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Research Article

Facilitating adoption of electric buses through policy: Learnings from a trial in Norway

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ABSTRACT

Learning from first experiences of battery-electric bus (E-bus) trials is important to facilitate uptake and develop effective public policy. Here we present initial E-bus trials in Oslo and use the case to 1) model total cost of ownership (TCO) of E-buses vs. diesel buses, and 2) discuss challenges, opportunities, and policy implications. Together, this yields a holistic analysis of requirements for speeding up E-bus adoption, spanning operators and policymakers. Results revealed that rapid E-bus roll-out was achieved through successful contract change order use combined with authority support to reduce operator risk. Challenges were encountered surrounding technical issues, climatization energy use and infrastructure establishment in dense urban areas. In addition, urban E-bus TCO is currently high, and since operation is mostly tender controlled with investment costs covered, higher costs must be covered by public budgets. Despite challenges, operators are positive to further E-bus use, suggesting that companies are willing to support innovation when financial risk is low. We expect E-bus operation to become competitive to diesel buses in Oslo by 2025; to facilitate adoption before economic parity, municipalities and transport authorities must continue to play a large role. Further regulation is also urgently needed to facilitate common infrastructure planning and development.

1. Introduction

The transport sector is the source of almost 25% of European greenhouse gas (GHG) emissions and is a major cause of air pollution in cities (EEA 2018). Although there have been vehicle efficiency improvements, transport has not seen the gradual emission decline achieved in many other sectors due to increases in transport demand (EEA 2018; ITF 2019). Local authorities have a crucial role in transforming the sector through implementing incentives for zero-emission transport and improving public transport (EC 2016). Accordingly, zero-emission buses, including battery electric buses or 'E-buses' and fuel cell electric buses are considered vital in the transition to a sustainable urban transport system (Bakker and Konings 2018; Borén 2019). Norway is currently a leading country in Europe for electromobility, and the Norwegian National Transport Plan further sets targets for all new city buses to be zero-emission or use biogas by 2025 (Norwegian Ministry of Transport, 2017).

Globally, many zero-emission bus projects have been initiated, with the vast majority in China (Bakker and Konings 2018). There has been particular focus on battery electric technology, using E-buses mainly in closed transport systems along fixed routes. Charging can take place at the depot (either during the day or at night) or at fast charging stations located at bus stops or endstops (Hovi et al., 2019).

Within Europe small pilot projects involving 1–2 E-buses had by 2016 grown into larger pilot projects involving entire bus lines (ZeEUS2016). The focus of such pilots has mainly been on 10–20 km long inner-city lines, which permit flexibility for battery and charging options. While in 2015, there were around 1 000 E-buses operating solely on batteries in Europe, (Bakker and Konings 2018), this extended to 1 560 in 2017 (Bloomberg New Energy Finance 2018) and 2 200 in 2019 (Busworld, 2019). In Norway specifically, initial practical experience from E-bus trials was gained from 2015 (city of Stavanger) and 2017 (from Oslo). Trials have since expanded nationally, and for 2020, 416 E-buses were planned to be in operation in eight Norwegian cities (NRK, 2019). In Oslo, all city buses are further planned to be electric by 2029 (Solberg 2020c). The increase in pilot projects has been reflected by a move to larger scale manufacturer production, with battery performance expected to improve (HEV TCP 2020).

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Much literature is available regarding E-bus operational experience and enablers and barriers to uptake. Advantages are apparent, since in addition to direct emission reductions, the buses are efficient, quiet, have good acceleration and can be charged overnight using renewable energy (Andwariet al., 2017). Consequently, many operators are positive to E-buses since they are liked by passengers and can offer reductions in energy use. Nonetheless, there are challenges surrounding use relating to technical and safety issues, charging requirements and grid impact (Andwariet al., 2017; Golubkov et al., 2018; Hannan et al., 2018), that make some operators hesitant to include E-buses in their fleet (Borénet al., 2016).

Additional challenges can be found in regions with cold climates, but fewer studies are available on this topic. Studies in Sweden (Borénet al., 2016; Xylia and Silveira 2017; Borén 2019) highlight changes in battery performance throughout the year and report significant energy use for climatization in winter (Borén2019). To our knowledge, no scientific articles reporting Norwegian experiences are available, but news reports have highlighted the main challenges as relating to installation of charging infrastructure, charging issues and - to an extent - range challenges in winter (Solberg 2020a, 2020b, 2020c). Good authority support is needed to cover these risks and overcome these barriers (Blynn and Attanucci, 2019).

High investment costs can also act as an uptake barrier (Blynn and Attanucci, 2019; Pedersen and Nielsen 2019). The total cost of ownership (TCO) is a measure that includes all direct and indirect costs and is used in comparative cost assessments. It is particularly useful for E-buses due to the way in which different cost components relate to other technologies (e.g. particularly high investment costs vs. low usage costs). However, there is wide spread in reported TCO results. Borén (2019) estimated E-bus TCO in Sweden, using collected data on energy use, investment and maintenance costs. The study found that E-bus TCO is lower than for diesel buses, reporting 12% lower costs for one bus route over a 10-year analysis period when opportunity charging. Bloomberg New Energy Finance (2018), Blynn and Attanucci (2019) and Meishner and Sauer (2020) also estimate that E-bus TCO can be competitive or lower today than for diesel buses. Conversely, when considering vehicle fleets under a probabilistic approach, Harris et al. (2020) estimated low chance that an E-bus fleet has lower TCO than a diesel fleet. Similarly, Grauers et al. (2020) found that E-bus TCO in Sweden is currently higher than for buses utilizing Hydrotreated Vegetable Oil (HVO) biodiesel, having accounted for routes, timetables and required number of buses. This was also echoed in average case study results for Finland and California by Lajunen (2018). Differences likely reflect variation between case study conditions and charging strategies utilized (Chen et al., 2018), sensitivities to annual driving distance (Blynnand Attanucci2019) and other assumptions including the extent to which service frequency changes are included.

Although future reductions in E-bus TCO are expected (Berckmanset al., 2017), fewer studies quantify this. Gohlich et al. (2018) found that under conditions examined in Berlin, both conductive and inductive opportunity charging concepts become cost-effective by 2025. Similarly, Ruter's analysis (2018) found that Norwegian E-bus services are likely to become competitive vs. diesel buses between 2023 and 2028, depending on the type of bus, bus line, and operating arrangements. Along with factors such as technological maturity and market availability, favorable TCO comparisons are important for uptake, although authorities may decide to accept higher costs simply to obtain zero-emission targets. Even when TCO is favorable, there is still a risk associated with selecting E-bus operation over diesel bus operation; tender periods in Norway run for 7–10 years, but since climatic and topographic driving conditions in Norwegian cities are tougher than most other places in Europe, battery life may be a main risk.

This article presents Norwegian experiences gained in trial E-bus operation of 12-m city buses, 18-m articulated buses and minibuses with up to 17 seats in the Oslo region, and puts these experiences in the context of the wider European setting and particularly other cold climates. Information gathered provides input to 1) an updated assessment comparing the cost competitiveness of E-bus fleets with conventional bus fleets with internal combustion engines (ICE), accounting for local conditions, capacity changes, vehicle availability and potential changes in future, which are often neglected in similar studies; and 2) a discussion of challenges, opportunities, and policy implications. Learning from these experiences, particularly in this challenging region with respect to topography and climate, is crucial to inform needed policies and ensure successful further urban E-bus uptake. The novelty of the work, aside from being (to our knowledge) the first scientific presentation of E-bus experiences from Norway, is that by combining results from qualitative and quantitative methods we provide policy-relevant information, derived from a holistic approach spanning both operators and policy-makers, focusing on factors that are needed for rapid phase-in.

2. Materials and methods

2.1. Interviews

Norwegian E-bus operators from the Oslo region were identified using information from the Norwegian Public Road Administration's vehicle registry, Autosys, per April 2018 (Statens vegvesen, 2018). The operators identified included Nobina, Norgesbuss, Unibuss, Taxus (representing Nedre Romerike Minibuss/Lillestrøm Minibuss) and Oslo Taxibuss. Semi-structured interviews were thereafter conducted as Skype meetings, with one interview held per operator. In addition, other bodies interviewed were the Norwegian Public Road Administration (NPRA, Statens vegvesen), the state enterprise Enova (a support agency for measures to reduce GHG emissions) and the public transport authority for Oslo and Akershus (Ruter) that procures services from the E-bus operators. For operators, persons responsible for investment decisions were interviewed, whilst for public bodies, persons in charge of the activity were interviewed. In total, eight interviews were held with two interviewers present in each.

As preparation, subjects were sent a list of questions in advance of the interviews (see supplementary material). Questions were based on the previous literature review on European E-bus pilots (Jordbakke et al., 2018), subsequent discussions with operators, and a previous study on the potential for E-buses in Norway (Hagman et al., 2017). Framed by this focus, open-ended questioning allowed study participants to articulate perceptions freely. Although specifics varied, interview topics related to the E-bus purchase process and choice of supplier, technology choice, operational experiences, decomposed investment and operation costs, as well as public frameworks and incentives that could contribute to faster diffusion of zero emission buses into the Norwegian market. After the Skype meetings, subjects were sent the interview notes for any corrections. This checked interview material was subsequently qualitatively analysed in NVivo (Version 12 Plus) to code for the topics.

From one operator, we further obtained disaggregated data on the charging solutions and fleet design they utilized as of 2019, and as they envisaged for an optimized case in 2025. This was in terms of the number and type of chargers (and the associated number of buses that can utilize these) with 1) depot 2) opportunity and 3) a mixture of depot and opportunity-based charging, and their associated unit costs.

A technical summary of the E-bus trial characteristics in the Oslo region that began 2017/2018, and whose operators formed the core of the interviews, is shown in Table 1. These are put in the perspective of previous, current and planned E-bus trials in Norway (as of the end of year 2019) in Table 2. Although some of the information was gained from the interviews themselves, since it is mostly now publicly available, it is shown here to aid the reader. Trials are listed in Table 1 according to size order (length), with subsequent analysis of operators given in a randomized order for anonymity. Scheduled city and articulated buses are typically operated between 05:00/06:00–24:00, leaving

Table 1
Electric bus (E-bus) trials beginning 2017/2018 in the Oslo region, that interviews were based on. Status as of December 31, 2019. PTA = Public transport authority.

Parameter	Oslo Taxibuss	Taxus	Norgesbuss	Unibuss	Nobina
Type of bus	Minibus	Minibus	City bus	City bus	Articulated bus
Manufacturer	Iveco	Iveco	Solaris	Solaris	BYD
Model	El-bus	El-bus	Urbino 12 Electric	Urbino 12 Electric	El-bus
Range on full charge (km)	150	160	240	45–50	180
Number tested	4	10	2	2	2
Registration year	2018	2017	2017	2017	2017/2018
Length (m)	–	7.13–7.33	12	12	18
Battery technology	Sodium-nickel chloride ($Na–NiCl_2$)	Sodium-nickel chloride ($Na–NiCl_2$)	Lithium-titanate(LTO)	Lithium-titanate(LTO)	Lithium-iron phosphate (LFP)
Battery capacity (kWh)	82	90	127	75	300
Depot charging (kW)	22	11	80[a] (250[b])	80[a]	80[a] (300[b])
Opportunity charging (kW)			400	300	
Charge time (hours)	8 (overnight)	4 (day time)	1/0.1 (slow/fast charging)	8/0.1 (slow/fast charging)	3.5
Typical operating time	Rush hour traffic	Rush hour traffic	05:00/06:00–00:00	05:00/06:00–00:00	05:00/06:00–00:00
Procurement process	Commercial purchase	PTA tender	Change contract to PTA tender	Change contract to PTA tender	Change contract to PTA tender
Usage	Public sector contracts	School transport	Public transport	Public transport	Public transport

[a] Twin charger.
[b] Charger use was planned.

Table 2
Overview of electric bus trials in Norway (as of December 31, 2019). Year is the starting year for the trial.

Year	Location	Authority	Operator	Bus type	Manufacturer	Number
2015	Stavanger	Kolumbus	Boreal (now Norgesbuss)	City	Ebusco	2
2017	Stavanger	Kolumbus	Boreal	City	Ebusco	3
2017	Lillestrøm/Jessheim	Ruter	Taxus	Mini	Iveco	10
2017/2018	Oslo	Ruter	Nobina	Articulated	BYD	2
			Norgesbuss	City	Solaris	2
			Unibuss	City	Solaris	2
2018	Oslo		Oslo Taxibuss	Mini	Iveco	4
2019	Trondheim	AtB	Tide	City	Volvo	28
			Tide	City	Heuliez	11
2019	Lillehammer	Opplandstrafikk	Unibuss	City	Volvo	2
2019	Drammen	Brakar	Nettbuss	City	Volvo	6
2019	Oslo and surrounding area	Ruter	Nobina	Articulated	BYD	42
			Unibuss	Articulated	VDL Citeas	30
			Unibuss	City	VDL Citeas	10
			Norgesbuss	City	Volvo	27

4–6 h for overnight depot charging (combined in some cases with end-stop charging), while minibuses are typically operated in morning and evening periods with good daytime charging opportunities.

2.2. *Cost analysis*

A cost model developed in previous studies (Hagman et al., 2017; Amundsen et al., 2018), was used to assess bus TCO (Fig. 1). The model divides cost elements into capital costs for the vehicle and charging

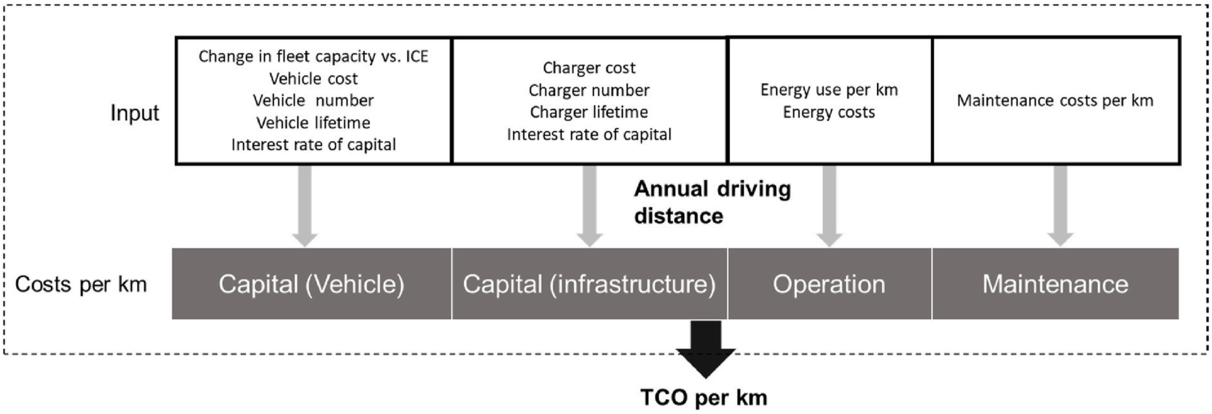

Fig. 1. Total cost of ownership (TCO) model for E-buses.

infrastructure, operation, and maintenance, and normalizes these (where applicable) per year using an annual annuity method. Subsequently, the cost per km is calculated based on the annual distance driven. The relative number of buses required in the fleet with different technologies, to account for changes in service, is also accounted for in the model. Resulting costs are given in NOK_{2019}/km, and reported also finally in EUR/km using the average 2019 exchange rate of 1 EUR = 9.85 NOK. For reference, 1 EUR = 1.12 USD.

The information obtained from interviews was used as model input to calculate comparative E-bus and ICE-bus TCO for the years 2019 and 2025. A summary of the input data is given in Table 3. In this table, information for 2019 was a direct result of the interviews (average values), aside from maintenance costs per km, which were taken from Amundsen et al. (2018). The values for 2025 were adjusted from this baseline based on input from the operators. The E-bus was assumed to be a city bus (12 m) with capital cost of 4.5 MNOK using electricity at a cost of 1.0 NOK/kWh (Amundsen et al., 2018). It was also assumed that the investment cost includes a battery guarantee, i.e. that the battery lasts the entire life of the tender, taken to be eight years, meaning that costs relating to uncertainty in battery lifetime are accounted for. By 2025 it was assumed that the technology has matured so that the battery lifetime is equal to the lifetime of the bus. An extra 10% E-buses were included in the fleet to cover charging downtime and to ensure there are always sufficiently charged buses to use (the number of drivers remained the same).

The relative numbers of fleet E-buses and chargers modelled were primarily based on a depot pantograph charging solution, using direct interview input from the aforementioned operator on current practices as well as anticipated future fleets. In addition, the model was used to compare TCO resulting from other charging solutions, i.e. combined depot and opportunity charging, and opportunity-based charging alone. Again, assumptions were based on direct operator input. Since use of opportunity charging alone is anticipated in future by the operator but not currently utilized in Oslo, this was only used as an option for the year 2025. Table 4 contains the data used for all charging solutions, whereby it should be noted that the level of service provided by the buses under the different solutions is not comparable; the table serves only to demonstrate the relative number of buses/chargers required under each solution, with the respective costs later normalized per km.

For the depot-based solution, charging costs were calculated given that the operator's fleet of 30 E-buses in Oslo currently share the use of 12 × 300 kW chargers and 18 × 50 kW chargers. Charger unit costs were taken to be 1.40 and 0.54 MNOK (0.14 and 0.05 M-EUR) for 300 kW and 50 kW chargers, respectively, based on the actual costs paid by the operator including mounting and cables. Costs were assumed to fall 10% by 2025.

Table 3
Assumptions used in the TCO calculations.

	E-bus		ICE-bus	
	2019	2025	2019	2025
Vehicles required to serve a route due to charging downtime requirements (normalized to 1)	1.1	1.1	1.0	1.0
Individual bus driving distance (km/y)	80 000	80 000	80 000	80 000
Vehicle lifetime (y)	8	8	8	8
Infrastructure lifetime (y)	8	8	8	8
Interest on invested capital (%)	3.5[d]	3.5[d]	3.5[d]	3.5[d]
Fuel costs excl. VAT (NOK/unit)[a]	1	1	11.3	11.3
Vehicle capital cost (MNOK)	4.5	3.0	2.0	2.0
Fuel/energy use (unit/km)[b]	2.30	2.00	0.42	0.41
Maintenance (NOK/km)[c]	2.0	1.5	1.8	1.8

[a] Unit of NOK/kWh for E-bus and NOK/l for ICE bus. The base price of diesel excluding VAT and levies was 6.24 NOK/l, with additional CO_2- and road use levy (excluding VAT) of respectively 1.33 NOK/l and 3.75 NOK/l. Electricity price at 1 NOK/kWh was composed of 0.67 NOK/kWh with additional 50% cost for fast charging.

[b] Unit of kWh/km for E-bus and l/km for ICE bus.

[c] Not including replacement costs for battery packs or cells.

[d] Based on national freight model, assuming low Norwegian discount rates.

The comparative ICE-bus modelled represents a Euro VI diesel with investment cost of 2 MNOK, with mandatory biofuel blend (10% in 2019 whereby 3.5% is HVO, at 11.3 NOK/l (Circle K, 2019)). These prices exclude VAT. The base price of diesel excluding VAT and levies was 6.24 NOK/l, with additional CO_2- and road use levy (excluding VAT) of respectively 1.33 NOK/l and 3.75 NOK/l. Refueling infrastructure for the ICE-bus was not included as it was assumed that existing infrastructure can be used. Vehicle lifetime was taken for all buses to be an assumed average tender period of eight years.

As with any model, inherent uncertainties are present. The TCO calculations do not account for operator risks posed, premature spare part changes not covered by service agreements and any residual value after the assumed lifetime. In addition, results do not include the costs (~15 million NOK for the depot charging solution in Table 4) of the expansion required to the grid with E-bus charger use, since the lifetime of these cables/transformers is high (>50 years) and can thus be considered a one-time transaction cost to enable E-bus operation for the foreseeable future. All other costs not specifically accounted for (such as insurance) are assumed to be similar with different technology types.

Since uncertainties about the future development of E-bus costs are large, we carried out a sensitivity analysis in which we varied key parameters in the TCO comparison between the E-bus depot charged case and ICE-bus case in 2025. Here, all input parameters to the model (i.e. all parameters in Table 3, including relative vehicle numbers required, driving distance, lifetimes, capital and use costs and associated interest rates and fuel/energy use) were varied separately ± 20%. The battery lifetime was always kept the same as the vehicle lifetime (and tender length) since this reflects the real situation in Oslo trials with operators demanding a battery guarantee. Aside from each parameter in question that was varied, other parameters were kept the same as the main analysis unless specified.

As an extension to the sensitivity analysis, operator feedback was included that 10% additional buses are a baseline requirement in all fleets (i.e. both ICE and E-bus fleets) for the same service level, to cover all downtime and maintenance. This is in addition to the 10% extra E-buses that are accounted for in the main analysis described previously to cover charging downtime.

3. Results and discussion

Results are presented according to the various topics investigated. Interview results are split into sections regarding the procurement process (3.1), technology choices (3.2) and operational experience (3.3). Ownership costs calculated using this information are thereafter presented in section 3.4.

3.1. *Procurement process*

Interviews revealed that Norwegian buses for urban use are generally purchased by operators for routes run on public tenders from counties, as a result of decisions made at operator management level. The city buses in Oslo are part of a seven-year trial with the public transport authority Ruter. While the terms of the trial were equal for all operators, each was free to decide which solutions to test. Trials were intended to be part of existing bus routes and tender periods, meaning a change contract was negotiated to the original tender for fast phase-in. There was little financial risk for the bus operators, since Ruter covered investment costs and lost transportation efficiency. This is similar to many other urban E-bus trials in Europe during 2017 which were funded by local transport, regional or National authorities using public and private grants (ZeEUS2017; Li et al., 2018), and is in line with research suggesting operators are willing to use E-buses when authorities take on

Table 4

Relative unit numbers and costs for three alternative charging strategies modelled in the analysis: depot based, opportunity based, and a combination of depot/ opportunity-based charging, based on the experience of one E-bus operator in Oslo. Un-optimized (year 2019) and optimized values are given (year 2025, projected only).

	Relative numbers of buses and associated charger units per charging solution						Costs per single bus or charger[a] unit (million NOK)	
	Depot based		Depot and opportunity-based		Opportunity based			
	2019	2025	2019	2025	2019	2025	2019	2025
# **Chargers**								
50 kW (depot)	18	18	10	10		0	0.54	0.49
80 kW (depot)	0	0	1	1		0	0.74	0.67
300 kW (depot)	12	12	0	0		0	1.40	1.26
300 kW (endstops)	0	0	2	2		1	2.95	2.66
# **Buses**	30	60	12	15		8	4.50	4.05

[a] Total cost of each charger includes hardware, mounting, cables etc.

most risks (Borénet al., 2016; Bakker and Konings 2018). Other buses, such as minibuses, long-distance buses and coaches are generally purchased un-tendered commercially, but in one case here, electric minibuses used as school-buses were acquired under a call for tenders. In this case, Ruter partially covered costs by allowing a slightly higher hourly rate than for diesel vehicles.

Operators established their own charging infrastructure, although the Norwegian state enterprise Enova contributed by offering economic support. This enterprise offers grants to organizations investing in zero-emission vehicles or publicly available charging infrastructure, covering up to 50% of additional investment costs compared to vehicles with ICE. Other research suggests that additional involvement of new stakeholders and third party players (such as utility companies and infrastructure manufacturers) in infrastructure establishment can lead to shared risks, increased efficiency and improved performance (Li et al., 2018).

Since urban buses reflect a market that is almost 100% controlled by public tenders, by weighting the environment highly (reduction of GHG emissions) or requiring zero emissions, authorities can de facto push towards full electrical public transport operation. This requires that there are sufficient suppliers of E-buses on the market for proper bidding and procurement processes to be carried out by the public transport companies and the bus operators.

Although an increasing number of E-bus models have become available on the European market (see ZeEUS (2017) for a detailed comparison of models and Figenbaum et al. (2019) for an overview of manufacturer strategy), operators interviewed here found that the choice of E-bus models available when they made their purchase decisions differed depending on the bus segment. For city bus operators, several models were available to choose from, whilst this wide choice was not available for minibuses. One explanation is that Norway is one of only a few countries to use 17-seater minibuses with ~8 m length. When purchasing E-buses outside of Europe, closer follow-up was found to be needed at the start, and a European type approval had to be obtained for Norwegian traffic. An additional issue in several Norwegian cities was that there were delays in the early phase of the trials related to E-bus delivery. Regional E-buses were not focused upon in the interviews, but it was noted that a Norwegian challenge has been access to 15 m E-buses with three axles with seat belts (Class 2 bus). This is primarily a Nordic bus size with low demand in the wider European region. The situation is now changing, with one operator planning to use Class-2 buses in Oslo, Hamar and Haugesund from 2020 (Unibuss, 2019).

3.2. Technology choices

Operators stated that batteries for the Oslo E-bus trials were dimensioned based on the bus type, route and charging solutions required (see Table 1 for summarised technical information). Resulting battery capacity utilized ranged between 75 kWh and 300 kWh, with a corresponding range on full charge between 45 and 240 km given that energy for climatization (heating/cooling) is provided by separate fuel fired systems. Two operators chose lithium titanate (LTO) batteries, with other operators trialing 300 kWh lithium-iron phosphate (LFP) batteries, or sodium ($Na–NiCl_2$) batteries, with 90 kWh and 82 kWh total capacity per E-bus, respectively. An advantage of $Na–NiCl_2$ is that the operating temperature is 270–320 °C, giving little difference in summer and winter battery performance. For new buses, one operator will trial lithium nickel manganese cobalt oxide (NMC) batteries.

The range of batteries and charging solutions trialed in Oslo illustrates the wide (and expanding) variation in battery types and chemistries used by bus manufacturers (Fig. 2a). This reflects ongoing experimentation and the possibility for different battery sizes and charging options to adjust to local conditions and operator preferences (ZeEUS2017). Du et al. (2019) estimate that in future, NMC may be a main battery used in light-duty E-buses, whilst LFP may be mainly utilized in heavy E-buses (as reflected by Fig. 2a). In general, many available E-bus models with larger batteries (>250 kWh) are designed to use plug-in charging at depot (Fig. 2b), as they are likely equipped with a large battery pack to allow for full day operation, whilst those with smaller batteries can be fast-charged at endstops to compensate for the smaller battery. This correlates with comments made by Ruter to Solberg (2020c).

Due to challenges with establishing fast chargers in Oslo's city center, most operators charge at the depot via plug or pantograph using 11/ 22 kW (for minibuses) and 50–80 kW chargers (for larger buses). Several operators either have - or had a plan to have - fast charging points at endstops. Pantograph charging with an arm raising up from the bus - rather than down - is popular since it is thought to minimize wear. Choices of charging solution and battery chemistry are also linked, as reported by Göhlich et al. (2019).

3.3. Operational experiences

Table 5 summarises the reported experiences in Oslo associated with the E-buses for 1) design, 2) energy use and range, 3) vehicle and charging performance and 4) driver, owner and passenger satisfaction categories. The ratings given in the table were assigned based on the operator feedback, which is subsequently described further below.

3.3.1. Design

The general design and capacity of the buses used in the Oslo trials was not particularly problematic. Nonetheless, one operator noted that little emphasis is currently placed on bus body design, and for another operator, added E-bus height caused a specific issue on a line due to low underpasses, and with a fast charge station with a pantograph. Since the E-bus that experienced this problem was the lowest among the available choices, this highlights a general design issue with the E-buses due to rooftop air conditioning/climatization units and (with the exception of the minibuses) the battery placement.

Regarding capacity, operators report only a small reduction in seat capacity, and that although the number of standing spots may be

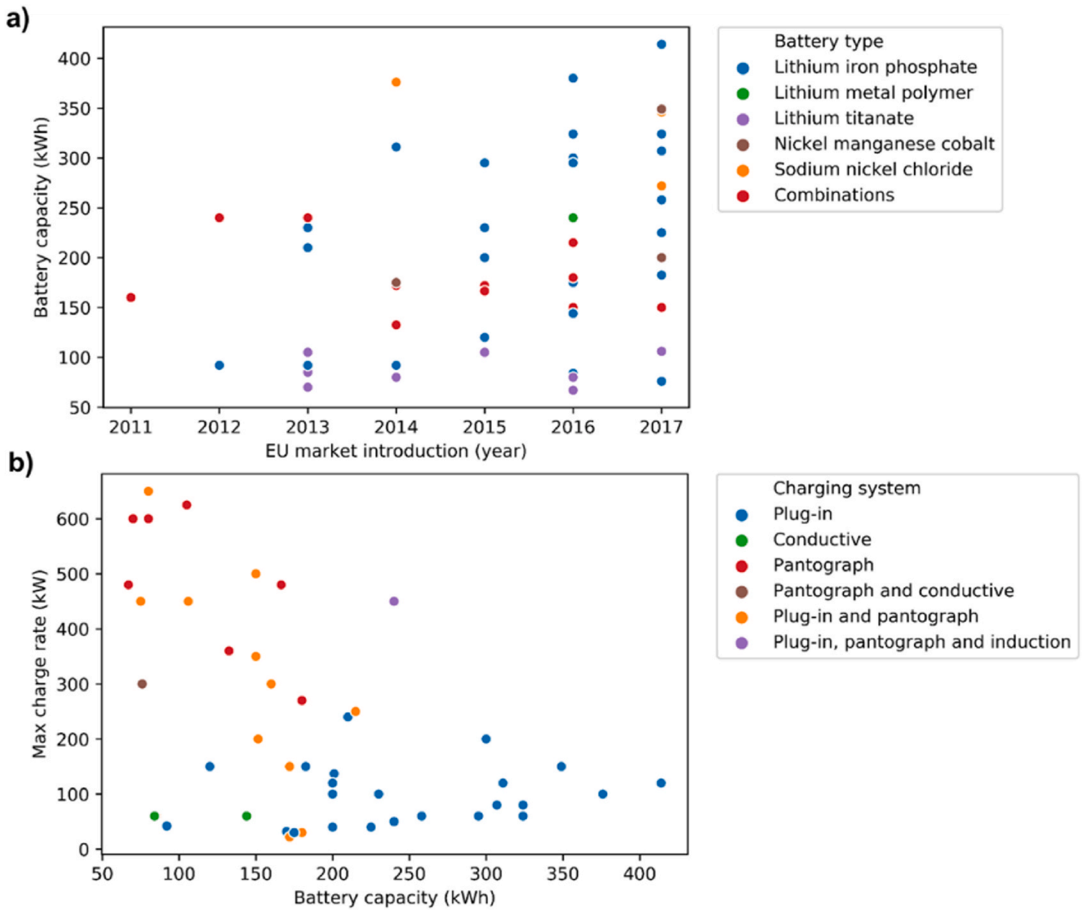

Fig. 2. a) Development of the types of city E-buses available on the European market between 2011 and 2017, and b) Range, battery capacity and charging options of selected city E-buses available on the European market in 2017. Data derives from example E-bus models available in Europe detailed in ZeEUS (2017).

Table 5
Mixed (orange), positive (green) and neutral (yellow) experiences associated with the E-bus trials in Oslo. No color means that no information was obtained in the interview.

	Operator:				
	1	**2**	**3**	**4**	**5**
Design (3.3.1)	🟨	🟧		🟨	🟨
Energy use and range (3.3.2)	🟨	🟧	🟨		🟩
Vehicle and charging performance (3.3.3)	🟧	🟧	🟧	🟧	🟧
Driver, owner and passenger satisfaction (3.3.4)	🟩	🟩	🟧	🟩	🟧

somewhat lower, in practice the allowed number of standing passengers is rarely fully utilized. However, operators comment that extra buses (around 5–10%) are still needed for the same amount of passenger transport on heavy and frequented routes, due to the added time for charging the buses during the day. This factor is complex to account for (see e.g. Grauers et al. (2020) for a model).

3.3.2. Energy use and range

The average energy consumption for driving the E-buses was reported to be between 0.6 and 1.5 kWh/km, which is significantly lower than the values for comparable ICE-buses (Fig. 3). However, energy for E-bus heating and cooling may not be sourced from the battery without reducing the driving range. Interviews revealed that since no heat comes up through the bus floor and little heat is produced in the drive system or the battery during operation, this additional energy use can be as significant as 50% of the total. To address this, operators currently install additional fuel burners for climatization. As these burners are powered by biodiesel (HVO), heating can be classified as carbon neutral but not as zero-emission. When this is included, total energy use is around 1.2 to 3 kWh/km.

The above results are generally consistent with other studies, although the auxiliary energy use estimated here is likely high when considered over a full year. Gallet et al. (2018) estimate averages of around 1.6 to 2.1 kWh/km depending on the bus type, and Borén (2019) calculates average energy use of 1.2–1.9 kWh/km, depending on the route. For the latter Swedish study, the additional monthly energy use varied widely with a maximum energy use of around 3 kWh on one route and month in winter (Borén2019). For this winter month, the auxiliary energy use was around 50% of the total, as was reported in Oslo, but for summer months, reported auxiliary energy use on some routes was low

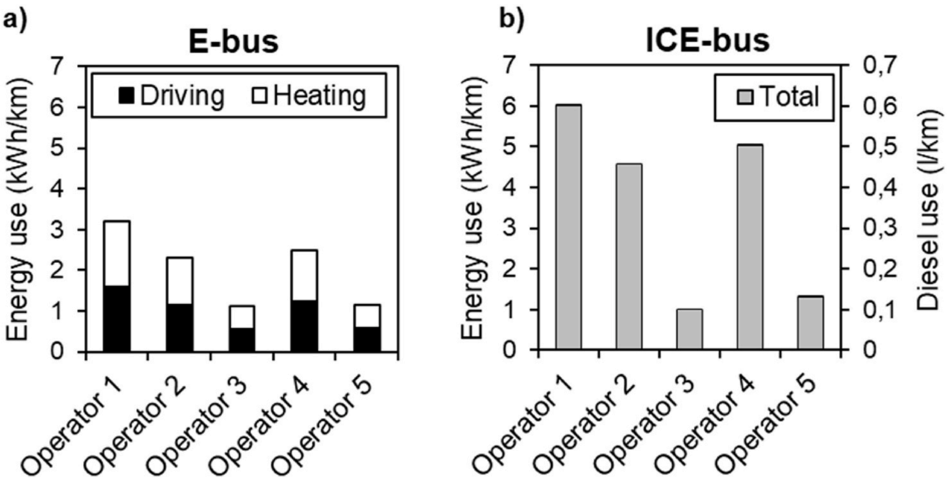

Fig. 3. Average total energy consumption of a) E-buses and b) ICE-buses. Note: only driving energy for the E-buses was directly reported by operators – E-bus heating energy was calculated manually assuming conservatively it represents 50% of the total energy use. Energy consumption for ICE-buses was calculated from the total average fuel consumption reported by operators and includes energy for both driving and heating.

or close to zero. The monthly variation may also be representative of Oslo, given its similar cold climate. In future, further E-buses from at least one operator will have larger batteries to allow for heating without an additional power source. More frequent charging can also enable electricity to be used for heating and cooling, but the risk is that added charging time requires more buses to run a route.

Range is also of concern for many operators. Although one operator stated that the E-bus delivers the range that is promised (even though it was the most concerning factor at the start), another commented that theoretical range deviates from actual range. This may be due to parasitic battery energy use from lights and doors, varying route topography, seasonal variation, number of passengers, varying driving style, or seasonal variation in battery performance. One operator also noted a correlation between temperature and battery performance and driving range. Since HVO-based heaters are used, differences in auxiliary energy use were not responsible.

3.3.3. Vehicle and charging performance

All E-bus operators aimed to deliver the same transport capabilities as with ICE-buses, and service existing lines with the E-buses. Despite this, the pilot E-buses were primarily used in peak (rush) hours because of various practical challenges related to charging infrastructure and design. Ruter accepted such re-arrangements in the Oslo tests, as these E-buses were set into service following a change contract to an existing tender. Due to these experiences, route arrangements were optimized, and driving was controlled within good margins of distance and range on set routes. According to one operator, 40 E-buses out of a fleet of 200 can be assimilated, and bus operation can be planned so that no additional buses are needed, as long as E-buses are put on carefully selected routes. According to other research, changes in the design of a transit route network are expected for optimum E-bus use that are dependent on the charging strategy chosen (Hall et al., 2019).

When working as they should, feedback was that E-buses had good performance, although some were reported as lacking enough power to keep speed up on steep gradients. However, at the time of the interviews the E-buses had been driven less than expected due to a suite of minor and major technical problems requiring workshop time (Fig. 4). For example, for one operator, the E-buses were only driven half of the expected distance in the first month. Key reasons were charging problems, many (non-propulsion) minor issues and part changes due to major faults in the battery module or electric motor. Issues with bus and charger reliability, compatibility, and performance were similarly highlighted in other research of user experiences in the Nordic region (Xylia and Silveira, 2018), which can act as barriers to E-bus procurement (Blynn and Attanucci, 2019).

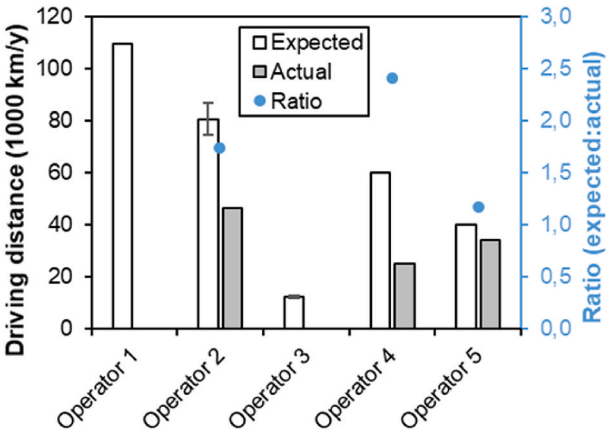

Fig. 4. Expected and actual annual driving distances for the E-buses at the time of the interviews (left axis), and the ratio between these parameters (blue, right axis). Note: where relevant, error bars show the range reported by operators. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Charging problems highlighted by the interviews included challenges related to the balance charger, transforming from 230 V to 400 V 3-phase, weak grid power, and voltage drops in the service battery. Ruter have also indicated that there have been problems with soft asphalt leading to surface indentations and pantograph connection issues, and differences between charger types. For the latter, they note that there have been more technical challenges with the fast chargers located in city environments than the 50 kW chargers at depot, as also reported by Solberg (2020c). Interviews performed with other electric heavy-duty vehicle operators in Oslo additionally showed that charging in winter can prove problematic (Hovi et al., 2020).

Whilst the technical problems resulted in unforeseen maintenance, it was noted that ordinary services were straightforward due to reduced brake-wear with regenerative braking and lack of required oil changes. In addition, not all operators experienced major faults; one operator only experienced 'teething' problems that they believe will be resolved in future production series. However, in general it was stated that it is necessary to have extra buses regardless of propulsion system type, due to extra maintenance needs resulting from extensive use and time out of service. Numbers are difficult to estimate, but one operator stated that an extra 10% buses are needed regardless of type. For E-buses tested in small numbers, reserve E-buses are often not directly available, leading to a need to use reserve ICE buses. Public tenders involving few E-buses should take this issue into account.

Several practical issues related to charging were also reported, mostly surrounding charger installment in central dense city zones due to 1) extensive planning and permitting required between operators and the municipality and 2) the large land-area required. For the latter, feedback was received that endstop charging of articulated buses is particularly problematic due to their size, since high route frequency means that up to four articulated buses must park along the roadside. Depot charging spatial constraints were not reported as problematic when pantograph solutions were used. An associated challenge related to infrastructure ownership; in the Oslo trials, operator collaboration was possible, but the operator who established the infrastructure had preferential rights. Charging installment issues were noted by Ruter to be one of the greatest tasks (Solberg 2020c).

These practical issues resulted in some operators using the E-buses during peak hours and depot-charging them at mid-day, setting limits on which routes can be electrified since there should not be too large a distance to the depot. This also led to one operator installing opportunity charging points outside of the city center; but due to Oslo topography with a low-lying city center surrounded by hillier terrain, this was not ideal since it limited utilization of regenerative braking energy.

The findings thus show that more is needed from authorities with regard to common infrastructure planning and implementation outside of the depot, echoing Bakker and Konings (2018) that institutional innovation and support is required. A long-term solution may be to allow third-parties to provide charging infrastructure as part of a business opportunity, bringing associated knowledge, experience and training (Li et al., 2018). In addition, appropriate regulation of access, ownership and turnover of rights at the end of tender periods should be made, to minimize delays in charging station construction and reduce difficulties in formation of operator partnerships (Xylia and Silveira, 2018). Other studies conclude that favorable electricity tariffs are required from authorities (Blynn and Attanucci, 2019), although this may not be so relevant in Norway where total electricity costs per kWh for non-household customers are under half the average price for the Euro area (Eurostat 2021).

3.3.4. Driver, passenger and owner satisfaction

It was widely commented that the E-buses contributed to a better onboard environment for drivers and passengers due to reduced noise and vibrations, as also reported elsewhere (Borén et al., 2016), and that interest has been high from passengers, the general public, and the press. However, noise in many cases has not been reduced as much as expected; one of the operators reported that there is still relatively high noise in the E-buses (measured at >70 dB) from the electric drive system, which they have attempted to rectify by better insulating. Two other operators reported that other noises, such as those connected with ventilation systems, are more noticeable. Other studies report that E-buses are 5 and 7 dBA less noisy than diesel and gas powered buses, respectively, when accelerating from 0 to 35 km/h (Borén, 2019).

Feedback regarding driving the E-buses was generally positive, but due to range anxiety and concerns for passengers and other road users, not all drivers wished to drive E-buses. According to one operator interviewed, driver utilization due to the charging requirements was more complicated, and complications were also experienced due to the extra training needed for drivers to operate the E-buses. The importance of this training for energy-efficient driving was highlighted in comments by Ruter reported in Solberg (2020c), and has been shown to be important elsewhere (Gunther et al., 2019).

Overall, bus operators were optimistic when considering the future of E-buses. Most operators acknowledged that E-bus fleets are vulnerable to technical and charging issues and that careful planning is needed, but felt positive nonetheless and were already planning expansion of E-bus operation at the time of the interviews. Operator optimism has since come to fruition, with 109 new E-buses introduced to Oslo within the year 2019 alone (Solberg 2020c).

Considering the technical challenges that were experienced and the significant adaptations that were required from each organization to accommodate the new technology, the positive attitude was perhaps surprising. The seeming conflict can likely be explained by the supportive business environment resulting from authority support for innovation in new technologies and E-bus operation. This rewards early adopters while simultaneously reducing risk. Adoption of electric vehicles in commercial operations is discussed further in Denstadli and Julsrud (2019), with results showing that a combination of attributes related to the vehicle, the firm and the firm-environment relationships drives adoption intentions.

3.4. Ownership costs

Fig. 5 presents the estimated change in TCO per km driven and shows comparative values for an E− and ICE-bus.

For 2019, the ICE-bus TCO was calculated as 10.2 NOK/km (1.0 EUR/km). This compares favorably with TCO calculations by Ruter (2018) at 10 NOK/km (excluding personnel costs). Similarly, other studies calculate ICE-bus TCO as 0.92 USD/km (8.4 NOK/km) for an annual driving distance of 80 000 km (Bloomberg New Energy Finance 2018) and 1.1 USD/km (9.7 NOK/km) with annual driving distance of 90 000 km (Gohlichet al., 2018).

E-bus TCO (2019), with depot charging, was calculated here as 14.9 NOK/km (1.5 EUR/km), which is higher than for ICE-buses mostly due to high vehicle capital costs despite low operating costs. This value is comparable to TCO calculated by Ruter for depot and fast charging, excluding personnel costs, at 12.7 and 14.4 NOK/km, respectively. The Swedish study by Borén (2019), however, finds a lower E-bus TCO, at around 12 SEK (12.5 NOK). These differences show the importance of calculating TCO on a case-by-case basis, as also reported by Grauers et al. (2020).

Looking ahead, results indicate that E-bus TCO will be comparable with ICE buses by 2025 at around 10 NOK/km (1.0 EUR/km). This is predominantly due to a reduction in assumed vehicle capital costs, assuming increased battery market maturity and large-scale E-bus production. These results are similar to those reported by Ruter (2018) that indicate that by 2025, city E-bus operation with depot charging will reduce to 10.7 NOK/km (excluding personnel costs) and be economically competitive with ICE-bus operation. For articulated buses, Ruter estimate that economic profitability will come around 2028. Other studies find that E-bus TCO becomes favorable to ICE-buses by 2025 (Gohlichet al., 2018), or is favorable at the current time (Bloomberg New Energy Finance 2018; Borén 2019). Differences between studies are due to variation in assumptions and large uncertainty; an example is lower investment costs used in the calculations coupled with a long vehicle lifetime.

The TCO analysis in the current study accounts for various charging strategies, with assumptions for these (relative number of chargers for each scenario and their cost) based on the current charging practices of one E-bus operator in Oslo. Results show that differences between charging strategy for the E-bus were small compared to the differences between bus type (Fig. 5). Nevertheless, depot charging and opportunity charging represented the charging solutions with the lowest TCO, with projected optimizations by the year 2025. Depot charging alone allows the use of chargers with relatively low cost, whilst for an optimized opportunity charging solution, the high cost of opportunity chargers at endstops is offset by the high number of buses that may use them. Where a mix of depot charging and opportunity charging is used, the high cost of the opportunity charging points is not offset over a high number of buses. However, charging solutions also come with varying practicalities. For example, where an opportunity charging solution alone is chosen, the buses may not be preheated before use. Consequently,

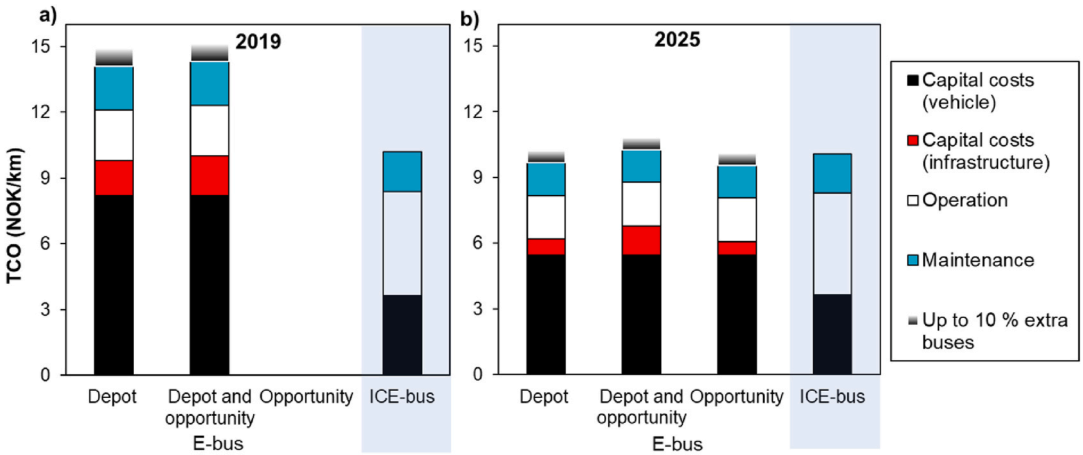

Fig. 5. A summary of the total cost of ownership (NOK/km) for E-buses with depot based, opportunity based and a mix of depot and opportunity-based charging solutions, both a) for 2019 and b) for an optimized case in 2025. TCO for an ICE-bus is shown in the shaded area for comparison. The cost of extra vehicles in the fleet required for the E-buses is presented in graduated fill, since there is large uncertainty here.

heating energy required (from the batteries) may be higher. This is not accounted for in the analysis.

With regard to variation in TCO with charging type reported in other studies, Lajunen (2018) found lowest costs when charging at endstops, whilst Ruter (2018) find that depot charging offers the lowest TCO (although note that the most favorable solution must be chosen on a case by case basis). Other studies suggest that further solutions such as battery swapping stations can offer lower costs (Chen et al., 2018).

To address the particular uncertainty of cost developments for E-buses, results from our sensitivity analysis (% change depot E-bus 2025 TCO compared to the benchmark ICE-bus) with variation of key input parameters are given in Table 6. As can be seen, resulting TCO ranges from 9.0 to 12.2 NOK/km (0.9–1.2 EUR/km). The analysis further shows that the key parameters to which comparative results are most sensitive are the relative number of vehicles required and vehicle capital cost. When an optimistic value is considered for the E-bus vehicle investment cost in 2025 (2.4 MNOK vs. 3 MNOK), TCO in 2025 is calculated as 9.0 NOK/km (10% lower than for an ICE-bus). In contrast, when a less optimistic E-bus investment cost is considered (3.6 MNOK vs. 3 NOK), E-bus TCO in 2025 is calculated as 11.4 NOK/km (13% higher than for an ICE-bus). Changing the assumed number of buses in the fleet to serve a route has a significant effect due to the associated change in vehicle

Table 6
Sensitivity analysis with variation of analysis parameters, using the depot charged E-bus case (2025) as a starting point. Parameters were varied ± 20% with the exception of *vehicles required to serve a route due to charging downtime requirements (lower boundary of −9%), and **vehicle and infrastructure lifetime (variation of 25% due to the annual annuity method used). Results are shaded to indicate the % increase (red) or decrease (green) compared to an ICE-bus.

	Assumption in main analysis	New assumption		Result E-bus, 2025 (NOK/km)	Result vs ICE-bus, 2025 (% increase or decrease)
		Value	% change		
Main analysis	**Parameters as given in Table 3**		**0**	**10.2**	**+1**
Vehicles required to serve a route due to charging downtime requirements (normalised to 1)*	1.1	1.0	-9	9.7	-4
		1.3	+20	11.4	+13
Individual bus driving distance (km/y)	80 000	64 000	-20	11.9	+8
		96 000	+20	9.1	-4
Vehicle and infrastructure lifetime (y)**	8	6	-25	12.2	+9
		10	+25	9.1	-4
Interest on invested capital (%)	3.5	2.8	-20	10.0	+1
		4.2	+20	10.4	+2
Energy costs excl. VAT (NOK/kWh)	1.0	0.8	-20	9.8	-3
		1.2	+20	10.6	+5
Vehicle capital cost (MNOK)	3.0	2.4	-20	9.0	-10
		3.6	+20	11.4	+13
Fuel/energy use (kWh/km)	2.0	1.6	-20	9.8	-3
		2.4	+20	10.6	+5
Maintenance (NOK/km)	1.5	1.2	-20	9.9	-2
		1.8	+20	10.5	+4

capital costs.

In our main calculations, we accounted for an additional 10% E-buses that are needed in the fleet with battery electric technology to deliver the same service level as an ICE fleet due to charging downtime. If it is assumed that by 2025 the fleet use is optimized so these extra vehicles are not required, E-bus TCO is found to be 4% lower than for an ICE bus (compared to ~1% higher with extra vehicles included).

Changing the assumed bus driving distances and lifetime also has a large effect, but in terms of relative changes, these parameters are less significant than E-bus capital costs since the ICE-bus is also affected by these assumptions (moving the baseline). Previous studies also show that E-bus TCO improves in relation to ICE-buses with longer bus routes (Bloomberg New Energy Finance 2018; Blynn and Attanucci 2019), but others note that in practice, this would be uncertain due to battery and charging limitations (Hagman et al., 2017; Amundsen et al., 2018).

As an extension, operator feedback was included that 10% additional buses are a baseline requirement in all fleets for the same service level, to cover all downtime and maintenance in city operation (in addition to the 10% extra E-buses that are accounted for in the main analysis described previously to cover charging downtime). This increases the E-bus TCO with depot charging (for 2025) from 10.2 NOK/km to 10.8 NOK/km, but relative to an ICE-bus that also would require 10% additional buses in reserve, the TCO only increases by ~2 %-points. It was assumed that the increase in fleet size to cover bus downtime did not increase other cost components.

The results thus show that, whilst not currently favorable to ICE-buses in Oslo, E-bus TCO is likely to become favorable by 2025. In the short run, policies are therefore needed to cover the higher TCO or reward zero emission operation, but for urban buses that are mainly tender controlled and with (in Oslo) investment costs covered under tender conditions, this seems to already be the case. Costs for urban buses can therefore be considered less important than for other transport segments and for long-distance buses and coaches that are purchased purely commercially, but are still important to the authorities themselves. This is because if authorities demand zero emission solutions or weight the environment so highly in tenders that zero emission solutions become the only alternative, they risk getting less transport capacity if costs are too high. These results are relevant also elsewhere, although since TCO varies on a case-by-case basis, care must be taken in application.

4. Conclusions and policy implications

The first E-bus trials in Oslo, Norway, showed promising experiences related to comfort, driving experience, energy savings from the efficient electric motor, and relative ease of use within optimized routes in urban areas. Simultaneously, the trials also revealed many challenges including installing streetside fast charging infrastructure within dense urban areas, supplying energy for heating and cooling the buses and potentially dealing with cold winter conditions. Further, the Oslo E-buses were found to have higher TCO than ICE-buses, at 14.9 NOK/km (1.5 EUR/km) vs. 10.2 NOK/km (1.0 EUR/km). Follow up studies are required of the full-fledged E-bus operation ongoing in Oslo, particularly regarding the actual relative number of E-buses needed to deliver the same transport capacity as ICE buses. This was shown to be a factor to which TCO results are particularly sensitive due to associated increases in capital costs, but there was still limited data regarding it at the time of the trials. In addition, a follow up is required to collect experiences of winter conditions, opportunity charging solutions, and maintenance cost differentials (vs. buses with ICE and other technologies) from the larger bus fleets now in use.

Although upcoming larger scale production of E-buses and a projected decrease in investment costs make it likely that E-bus operation will become competitive to ICE-bus operation by 2025, this illustrates a need for support covering higher investment costs to facilitate early-phase adoption. Such support can either come 1) from public tenders, as was mostly the case in Oslo, or alternatively (as in Norway), 2) from a fund supporting early-phase zero emission technologies within other segments of the non-tendered transport industry. For 1), Pressure on public transport authorities to reduce GHG emissions from regional policy makers in Oslo has resulted in change orders to existing contracts, enabling rapid uptake of E-buses. Other means to enforce rapid in-phasing in public tenders are high weighting of the environment or GHG emission reductions as award criteria, or by simply requiring zero-emission solutions. For 2), The state enterprise Enova in Norway offers grants to organizations investing in zero-emission vehicles or publicly available charging infrastructure, covering up to 50% of additional investment costs compared to vehicles with ICE.

These policy factors have seemingly built a business environment for bus operators that drives innovation in new technology and electric bus operation while simultaneously reducing risk. In effect, this policy has pushed bus operators into and awarded them for developing an early adopter company culture, and was evidenced in the interviews by the fact that despite challenges, operators remain highly positive for further E-bus uptake.

Overall, the authorities have thus played a large part in the expanding use of urban E-buses in Norway, and can continue to use their influence to rapidly push towards full electrification targets. However, more is needed to support operators, particularly for facilitating infrastructure development. Since the municipal administration does not yet facilitate fast charging station establishment, E-buses still remain most appropriate where there is a short distance to the bus depot, limiting their use to an extent. Allowing and regulating outside investment to provide common charging infrastructure within city centers may be one solution. These findings are relevant also elsewhere, but care must be taken since there exists much case-specific variation.

CRediT authorship contribution statement

Rebecca Jayne Thorne: Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Inger Beate Hovi:** Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Supervision, Project administration. **Erik Figenbaum:** Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Daniel Ruben Pinchasik:** Writing – original draft, Writing – review & editing. **Astrid Helene Amundsen:** Investigation, Data curation. **Rolf Hagman:** Methodology, Investigation, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enpol.2021.112310.

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