EVS32 Symposium
Lyon, France, May 19-22, 2019

Experiences from trials with battery electric buses in Norway

Inger Beate Hovi[1*], Rebecca Jayne Thorne[1], Erik Figenbaum[1], Astrid Helene Amundsen[1], Rolf Hagman[1] and Daniel Ruben Pinchasik[1]

[1]Institute of Transport Economics (TØI), Gaustadalléen 21, 0349 Oslo, Norway

**Corresponding author: ibh@toi.no*

Executive Summary

This article presents Norwegian battery electric bus (E-bus) operation experiences in Oslo, and barriers and enablers to E-bus use. Results show that experience has been positive, although tailoring has been needed for efficient utilization. Vehicle investment cost remains the greatest challenge, and currently total cost of ownership (TCO) is higher for E-buses than those with internal combustion engine (ICE). Nevertheless, with forthcoming developments E-bus TCO is likely to become competitive by 2025 (9-10 NOK/km for E- and ICE-buses). To speed up phase-in, transport authorities can introduce contract change orders (emphasizing zero emission requirements) and municipal administrations can better facilitate infrastructure-establishment.

Keywords: BEV (battery electric vehicle), bus, case-study, cost

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. Despite efforts over the last decades, transport has not seen the gradual emission decline seen in other sectors [1]. Cities and local authorities have a crucial role in transforming the sector (as laid out in the European Commission's low-emission mobility strategy [2]), through implementing incentives for zero-emission transport use, improving public transport and encouraging active travel. Zero-emission buses are thus considered vital in the transition to a more sustainable urban transport system [3].

Many zero-emission bus pilots/projects have now been initiated globally, including use of battery-electric and hydrogen fuel cell technology. Nonetheless, as of the year 2015, 98 % of these (out of a total of 173,000) were located in China [3]. Within Europe, the effort has mainly been centred opon battery-electric technology; small European pilot projects (involving 1-2 battery electric buses, or 'E-buses') have grown since 2013 into larger pilot projects involving entire bus lines [4]. The focus is mainly on 10-20 km long inner city lines, which permit flexibility for battery capacities and charging options. In the year 2015, there were around 1,000 buses operating solely on batteries (with another 100 fuel cell buses) [3], extending to ~1,560 fully electric buses in operation by the end of 2017 [5]. This represents 1.6 % of all public transport buses in Europe. In Norway, initial practical experience has been gained from E-buses in two cities, Stavanger and Oslo. Oslo will be the European Green Capital in 2019, and has decided to expand the ongoing test operation from 6 to 76 city E-buses, with an additional 39 E-buses in the suburban areas surrounding Oslo.

In addition, there are trial operations with small electric school buses. The increase in the number of European E-bus pilot projects is reflected by a move to larger scale production from European manufacturers.

Whilst advantages of E-buses are apparent (in addition to emission reductions, they are efficient, quiet, have good acceleration and can be charged overnight on electricity produced by any type of power station[6]), there are also challenges. In addition to required improvements in the batteries themselves (and safety issues), electricity storage can be expensive, charging of batteries can be time consuming and requires significant infrastructure, some battery elements have led to resource depletion concerns and there may be damaging grid impacts if not managed properly [6-8]. There are also social acceptance challenges due to e.g. range anxiety. These issues should be overcome and cost-effectiveness to other technologies (e.g. conventional internal combustion engines ('ICE-buses'), hydrogen fuel cells ('H_2-buses') and biodiesel fuel ('Bio-buses') shown, in order to obtain full market penetration of battery technology. Although battery-electric vehicles currently have a higher investment cost than ICE vehicles, large reductions in battery costs are expected [9].

The aim of the present paper is to present experiences gained in trial Norwegian E-bus operation in the Oslo region, including minibuses (up to 17 seats), 12 meter city buses and 18 meter articulated buses. Mapping out the positive and negative user experiences associated and vehicle performance, as well as identifying barriers and enablers to E-bus use from the operator perspective, is crucial to pave the way for further E-bus uptake. In addition, information gathered provides input for an updated assessment comparing the cost competitveness of battery electric technology with other technologies. The study methodology is presented in section 2, analysis of the results in section 3 and conclusions in section 4.

2 Methodology

A sample of Norwegian E-bus operators were identified using the Norwegian Public Road Administration's vehicle registry, Autosys, per April 2018 [10]. These included Nobina, Norgesbuss, Unibuss and Taxus (representing Nedre Romerike Minibuss/Lillestrøm Minibuss). Semi-structured interviews were thereafter conducted as Skype meetings. In addition, other relevant bodies interviewed were the Norwegian Public Road Administration (NPRA, Statens vegvesen), ENOVA and Ruter (the public transport authority for Oslo and Akershus counties in Norway). For operators, persons responsible for investment decisions were interviewed, whilst for government bodies, the person in charge of the activity was interviewed. As preparation, subjects were sent a questionnaire in advance of the meetings. Framed by this focus of the enqiry, the open ended questioning allowed study participants to articulate perceptions freely. For operators, questions related to the process behind the purchase of the E-buses, general information on technology, performance, service/maintenance, charging infrastructure, the decomposed investment (and operation) costs, as well as public frameworks, incentives, dispensation that could contribute to faster phasing in of low emission vehicles. After meetings, subjects were sent interview notes to correct misunderstandings.

The interview analysis was based on qualitative and quantitative content analysis, as defined by Krippendorff [11]. After finalization of interview material, data was analysed in NVivo (Version 12 Plus). Due to the semi-open ended questioning, the interview data was partly grouped according to pre-defined formats, but was also thematically distributed. Thus, categories of meaning were derived from the data through a process of inductive reasoning known as coding units [12]. To ensure accuracy, the autocoding features of NVivo were not used. Thus, the qualitative data analysis software was only used as a tool for efficiency and transparency.

Cost information was combined with prior semi-structured interviews [13, 14], to give updated comparative total costs of ownership (TCO) of E-buses and ICE, H_2 and Bio-buses for years 2017, 2020 and 2025. Costs are given in NOK_{2017} in constant prices. Here, the ICE-bus represents a Euro VI diesel, with mandatory biofuel blend (10 % in 2018 whereby 3.5 % is HVO, at 10 NOK/l [14]), the H_2-bus has a commercial fuel cell (H_2 at 90 NOK/kg [15], assumed to reduce to 0.45 NOK/kg with moderate production increases [16]) and the Bio-bus represents a Euro VI diesel with 100 % advanced renewable biofuel (at 12 NOK/l [14]). The E-bus is assumed to have 1-300 kWh batteries and charging infrastructure (electricity at 1.0 NOK/kWh [14]). TCO calculations do not account for operator risks posed, premamature battery/part changes, any expansion required to the grid, or any residual value after the assumed lifetime (taken as the length of a typical tender period). Refuelling infrastructure for Bio- and ICE-buses was not included (i.e. it was assumed that existing infrastructure can be used), whilst for H_2-buses the infrastructure was included as part of the fuel cost.

3 Results

An overview of the current trials in the Oslo region, a discussion of the E-bus procurement process, and the technology types chosen for testing is given in sections 3.1, 3.2 and 3.3, respectively. A summary of the user experience obtained by the operators is given in section 3.4. All information presented in the results was collected from the interviews. Subsequently, a discussion on technology costs is presented in section 3.5, using information obtained from the operators to present updated TCO figures.

3.1 The trials

E-bus trials were initiated and financed by public transport authorities Ruter in Oslo and Kolumbus in Stavanger. In Oslo, the pilot projects are run between Ruter, Nobina, Unibuss, Norgesbuss and Taxus, whilst in Stavanger they are run between Kolumbus, Boreal Transport, Lyse and ENOVA (note: Norgesbuss has now taken over the driving from Boreal). In general, bus operators are steered by public tenders.

A summary of the E-bus trials in the Oslo region, whose operators formed the core of the interviews, is shown in Table 1. The city buses are part of a seven year trial with Ruter, where terms were equal for all operators but each was free to decide which solutions to test. The trials were intended to be part of existing bus routes (and tender periods), thus a change contract was negotiated. There was no financial risk for the companies, since Ruter covered investment costs and lost transportation efficiency. The electric minibuses were acquired by Taxus AS in connection with a Ruter call for tenders (five years with an optional year extension). Two minibus companies (Nedre Romerike Minibuss AS and Lillestrom Minibuss AS) are subcontractors. Additional cost for E-buses is partly reflected in a higher hourly rate from Ruter for bus operation.

In general, all operators aim to deliver the same transport capabilities as with ICE-buses. Schedule buses are typically operated between 05:00/06:00-00:00 leaving 4-6 hours for depot charging, while the minibuses are only typically operated in morning and evening periods with good opportunities for charging.

Table 1: Electric bus (E-bus) trials currently ongoing in the Oslo region. *Based on the average driving distance of a corresponding ICE-bus. **Calculated from the planned daily operation hours and average speed.

	Operator 1	**Operator 2**	**Operator 3**	**Operator 4**
Type of bus Manufacturer	Articulated bus BYD	City bus Solaris	Mini bus Iveco	City bus Solaris
Model	El-bus	Urbino 12 Electric	El-bus	Urbino 12 Electric
Expected driving range (km/y)	110,000*	74,000-87,000**	12-13,000	60,000
Range on full charge (km)	180	240	160	45-50
Number tested	2	2	10	2
Registration year	2017/2018	2017	2017	2017
Length (m)	18	12	7.13-7.33	12
Battery technology	Lithium iron phosphate (LFP)	Lithium-titanate (LTO)	Sodium-ion (SIB)	Lithium-titanate (LTO)
Battery capacity (kWh)	300	127	90	75
Depot charging	80 kW charger at depot (cable) (300 kW charger planned)	80 kW double charger at depot (250 kW pantograph/150 kW charger at depot planned	11 kW charger at depot (stick wall mount contact)	80 kW twincharger at depot
Opportunity charging		Fast-charger at one station (pantograph)		300 kW chargers at endstations (planned)
Charge time (hours)	3.5	1/0.1 (fast-charging)	4	0.1

3.2 Procurement process

It was generally the operator leadergroups that made decisions for testing battery-electric technology. Nevertheless, some operators stated that drivers also participated in the technical bus specification decisions (and for factory visits where buses were reviewed). Technology is tailored by technology departments to the required topography and operation conditions, and risk and cost benefit analyses are carried out.

Several E-bus manufacturers were available for city bus operators to choose from. One operator stated they initially discussed with 5-6 manufacturers, where price and quality were crucial for the choice. However, this wide choice was not available for all types of buses, especially if it was preferred to manufacture from scratch around the battery to achieve the best possible battery capacity. Purchasing internationally required closer follow-up at the start, and required type approval for Norwegian traffic. A limited selection was also encountered for minibuses; Operator 3 ordered their E-buses from Iveco, who at the time was the only provider available for electric minibuses suitable for use. The limited vehicle supply may be since Norway is one of only a few countries to use 17 seater minibuses with ~8 m length.

Operators could collaborate on charging infrastructure at end stations, but the one who established the infrastructure had preferential rights. Access was regulated in the form of agreements, which seemingly works well. In addition, operators have to cooperate with the municipality for land access.

3.3 Battery and Charger Technology

The batteries were dimensioned out from the route and charging solutions required. Resulting battery capacity utilised by the bus companies ranged between 75 kWh and 300 kWh, with a corresponding range (on full charge) between 45-240 km, given that cabin heating in the winter season is provided by a fuel fired heater system. A summary of the selected battery capacity, associated E-bus range on full charge (nominal from manufacturer), and charger solution chosen by operators is shown in Figure 1.

The battery technology itself varied, depending on route and operation. Operator 2 and 4 chose 127 kWh and 75 kWh lithium titanate (LTO) batteries respectively, of which 85 % is usable. The advantage with LTO is that it can be rapidly charged (up to 400 kW) and has high efficiency. It can also tolerate more charging cycles than other batteries (10,000 versus 3,000, according to the supplier). For new buses, Operator 2 will use 250 kWh lithium nickel manganese cobalt oxide (NMC) batteries, which although can only be charged at maximum 250 kW, are low cost. Operator 3 chose to use 3x30 kWh sodium ion batteries (SIB, $Na\ NiCl_2$), giving 90 kWh total capacity per vehicle. An advantage is that the operating temperature is 270-320 °C, giving little difference in summer and winter performance. SIB lifetime, according to the supplier, is 7-800 charging cycles (approximately 5 years). Operator 1 chose 300 kWh lithium iron phosphate (LFP) batteries.

Regarding charging solutions chosen, due to challenges with establishing fast chargers in Oslo city centre, most operators charge at the depot using 11 kW or 80 kW chargers. One has a fast-charging point at an end station also, but it is rarely used due to bus-line operational issues. Operators have various plans for larger fast-charger installment (e.g. 250 kW with pantograph). In this case, the operator chose pantograph charging where the arm goes up from the bus (rather than down) since they believe that it will cause less wear.

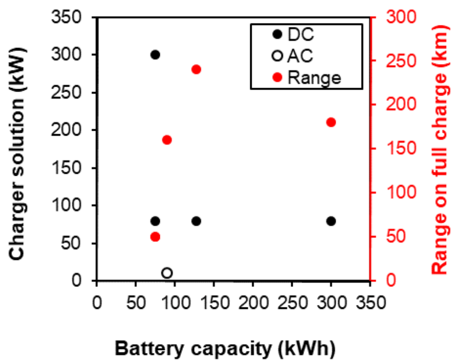


Figure 1: Summary of the battery capacity (kWh) and relating charging solution (AC or DC, kW) used by the E-bus operators. The range on full charge is also shown (red).

3.4 Experience from operation

Table 2 summarises the reported experiences associated with the vehicles for a range of parameters. Subsequently, each parameter indicated in the table is further described in the sections below.

Table 2: Negative (red), positive (green), neutral (yellow) and mixed experiences (orange) associated with the E-bus trials in Oslo. No color means that no information was obtained in the interview.

	Operator 1	**Operator 2**	**Operator 3**	**Operator 4**
Design (3.4.1)	(yellow)	(red)		(yellow)
Owners/drivers/passengers (3.4.2)	(green)	(green)	(orange)	(green)
Energy use (3.4.3)	(yellow)	(red)	(yellow)	
Range (3.4.4)	(yellow)	(red)	(yellow)	
Vehicle performance (3.4.5)	(red)	(red)	(red)	(red)
Charging performance (3.4.6)			(red)	(red)

3.4.1 Design

The general design of the buses used has not been problematic. Nonetheless, for one city bus operator, the added height of the E-bus caused a specific issue on a line due to low underpasses. Although the E-bus has equipment installed to lower it when passing the bridge (via a geofencing system), permission to drive under this bridge has not been gained. Since the lowest E-bus had been chosen, 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. In addition, one street-side oppcharge fast charge station used by this bus had to be lowered to less than the maximum height for road-traffic and has resultingly been hit by passing vehicles. Regarding vehicle capacity, whilst one operator reports a small reduction (two seats) in passenger capacity compared to a regular ICE bus, another states that the capacity is identical for E-buses and buses with ICEs. However, more buses are still needed for the same amount of passenger transport on heavy and frequently trafficated routes due to the added time for charging the buses during the day.

It was also noted that a challenge for regional E-bus operation is access to 15-meter E-buses with three axles. This is primarily a Nordic bus size and the market is therefore too small for these to be currently offered.

3.4.2 Owners/drivers/passengers

It was widely commented that the E-buses contributed to a better environment for the drivers and for the passengers, and generally, feedback from drivers regarding driving the buses was good. For the minibuses, drivers specifically comment that they are easy to drive and flexible in traffic. The biggest challenge is range anxiety. Some drivers do not cope well with it due to concerns for the passengers, and, when the driving range indicated is less than required to get to the endstop, may forget that E-buses additionally charge from regenerative breaking en-route. Due to this, not all drivers want to drive E-buses. In a regular operation based on ICE-buses, two drivers are usually dedicated per bus and each driver works around 154 hours per month. Since E-buses require charging, driver utilization is more complicated, and it was discovered that a higher number of drivers had to be used. To optimize E-bus use, there is therefore a need to optimize the routes to allow for a better utilization of the drivers. In addition, extra training is required in order to drive the E-buses (requiring time). There are also new routines that are different for a bus with a regular ICE (particularly charging routines, which must be followed rigorously to allow for optimal bus utilisation the following day), and it is not just the new drivers, but the whole organisation that must learn how to use the new technology.

Comments were also received that E-bus interest has been high from passengers, the general public and even the press. It was noted that passengers generally have improved comfort compared to when using ICE-buses, associated with the reduced noise and vibrations. However, due to this, it was also commented by one operator that other noises, e.g. connected with ventilation systems, are more noticeable. Similarly, another operator had hoped the buses would be even more quiet, and also highlighted the fan noise (ventilation), which they reported is higher than in ICE-buses.

3.4.3 Energy use

E-bus energy use is significantly lower than those with ICE (Figure 2) at 1-1.5 kWh/km. It is challenging to compare these values to other studies, but [5] estimates a 110 kWh E-bus uses 0.8 kWh/km. However, energy for heating in winter and cooling in summer may not be sourced from the battery without reducing the driving range. This means in practice that energy for heating/cooling must come in addition, and since no heat comes through the floor as for the ICE, this energy may be significant. According to Scania, around 50 % of the energy for operating an E-bus is related to heating and ventilation, and it was estimated by one operator as an additional 1.2 kWh/km. To sort this, additional burners are often installed for interior heating powered by biodiesel (HVO), which is classified as carbon neutral (but not zero emission). However further E-buses from at least one operator will have larger batteries to allow for heating. More frequent charging can also enable electricity to be used for heating and cooling, but the risk is that added charge time requires more buses to run a route and therefore higher costs. Other factors that heavily influence the energy consumption will be the topography, the road conditions and characteristics of the route.

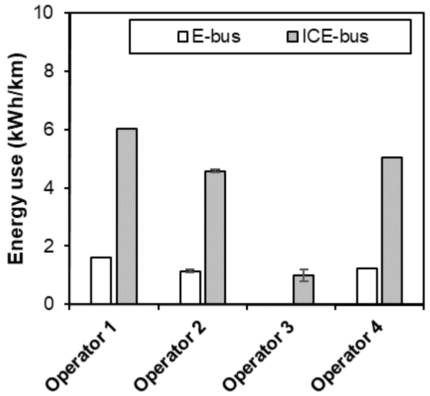


Figure 2: Average energy use reported by the operators per km, for E-buses and buses with ICE. Note: energy for heating the E-buses is additional to that shown on the figure. Energy use for ICE-buses was calculated from the average fuel consumption. Where relevant, error bars show the range reported by operators.

3.4.4 Range/route

The E-buses were intended to service existing lines, but have primarily been used in peak (rush) hours due to various practical challenges related to e.g. charging infrastructure and design. Due to this, route arrangements have been optimized, and driving is normally controlled within good margins of distance and range. One operator has 10 suitable routes for electrical operation, and similarly, the city buses have set routes around the city centre. 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 more buses are needed, if E-buses are put on carefully selected routes.

The theoretical range has been reported by some operators to vary from the actual range, which must be used for route planning. This may be due to the parasitic battery energy use from lights and doors, varying route topography or seasonal variation. Although winter operation was not noted to significantly affect the driving range by one operator, another commented that temperature affected the battery and driving range to a small degree. Both operators use HVO based heaters for interior heating.

3.4.5 Vehicle performance

When working as they should, feedback was that E-buses have good performance (although perhaps lacking power for steep gradients). However, the E-buses have been driven less than expected due to a suite of technical problems ranging from minor to major (Figure 3). Key reasons for reduced operating time are charging problems, reduced range due to winter operation and a number of issues not associated with propulsion (such as door opening closing, warning lights, etc). Major technical problems were reported by one operator, resulting in multiple fleet battery changes in the first year. Others also report part changes due to e.g. major faults in the battery module or electric motor. In contrast, another operator only experienced ‘teething’ problems, which they believe will be sorted out in future production series. Whilst the technical problems have resulted in unforeseen maintenance, it was noted that ordinary services are more straightforward due to there being less brake-wear due to the regenerative braking feature.

The technical issues, as well as other factors related to the technology changes, have led to a decreased driving distance compared to what was originally expected. In the case of one operator, an E-bus had only been driven 5,000 km out of the 60,000 km annual target at the time of the interview (although it was expected it would still reach 25,000 km by the end of the year). For another operator, the E-buses produced half of what they should in the first month. In general, it is necessary for operators to have access to extra buses regardless of propulsion system, due to extra maintenance needs resulting from the extensive use (and resulting time out of service). This also leads to a need to use reserve ICE buses when E-buses need maintenance. Numbers of these are difficult to estimate, but one operator stated that for a fleet of ICE-buses, an extra 10 % buses are needed. However, for E-buses tested in small numbers, reserve buses are often not directly available.

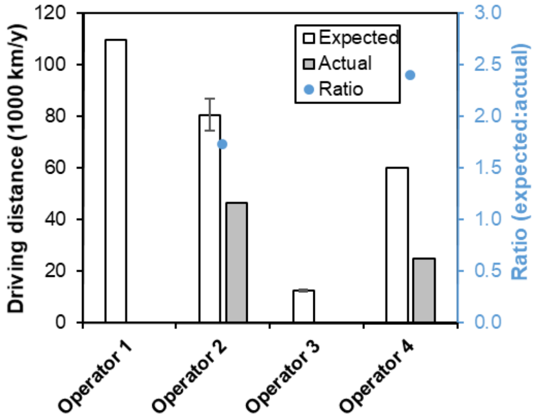


Figure 3: Expected and actual annual driving distances for the E-buses (left axis), and the ratio between these parameters (blue, right axis). Note: where relevant, error bars show the range reported by operators.

3.4.6 Charging performance

Several practical (as well as technical) charging issues were reported. A major problem was highlighted relating to difficulties in establishing charging infrastructure in central dense city zones. Reasons for this are 1) the extensive planning and permitting required and 2) the land-area required (especially for large articulated buses). This has resulted in the 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. Regarding technical issues, one operator commented that the need for a "balance charger" to slow charge the batteries to balance the state of charge of each cell of the battery system has created operational issues. Another reported issues resulting from a need to transform from 230 V to 400 V 3-phase, and that the power available to them (from the grid) has not been strong enough to charge to double power (22 kW instead of 11 kW). Power outages, that could result in stranded buses, have not posed a problem.

3.5 Ownership costs

3.5.1 E-buses

TCO costs associated with the use of E-buses can be broken down into the following components: 1) vehicle investments, 2) charging infrastructure investments, 3) operating costs (energy) and 4) maintenance costs. In this section, a discussion is presented for each of these parameters based on the operator feedback.

The purchase price of an E-bus was quoted by operators as around twice that of a similar bus with ICE (Figure *4*), as also revealed from previous semi-structured interviews [13, 14]. Nevertheless, Scania note that willingness to pay is often higher for buses than for other types of vehicle such as trucks. The battery pack is a significant part of the cost, with some operators citing it as around half the total vehicle cost. In addition, the larger the battery pack, the greater the likely price (Figure 5a) and cost difference vs. an ICE-bus. The investment lifetime was cited by operators as between 5-12 years, with variation due to technology, lengths of bus operation contracts, and operational changes (e.g. minimising fast charging will increase battery lifetime). It was also noted by one operator that the same depreciation period is used for E- and ICE-buses.

Charging infrastructure purchase price is dependent on the solution chosen (Figure 5b). Depot charging can be optimum for trial operation, whilst fast-charging may be more economical where there are a higher number of vehicles used. Fast chargers mounted in depots were cited by operators as costing 0.5-1 MNOK and ~0.4 MNOK, respectively (fully mounted). If using pantographs, additional costs are ~0.2 MNOK (per bus).

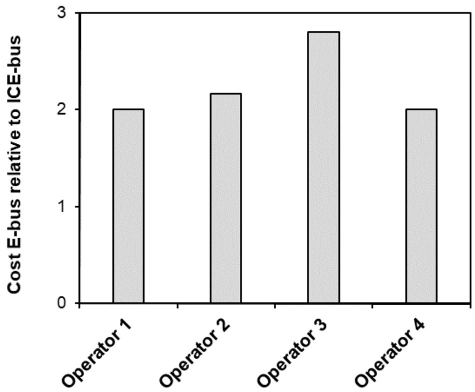


Figure 4: A summary of the investment E-bus costs relative to similar ICE-bus investment costs, as reported by the E-bus operators interviewed.

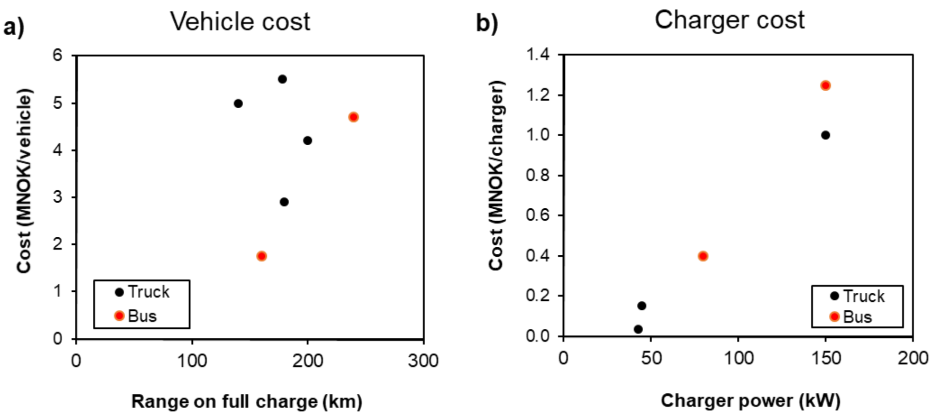


Figure 5: A summary of the investment vehicle (a) and charger (b) costs reported by the operators interviewed. For comparison (and due to the limited data), data gathered for E-trucks, as presented in [17] is also shown.

Although the purchase price per vehicle is higher, operating costs are significantly lower for E-buses. This is both since energy consumption is reduced by around 75 % for electric propulsion versus ICE (Figure *2*), and because the electricity cost (per kWh) may be less than for e.g. diesel fuel. However, one operator added that additional indirect costs have been incurred by them due to the fact that a large reserve of older ICE buses had to be kept to operate during periods of E-bus downtime, that would have otherwise been sold.

Maintenance costs vary depending on whether service agreements are in place, or whether own personnel are used for service and repair. E-buses from international manufacturers are unlikely to have service agreements in place in Norway, meaning that own personnel may be used for service (for everything except for the battery). Regarding maintenance costs, one operator commented that ordinary services are cheaper than regular buses with ICE, due to the lack of brake-wear and oil changes; although it was too early to know specifically, they believed the costs are around 20-30 % lower than for a similar bus with ICE engine. However, others reflected that although they originally thought maintenance costs may be cheaper for E-buses, in practice they are similar to ICE buses, for instance factoring in the risk of battery replacement costs. Due to the considerable cost, the question of whether batteries have to be replaced during bus lifetime is of utmost importance for operators, but little information is available for risk assessment.

3.5.2 Comparisons of total cost of ownership between low emission technologies

A favourable comparison of TCO with both ICE-buses and other low/zero emission technologies is of key importance to E-bus uptake. Ruter expects that by 2025, city E-bus operation will be economically competitive with ICE-bus operation due to increased demand and larger production volumes of both batteries and vehicles. For articulated buses, they believe that economic profitability comes somewhat later (~2028). Some operators also believe that prices will soon be competitive with ICE-buses, although others are concerned that increased demand may actually cause scarcity of raw materials and a price increase. Comparison of TCO between technology types is even less clear to operators. From the supplier side, battery availability (and quality) for both buses and heavy duty vehicles was raised as a concern.

Information obtained from interviews was thus used to calculate E-bus TCO, which was compared to other technologies (H_2-, Bio- and ICE-buses). The bulk of these assumptions are as for [13, 14], but information collected here allowed for updated E-bus parameters for operating energy (increased to include heating energy, i.e. from 0.9 kWh/km to 2.3 kWh/km in 2017), and maintenance costs (adapted to be lower than ICE by 2025, i.e. 1.5 NOK/km instead of 1.8 NOK/km) (Table 3). Charging costs were recalculated assuming 10 E-buses could share the use of two chargers (each at a cost of 1 MNOK), which was divided over the 8 year lifetime of the infrastructure (lifetime was assumed as the typical length of a full tender period). Costs were consequently adapted from 2.2 NOK/km to 0.36 NOK/km in 2017.

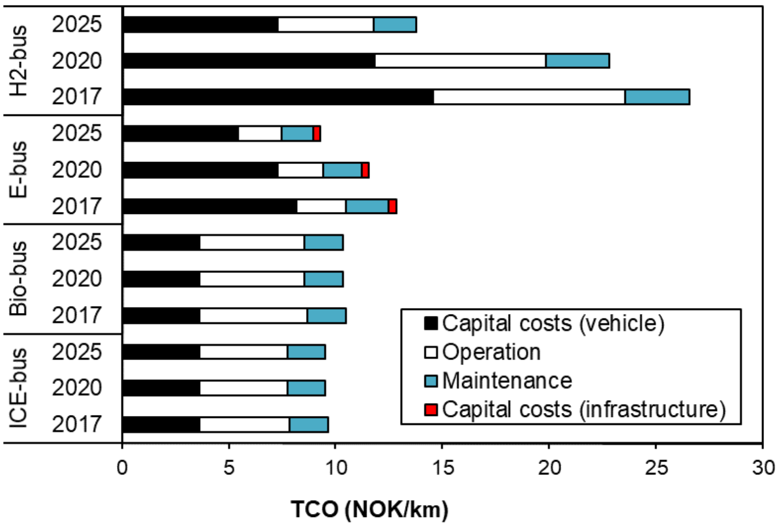


Figure 6: A summary of the total cost of ownership (NOK/km) for E-buses, H_2-buses, Bio-buses and ICE-buses in 2017, 2020 and 2025 (NOK_{2017} in constant prices).

Figure 6 presents the resulting change in TCO, per km driven. For 2017, the ICE-bus TCO was calculated as 9.6 NOK/km. This compares favourably with studies where calculated TCO was 0.92 USD/km (8 NOK/km) for a driving distance of 80,000 km [5] and 1.1 USD/km (9.7 NOK/km) where driving distance was 90,000 km [18]. The results indicate that although in 2017, E- and H_2-buses have a higher TCO than Bio- and ICE-buses (mostly due to the high vehicle capital costs for these technologies), by 2025 E-bus TCO is comparable/favourable with Bio- and ICE-buses (10 % lower TCO than a Bio-bus and 3 % lower TCO than an ICE-bus). In contrast, H_2-bus TCO does not reach competitive levels. Similarly, other studies find that E-bus TCO becomes favourable to ICE-buses by 2025 [18], or is already favourable at the current time [5]; differences between studies are due to variation in assumptions. An example is lower investment costs used in the calculations coupled with a long vehicle lifetime.

The ~30 % reduction in E-bus TCO calculated here between 2017 and 2025 is predominantly due to a reduction in assumed vehicle capital costs, assuming battery market maturity and large-scale E-bus production. Since the greatest cost component is vehicle investment costs, parameters affecting this factor were varied for a sensitivity analysis. Firstly, operator feedback was accounted for that an additional 10 % vehicles are a baseline requirement in all fleets for the same transport demand, to cover downtime and maintenance. It was assumed that the increase in fleet size to cover vehicle downtime did not increase the other cost components. This increased the E-bus TCO (for 2025) from 9.3 NOK/km to 9.8 NOK/km, but relative to an ICE-bus, the TCO only increased by 2 % (i.e. from 3 % lower to 1 % lower). If an optimistic value is considered for the E-bus vehicle investment cost (2.5 MNOK vs. 3 MNOK), TCO in 2025 is reduced by 12 % compared to an ICE-bus. In contrast, if a less optimistic E-bus investment cost is considered (3.5 MNOK vs. 3 NOK), TCO in 2025 is 7 % higher than an ICE-bus. Changing the interest parameter from 3.5 % to 6 % did not greatly change the result.

There are also TCO differences with battery size [5] and charging option [18]. If it is assumed that charging electricity costs 1.5 NOK/kWh, instead of 1 NOK/kWh as assumed in the main analysis, the E-bus in 2025 has a 8 % higher TCO per km than the ICE-bus. This may be more likely when fast charging using a 300 kW fastcharger. Previous studies show that E-bus TCO improves further in relation to ICE-buses with longer bus routes [5], but others note that this is uncertain due to battery and charging limitations [13, 14]. Analysis here for consistency assumes that two fast-chargers may be shared between ten buses, but this assumption would vary in practice.

Due to this variation of TCO with input parameters, results presented here are only indicative and have high associated uncertainty. Nevertheless, it is clear that with mass vehicle production, the potential is high for competitive E-bus TCO compared to other technologies.

Table 3: Assumptions used in the total cost of ownership (TCO) calculations. Note: parameters are adapted from [13, 14], modified based on interviews. *unit of NOK/kWh for E-bus and NOK/kg for H_2-bus. **Calculations assume ten buses share use of two chargers ***unit of kWh/km for E-bus and kg/km for H_2-bus. **** As based on the national freight model, assuming discount rates are low in Norway.

	E-bus			**H_2-bus**			**Bio-bus**			**ICE-bus**		
	2017	**2020**	**2025**	**2017**	**2020**	**2025**	**2017**	**2020**	**2025**	**2017**	**2020**	**2025**
Driving distance (km/y)	80,000			80,000			80,000			80,000		
Vehicle lifetime (y)	8			8			8			8		
Infrastructure lifetime (y)	8											
Interest on invested capital (%)	3.5****			3.5****			3.5****			3.5****		
Fuel costs excl. MVA (NOK/l*)	1			90	80	45	12			10		
Vehicle capital cost (MNOK)	4.5	4.0	3.0	8.0	6.5	4.0	2.0			2.0		
Infrastructure capital cost (MNOK/charger)**	1.00	0.95	0.90									
Fuel/energy use (l/km***)	2.30	2.15	2.00	0.10			0.42	0.41	0.41	0.42	0.41	0.41
Maintenance (NOK/km)	2.0	1.8	1.5	3.0	3.0	2.0	1.8			1.8		

4 Conclusions

E-buses are ideally suited for operation in city centres or other urban areas where zero emissions are required, and can be phased in through new tenders. In order to speed up the phase-in, public transport companies can introduce change orders to existing contracts; this was done in the ongoing trial in Oslo and will also be used in the extended trial commencing this year. Efficient operating schemes for E-buses are even more important than for ICE-buses; this is because E-buses need to be recharged during the working day which can be longer than 18 hours. A higher number of vehicles are thus needed to be able to achieve the same passenger transport volume than with ICE-buses, unless routes and charging times are carefully optimised. However, there are major issues with installing streetside charging infrastructure within urban areas. Although there is a political goal for E-bus operation, the municipal administration does not yet facilitate of fast-charging station establishment. Unless these issues are solved, E-buses will be most appropriate where there is a short distance to the bus depot. The challenge is not to be neglected; bus lines may require two or three buses to fast-charge simultaneously, potentially requiring large amounts of space in dense areas.

The greatest challenge relating to E-buses is their high upfront cost compared to diesel buses. Although operation-related and maintenance costs are comparable (or lower) TCO is currently higher for E-buses than ICE-buses. Nevertheless, with upcoming larger scale production of E-buses and a projected decrease in investment costs, TCO is likely to become competitive with other technology in the coming years.

In summary, bus operators are in general optimistic when considering the future of electric buses. Nevertheless, many agree that a mixture of different propulsion technologies will be optimal for buses in the foreseeable future. Whilst battery-electric buses are ideal to use in city centre areas, hydrogen (fuel cell) vehicles may be more suitable where a longer range is important, highlighting a complementarity between technologies. Crucially, the higher number of E-buses in a fleet, the more careful planning is required to adapt.

Acknowledgments

This work was performed within MoZEES, a Norwegian Centre for Environment-friendly Energy Research (FME), co-sponsored by the Research Council of Norway (project number 257653) and 40 partners from research, industry and the public sector. Thanks are due to interview participants who provided case-study input to this study.

References

1. EEA, *Air quality in Europe - 2018 report. EEA Report No 12/2018*. 2018: European Envionment Agency.
2. EC, *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. A European Strategy for Low-Emission Mobility: COM(2016) 501 final* 2016: European Commission.
3. Bakker, S. and R. Konings, *The transition to zero-emission buses in public transport - The need for institutional innovation.* Transportation Research Part D-Transport and Environment, 2018. **64**: p. 204-215.
4. ZeEUS, *An overview of electric buses in Europe*. 2016: European Commission.
5. Bloomberg New Energy Finance, *Electric Buses in Cities. Driving Towards Cleaner Air and Lower CO2*. 2018.
6. Andwari, A.M., et al., *A review of Battery Electric Vehicle technology and readiness levels.* Renewable & Sustainable Energy Reviews, 2017. **78**: p. 414-430.
7. Golubkov, A.W., et al., *Thermal runaway of large automotive Li-ion batteries.* Rsc Advances, 2018. **8**(70): p. 40172-40186.
8. Hannan, M.A., et al., *State-of-the-Art and Energy Management System of Lithium-Ion Batteries in Electric Vehicle Applications:Issues and Recommendations.* Ieee Access, 2018. **6**: p. 19362-19378.
9. Berckmans, G., et al., *Cost Projection of State of the Art Lithium-Ion Batteries for Electric Vehicles Up to 2030.* Energies, 2017. **10**(9).
10. Statens vegvesen. *Forhandlerregistrering av nye og brukte kjøretøy*. 2018 [cited 2018 1 April]; Available from: https://www.vegvesen.no/kjoretoy/Kjop+og+salg/for-forhandlere.

11. Krippendorff, K., *Content Analysis: An Introduction to Its Methodology (2nd ed.).* 2004, CA: Sage: Thousand Oaks.

12. Stemler, S., *An Overview of Content Analysis* Practical Assessment, Research & Evaluation, 2001. **7**(17).

13. Hagman, R., et al., *Klima- og miljøvennlig transport frem mot 2025. TØI rapport 1571/2017 (in Norwegian)*. 2017.

14. Amundsen, A.H., et al., *Klimatiltak innenfor kollektivtransport. Menon-publikasjon nr. 79/2018.* 2018.

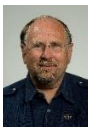
15. Uno X. *Hydrogen: Spørsmål og svar (in Norwegian)*. 2019 [cited 2019 13 March]; Available from: https://unox.no/hydrogen/sporsmal-og-svar/hydrogen-sporsmal-og-svar#2.

16. Greensight, *Hydrogen i tungtransporten (in Norwegian)*. 2017.

17. Hovi, I.B., et al., *Experiences from battery electric truck users in Norway.* EV32 Symposium: Lyon, France, May 19-22 2019, 2019.

18. Gohlich, D., et al., *Design of urban electric bus systems.* Design Science, 2018. **4**: p. 28.

Authors

	**Inger Beate Hovi** is Chief Research Economist at the Institute of Transport Economics. Her research includes freight transport modelling, network models, commodity flow matrices, forecasting freight transport/competition, cost-benefit analysis and effects on local/global emissions. She is responsible for developing forecasts for freight transport for the national transport master plan, is member of Statistics Norway's advisory board for freight transport statistics and has developed the national freight flow survey framework.
	**Rebecca J. Thorne** is a researcher at the Institute of Transport Economics. She has an interdisciplinary background related to industrial processes and sustainability and a PhD in physical chemistry. Her research involves studying battery and hydrogen fuel cells for heavy transport, and policy/techno-economic analysis. Previous experience was at the Norwegian Institute for Air Research (NILU) studying energy/industry and environmental pollution.
	**Erik Figenbaum** is a Chief Research Engineer working at the Institute of Transport Economics. He has an M.Sc. in electrical engineering and leads a research field focusing on energy and emissions from vehicle usage and electromobility. He led the Electromobility+ research project COMPETT between 2012 and 2015. He has previous worked on electromobility and transport sector policy development, led the electrical team that developed the electrical systems for the Think electric vehicle and worked on systems engineering on a later Think model up to 2003.
	**Astrid Amundsen** is a Geographer from the University of Oslo and is a researcher at the Institute of Transport Economics. Her field of expertise covers analyses of the effects of various environmental and security measures, human perception of environmental challenges and attitudes towards transport. She has broad experience as project leader within the fields of road traffic security and environmental issues, and is responsible for the "TØI Environmental Handbook".
	**Rolf Hagman** is a Senior Research Engineer at the Institute of Transport Economics. He has vehicle development experience and has been head of the Norwegian vehicle emission laboratory. Rolf Hagman is a leading independent national expert on vehicle emissions, engine technology and alternative fuels. Recent publications are on emissions, sustainability and particulate traps.
	**Daniel R. Pinchasik** works as Research Economist at the Institute of Transport Economics after previous employment at the Dutch Central Bank. He holds an M.Phil in Environmental Policy and M.Sc in Transport and Environmental Economics. Current activities revolve around freight transport and include (inter)national economic and policy analyses with a large environmental focus. Most recently, Daniel was main author on a report for the Nordic Council of Ministers.