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3.2

REPORT ON OPERATIONAL TOOL WITH TCO, LCA AND SOCIO-ECONOMIC OPTIMIZATION

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4	TECNALIA	Spain
5	IDIADA	Spain
6	Cenex Nederland	The Netherlands
7	ICCS	Greece
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ACRONYMS

AB	Advisory Board
AC	Alternating current or Air conditioning
AHP	Analytic Hierarchy Process
ANP	Analytic Network Process
APC	Advanced Propulsion Centre
BETT	Battery Electric Truck Trial
BRT	Bus Rapid Transit
CBA	Cost benefit Analysis
CEA	Cost Effectiveness Analysis
CO	Colombia or carbon monoxide
CO_2	Carbon dioxide
CZ	Czechia
DC	Direct Current
EC	Equador
EEA	European Economic Area
ELECTRE	ELimination Et Choice Translating REality
ES	Spain
EU	European Union
EV	Electric Vehicle
GAIA	Geometrical Analysis for Interactive Aid
GHG	GreenHouse Gas
GR	Greece
IT	Italy
KE	Kenya
KPI	Key Performance Indicator
LA	Latin America
MAUT	Multiple Attribute Utility Theory
MCA	MultiCriteria Analysis
MCDA	MultiCriteria Decision Making
MWh	Megawatt-hour
NL	The Netherlands
NO_x	Nitrogen oxides
PHEV	Plug-in Hybrid Electric Vehicle

PT	Public Transit
PTO	Public Transport Operator
SAW	Simple Additive Weighting
SSH	Social Sciences and Humanities
SUMI	Sustainable Urban Mobility Indicator
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
TTW	Tank-To-Wheel
TCO	Total Cost of Ownership
TRL	Technology Readiness Level
TZ	Tanzania
WTW	Well-To-Wheel
WP	Work Package

EXECUTIVE SUMMARY

eBRT2030 is a 4-year Horizon Europe project that develops innovative solutions for future zero-emission rapid transit for public transport. The project aims to support the next generation of innovative and effective public transport by demonstrating real-life electric Bus Rapid Transport (eBRT) concepts with fully electric buses in cities of Europe and partnering countries.

Within this project, Work Package 3 (WP3) aims to create a planning tool to assist the development of eBRT systems. Within WP3, the contribution of Task 3.1.2 is to develop specific tools for evaluation of eBRT systems in the project. Based on the activities in Task 3.1.2, this report (D3.2) outlines the methods used by the three tools developed.

1) The first tool is designed to enable bus operators to calculate the **total cost of ownership (TCO)** of individual buses and entire bus fleets.
2) The second tool is designed to enable public transport authorities, operators or local government to estimate the **reduction in greenhouse gas emissions** in the tank-to-wheel stage of operation enabled by transition from diesel Euro VI buses to electric buses.
3) The third tool is designed to enable public transport authorities, operators or local government to calculate the **reduction in exhaust-based air pollution** enabled by transition from diesel Euro VI buses to electric buses.

This report also develops a methodology for multi-criteria analysis of the eBRT innovations used in this project. Through the analysis, stakeholders are informed about how eBRT systems can be used in manner contributing to the maximal social benefits. Accompanying descriptions of the tools and methods are details on their scope of application, guidelines for their use and limitations.

The report is expected to be of interest to public and private bus fleet operators as well as planners, researchers and other stakeholders in the bus, public transport and heavy-duty electric vehicle sectors.

1 INTRODUCTION

eBRT2030 is a 4-year Horizon Europe project that will develop innovative solutions for future zero-emission rapid transit for public transport, running from 1 January 2023 until 31 December 2026.

The project aims to support the next generation of innovative and effective public transport by demonstrating real-life electric Bus Rapid Transit (eBRT) concepts with battery electric buses (e-buses) in cities in Europe and cities in partnering countries outside Europe. As such, eBRT2030 aims to accelerate the transition to zero emission road mobility across Europe.

eBRT2030 develops several innovations in eBRT systems enabling their application in various urban contexts. These innovations range from those in vehicles and their charging systems to the development of tools and services for automation, energy management and increased connectivity. Collectively, the project is expected to result in reduced cost of eBRT systems for both operators and passengers, reduced greenhouse gas emissions associated with Bus Rapid Transport systems, increase in passenger capacity and a mode shift towards the use of eBRT system across Europe.

The eBRT2030 project consortium consists of 49 participating organisations from 12 countries: Belgium, Austria, Spain, The Netherlands, Greece, Finland, Sweden, France, Czechia, Italy, Türkiye and Germany. The project coordinator is the International Association of Public Transport (UITP[1]).

As part of eBRT2030, real world demonstrations of eBRT systems will be tested in five Europeans cities: Barcelona (ES), Amsterdam (NL), Athens (GR), Prague (CZ) and Rimini (IT)[2]. Additionally, there will be one international demonstration in Bogotá (CO), and three small scale replications, most probably in Quito (EC), Dar es Salaam (TZ) and Nairobi (KE), all outside Europe.

1.1 PURPOSE OF THE DELIVERABLE

As part of work package 3 subtask 3.1.2, three digital tools were built to

1) calculate the total cost of ownership (TCO) associated with electric buses

2) calculate the tank-to-wheel (TTW) CO_2 emission reduction caused by the shift to electric buses from diesel buses and

3) calculate the air pollution reduction caused by the shift to electric buses from diesel buses.

[1] Union Internationale des Transports Publics in the original French.

[2] The original project also included demonstration in Eindhoven the Netherlands. However, due to technical challenges, the demonstration and activities in Eindhoven will not take place.

The TTW and air pollution reduction tools together form the life cycle assessment (LCA) tool. This report describes the methods used for these calculations and is meant as a guide alongside these three tools.

It also describes the multi-criteria analysis utilised for the societal optimisation of the eBRT2030 innovations. The societal effectiveness of these innovations is determined by assessing their social risks and benefits and optimising their impact through the six-step framework.

The TCO, TTW CO_2 emissions, and air pollution tools have been integrated into the larger digital project platform developed and maintained by the Vrije Universiteit Brussels. However, they may also be used individually. The multi-criteria analysis serves as a foundational tool that utilised the Social Sciences and Humanities (SSH) and Advisory Board knowledge and experience, to ensure that project innovations are strategically optimised for societal benefit. By recognising and addressing interdependencies with other eBRT2030 activities, the analysis evaluates the holistic impact of the innovations, thereby enhancing planning and development processes to align with broader societal goals.

1.2 INTENDED AUDIENCE

The LCA (i.e., TTW CO_2 emissions and air pollution tools) and TCO tools developed will be public facing, and openly available for wider use and exploitation later in the project. This report is meant as a reference book and operating manual for those using these online tools.

For Public Transport Authorities and Public Transport Operators that are interested in transitioning from diesel to battery electric drive, these tools are expected to be of considerable value. They are expected to be most helpful at an early stage in planning before initiating calls for tenders.

The tool can also be applied innovatively by PTAs and PTOs who have already gained some experience with electric buses, or by researchers. The tools can be applied retrospectively to learn more about bus electrified fleets. Some applications include:

a) identification of bus routes where the TCO of electric buses is low enough to be competitive, and therefore prioritizing the order in which routes to be electrified.

b) running simulations with several bus models to find which bus can be used with lowest TCO on a specified route.

c) running a low-cost estimation study of the emission reduction and air pollution reduction enabled by an electrified bus fleet.

As such, this report and the corresponding tools are expected to be of interest to public and private bus fleet operators as well as planners, researchers and other stakeholders in the bus, public transport and heavy-duty electric vehicle sectors.

The tools will also be integrated in the broader eBRT2030 tool developed by the Vrije Universiteit Brussels, which remains sensitive.

1.3 STRUCTURE OF THE REPORT

The report is structured as follows: Section 2 initially defines the theoretical frame behind the first tool: the total cost of ownership (TCO) as a financial metric for electric buses. It also describes the procedure used to estimate the TCO for a given electric bus fleet. Section 3 describes the scope of emissions covered by the second tool and how the reductions of greenhouse gas emissions in operation are calculated in comparison with diesel buses. Similarly, Section 4 describes the types of air pollutants covered by the third tool and describes the methods used to calculate the pollution reduction expected through operation of an electric bus fleet when compared with a diesel fleet.

Section 5 describes the method used for the calculation of the Social Optimization Index (SOI) of eBRT2030 innovations, thus allowing for further discussion over the improvement of the innovations' "social performance". Finally, Section 6 summarises the report and concludes the study.

2 TCO OF ELECTRIC BUSES

To estimate the overall costs associated with a vehicle or vehicles fleet, working with a total cost of ownership (TCO) framework is common. This framework provides a comprehensive overview of costs over the vehicles or fleets' operational life. It is a robust method for evaluation over vehicles with different initial costs, different operational and maintenance costs, and is therefore well-suited for comparison of alternative powertrains over longer terms.

2.1 TCO DEFINITION

The total cost of ownership (TCO), sometimes known as lifetime cost or Life Cycle Cost (LCC), is broadly defined as *"the cost of an asset throughout its life cycle, from acquisition through operation to disposal, while fulfilling the performance requirements*", based on Dodd et al. (2021). It is commonly applied to vehicles and fleets, but has many wider applications across buildings, consumer goods and other assets.

In this study, we use a more specific definition, suitable for vehicles and fleets, *"The Total Cost of Ownership (TCO) provides an estimate of the comprehensive costs incurred by a vehicle or fleet owner over the expected vehicle lifetime"* (Burnham et al. 2021).

2.2 TCO SCOPE

The scopes of the TCO studies of vehicles depend on both the purpose of the analysis as well as the user of the vehicle. For example, analyses focusing on a single user of vehicle from point of purchase to point of sale may consider a fraction of the lifecycle of the vehicle. TCOs for non-commercial vehicles can safely neglect labour costs while studies for fleet managers must necessarily include costs of labour including wages and benefits.

For the tool developed in this study, the main objectives are:

1) To compare the TCO of electric buses with an existing bus fleet of an operator
2) To identify the most important parameters affecting the TCO of electric buses
3) To identify bus routes where the TCO of electric buses is low enough to be competitive
4) To identify which buses can be used with low TCO on given routes
5) To make estimates for financing of electric bus procurement

As such, the TCO tool considers within its scope:

1) Vehicle cost: This includes the cost of the initial purchase of the vehicle from which the residual value of the vehicle at the end of the analysis timeframe is deducted. We assume the vehicle to be driveable and in good condition at the end of the analysis horizon and thus implicitly assume maintenance and repairs. We also assume a depreciation of the vehicle value over this horizon.

2) Financing costs: Financing costs are associated with the payment of interest beyond the retail price of the vehicle.

3) Charging costs: Costs of charging cover the cost of charging infrastructure as well as the costs of electricity. Electricity costs are proportional to bus driven distance, route characteristics, vehicle efficiency, ancillary loads (like heating and cooling) and electricity costs. In some cases, electricity costs may vary over the course of the day or year, leading to timing of charging rather than the scale of energy used for charging to also influence charging costs.

4) Maintenance and repair costs: These costs cover scheduled vehicle servicing (maintenance) and unscheduled vehicle servicing (repair).

The tool does not consider fees such as vehicle registration, parking, tolls, etc. Although labour is an important and essential cost associated with bus operation in any commercial setting, the labour costs are considered out of scope of this tool. They are unlikely to change when compared with the labour costs associated with operating diesel vehicles in the long term[3]. Insurance costs covering both liability, and extra-ordinary replacement and repair are not considered. Further, we do not consider external costs (positive or negative) to society or the environment, such as urban congestion, air pollution, noise pollution, etc.

2.3 TCO CALCULATION METHOD

The TCO is calculated as:

$$TCO = \sum_{i=1}^{N} \frac{C_i}{(1+d)^i}$$

where *N* is the total length of the analysis window in years,

i is the year of the cash flow,

d is the discount rate accounting for opportunity cost in % and

C_i represents the cash flow in the i^{th} year in real inflation adjusted Euros (€).

For an extended description of the methods, refer Burnham et al. (2021).

2.3.1 ANALYSIS TIMEFRAME AND VEHICLE LIFETIME

The timeframe of analysis of heavy-duty vehicles is typically 10 years (Burnham et al. 2021). The technical lifetime of buses is typically longer, ranging from 10 to 20 years (Kim et al. 2021; UITP 2021). During the vehicle lifetime, there may be multiple users of the bus, for each of which the analysis timeframe is shorter – limited to their individual duration of ownership.

[3] Some studies report as a difference between diesel and electric buses, the 'labour cost of charging'. This covers the costs associated with the time spent by the driver or other personnel on ensuring vehicles are adequately charged. We do not consider these costs here, and expect that as operators become more familiar with electric buses, these costs will reduce.

Around 80 to 90% of European buses are used for their entire operational life and then scrapped. The fraction of buses used in a second life in a different location is relatively small – at around 10 to 20%. This is mainly due to competitive tendering regimes in the wealthier European countries, which result in buses being sold after 7 to 10 years (UITP 2021).

Earlier studies on TCO of electric buses take various values on the timeframe of analysis, as shown in Table 1. These values range from 10 to 15 years.

Table 1: Timeframe of analysis in TCO studies on electric buses

TCO timeframe of analysis	Location/scope of study	Year of study	Source
10 years	Bratislava, Slovakia	2018	Potkány et al. (2018)
12 years	US and EU	2016	Lajunen and Lipman (2016)
12 years	Offenburg, Germany	2021	Kim et al. (2021)
15 years	E-buses with batteries ranging from 110 kWh to 350 kWh globally	2018	O'Donovan (2018)
15 years	Jakarta, Indonesia	2023	Triatmojo et al. (2023)

Similarly, the contract durations for electric buses (e-buses) are shown in Table 2, sourced from triatmojo et al. (2023). Internationally, e-bus contract durations are frequently longer than those for diesel buses. The main reason is that the low operational cost of electric drive pays off over longer periods.

Table 2: Contract durations for electric buses compared with diesel buses around the world

Location	E-bus contract duration (years)	Diesel bus contract duration (years)
Indonesia (Jakarta)	10	7
India	10-16	7
Chile (Santiago)	10-14	5-7
China (Shenzhen)	8	8
Colombia (Bogotá)	14	10

Internationally, a frequent choice for e-bus contract duration is in the range of 15 years. This is also suggested by some best practice guidelines (Triatmojo et al. 2023). However, European legislation for tendering restricts maximum duration of contracts to 10 years. To take advantage of longer lifetimes with low TCO, some countries work around this. As an example, in the Netherlands, where around 16% of buses were battery electric in 2022 (ACEA 2024), there is an option for operators to extend the contract by 5 years at the end of the initial 10 year contract (CROW 2024, 96).

For this reason, the default timeframe of analysis is 15 years in this study. We consider the bus to be used for its entire operational life with re-use rather than scrappage at the end of first life. We explicitly consider a second life of the battery, since 15 years from now, we expect a mature market for second life batteries to exist. Second life values of batteries are then expected to have a favourable influence on the TCO. For shorter time frames of analysis, as chosen by the user, we consider resale of the bus for mobility application – more details are provided in section 2.3.8.

2.3.2 PURCHASE COSTS OF CHARGING AND CHARGING INFRASTRUCTURE

For the purchase costs of charging and charging infrastructure, we conducted a brief survey of current literature and utilised of the authors' expertise in bus tendering operations. An initial overview of costs for bus and charger types is provided in Table 3.

Table 3: Overview of battery electric buses and charger costs

<table>
<tr><th colspan="6">Electric Buses</th></tr>
<tr><th>Bus type</th><th colspan="3">Purchase cost (€)</th><th colspan="2">Source</th></tr>
<tr><td>Depot charging 12m</td><td colspan="3">473.4k</td><td colspan="2">Kim et al. (2021)</td></tr>
<tr><td>Pantograph charging 12m</td><td colspan="3">390k</td><td colspan="2">Kim et al. (2021)</td></tr>
<tr><td>Depot charging 9-10m</td><td colspan="3">550k</td><td colspan="2">(Sustainable Bus 2023; AutoBus Web 2023)</td></tr>
<tr><td>Depot charging 11m</td><td colspan="3">575k</td><td colspan="2">(Sustainable Bus 2023; AutoBus Web 2023)</td></tr>
<tr><td>Depot charging 12m</td><td colspan="3">600k</td><td colspan="2">(Sustainable Bus 2023; AutoBus Web 2023)</td></tr>
<tr><td>Depot charging 18m articulated</td><td colspan="3">800.5k</td><td colspan="2">(Sustainable Bus 2023; AutoBus Web 2023)</td></tr>
<tr><th colspan="6">Chargers</th></tr>
<tr><th>Charger type</th><th>Purchase cost (€)</th><th>Project costs (€)</th><th>Civil Works (€)</th><th>Opex (€/year)</th><th>Source</th></tr>
<tr><td>AC 11 kW</td><td>1800</td><td>370</td><td>90</td><td>90</td><td>Tettero et al. (2022)</td></tr>
<tr><td>AC 22 kW</td><td>2100</td><td>370</td><td>105</td><td>434</td><td>Tettero et al. (2022)</td></tr>
</table>

DC 50 kW	17500	1600	7000	1745	Tettero et al. (2022)
DC 150 kW	52500	4200	21000	4895	Tettero et al. (2022)
DC 350 kW	122500	4200	49000	11195	Tettero et al. (2022)
Pantograph charging (300 to 450 kW)	457000	58500		5000	Kim et al. (2021)

These costs are only indicative figures – we do not expect hardware costs to vary widely across Europe though there might be some differences. However, we do expect unit costs to change with the lot size i.e. the number of buses purchased. When using the tool, bus operators will be able to insert more accurate data based on recent tenders or market knowledge.

2.3.3 ENERGY REQUIREMENT OF ELECTRIC BUSES

For calculating the energy required for the e-buses, we use a model developed internally, where the energy is calculated based on bus weight, loading, route characteristics (hilliness, urban/ highway/ rural), driving behaviour and annual mileage.

A publicly available version of this model, initially developed for electric trucks and the accompanying report may be referenced at Cenex (2024) and Allerton et al. (2024). Some of the original data, showing the truck powertrain efficiency variation with temperature and drive cycle is shown in Figure 2. Equations based on this data were used to construct the energy use based on vehicle mass, temperature and drive cycle.

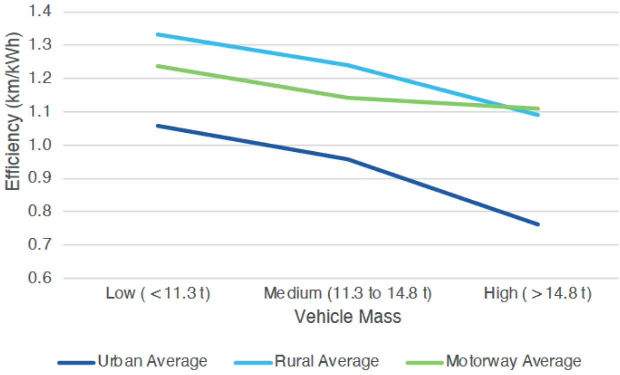


Figure 1: Variation of truck range per unit energy supplied by the battery with vehicle mass

Figure 2: Variation of truck range per unit energy supplied by the battery with temperature

2.3.4 COST OF ELECTRICITY

We use the costs for industrial customers, annually consuming 2000 MWh or more but less than 20000 MWh[4], sourced from Eurostat (2024). Basic calculations suggest annual electricity consumption per bus in the range of 50 MWh to 200 MWh. Thus, for a bus operator with several tens to hundreds of e-buses, this is a suitable category.

These costs, shown in Figure 3, show the split between electricity, taxes and VAT. VAT is a recoverable expense for industrial consumers in all these countries, and is therefore excluded, as in Smith et al. (2024).

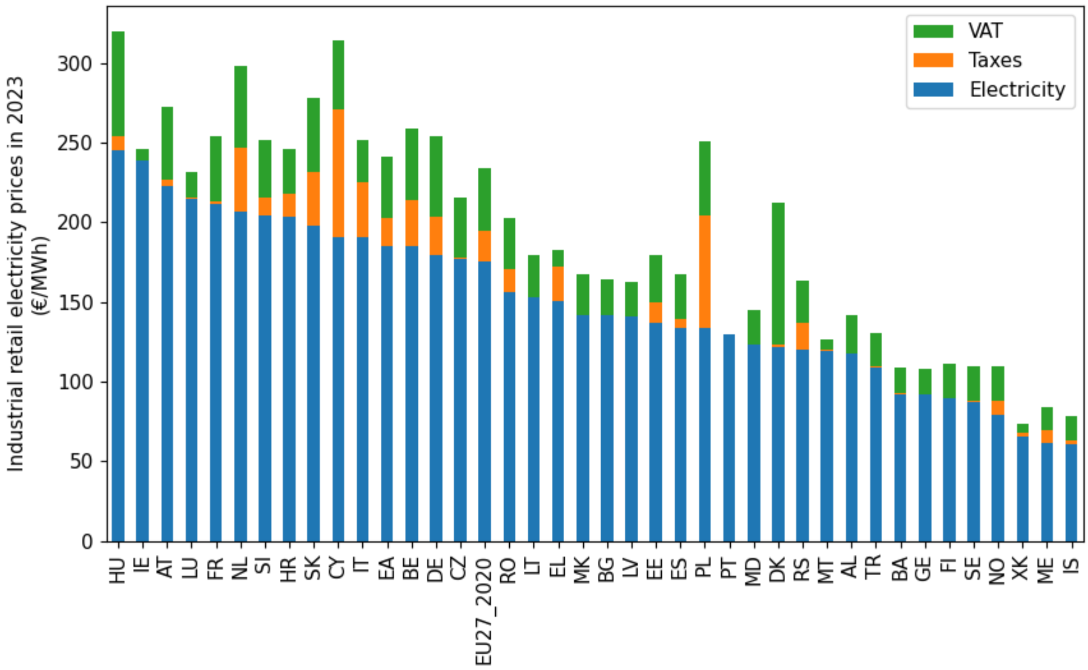


Figure 3: Cost of electricity for industrial customers consuming between 2000 MWh and 20000 MWh in each country within the EU27 in 2023

2.3.5 DISCOUNT RATE

The discount rate, *d*, is used to convert future cash flows into an equivalent present value. It represents the opportunity cost of cash flows at different times. For an upfront cost, the opportunity cost is typically the interest rate offered by a standard savings account or short-term investments.

A historic subset of discount rates for 2023 and 2024 for the countries in which the eBRT2030 demos will take place is shown in Table 4 (European Commission 2024). In the tool, we use the most recent discount rates for mid-2024 reported by the European Commission.

[4] Eurostat band: ID i.e. customers consuming between 2000 MWh and 20000 MWh annually

Table 4: Discount rates in the eBRT2030 demo countries as of mid-2024

From	To	CZ	EL	ES	IT	NL
1.7.2024	31.08.2024	4,68	4,11	4,11	4,11	4,11
1.4.2024	30.06.2024	5.56	4,11	4,11	4,11	4,11
1.1.2024	31.3.2024	6,64	4,11	4,11	4,11	4,11
1.11.2023	31.12.2023	7,43	3,64	3,64	3,64	3,64
1.9.2023	31.10.2023	7,43	3,64	3,64	3,64	3,64
1.8.2023	31.8.2023	7,43	3,64	3,64	3,64	3,64
1.7.2023	31.7.2023	7,43	3,64	3,64	3,64	3,64
1.6.2023	30.6.2023	7,43	3,64	3,64	3,64	3,64
1.5.2023	31.5.2023	7,43	3,06	3,06	3,06	3,06
1.4.2023	30.4.2023	7,43	3,06	3,06	3,06	3,06
1.3.2023	31.3.2023	7,43	3,06	3,06	3,06	3,06
1.2.2023	28.2.2023	7,43	2,56	2,56	2,56	2,56
1.1.2023	31.1.2023	7,43	2,56	2,56	2,56	2,56

2.3.6 FINANCING AND LOAN REPAYMENT

If a loan is used to finance the vehicle purchase, the cost to the borrower is the cost of loan repayment. In case the discount rate is lower than the interest rate on the loan, it may be advantageous to finance the loan. However, interest rates on loans are typically higher than discount rates.

The costs of loan repayment assuming monthly cashflows are calculated as follows:

$$\text{Monthly loan repayment} = Vehicle\ \text{cost} \times \frac{r \times (1 + r)^p}{(1 + r)^p - 1}$$

where *r* is the monthly interest rate, which is 1/12th of the annual percentage interest rate,
p is the loan term in months, and
vehicle cost is the cost for the initial purchase of the vehicle from which the residual value of the vehicle at the end of the analysis timeframe is deducted.

A default down payment of 12% is assumed in case of financing e-bus purchase through a loan. All payments except the down payment need to be discounted to present value using the discounting factor.

2.3.7 ADJUSTMENT FOR INFLATION

The inflation rate describes the rise in prices over time and the corresponding fall in the purchasing power of a given currency. For this tool, we consider the base year to be 2023, the last year for which we have complete data. Thus, all future cashflows are converted to 2023-equivalents.

Due to inflation, future cashflows in currency amounts which are actually spent (nominal values) are adjusted to 2023-equivalent value of currency in terms of the purchasing power equivalence based on the expected interest rate, *i*.

For bus operations, the majority of costs are expected to be related to electricity[5] (Potkány et al. 2018). Electricity prices in Europe differ considerably across the different countries in Europe, each of which has a different generation mix, trading partners and seasonality. Further, the electricity prices in Europe are also subject to price shocks from events such as the Russia-Ukraine war.

Figure 4 shows the average national price in Euro per kWh without taxes for medium size industrial consumers (Eurostat 2024), the expected customer category for bus operators. The large relative difference in costs across the countries as well as the large increases in 2022 are seen. Similar price changes in the future 15 years over the bus lifetime are largely unpredictable.

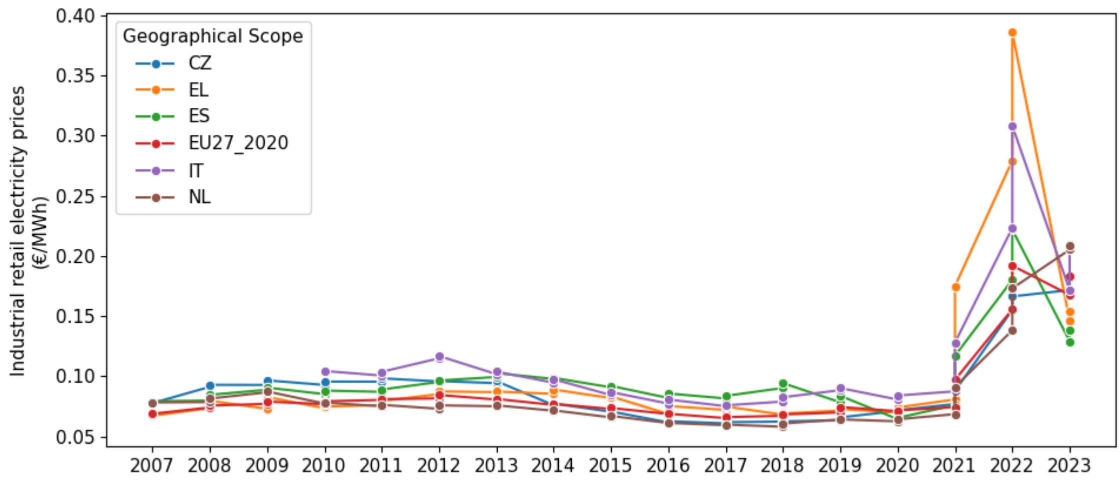


Figure 4: Cost of electricity in the countries where the different eBRT demos are located

Note: CZ – Czechia, EL – Greece, ES- Spain, EU27_2020 includes the UK in the EU28 until 2020 and neglects the UK after 2020, IT- Italy, NL – the Netherlands.

In this study, we take a simplified approach. A European Commission 2023 study on energy costs throughout the EU27 shows that electricity prices for industrial customers has increased at an average rate of 2% per year in the pre-war decade, from 96 €/MWh in 2010 to 124

[5] This assumes the exclusion of labour costs from the scope, refer Section 2.2: TCO Scope.

€/MWh in 2021 (Smith et al. 2024, 35). The data is shown in Figure 5. We assume this rate of increase in prices to be extrapolated to the future, subject to discounting to present value.

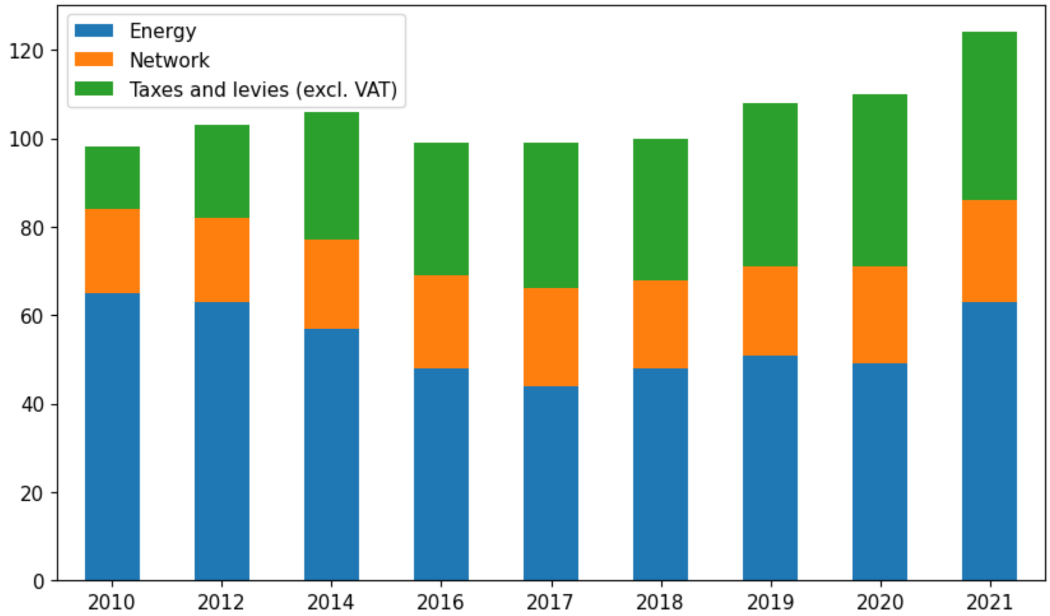


Figure 5: Cost of electricity for industrial customers in the EU

Further, the prices for industrial consumers have been converging over time as a result of the greater integration of wholesale markets, international competition and trading across borders. Though there still remain significant price differences between countries, with German prices far exceeding French ones (see Figure 3), we take the standard 2% increase per year across all countries in this study, neglecting individual variations in rate of change of electricity prices over time.

2.3.8 VEHICLE DEPRECIATION, BATTERY SALVAGE AND SCRAPPAGE

In treatment of the vehicle depreciation, salvage value of batteries for repurposing and scrap value of the buses, we follow methods outlined in (Burnham et al. 2021). Over the e-bus lifecycle, there are three options for an owner who wishes to discontinue the operation of the bus at any given moment:

1) Bus resale: The electric bus is sold for reuse as an e-bus for mobility purposes in another location.
2) Battery salvage: The vehicle body is scrapped, and the batteries reach their end-of-first-life, with around 80% state-of-health[6]. These batteries still have some value and

[6] While the 80% limit in battery state-of-health is commonly considered in academic works, in actual operations, the state-of-health is difficult to measure with certainty and can be improved through cell-level diagnosis and replacement or better battery management systems (BMS). Several innovative providers of battery monitoring systems have emerged (Volytica, Twaice, Voltaiq, etc.) to optimise battery performance through rapid diagnostics, corrective maintenance, predictive maintenance, thereby extending battery lifetime and reducing the TCO.

can be sold independent of the vehicle body for repurposing or remanufacturing for second lifetime.

3) Scrappage: The bus including its batteries are scrapped. The batteries are expected to be recycled, as per the European Battery Directive (European Parliament 2023).

Figure 6 shows the trend in market value of the three options over the vehicle lifetime. The solid lines show the highest value option at any given moment, while the dotted lines show the other values.

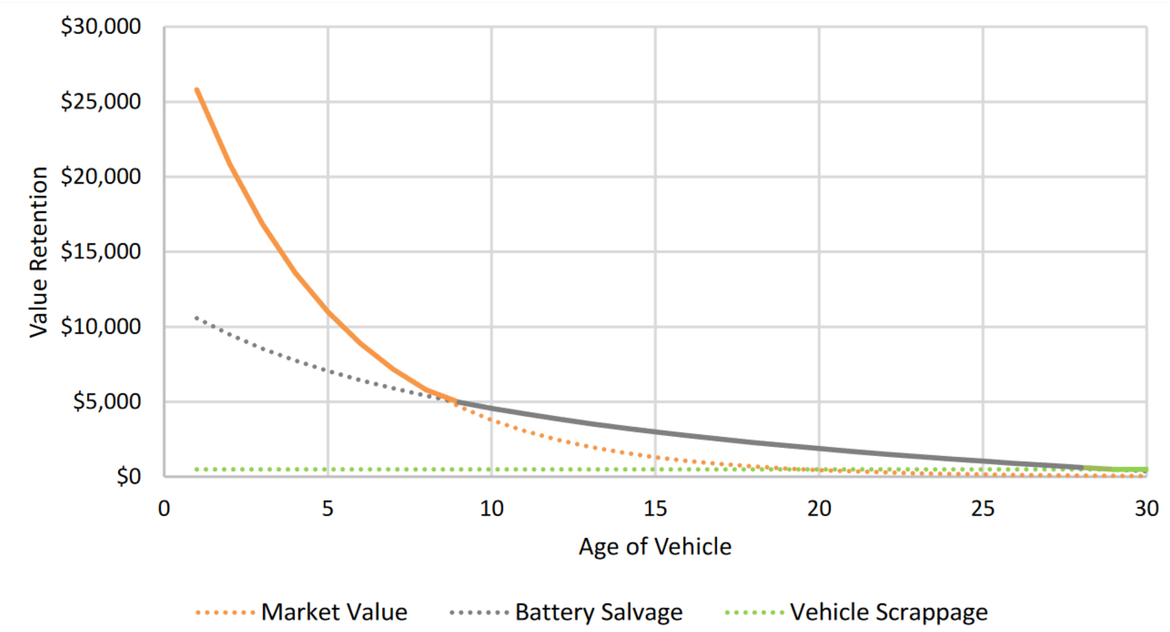


Figure 6: Changes in market value of an electric bus for resale as a bus, battery salvage and vehicle scrappage

Note: The numbers shown, related to passenger vehicles in the USA [Source: (Burnham et al. 2021)], are only for illustrative purposes. The orange line shows the resale value as a bus, the grey line shows the battery salvage value while the green line shows the scrap value. The highest value option for disposing of the bus at any given moment is shown as a solid line, while the dotted lines show the other options.

For most of the first decade of use, the bus is expected to have highest end-of-first-life value as a bus. After a certain period, in this figure shown around year 8, the resale value of the bus decreases below the salvage value of the batteries. Thus, the most profitable option is selling the batteries independently. This position remains for the rest of the vehicle life over which the battery salvage value keeps declining until the point where the only value is the scrap value of the materials. However, this point is well beyond the vehicle lifetime of 15 to 20 years, suggesting that in most cases when vehicles are used for 15 to 20 years, salvaging value from the batteries is the best option for bus operators. In this study, given the long periods of bus ownership by the first owner/operator, we mainly consider the salvage value of the battery as the end-of-first-life option. Bus resale for re-use in mobility are not explicitly considered, though the tool includes the option of adding a value by the user.

While this outlook on battery second lifetime remains promising from a circular economy perspective, the scale at which demand for new batteries is growing is leading to very low future battery prices. Figure 7 shows the historic decline in lithium ion battery prices between 2013 and 2023 covering batteries for passenger vehicles, buses and stationary storage (Catsaros 2023).

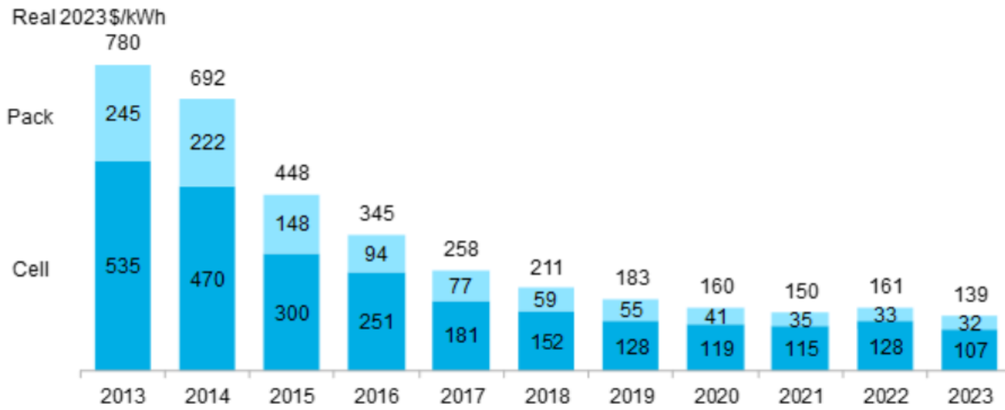


Figure 7: Battery prices at the cell and pack level in the decade from 2013 to 2023

Battery prices are expected to drop further in the future (Kuhn, Bubna, and Anculle 2021), with several forecasted trends shown in Figure 8. These include forecasts for battery packs from Bloomberg New Energy Finance (BNEF), IHS Markit (now part of S&P Global) and the UK's Advanced Propulsion Centre (APC).

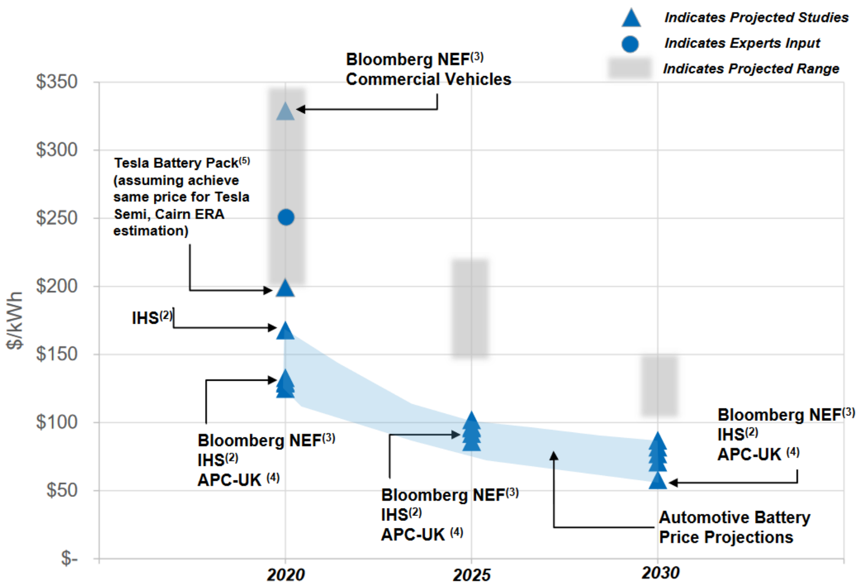


Figure 8: Battery pack price forecasts

Note: (1) Ricardo analysis, (2) IHS Next Generation Battery Technologies and Market Trends NAATBatt Annual Conference 9 February 2021, (3) Passenger Electric Vehicle Outlook, NaatBatt 2021, February 2021, (4) APC UK Electrical Energy Storage Roadmap 2020, (5) Cairn ERA estimation

$187/kWh, https://www.cnbc.com/2021/03/10/teslas-lead-in-batteries-will-last-through-decade-while-gm-closes-in-.html

On comparing, the initial period of the forecast (2021 to 2023), we see that the battery pack prices are dropping fast, close to the lower limits of the Automotive Battery Price Projections, shown in light blue. For this reason, we choose the APC battery price forecasts in this study (Greenwood 2021).

Following Burnham et al. (2021), we calculate the battery salvage value at end-of-life as:

$$V_{salvage} = (1 - K_r - K_u)(1 - K_h) \times C_{new} \times F_{RPE}$$

where $V_{salvage}$ is the salvage value of the battery pack,
K_r is the refurbishment cost factor of 15%,
K_u is the used product discount factor of 15%,
K_h is the battery health factor, beginning with 0% in the first year and increasing by 3% per year,
C_{new} is the cost per usable kWh of battery pack capacity for a new battery in the year the pack is salvaged, sourced from (Greenwood 2021), and
F_{RPE} is the ratio of the retail price to manufacturing cost, taken as 1.5 retail price equivalent.

Details on the original model for salvage value of the battery pack may be referenced at Neubauer and Pesaran (2010).

2.4 TCO AND CASH FLOW CURVES

Finally, the total cost of ownership (TCO) of e-buses purchased are presented both as net present value (NPV) and as a cash flow curve, over the lifetime of the bus (with a default value of 15 years). An example of such a cash flow curve is shown in Figure 9. The down payment in the first year, the repayment of the loan used to finance the vehicle purchase in 5 years, the annual payments for electricity, operation and maintenance (O&M) over the 15-year vehicle lifecycle and the final scrap value through vehicle sale are all marked.

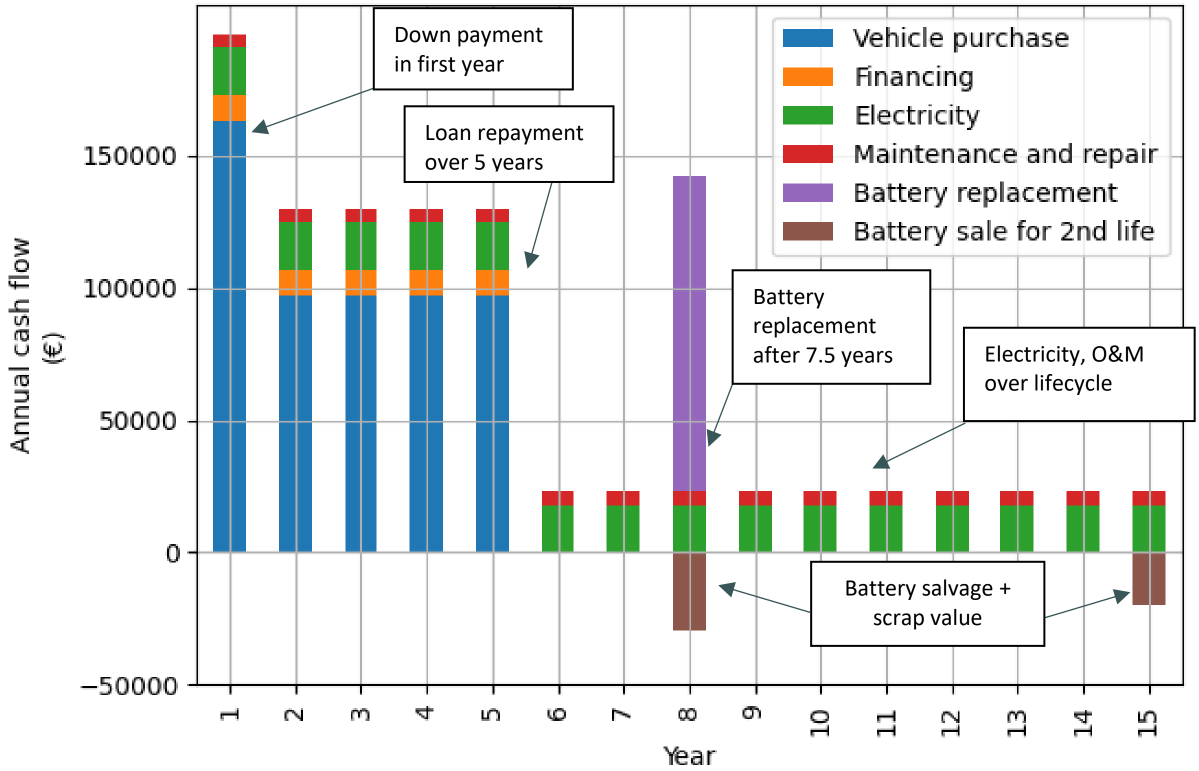


Figure 9: Illustrative example of an annual cash flow curve for a single electric bus

As shown in the example in Figure 9, the down payment results in larger outward cash flow (shown as positive) in the first year. The financing loan is paid off over a 5-year period, with payment for both the vehicle (in blue) and the interest associated with the loan (in orange). Throughout the entire lifecycle, there are payments for electricity (in green) and maintenance and repair (in red). In the 15th year, the batteries are sold for salvage value while the vehicle body is scrapped, leading to revenue (shown as negative).

The values of the cash flow from the cash flow curve, or their conversion through discounting to a net present value represent the total cost of ownership of the tool. For PTOs or private fleet operators, this information when combined with revenue streams provides the business case for a bus or the entire fleet. Assuming that out-of-scope costs such as insurance and labour, as well as ticket and non-ticket based revenues do not change with electrification of buses, the TCO as calculated in this tool provides key financial information on the costs of electrification of bus fleets.

3 GHG EMISSION REDUCTION THROUGH ELECTRIC BUSES

The scope of the tool is not a complete lifecycle assessment (LCA), but is limited in scope to greenhouse gases (GHGs) which contribute to climate change and air pollution caused by vehicle exhaust. A comprehensive LCA of buses would need inputs that vary and are specific per bus, per usage and country of deployment. This information is yet unavailable at this stage of the project.

Further, a comprehensive LCA covers many aspects of e-buses which are out of scope of actionable decision-making by Public Trasport Authorities (PTAs) and Public Transport Operators (PTOs), such as the manufacturing phase and regional electricity generation. To make the insight provided by the tool concrete, specific and actionable, the LCA was reduced in scope to the tank-to-wheel (TTW) emission reduction and air pollution reduction.

The GHG emission reduction calculated in the second tool describes one aspect of the environmental impacts of the electric buses – Tank to Wheel greenhouse gas reductions. These are the emissions released at the tailpipe during operation of the vehicle.

3.1 SCOPE OF GHG EMISSION REDUCTION OF ELECTRIC BUSES

The reduction in greenhouse gas (GHG) emissions attributed to electric buses is expressed as a comparison with the buses they are expected to substitute – diesel buses of a similar size.

Within greenhouse gas emissions, a comprehensive approach would consider the well-to-wheel (WTW) emissions i.e. the emissions involved in the production of fuel and its delivery to the vehicle (well-to-tank emissions) and use in operation (tank-to-wheel or tailpipe emissions). As a reference, the representative well-to-wheel emission of buses and coaches in the EU are around 80 gCO_2-eq. per passenger-km based on average occupancy rates (European Environment Agency. 2022).

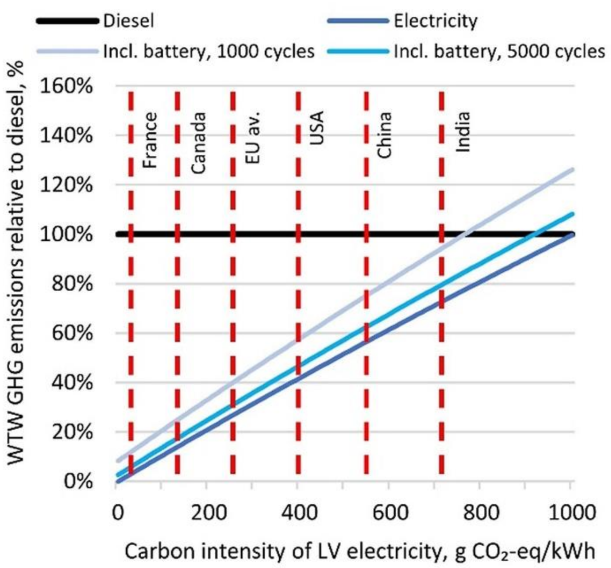


Figure 10: Sensitivity of WTW greenhouse gas emissions associated with suburban bus driving cycles to the carbon intensity of low voltage electricity [Source: Gustafsson et al. 2021]

However, the well-to-wheel emissions are highly sensitive to the carbon intensity of electricity used for charging and therefore to the location (Gustafsson et al. 2021). With the mix of electricity sources within the 6 countries in the eBRT2030 project differing from each other and also expected to change over the coming years, the estimation of emission factors associated with carbon intensity of electricity in each country's electricity grid is complex to calculate and also subject to considerable uncertainty. Further, since the geographical focus of this tool is the cities where the buses run, rather than the powerplants where the electricity is generated, the scope of this tool is limited to tank-to-wheel (TTW) or tailpipe emissions.

The results of the greenhouse gas emissions calculated by this tool should therefore be interpreted with the caveat that they do not represent a comprehensive overview of the lifecycle of the vehicles under consideration, but only the tank-to-wheel phase. This is particularly important to note for the comparison between electric and fossil-based drivetrain.

As shown in Figure 10, the well-to-wheel (WTW) emissions associated with suburban bus driving cycles are between around 25 to 40% of similar diesel powered drive cycles (Gustafsson et al. 2021). On comparison with diesel, electric drive has lower emissions on average throughout most place in the world – only the extent varies with location. Figure 11 shows the ratio of diesel and non-diesel buses in the different eBRT demonstrators' countries as well as in the EU.

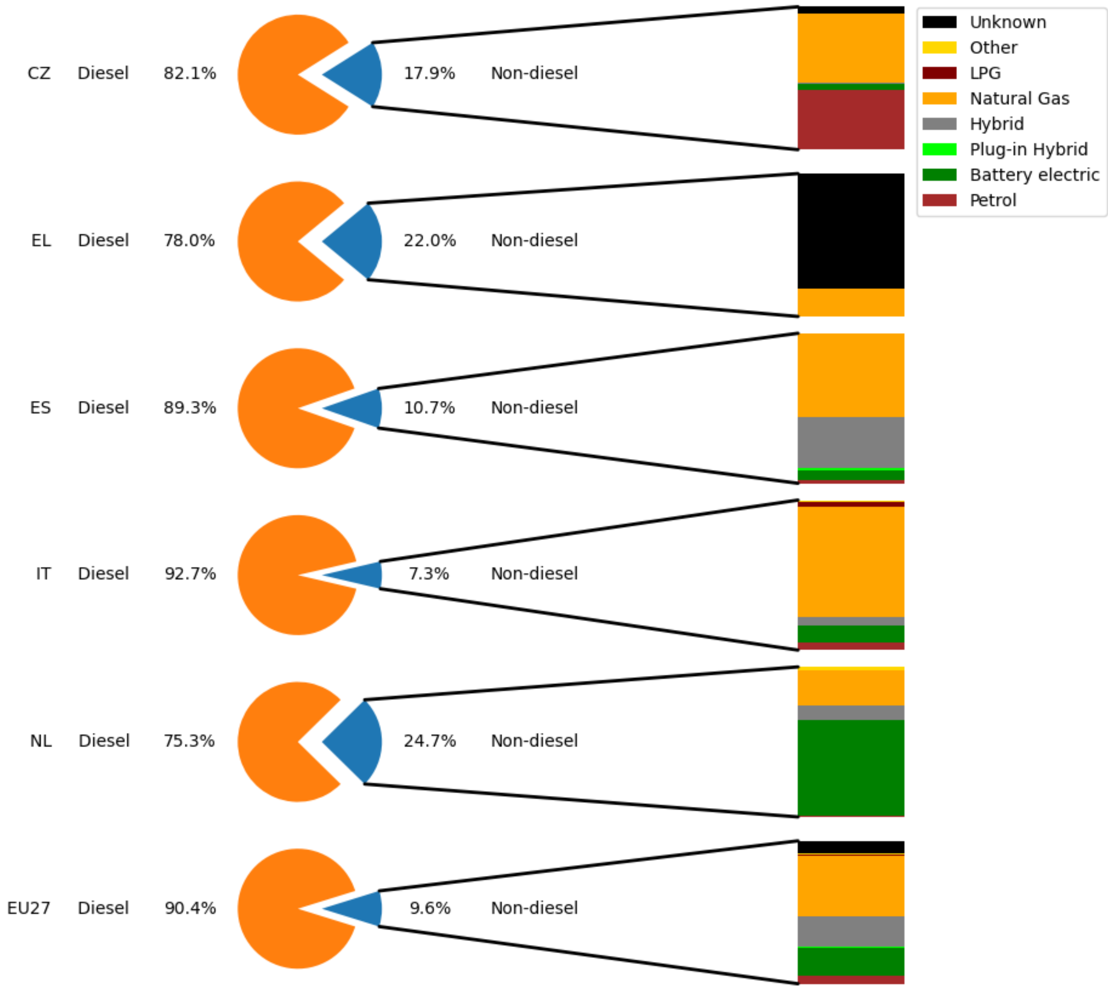


Figure 11: Share of diesel and non-diesel powered buses in the eBRT2030 demonstrator countries and the EU27 in 2022 [based on data from (ACEA 2024)]

It is clear from Figure 11 that the majority of existing buses in operation are powered by diesel, with over 75% of buses powered by diesel in each of the countries (CZ, EL, ES, IT and NL) and over 90% at the EU level. In this report, we therefore focus on diesel substitution. This tool aims to provide an extent of GHG emission reduction at the tailpipe through the transition from diesel to electric buses.

3.2 METHODOLOGY

The Tank-to-Wheel (TTW) emissions reported are based on a simplified version of the VECTO tool. These are the emissions released at the tailpipe during operation of the vehicle, reported in gCO_2/km. These emissions therefore neglect any emissions during maintenance conducted during the operational phase but are restricted to the emissions resulting from fuel combustion within the vehicle.

VECTO is the EU recommended simulation tool for the determination of the CO_2 emissions and fuel consumption of heavy-duty vehicles as required for certification under regulation 2017/2400 (European Parliament 2017). The values per vehicle are also monitored and publicly reported as per EU regulation 2018/956 (European Environment Agency 2024).

The CO_2 emission factor, *C*, calculated over a given drive cycle in g/km are given by the general equation (Broekaert, Bitsanis, and Fontaras 2021):

$$C = a_0 + a_1 \frac{Cd \times A}{\eta} + a_2 \frac{m}{\eta} + a_3 \frac{m.RRC}{\eta} + a_4 \frac{Cd \times A.m}{\eta} + a_5 P_{aux}$$

where C_d is the unitless drag coefficient and *A* is the area, with the combined term $Cd \times A$ representing the air drag in m^2,

η is the unitless drivetrain efficiency,

m is the total vehicle mass in tons,

RRC is the unitless tire rolling resistance coefficient,

P_{aux} is the mechanical power for the auxiliary systems in kW,

and the terms a_0, a_1, a_2, a_3, a_4 and a_5 represent a set of model coefficients for the bus for each of the following drive cycles: interurban, suburban, urban and heavy urban.

Running full VECTO simulations requires complex input data, such as gearbox efficiency maps which are neither publicly available nor easily accessible. The use of this simplified model reduces the data requirement to that which is available in the bus technical specifications and route data, while still providing highly correlated results with a full VECTO simulation (Broekaert, Bitsanis, and Fontaras 2021). This is the reason why this simplified approach has been chosen.

The parameter values used for different buses are provided in Table 5.

Table 5: Parameters for calculating CO2 emissions of buses in a simplified VECTO model

Parameter	Symbol	Value				
Air drag [m^2]	$Cd \times A$	3.5	4.5	5.5	6.5	7.5
Curb mass [tons]	m	8	12	16	20	20
Drivetrain efficiency [%]	η	95	97	97	99	99
Rolling Resistance Coefficient	RRC	0.0035	0.0055	0.0055	0.0075	0.0075
HVAC configuration	HVAC	1	3	3	6	6

The Heating Ventilation and Air Conditioning (HVAC) configuration is a function of vehicle mass, as shown above. The designated meaning of each HVAC configuration is provided in Table 6.

Table 6: HVAC configurations and their meanings

HVAC Configuration	Meaning
1	no thermal comfort system for the passengers and no air conditioning
3	thermal comfort system for the passengers and no air conditioning
6	thermal comfort system for the passengers and air conditioning with 1 air conditioning compressor

The auxiliary power P_{aux} is a function of the HVAC configuration, the loading (or passenger count) and the drive cycle. With the assumption that low floor buses will be used in the eBRT2030 project, the P_{aux} values are given in Table 7.

Table 7: Auxilliary power values as a function of drive cycle, loading and HVAC configuration for low floor buses

Drive cycle	Loading	Passenger count	HVAC Configuration		
			1	3	6
Interurban	low	13.23	6.0	6.4	6.5
	reference	52.92	6.0	6.5	7.0
Suburban	low	14.43	6.1	6.5	6.7
	reference	72.16	6.2	6.7	7.3
Urban	low	14.43	6.1	6.5	6.7
	reference	72.16	6.2	6.7	7.4
Heavy urban	low	14.43	6.2	6.6	6.7
	reference	72.16	6.2	6.8	7.4

The power required to run auxiliary systems cover the following loads:

1. Steering pump: Variable displacement pump with electronic control
2. Engine cooling fan: Hydraulic driven fan by a constant displacement pump
3. Pneumatic system: Large displacement (>500cm3) air supply with 2-stage compressor
4. Door drive: Pneumatic
5. Engine heat recovery
6. Fuel auxiliary heater
7. Light: LED (all)
8. Separate air distribution ducts

Heat pumps are not considered.

The model coefficients for diesel low floor buses for each drive cycle (interurban, suburban, urban and heavy urban) are provided in Table 8.

Table 8: Model coefficient values for diesel low floor buses for calculating CO2 emissions of buses in a simplified VECTO model

Drive cycle	a_0	a_1	a_2	a_3	a_4	a_5
Interurban	51.37	23.22	28.82	1149.55	-0.34	8.97
Suburban	174.81	0	34.45	1183.97	0	6.61
Urban	173.53	0	37.94	1062.9	0	11.83
Heavy urban	223.46	0	46.51	1020.95	0	18.60

3.3 GUIDELINES FOR ELECTRIC BUS SELECTION

For the use of the tool, it is necessary to correctly select the parameters of the bus which is being replaced. Selection of several of these parameters such as HVAC configuration and passenger count are self-explanatory. However, for some parameters, some additional required guidelines are provided below.

3.3.1 SELECTION OF THE AIR DRAG COEFFICIENT

Air drag has a low influence on bus energy consumption at low speeds. For driving cycles with start-stop rather than high speed sections, as in suburban, urban and heavy urban, air drag can be set to a value of around 4.9 (Broekaert, Bitsanis, and Fontaras 2021). For higher speeds, we use a value of 5.3, suggested for VECTO class 5 generic vehicles[7] when used for long haul (average speed of 60km/h) and regional delivery (average speed of 80km/h) (Tansini et al. 2019).

Although bus OEMs are expected to publish the range of $C_d \times A$ values for each certified bus in the European market as part of the European regulation 2018/956, the dataset published in March 2024 (European Environment Agency 2024) does not include these values.

3.3.2 SELECTION OF DRIVETRAIN EFFICIENCY

For accurate estimation of the drivetrain efficiency, further information on losses in the axle, gearbox, clutch operation in manual drive and retarder are needed even for simplified models. Here, we simply use the 75th percentile value reported in (Tansini et al. 2019) for trucks, yielding an efficiency value of around 97%.

[7] The reported value is used for trucks. However, in the absence of better data on buses used for interurban missions, we use the truck value.

3.3.3 SELECTION OF ROLLING RESISTANCE COEFFICIENT

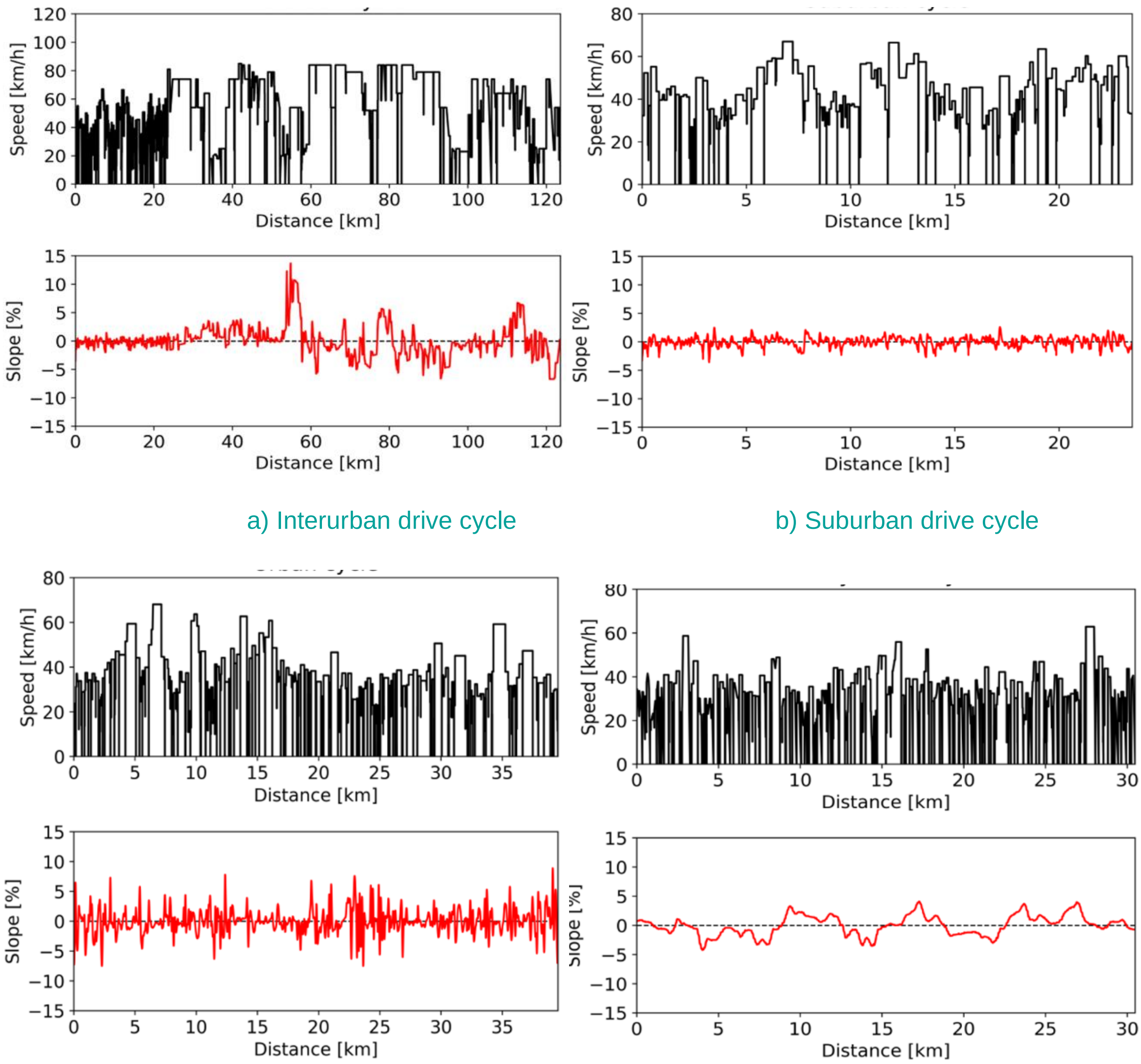
The rolling resistance is based on the tyre selection. M type vehicles (buses) are required to use C3 type tyres. The C3 type tyres are separated into fuel efficiency classes from A to E and labelled accordingly (European Parliament 2020). The rolling resistance coefficient is selected based on the tyre labels on the bus, as shown in

Table 9: Rolling resistance coefficients based on C3 tyre classes

Fuel Efficiency Class	**C3 Tyre Rolling Resistance Coefficient (N/kN)**
A	≤4.0
B	4.1 to 5.0
C	5.1 to 6.0
D	6.1 to 7.0
E	≥ 7.1

3.3.4 SELECTION OF DRIVE CYCLE

The representative drive cycles considered in this work are interurban, suburban, urban and heavy urban. Each drive cycle is characterised by standardise assumptions of slope, speed, start-stop cycles over the route (Broekaert, Bitsanis, and Fontaras 2021). An informed selection can be made by the user by comparing the drive cycles shown below in Figure 12 with the actual routes undertaken by the buses for which the tool is used.



a) Interurban drive cycle b) Suburban drive cycle

c) Urban drive cycle d) Heavy urban drive cycle

Figure 12: Drive cycles for buses

Interurban drive cycles have speeds up to 80 km/h with highway driving for longer distances, over 100 km. There are occasional periods with high slopes, going over 10% gradient. Suburban drive cycles have lower speeds, occasionally reaching speeds higher than 60 km/h and less range of slope distribution. Distances are much shorter than interurban driving distances. Urban drive cycles have similar maximum but lower average speeds as suburban drive cycles, but more frequent braking and start-stop cycling. Urban slopes are more widely distributed than suburban ones. Heavy urban drive cycles are characterised by extremely frequent start-stop cycles and the shortest driven distances, with few changes in slope in densely packed urban areas.

Basic knowledge of the bus routes is expected to be sufficient for users to make choice of which drive cycle is most suitable. For the selected drive cycle, the passenger loading and HVAC configuration, the auxiliary power from Table 7 can be selected while the selected drive cycle is sufficient for selecting the model coefficients from Table 8.

4 AIR POLLUTION REDUCTION THROUGH ELECTRIC BUSES

The third tool describes another aspect of the environmental impacts of the electric buses additional and distinct from greenhouse gas emissions: contribution to air pollution.

4.1 SCOPE OF AIR POLLUTION REDUCTION

The purpose of the air pollution tool is to estimate the reduction in air pollution of electric buses in comparison with the buses they are expected to substitute – diesel buses of a similar size.

As a broader concept, air pollution covers ozone precursors, acidifying substances, greenhouse gases, particulate matter and heavy metals among others. Within air pollution, particulate matter with diameter of 2.5 micrometre or smaller ($PM_{2.5}$) and nitrogen oxide (NO_x) emissions were the categories that caused the highest mortality (premature deaths) in Europe (European Environmental Agency 2023). Heavy duty vehicles running on fossil fuels contribute a large fraction of these pollutants. Hence, electrification of these vehicles has the largest health benefits in these categories.

For this reason, in this study, we limit our scope within air pollution to $PM_{2.5}$ and NO_x emissions. Only exhaust-based emissions are considered. Non-exhaust emissions such as evaporation of fuel from vehicles, brake and tyre wear and road wear are not considered. Non-exhaust emissions remain with the use of electric vehicles, and any change in these emissions as compared with diesel drive are not considered here[8].

For this study, we use definition and methods from the COPERT Guidebook - version 5.7 (Ntziachristos and Samaras 2023), which is the EU's standard vehicle emissions calculator.

4.1.1 $PM_{2.5}$ EMISSIONS

Particulate matter refers to fine inhalable particles where the diameter of each particle is 2.5 micrometres and smaller. Coarser fractions (PM2.5-10) are negligible in vehicular exhaust (ibid., p.3) and are not considered in this report. The values reported are the mass of particles collected on a filter kept below 52℃ during diluted exhaust sampling. This corresponds to total (filterable and condensable) $PM_{2.5}$.

4.1.2 NO_X EMISSIONS

The NO_x emissions cover nitric oxide (NO) and nitrogen dioxide (NO_2) and are reported as NO_2 equivalent mass.

[8] For a detailed and up-to-date report on the contribution of brake emissions at bus depots, refer the Horizon2020 funded AeroSolfD project report (Moreno et al. 2024).

4.2 METHODOLOGY

The methods used here are derived from the COPERT Guidebook - version 5.7, which is the EU standard vehicle emissions calculator. It is globally recognised, used by many European countries for official reporting, peer reviewed and openly accessible. For further elaboration, the original guidebook can be referenced (Ntziachristos and Samaras 2023). This methodology calculates emissions and pollution based on estimations of the type and quantity of fuel consumed by standardised vehicle categories.

Within the COPERT framework for calculation of air pollution from road transport, there are several methodologies which can be applied depending data availability. The decision tree for choosing such the suitable methodology is shown in Figure 13.

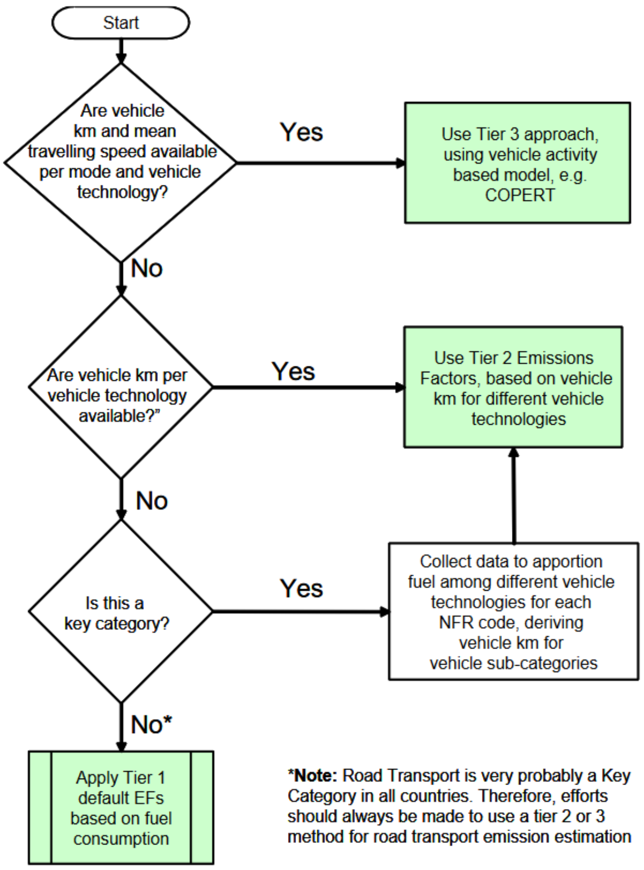


Figure 13: Decision tree for choosing a method for calculating emissions from road transport

Within the eBRT2030 project, where the method is applied to prospective bus routes to be deployed at a later stage in the project, there is currently no measured data on the vehicle kilometres driven and mean travelling speed.

At this stage, the number of buses and their vehicle category are known, along with an estimate of the kilometres that they will drive in anticipated operation. For this reason, the Tier 2 emission factors are used. These Tier 2 emissions factors are provided in units of grammes per vehicle-kilometre for each vehicle technology.

4.2.1 BUS FLEET-LEVEL CALCULATION

The general formula used for calculation of annual air pollution of type *p* through the COPERT Tier 2 method is:

$$E_p = \sum_{i=1}^{n} (M \times EF_p)$$

where *n* is the total number of buses of the technology/ powertrain under consideration,
i is the index of any given bus ranging from 1 to *n*,
M is the average annual distance driven per vehicle (in km/vehicle), and
EF_p is the technology-specific emission factor of pollutant *p* for the bus.

4.2.2 TECHNOLOGY SPECIFIC EMISSION FACTORS

We compare e-buses with diesel buses, which can use various types of fuels based on the Euro standards. The diesel VI D/E is the latest diesel standard with vehicles already on the road. We aim to compare e-buses with the technology which a new diesel bus would use rather than older diesel technologies, and therefore use diesel VI D/E as the diesel benchmark.

New legislation is expected to be passed in Q2 2024, pushing for more stringent Euro VII standards for M3 vehicles. Four years after publication (2028), this will apply to all new M3 vehicle models while 5 years after publication (expected 2029), this will apply to all vehicle models. The timeline for Euro VII is beyond the eBRT2030 timeline, and therefore not considered here.

The emission factors presented in Table 10 are calculated using typical values for driving speeds, ambient temperatures, highway-rural-urban mode mix, trip length, etc. for buses in Europe.

Table 10: Bus emission factors for diesel Euro VI D/E fuel based on COPERT Tier 2 methods

Vehicle category	NO_x (gNO_2-eq/km)	$PM_{2.5}$ (g/km)
Bus (M3): vehicles used for the carriage of passengers, comprising more than eight seats in addition to the driver's seat, and having a maximum weight over 5 tonnes.	1.5[9]	0.0023[10]

[9] (Ntziachristos and Samaras 2023, tbl. Table 3-23: Tier 2 exhaust emission factors for buses, NFR 1.A.3.b.iii)
[10] (Ntziachristos and Samaras 2023, tbl. Table 3-24: Tier 2 exhaust emission factors for buses, NFR 1.A.3.b.iii)

5 SOCIETAL OPTIMISATION INDEX (SOI) OF EBRT2030 INNOVATIONS

This chapter discusses the societal optimisation of the eBRT2030 innovations, utilising the Societal Optimisation Index (SOI). It provides a first mapping of the social risks and benefits related to the eBRT2030 innovations and the methodology for the identification of their social effectiveness. Under a multi-criteria approach, based on stakeholders and experts' opinions, the methods and tools presented in the following sections are proposed to be applied under WP3 activities, so that eventually the eBRT2030 innovations can be ranked according to their social effectiveness. The social effectiveness reflects the level of which the eBRT2030 innovations fulfil citizens' demands; the better the quality, the more socially effective the innovations are (Vasilev, 1997). The SOI will identify the most "socially ineffective innovation" performances, thus allowing for further discussion taking place during the project to address them (i.e. through a set of recommendations).

5.1 INTRODUCTION

For many years, the most common form of evaluation in transport-related decisions was the cost-effectiveness analysis (CEA), according to which the cost of alternative ways of providing similar kinds of output are compared. Any differences in output are compared subjectively with the differences in costs. Furthermore, still widely used is the method of cost–benefit analysis (CBA), which is based on the calculation of the total cost of the examined project on one hand and benefits on the other. Both these methods (CEA and CBA) are analytical ways of comparing different forms of input or output, in these cases by giving them monetary values, and might themselves be regarded as examples of multicriteria analysis (MCA) (Department for Communities and Local Government 2009). However, CEA and CBA methods have certain limitations, mostly related to the fact that many impacts due to their nature (such as social, health, safety) cannot objectively be quantified in monetary terms (Yannis et al. 2020).

Due to this limitation and given that the transport infrastructure planning problems can be characterised as structured problems, they can be analysed using multicriteria decision analysis (MCDA) methods. The MCDA methodology is considered the most appropriate method for evaluating various measures and/or projects. Used by many cities during a series of workshops, the MCDA enables the selection of the most significant ones, by considering their impact and effect on different social aspects.

Multi-Criteria Decision-Making (MCDM) techniques are increasingly used nowadays in transport-related decision-making, offering the following benefits (Sałabun, et al., 2010).

- leads to better-considered, justifiable, explained and transparent decisions once it allows the often conflicting and contradictory views to be addressed simultaneously and transparently;
- helps to organise, manage and in many ways simplify the immense amount of technical information and data, which is often available in transport sector problems;

- The process can be fully controlled: scores and weights are given based on established techniques, the values may also be cross-referenced to other sources of information and the possibility for modifications at a further stage is given, in case the decision model, the options considered, or the data provided are not adequate.

The AHP method (Analytic Hierarchy Process) is the most frequently used compared to other MCDA methods (Beria, Maltese, and Mariotti 2012; Khaki and Shafiyi 2011; Tudela, Akiki, and Cisternas 2006). More often used MCDA methods are the PROMETHEE, SAW (Simple Additive Weighting), and then ELECTRE (ELimination Et Choice Translating REality), ANP (Analytic Network Process), REGIME, MAUT (Multiple Attribute Utility Theory) and TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) (Basbas and Makridakis 2007).

The comparison of the different MCDM methods revealed that when choosing the MCDA method, not only the method itself but also the method of normalisation and other parameters should be carefully selected. Almost every combination of the method and its parameters yields different results (J. P. Brans, Mareschal, and Vincke 1984).

The use of the MCDM methodology for understanding the societal implications of the eBRT innovations, thus supporting the planning and development of more socially effective systmes in the real-world, is a challenging case. First a detailed analysis of the technological innovations should take place, to explore the social risks and benefits behind them. Then, the importance rate of each risk and benefit should be calculated, merging the opinions of all the relevant stakeholders and experts. Based on the results of these steps, the multicriteria analysis will take place, ranking the innovative technologies according to their social effectiveness.

For implementing the MDCM for the eBRT2030 innovations and evaluating them according to their effects on societal optimisation, a comprehensive methodological framework was developed and proposed. The next section presents the methods and tools that were used for formulating the framework. The rest of the chapter is structured as follows; firstly, the Promeethee method for formulating and implementing the methodological framework is analysed; next, the 6-step evaluation framework is established; and finally, the framework application and the interlinks with other activities are presented.

5.2 THE PROMETHEE METHOD

PROMETHEE has been chosen as the most appropriate method to formulate and implement the methodological framework for ranking sustainable mobility measures and improve decision-making in the sustainable urban mobility planning process.

The preference ranking organisation method for enrichment of evaluations (PROMETHEE) method, which is used for the current work, belongs to the outranking family of MCDA methods and is developed by Brans et al. (J. P. Brans, Mareschal, and Vincke 1984) and Brans and Vincke (J. P. Brans and Vincke 1985). The method has been later complemented by geometrical analysis for interactive aid (GAIA), an attempt to represent the decision problem graphically in a two-dimensional plane. This interactive visual module can assist in complicated decision problems.

PROMETHEE results in a ranking of actions (as the alternatives are known in the method's terminology) and is based on preference degrees. Briefly, steps include the following:

- the pairwise comparison of actions on each criterion,
- the computation of unicriterion flows,
- finally, the aggregation of the latter into global flows.

It has been applied successfully in various application areas, including nuclear waste management, the productivity of agricultural regions, risk assessment, web site evaluation, renewable energy, environmental assessment, selection of contract type and project designer.

According to Brans and Mareschal (J. Brans and Mareschal 2005), PROMETHEE is designed to tackle multicriteria problems when a set of possible alternatives {a1, a2, · · · , am} are available in a decision-making process. PROMETHEE uses functions to represent a set of evaluation criteria {g1(·), g2(·),· · · , gn(·)}, and assigns weights {w1, w2, …, w_n) to each of the criteria. The objective to maximize or minimize the values obtained from these criteria. For doing so, the decision-maker need to construct the evalution table as in Table 10 below. Table 11

Table 11: Evaluation table for decision maker as part of the PROMETHEE method

a g1(·) g2(·) · · · gn(·)
w1 w2 · · · wn
a1 g1(a1) g2(a1) · · · gn(a1)
a2 g1(a2) g2(a2) · · · gn(a2)
…
am g1(am) g2(am) · · · gn(am)

It must be pointed out that MCDA techniques generally place the decision-makers in the centre of the process. Different decision-makers can model the problem in different ways, according to their preferences (it also must be mentioned here that the methods assist the decision-maker, they do not make the final decision for them; thus, the word "aid" in the later complemented GAIA acronym. The responsibility for the final decision rests with the decision-maker alone). In PROMETHEE, a preference degree is an expression of how one action is preferred against another action. For small deviations among the evaluations of a pair of criteria, the decision-maker can allocate a small preference; if the deviation can be considered negligible, then this can be modelled in PROMETHEE too. The exact opposite stands for large deviations where the decision-maker must allocate a large preference of one action over the other; if the deviation exceeds a certain value set by the decision-maker, then there is an absolute preference of one action over the other. This preference degree is always a real number between 0 and 1.

5.3 A SIX-STEP EVALUATION FRAMEWORK

The framework for calculating the Societal Optimisation Index (SOI) of the innovations that will be developed and implemented during the eBRT2030 project, was formulated as a six-step methodology, shown in Figure 14.

STEP 1. As a first step, the eBRT2030 innovations were analytically reviewed by CERTH to produce a **draft list** of expected social risks and benefits related to them. The validation and finalisation of the list will be carried out by the project's technical and social partners. Table 12 presents the eBRT2030 innovations, based on the eBRT2030 deliverable 2.2, *"Requirements of innovative eBRT systems"* (Stanje, 2023) and the innovation clusters defined in the project. The preliminary analysis of the social risks and benefits and their correlation to eBRT2030 innovations is given in Table 13.

STEP 2. As a second step, weights in each one of the social parameters (risks and benefits) will be assigned. A group of experts from the project's Advisory Board and the SSH community will assign specific weights to the social risk or benefit parameters as regards their importance and influence in achieving the operation of an innovative but also socially effective eBRT system. Their input will be analysed and the mean weights for each parameter will be calculated and used for the multicriteria analysis.

STEP 3. The matrix of innovations/social risks & benefits will be then sent to the eBRT2030 local ecosystems for final evaluation (third step). At least ten experts of each pilot case will be selected to share their experience and give specific rate (1-5) to the risks and benefits of the installed innovations. The local group of experts will include representatives of the:

- Municipalities' (technical departments)
- Public transport (eBRT) system operators,
- Suppliers of the technological innovations,
- Social community experts
- Citizens' groups/ representatives, including European citizens' associations (i.e. European Passenger Federation, European Cyclist Federation).

The eBRT local ecosystems will declare the way that each one of the innovations can affect the specific social parameter (risk and benefit) giving a score between 1-5 (1=limited effect, 5=high effect).

STEPS 4 AND 5. After the collection of the relevant evaluation forms, a separate multicriteria analysis will take place ranking the different innovations according to the social risks (fourth step) and benefits (fifth step) that they can bring.

STEP 6. Finally, as a last step of the procedure (sixth step), a combined analysis will take place calculating the societal optimisation index of each innovation and the final ranking of them according to this index.

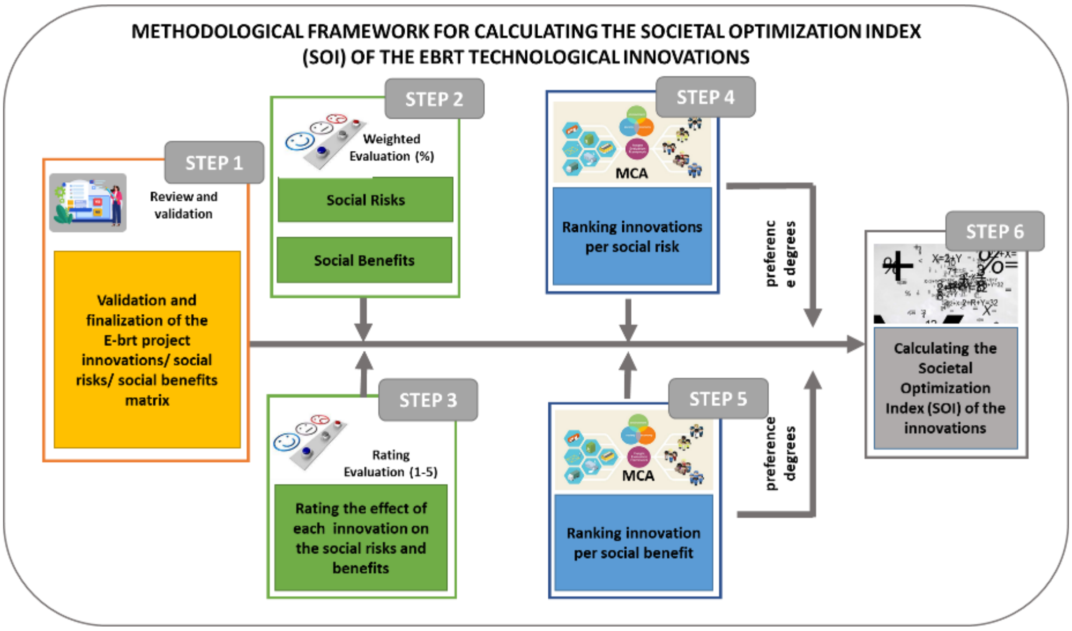


Figure 14: Methodological framework for calculating the societal optimization index of the eBRT technological innovations

Table 12: List of eBRT innovations

ID*	Innovation	Short description of the innovation	Pilot cities applying the innovation
INNO A1	Predictive Maintenance Strategies & Battery State-of-Health Estimation	Forecasting the health of electric bus components (i.e. battery), through big data analysis	Barcelona Rimini
INNO A2	Intelligent Driver Support and Safety Systems	Cameras and radar systems to enhance driver safety, by providing real-time data on road safety risk conditions (i.e. obstacles). Docking assistance, assisted braking, blind spot monitoring, assistance through narrow navigation are some of the features. Automated traffic signal control and zone management can be also utilized.	Barcelona Rimini
INNO A3	Optimized Connected Vehicle Digital Twin and Monitoring System	Digital twin replicating both transport and power supply operations (aids intelligent operator assistance, autonomous navigation and lifetime testing)	Athens
INNO A4	Advanced Energy and Thermal Management	Management of battery + optimal usage of the vehicle including the heating, ventilation and air conditioning system under all circumstances.	Amsterdam Prague
INNO B1	Bi-directional Modular Charging Systems for Bus-to-Grid Services	Enabling buses to supply energy back to the grid (stabilizes energy supply, reduces peak loads)	Barcelona
INNO B2	Hybrid Charging System with Stationary Battery Buffer	Combines grid connection with energy storage via batteries. A system that enables charging from either a stationary buffer or the grid (manages grid limitations and optimizes eBRT operations)	Amsterdam
INNO B3	Mobility Hub Charging System	Charging infrastructure integrated in mobility hub (facilitates shared used among various electric modes)	Rimini
INNO B4	In-Motion (Hybrid) Charging Systems	Use of overhead contact lines for charging (reduces needs for depot chargers)	Athens Prague Rimini
INNO B5	High Power Charging	Automatic recharge system with the capacity to deliver over 1MW	

INNO C1	IoT Monitoring Platform with Connected ITS Systems	5G-based IoT system for vehicle and charging infrastructure monitoring (facilitates condition monitoring, predictive maintenance, optimizing energy consumption)	Barcelona Amsterdam Athens Prague Rimini
INNO C2	Efficient, Integrated, and Smart Charging Management Systems	Smart charging strategies that reduce costs, battery wear and grid utilization, while considering passengers' demand variations and weather conditions	Barcelona Amsterdam Prague
INNO C3	Adaptive Fleet Scheduling and Planning Tool	AI-based adaptive scheduling strategies, considering real-time parameters (optimization of eBRT fleets, minimization of costs, emission reduction). Data related to passenger's demand can be used in real time information exchange with users, keeping them informed about service changes, delays and disturbances	Athens Rimini

*cluster A: vehicle systems, cluster B: eBRT charging infrastructure and cluster C: Automation, Management and IoT Connectivity Systems

Table 13: Preliminary list of social risks and benefits and correlation to the eBRT2030 innovations

Social risk	Social risk description	Social risk relevant to innovations:	Social benefits	Social benefit description	Social benefits relevant to innovations:
Skill gaps / jobs uncertainty and labour disputes	• Traditional bus drivers and operators may face employment risks if they are not absorbed into the new system, which can lead to social tensions and labour disputes. (INNO A3) • Skill gaps may appear (drivers/ operators not being able to adapt and acquire new skills) (INNO A2)	INNO A2 INNO A3	Enhanced efficiency of professionals	For drivers (INNO A2), operators (INNO A1, A3, C1, C2, C3), maintenance staff (INNO A1, C1), due to new/ optimized monitoring systems, intelligent driver support and safety systems, battery maintenance strategies, etc.	INNO A1 INNO A2 INNO A3 INNO C1 INNO C2 INNO C3
Safety/ security/ cybersecurity risk	• Non-compliance with insulation and grounding, fire prevention requirements (INNO B1, B3), especially for high power charging (INNO B4) • Property security issues in multimodal hubs (i.e. lockers or cages for e-bikes and e-scooters not provided) (INNO B3) • IoT systems are vulnerable to cyber threats, which could compromise not only service operations but also user data (the last one is especially crucial when payment or account details are required by the user) (INNO A2, B3, C1, C3)	INNO A2 INNO B1 INNO B3 INNO B5 INNO C1 INNO C3	Enhanced safety for all road users	Especially due to safety systems installed in the vehicles (INNO A2)	INNO A2
Accessibility/ access, complexity and inequality	• Unequal access to real-time information, if this is shared through smartphones (INNO C3) • Complexity in charging payment option, which may exclude specific users (i.e.	INNO B3 INNO C3	Improved experience of eBRT user	• Increased comfort (less vibrations, quieter journey, better in-vehicle temperature) (INNO A4) • Improved feeling of safety/ security (INNO A2)	INNO A2 INNO A4 INNO C3

Social risk	Social risk description	Social risk relevant to innovations:	Social benefits	Social benefit description	Social benefits relevant to innovations:
	those not familiar with payment apps) (INNO B3) • More complex charging processes (INNO B3)			• Improved accessibility to vehicles and stations (INNO A2) • Improved overall customer experience through real-time information shared with passengers (INNO C3)	
Compromised reliability	High dependency on IoT systems, may lead to compromised reliability of system services in case of IoT systems failures (INNO C1, C2, C3)	INNO C1, C2, C3	Increased service reliability	Improved punctuality (service reliability) due to adaptive fleet scheduling and planning tool (INNO C3)	INNO C3
Negative impacts on city landscape/ land use	• Public space occupation of charging infrastructure may lead into conflicts for land use, especially when competing interests apply (INNO B3) • Non-optimal use of public space • Pantographs or catenary use compromise visual aesthetics of urban environment (INNO B4)	INNO B3 INNO B4	Increased sustainability of city/ improvement of city image	• City benefits from energy savings and reduced pollution (INNO A3, A4, B1, C2, C3) • Optimization of public space usage (i.e. limit of charging infrastructure occupation) (INNO B3, B4) • Improvement of city image > creation of community pride • Increase of overall city's accessibility to Public Transport, without disturbing existing sustainable design (INNO B3) • Foster community interaction	INNO A3 INNO A4 INNO B1 INNO B3 INNO B4 INNO C2 INNO C3
Power supply instability/ breakdowns	Large-scale deployment of electric buses could increase the demand on the electrical grid, leading to potential supply issues if the	INNO B3 INNO B4 INNO B5	Increased system resilience	• Reduce fossil fuel dependency, thus protecting community from volatile fuel prices (INNO A3, A4, B1, C2)	INNO A3 INNO A4 INNO B1 INNO C2

Social risk	Social risk description	Social risk relevant to innovations:	Social benefits	Social benefit description	Social benefits relevant to innovations:
	grid is not upgraded accordingly (INNO B3, B4, B5)			• Perform adaptations to fleet operation to address disruptive situations (INNO A3)	
			Support a cultural transformation	• Support a cultural shift to more sustainable modes of transport • Encourage active living eBRT systems can serve as a platform for educating the public about environmental sustainability and the role of clean energy in urban transport	All innovations

5.4 APPLICATION OF THE FRAMEWORK AND INTERDEPENDENCIES WITH OTHER TASKS

One of the main aspects that should be considered during social optimisation is to organise a core group of representatives from the technical, policy and social domain and work closely with them. A **quadruple helix approach** is crucial, bringing together government, industry, research and academia and civil society players.

As regards the proposed work of the SOI calculation of eBRT2030 innovations, a specific pool of relevant experts and stakeholders will be set up, including representatives both at the level of the local demo ecosystems and at project level. A core team will, of course, consist of the scientific and technical community of the partners, but strong linkage to demo stakeholders (i.e. municipalities, public transport system operators, citizens' groups) is expected (also to be facilitated not only through the demo but also through the impact assessment activities of the project). Cooperation for the needs of the MCDA framework will be complemented with targeted participation of the Advisory Board members and European associations of citizens'/ passengers' interests. This engagement approach will enable a multi-stakeholder understanding of the social performance of the eBRT innovations recognizing, though, the limitations caused from the absence of the wider public.

Table 14 summarises the groups of project partners and external stakeholders that need to be engaged for the implementation of the MCDA framework, specifying the specific step of the process in which input is required, the interdependencies with other WPs and tasks, the method of engagement and the timing for carrying out the activity. Figure 15 presents the timeline of the 6-step MCDA framework.

As a follow-up step to the application of the MCDA framework, a stakeholders/ experts' consultation process is proposed, for discussing on the optimization of the social performance of the eBRT innovations that score low in the SOI. This could take the form of a round table with partners and external stakeholders and experts (including EU citizens groups), advising on practical ways to address the social risks associated with the eBRT2030 innovations. A short summary report with recommendations, prepared by CERTH, is proposed as the final product of this process.

Table 14: Implementation of the MCA evaluation framework: players to be engaged, methods to be used, interdependencies with other project activities and timing

STEP	TARGET GROUP INVOLVED	INTERDEPENDENCIES WITH OTHER PROJECT ACTIVITIES	METHOD OF ENGAGEMENT	TIMING
Step 1. Validation and completion of the list of social risks and benefits related to eBRT2030 demonstrators.	Partners: 1. UITP (project coordinator, WP6 leader) 2. VUB (WP3 leader) 3. CENEX (ST 3.1.2 leader) 4. FIT (WP6 co-leader) 5. ERT (Innovation Manager) 6. AVL – Task 2.2 leader (innovation enablers) 7. FACTUAL (contributor to social KPIs for the project) Demos clusters (partners): 1. CONNEXION, HELIOX, EBRUSCO – Amsterdam Cluster 2. TMB, FAC, IDI, IRIZAR, CRM, UPC, NEMI – Barcelona Cluster 3. DPP, SELC, Electro, UPCE – Prague Cluster	• WP6 (set up of demos) • Task 2.2 (identifying innovation enablers)	Online survey	Survey sent end of Aug. 24 (end M20), beginning of Sept. 24 (beg. M21). Input requested by end of Sept.24 (M21).

STEP	TARGET GROUP INVOLVED	INTERDEPENDENCIES WITH OTHER PROJECT ACTIVITIES	METHOD OF ENGAGEMENT	TIMING
	4. START, UNIBO, ENEL-X, RINA-C – Rimini Cluster 5. ICCS, OSY, OASA, NTUA, TEMSA – Athens Cluster			
Step 2. Assigning weights in each social parameter (risks and benefits)	At least 10 experts: Advisory Board Members SSH experts and European citizens associations (contacted by CERTH)	Task 1.1. (management of the Advisory Group)	Online workshop	AB meeting held on the 22 Oct. 24 (M22). Workshop with SSH experts organized within Oct. 24 (M22)
Step 3. Ranking the risks and benefits across the eBRT2030 innovations	At least 10 stakeholders from each demo Demo partners: 1. CONNEXION, HELIOX, EBRUSCO – Amsterdam Cluster 2. TMB, FAC, IDI, IRIZAR, CRM, UPC, NEMI – Barcelona Cluster 3. DPP, SELC, Electro, UPCE – Prague Cluster 4. START, UNIBO, ENEL-X, RINA-C – Rimini Cluster	WP6 and especially Task 6.2, where the demo local ecosystems are mobilised for data collection.	1st run: workshop with demo partners 2nd run: Online survey with demo stakeholders	1st run: workshop implemented back-to-back with project General Assembly (M22) 2nd run: survey sent out beginning of November (M23) to demo stakeholders. Feedback received

STEP	TARGET GROUP INVOLVED	INTERDEPENDENCIES WITH OTHER PROJECT ACTIVITIES	METHOD OF ENGAGEMENT	TIMING
	• ICCS, OSY, OASA, NTUA, TEMSA – Athens Cluster Demo stakeholders: Municipalities' (technical departments) Public transport (eBRT) system operators, Social community experts Citizens' groups/ representatives European associations (i.e. EPF, ECF)			by end of November (M23).

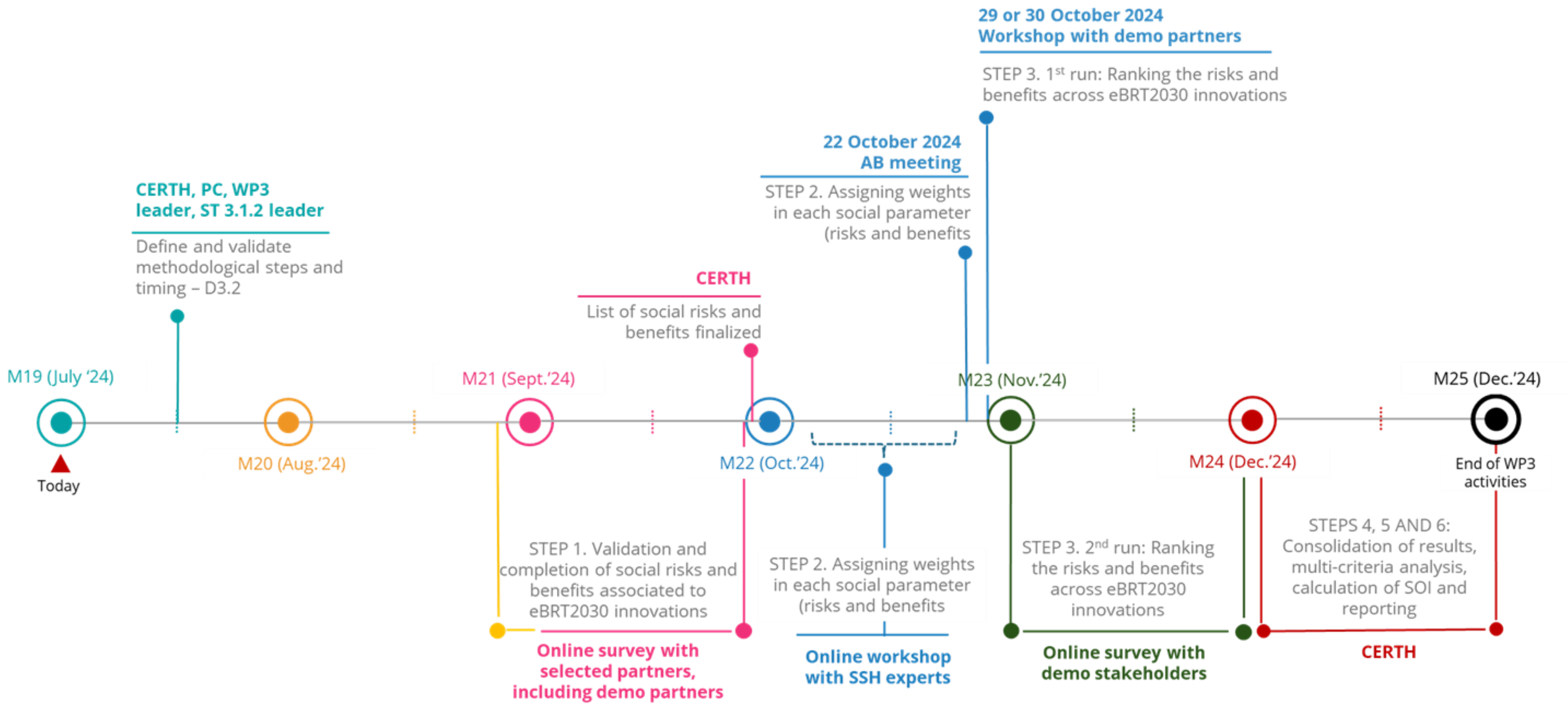


Figure 15: Timeline of the six-step evaluation framework for calculating the societal optimization index of the eBRT technological innovations

6 CONCLUSIONS

This report describes the methods used to develop three tools for evaluating electric bus fleets.

4) The first tool helps calculate the total cost of ownership (TCO) of individual buses and entire bus fleets.
5) The second tool helps calculate the reduction in greenhouse gas emissions in the tank-to-wheel (TTW) stage of operation enabled by transition from diesel Euro VI buses to electric buses.
6) The third tool helps calculate the reduction in exhaust-based air pollution enabled by transition from diesel Euro VI buses to electric buses.

Additionally, a methodology describing the multi-criteria analysis used to ensure that the eBRT innovations used in the project lead to the highest social benefits is developed. For each of these tools and methods, scope of application, detailed guidelines for usage and limitations are discussed in detail.

The report is expected to be of interest to both the users of these tools – public and private bus fleet operators – as well as researchers, planners and other stakeholders in the bus, public transport and heavy-duty electric vehicle sectors.

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