i(X_{i,\text{env}})}{X_{i,\text{env}}} \tag{23}$$

Substituting the respective empirical lifecycle values yields the following dimensionless environmental attribute scores:

- Battery Electric Bus: $N_{\text{BEB,env}} = \frac{0.21 \text{ kg } CO_2\text{e/km}}{0.30 \text{ kg } CO_2\text{e/km}} = 0.700.$
- Fuel Cell Electric Bus: $N_{\text{FCEB,env}} = \frac{0.21 \text{ kg } CO_2\text{e/km}}{0.21 \text{ kg } CO_2\text{e/km}} = 1.000.$

Under these analytical boundaries, the FCEB configuration achieves the optimal environmental index threshold (1.000), reflecting its minimal lifecycle greenhouse gas footprint when coupled with dedicated renewable electrolysis. The BEB platform receives a normalized score of 0.700, demonstrating that its lifecycle carbon mitigation efficiency reaches exactly 70.0% of the green hydrogen alternative within the target regional energy mix.

6.1.3. Total Cost of Ownership Economic Vector Optimization

The economic suitability attribute vector ($N_{i,\text{econ}}$) is parameterized using the unit results extracted from the lifecycle Net Present Value TCO model (Section 4.4.2), expressed in euros per operational vehicle-kilometer (€/km).

The integrated financial models establish the lifecycle unit metrics at 1.19 €/km for the BEB platform and 1.84 €/km for the FCEB configuration. As the lifecycle economic expenditure represents a performance cost to be minimized, the normalization ratio is operationalized identically to the environmental vector:

$$N_{i,\text{econ}} = \frac{\min_i(X_{i,\text{econ}})}{X_{i,\text{econ}}} \tag{24}$$

Executing the normalization calculations for each alternative technological choice yields:

- Battery Electric Bus (BEB): $N_{\text{BEB,econ}} = \frac{1.19 \text{ €/km}}{1.19 \text{ €/km}} = 1.000.$
- Fuel Cell Electric Bus (FCEB): $N_{\text{FCEB,econ}} = \frac{1.19 \text{ €/km}}{1.84 \text{ €/km}} \approx 0.647.$

The direct-charging battery electric alternative achieves the maximum economic performance score (1.000), showing its high cost-effectiveness per kilometer. The fuel cell configuration achieves a lower financial suitability score of approximately 0.647. This economic penalty is driven by the operational fuel market pricing in Belgium, where high green hydrogen retail tariffs create a significant lifecycle OPEX burden that diminishes the technology's short-to-medium-term commercial viability.

6.1.4. Operational Practicality Vector Optimization

The qualitative attributes governing the operational feasibility and network deployability of each vehicle technology are quantified using a multi-step linguistic transformation framework inspired by multi-criteria transit evaluation methodologies [55].

Primary empirical data harvested from the STIB expert panel are first mapped onto a five-tier qualitative ordinal descriptor scale, where each level defines a distinct threshold of operational risk and asset deployability:

- Excellent: Seamless integration; zero technical, spatial, or scheduling constraints identified.

- Good: Minor localized constraints requiring manageable adjustments with negligible impact on net network practicality.
- Moderate: Identifiable operational or technical trade-offs that alter deployment parameters without causing system failure.
- Low: Cumulative infrastructural or logistical bottlenecks that impose a significant negative impact on service deployability.
- Very Low: Severe, systemic barriers that disrupt operational continuity and introduce major institutional risks.

Table 7 compiles the consensus qualitative engineering assessments provided by the STIB transit experts across the five operational practicality sub-criteria.

To integrate these linguistic variables into the multi-criteria mathematical optimization core, the ordinal descriptors are converted into a discrete numerical scale ranging from 1 to 5 (1 = Very Low, 2 = Low, 3 = Moderate, 4 = Good, 5 = Excellent). Table 8 displays the resulting quantified operational operational matrix.

Table 7. Qualitative expert assessment of operational practicality parameters within the STIB network.

Operational Practicality Sub-Criterion	Battery Electric Bus (BEB)	Fuel Cell Electric Bus (FCEB)
Fuel Replenishment/Recharging Duration	Moderate	Excellent
Spatial Driving Autonomy (Range)	Good	Excellent
Depot Structural Layout Adaptability	Moderate	Low
Upstream Energy Supply Chain Reliability	Excellent	Very Low
Technical Maintenance & Overhaul Complexity	Good	Low

Table 8. Quantified numerical scoring matrix for operational practicality attributes.

Operational Practicality Sub-Criterion	Battery Electric Bus (BEB)	Fuel Cell Electric Bus (FCEB)
Fuel Replenishment/Recharging Duration	3	4
Spatial Driving Autonomy (Range)	4	5
Depot Structural Layout Adaptability	3	2
Upstream Energy Supply Chain Reliability	5	1
Technical Maintenance & Overhaul Complexity	4	2

Because the expert panel did not establish a distinct internal hierarchy among the operational sub-parameters, an equal-weighting protocol is applied to the vector. The unnormalized operational suitability index (P_i) is calculated as the arithmetic mean of the five discrete sub-scores:

- Battery Electric Bus : $P_{\text{BEB}} = \dfrac{3+4+3+5+4}{5} = 3.800.$
- Fuel Cell Electric Bus : $P_{\text{FCEB}} = \dfrac{5+5+2+1+2}{5} = 3.000.$

The unnormalized evaluation shows that the BEB platform achieves a higher practical performance index (3.800) compared to the FCEB alternative (3.000). While the hydrogen platform demonstrates strong performance in raw spatial range and fast refueling windows, its practical score is lowered by severe bottlenecks, including low hydrogen supply

chain reliability, high maintenance complexity, and strict ATEX depot safety requirements. Conversely, the BEB fleet displays a more stable operational profile, benefiting from high infrastructure maturity and a reliable grid power supply.

To maintain mathematical consistency with the environmental and economic vectors, these unnormalized operational indices are transformed via linear ratio maximization, where a higher score represents a benefit to be maximized:

$$N_{i,\text{prac}} = \frac{P_i}{\max_i(P_i)} \tag{25}$$

Substituting the respective empirical values yields the final normalized operational practicality attribute scores:

- Battery Electric Bus : $N_{\text{BEB,prac}} = \frac{3.800}{3.800} = 1.000.$
- Fuel Cell Electric Bus : $N_{\text{FCEB,prac}} = \frac{3.000}{3.800} \approx 0.789.$

Consequently, the battery electric configuration reaches the optimal operational suitability threshold (1.000) within the STIB network context. The fuel cell configuration achieves a normalized practical index of approximately 0.789, indicating that its real-world deployability reaches 78.9% of the direct-charging alternative under current regional infrastructure parameters.

6.1.5. Integrated Multi-Criteria Synthesis and Weighted Sum Model (WSM) Aggregation

To establish the definitive technological ranking for the Brussels surface transit fleet substitution program, the individual normalized attribute vectors-Environmental ($N_{i,\text{env}}$), Economic ($N_{i,\text{econ}}$), and Operational Practicality ($N_{i,\text{prac}}$)-are compiled into a unified global suitability score. This synthesis applies the multi-attribute Weighted Sum Model (WSM) formalized in Section 6.1.1.

The weighting vectors (w_j) represent the corporate prioritization matrix provided by the STIB expert panel [17]. Financial feasibility constitutes the primary driver for public transit asset procurement and is assigned a dominant weight of 55%. Operational deployability and service reliability follow with a weight of 25%, while long-term lifecycle environmental mitigation targets receive a localized weight of 20%. Because this localized allocation satisfies the boundary normalization condition ($\sum w_j = 1.00$), the parameters are integrated into the linear utility core without further numerical conversion. Table 9 summarizes the structural criterion weight distribution.

Table 9. Macro-criteria weight distribution derived from STIB executive.

Analytical Dimension/ Primary Pillar	Lifecycle Economic Cost (TCO)	Operational Practicality Vector	Lifecycle Environmental Impact (LCA)	Aggregate Sum
Normalized Criteria Weights (w_j)	0.55	0.25	0.20	1.00

The integrated linear utility function compiled for each alternative zero-emission technology is formalized as follows:

$$A_i = (0.20 \times N_{i,\text{env}}) + (0.55 \times N_{i,\text{econ}}) + (0.25 \times N_{i,\text{prac}}) \tag{26}$$

Substituting the previously calculated normalized attribute scores into the WSM function yields the final quantitative results itemized in Table 10.

Table 10. Final multi-criteria decision-making (MCDM) matrix and weighted suitability scores.

Primary Evaluation Criteria	BEB	FCEB	Criterion Trajectory	Attribute Weight (w_j)
Lifecycle Environmental Impact	0.700	1.000	Minimize (Cost)	0.20
Total Cost of Ownership	1.000	0.647	Minimize (Cost)	0.55
Operational Practicality Index	1.000	0.789	Maximize (Benefit)	0.25
Global Suitability Score (A_i)	0.940	0.753	Maximize	1.00

The multi-criteria aggregation demonstrates that the Battery Electric Bus (BEB) represents the optimal technological pathway for STIB, achieving a global suitability index of 0.940 compared to 0.753 for the Fuel Cell Electric Bus (FCEB) alternative.

This multi-attribute outcome is analyzed across three key parameters:

1. Financial and Operational Dominance:

While the FCEB configuration achieves the maximum environmental score (1.000) due to the high carbon mitigation efficiency of offshore wind-powered green hydrogen, the BEB platform offsets this advantage by securing optimal performance scores (1.000) across both the economic and operational dimensions.

2. Impact of Corporate Weighting:

The structural gap between the final suitability indices ($\Delta A = 0.187$) is heavily driven by the high weight (55%) assigned to the economic criterion by STIB management. The lower capital asset price and high well-to-wheel energy efficiency of direct grid-charging systems strongly align with the utility's cost-minimization mandates, shifting the final ranking in favor of the BEB.

The criterion weights (55% economic, 25% practical, 20% environmental) rely solely on two internal STIB experts. To avoid this subjectivity, we conducted a sensitivity analysis. If adjusted to plausible alternatives (e.g., increasing the environmental weight to 35% and lowering the economic weight to 40%), the recommended solution remains BEBs, with a score of 0.895 compared to 0.806 for FCEBs. The break-even point is achieved increasing the environmental weight to 49% and lowering the economic weight to 26%. Consequently, for FCEBs to become the more attractive alternative, the criteria would need to be set at 50% for the environment, 25% for the economy, and 25% for practicality. This scenario seems unlikely.

3. Sensitivity and Boundary Constraints:

Crucially, while this integrated assessment supports wide-scale battery electrification within the current planning horizon, this optimization is bound to the baseline parameters, utility tariffs, and technological weights applied throughout this research. Changes in macro-environmental variables—such as localized grid constraints, infrastructure grants, or structural deflation within the green hydrogen supply chain—could adjust the multi-criteria trade-offs over time.

6.2. Limitations and Opportunities for Future Research Avenues

While this study provides a comprehensive, multi-criteria decision framework for transit fleet decarbonization, several inherent limitations must be acknowledged when interpreting the empirical and quantitative results. These constraints identify critical parameters and boundaries that outline opportunities for future academic and operational research.

6.2.1. Spatial Boundaries and Regional Generalizability

The primary limitation of this research stems from its high context-specificity, as the quantitative input data, cost parameters, and operational constraints are explicitly modeled around the unique ecosystem of the Brussels Intercommunal Transport Company (STIB). Consequently, the specific technological ranking and final numerical suitability scores ($A_{\mathrm{BEB}} = 0.940$ vs. $A_{\mathrm{FCEB}} = 0.753$) cannot be directly generalized or transferred to public transit operators in other geographic or macroeconomic jurisdictions.

For instance, a municipal transit agency operating in an urban network such as Bergen, Norway, would feature a vastly different operational and financial profile:

- Energy Systems: High access to low-cost, 100% renewable hydroelectric power arrays, significantly reducing direct grid-charging costs.
- Topography and Climate: Severe mountainous gradients and colder seasonal temperatures that alter vehicle energy consumption and exacerbate auxiliary HVAC battery drains.
- Infrastructural Ecosystem: Different national hydrogen infrastructure strategies, altering the localized refueling station supply chain constraints.

Nevertheless, while the numerical outputs remain bound to the Brussels-Capital Region, the core multi-criteria analysis (MCA) methodology developed in this study maintains broad external validity. The underlying framework-combining standardized cradle-to-grave LCA metrics, discounted NPV TCO modules, and a linear ratio-based normalization core-can be systematically adapted to any domestic or global transit network by recalibrating the local boundary conditions, utility pricing matrices, and technical operational profiles.

6.2.2. Stakeholder Sample Size and Qualitative Scoring Robustness

A second limitation relates to the boundary conditions of the qualitative data collection component used to evaluate the operational practicality index. The linguistic transformations and discrete numerical scoring models are constructed from semi-structured interviews with two elite informants from STIB. While these specific experts provide high-fidelity operational data and represent the core technical decision-making body of the target transit authority, relying on a small expert cohort introduces potential institutional bias.

To enhance the mathematical robustness and reduce the subjectivity of the operational practicality matrix, future research should expand the empirical stakeholder sample size. Incorporating multi-attribute survey panels that include a broader array of transit actors—such as procurement directors, maintenance engineers, safety officers, and trade union representatives—would provide a more comprehensive overview of organizational readiness.

Furthermore, integrating international fleet managers from municipal networks with high institutional maturity in hydrogen deployments (e.g., transit agencies in London, Cologne, or Pau) would provide valuable benchmarking data, refining the qualitative risk indices used in the decision model.

6.2.3. Technological Scope and Alternative Propulsion Pathways

Finally, this comparative analysis operates within a strict dual-technology paradigm, focusing exclusively on the trade-offs between two battery and fuel cell configurations: Battery Electric Buses (BEBs) and Fuel Cell Electric Buses (FCEBs). This narrow boundary excludes other established or emerging low-carbon alternative propulsion systems that currently participate in the decarbonization of heavy-duty transport networks.

To establish a more comprehensive and holistic decision-making matrix, future research models should broaden the technological scope by integrating additional alternative fuel pathways into the MCA evaluation framework:

- Advanced Biofuels and Biomethane (Biogas): Incorporating compressed or liquefied biomethane powertrains, which leverage existing internal combustion architecture while reducing net carbon cycles.
- E-Fuels and Synthetic Hydrocarbons: Evaluating the lifecycle and economic trade-offs of carbon-neutral synthetic fuels.
- Dynamic Charging Infrastructures: Assessing the integration of catenary-free electric roads or dynamic in-motion induction charging systems.

Expanding the technological scope will allow future multi-criteria frameworks to provide municipal planning authorities with a comprehensive matrix to optimize fleet transitions under evolving regulatory, economic, and technological conditions.

7. Conclusions and Policy Recommendations

This research developed an integrated techno-economic and environmental decision-making framework to evaluate the optimal technological pathway for the gradual replacement of the diesel surface transit fleet operated by the Brussels Intercommunal Transport Company (STIB). By conducting a comparative analysis between Battery Electric Buses (BEBs) and Fuel Cell Electric Buses (FCEBs), this study established a holistic evaluation matrix.

The core methodological contribution of this paper lies in the development of a region-specific, multi-criteria decision analysis (MCDA) that simultaneously synthesizes a cradle-to-grave Life Cycle Assessment, a multi-year discounted Net Present Value TCO model, and empirical qualitative insights derived from semi-structured interviews with elite transit engineering professionals. Unlike traditional optimization frameworks that focus strictly on environmental indicators or immediate capital procurement costs, this unified model incorporates real-world infrastructural, spatial, and organizational constraints faced by urban fleet operators. While the quantitative and empirical inputs are bound to the specific geography of the Brussels-Capital Region, the multi-criteria analysis (MCA) structure maintains strong external validity and can be recalibrated to assess heavy-duty fleet transitions in other international urban ecosystems.

The individual vector assessments generated the following key findings:

- Environmental Lifecycle Vector: Cradle-to-grave performance is fundamentally driven by upstream fuel synthesis pathways. Under deep decarbonization conditions-assuming an exclusive supply of offshore wind-powered green hydrogen and charging cycles tied to the projected low-carbon Belgian grid mix (145 g CO_2e/kWh)-the FCEB configuration achieves superior environmental performance, dropping to 0.21 kg CO_2e/km compared to 0.30 kg CO_2e/km for the BEB. However, this environmental dominance is highly sensitive to supply chains; utilizing fossil-derived grey hydrogen removes any carbon mitigation advantage, shifting the ecological burden upstream.
- Economic Expenditure Vector: The discounted lifecycle NPV model demonstrates a distinct economic advantage for the direct-charging electromobility paradigm. A standard 12-m BEB achieves a lifetime unit cost of €1.19 per kilometer (aggregate TCO of €801,498), whereas the FCEB alternative escalates to €1.84 per kilometer (aggregate TCO of €1,242,196). This 55% financial penalty is primarily driven by contemporary green hydrogen market pricing premiums (€9.00/kg) in Belgium relative to high-efficiency industrial electricity tariffs (€0.1590/kWh).

- Operational Practicality Vector: Empirical data from the field show that BEBs are significantly more practical for STIB's near-term planning. This dominance stems from a strong organizational path dependency, including pre-existing smart slow-charging depot hubs, automated terminal pantograph lines, and a developed maintenance expertise. Conversely, while FCEBs provide high spatial range (400 km) and rapid refueling windows (5–10 min) that simplify scheduling, their practical deployability is constrained by severe uncertainties in regional green hydrogen supply chain continuity, complex technical maintenance requirements, and capital-intensive ATEX depot safety overhauls.

When these distinct vectors are compiled within the final Weighted Sum Model (WSM), the Battery Electric Bus emerges as the heavily optimal technological option for the STIB network, securing a global suitability index of 0.940 compared to 0.753 for the FCEB. This final prioritization is strongly influenced by corporate planning parameters; because STIB executive management identifies financial feasibility as the dominant operational pillar-assigning the TCO criterion a standalone weight of 55% (outweighing the combined weight of the environmental and practical attributes)-the lower capital requirements and high energy efficiency of direct grid-connected BEBs determine the final ranking. Based on these integrated findings, it is recommended that STIB and the regional planning authorities of the Brussels-Capital Region prioritize the progressive, large-scale deployment of Battery Electric Buses in the short-to-medium term to maximize socioeconomic returns and comply with the strict regulatory mandates of the local Low Emission Zone (LEZ).

Concurrently, given the shifting nature of energy markets, STIB should maintain an active technological observation program to track ongoing developments in fuel cell manufacturing economies of scale, heavy-duty powertrain reliability metrics, and localized green hydrogen infrastructure projects (such as the HOPEoffshore pilot cluster). Future vehicle procurement and depot transformation roadmaps must retain high technical flexibility to adapt if macro-environmental variables reduce the current lifecycle cost gap.

What specific price targets for green hydrogen would prompt STIB to prioritize the procurement of FCEBs? To answer this strategic question, we conducted two sensitivity analyses. If the current weightings of the three criteria are maintained (55% for economics, 20% for the environment, and 25% for practicality), the price of green hydrogen would need to drop to €1.00 per kg for the FCEB option to be the most advantageous. However, if more plausible weighting factors are applied (increasing the environmental component to 35% and reducing the economic weighting to 40%), the FCEB option becomes the most advantageous once the price of hydrogen reaches €3.00 per kg.

Nevertheless, several boundary limitations apply to this research. The quantitative results remain context-specific to the operational and topographic parameters of Brussels, which restricts direct numerical transferability to other public transit operators. Furthermore, the qualitative scoring core is built from a concentrated expert sample size, and the technological boundaries exclude other low-emission fuel corridors such as advanced compressed biomethane (biogas) layouts.

To expand upon this study, future research avenues should focus on four main optimization pathways:

1. Expanding the empirical qualitative stakeholder base by conducting broader multi-attribute consensus surveys with procurement directors, maintenance mechanics, and international transit operators who manage mature zero-emission fleets.
2. Broadening the technological scope of the multi-criteria aggregation framework by integrating a wider array of alternative propulsion pathways, including synthetic e-fuels and dynamic in-motion induction charging infrastructure networks, to provide municipal planners with a comprehensive decision matrix for sustainable urban transit.

3. Our model is based on a number of key parameters (such as the hydrogen price submitted to important fluctuations). A sensitivity analysis of the results regarding these various parameters could be conducted using Monte Carlo simulations based on historical data, thereby providing 95% confidence intervals rather than fixed values.
4. Finally, our model consider only one aspect of the strategy of Brussel's city for decarbonation. Many international cities have diverse carbon reduction pathways, not limited to this one (See exemples illustrated on Figure 2). While this study focuses on bus electrification for Brussel's city, the mathematical model is inherently scalable and adaptable to some alternative carbon reduction strategies which imply public investment (such as bus electrification in London, expanding cycles lanes in Copenhagen and Brussels). They can be integrated into the model by updating the parameter vectors and incorporating pathway-specific constraints into the optimization framework. However, transport models [56] are better suited for incorporating more complex solutions, such as the introduction of LEZs in London, Paris, or Brussels.



Figure 2. Examples of carbon reduction pathways of international cities

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