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

Experiences from battery-electric truck users in Norway

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Executive Summary

This paper presents experiences from pilot-projects with battery-electric trucks in Norway, focusing on purchasing processes, technology, vehicle choices, use and different performance aspects. Further, we discuss the electrification potential for light distribution trucks given typical user patterns, and compare ownership costs vs. trucks with internal combustion engine (ICE) for different technological maturity stages. Results show that experiences have generally been positive, but often require tailoring. Further, current battery-electric technology could to some extent cover typical use of ICE-trucks, but is situation-dependent. In terms of costs, battery-electric light distribution trucks first become competitive vs. ICE when technology reaches mass production.

Keywords: BEV (battery-electric vehicle), case study, truck, cost, ZEV (zero-emission vehicle)

1 Introduction

Norway's National Transport Plan for the period 2018-2029 sets ambitious targets for the introduction of zero-emission commercial vehicles as a means to reach goals of reduced CO2 emissions by 2030. By 2025, all new lighter vans are to be zero-emission vehicles. By 2030, the same applies to all new heavy vans and 50% of new Heavy Goods Vehicles (HGV) [1].

Although several manufacturers have announced intentions to start series production in 2019-2020 [2], the market for zero-emission freight vehicles has so far largely consisted of pilots, and most trucks with battery-electric powertrains are rebuilt versions of standard trucks with internal combustion engine (ICE). In Norway, the first battery-electric truck for example became operative as late as September 2016. When starting the current study, in April 2018, this had increased to 7 trucks, while by the end of 2018, the Norwegian fleet still counted only 13 zero-emission trucks, all utilizing battery-electric technology. With these numbers, freight vehicles lag behind compared to zero-emission vans and buses, for which production stages are somewhat more mature [2,3].

The aim of the present paper is to identify and present experiences gained in pilots with battery-electric trucks in Norway so far. Understanding user experiences and the barriers and enablers perceived by operators is crucial for achieving the ambitious uptake of zero-emission vehicles that Norway envisions over the next decade. Building on information from pilot users, the present paper further provides insights into the current potential for electrification. This is done by looking at how pilot vehicle use capabilities relate to typical Norwegian user patterns in the corresponding vehicle segments, and by developing a model that compares ownership costs of battery- (and hydrogen-electric) versus ICE vehicles in a number of scenarios for technology maturity. The latter provides insights in competitiveness, in which cost components are the most important drivers of competitiveness, and in relative cost impacts of a number of policy levies.

2 Methodology

Effectively, the current paper builds on three interrelated analyses: (1) User experiences, (2) Electrification potential in light of typical user patterns, and (3) Comparisons of ownership costs.

Results from the first analysis are presented for different vehicle classes (light and heavy distribution trucks, tractors for semitrailers, refuse collection vehicles, and to a lesser extent vans)[1]. Results from the second and third analysis are only presented for light distribution trucks[2], which also seems to be the vehicle segment with main potential for electrification in the short term, in addition to vans that are already a commercial product category.

2.1 User experiences

To assess user experiences, we carried out a case study based on semi-structured interviews of enterprises with experience in operating battery-electric trucks in Norway. Sample selection was done using the project list of ENOVA [4] (the Norwegian Government Agency for the transition towards a low-emission society), and the Norwegian Public Road Administration's vehicle registry Autosys, as of April 2018 [5]. In addition to truck operators such as freight forwarders, a number of relevant government/public policy bodies and manufacturers were also interviewed.

Interviews themselves were conducted as Skype meetings with people closely involved in investment or policy decisions of each of the identified organizations. As preparation, subjects were sent a questionnaire, after which the open-ended interview questioning allowed them to articulate perceptions freely. To allow clarifications and the correction of any misunderstandings, subjects were sent the interview minutes for comments and approval. Although specifics varied, interview questions related to the vehicle purchase process, general information (technology, performance, service/maintenance, charging infrastructure, use of the existing fleet), decomposed investment and operation costs, as well as public frameworks and incentives that could contribute to faster phasing in of zero-emission vehicles.

2.2 Electrification potential given typical vehicle user patterns

Given the current technology status, an important barrier for the electrification of vehicle fleets are the driving range limitations of battery-electric vehicles, which are especially relevant for freight transport by road. Compared to buses, freight vehicles generally cover larger catchment areas and can have less predictable daily routes, which often also complicates daytime charging. In addition, owners of freight vehicles rely on their vehicles to generate income. Loss of cargo capacity due to large and heavy batteries, or time required for daytime charging translate directly into cost increases, and also lead to more vehicle-km.

In our analysis, we look at the Norwegian potential for electrifying light distribution trucks by relating driving ranges found from the pilot sample, to how light distribution trucks with internal combustion engines are typically used in practice. As a first step, we again used the Autosys registry, but now extended to ICE vehicles and complemented with information from periodic vehicle inspections. The resulting dataset allowed us to assess how annual mileages vary with vehicle age, and which part of the annual driving could potentially also be served with the battery-electric pilot trucks.

However, annual mileages are only one indicator. If there are large day-to-day variations in vehicle usage, electric vehicles will face challenges with respect to battery sizing, predictability, and charging requirements during longer trips, as seen in an analysis of the potential for use of battery-electric vans by Craftsmen [6]. As second step, we therefore used base data from Statistic's Norway's 'survey of trucks' [7] to map daily user patterns and variations. Based on this, we then again looked at whether and to what extent the battery-electric pilot vehicle could be capable of replacing current ICE trucks, given typical user patterns.

[1] A similar analysis for zero-emission buses in Norway is presented separately at the EVS32 symposium [8]

[2] Analyses and results for other vehicle classes will be available in [3].

2.3 Cost competitiveness of electric vs. ICE operation

In our third analysis, we look at the cost-competitiveness of electric vehicles vs. light distribution trucks with internal combustion engines. This is done by developing a model for comparing total costs of ownership. Similar to e.g. [9,10], we established a (detailed) cost function. Here, we distinguish between technology-dependent costs (which vary between technologies), and technology-independent costs (equal or assumed equal for all technologies).

As inputs for our cost function, we use validated base parameters from the National Freight Model for Norway [11]. Amongst others, this means that we consider typical leasing periods of 5 years as period of analysis. For electric vehicles, input parameters are complemented with data collected in the user interviews, , [12], feedback from actors in the Norwegian transport sector, [2], and cost development forecasts [e.g. 13]. Since residual values at the end of the leasing period are uncertain due to the lack of a second-hand market, these are initially set conservatively, after which they increase with maturity phase to the same residual shares as for ICE vehicles. It should be noted that for battery- and hydrogen-electric vehicles, available data on cost premiums and operation is currently still limited in many studies [e.g. 14], but is expected to improve with future adoption. Our flexible model set-up is designed to allow easy incorporation of new estimates, e.g. changes in energy prices or levies.

In short, Table 1 summarizes the cost aspects considered in our model. Not presented in the present paper are costs related to infrastructure construction, charging/filling time, any need for back-up capacity, and any decreases in cargo capacity given heavy batteries.

Table 1. Overview of main cost aspects considered in the cost-comparison model.

Cost category	**Main aspects taken into account**		
Time-dependent	Investment/capital costs excl. subsidies [a]	Depreciation, residual values and discount rate [b]	
Distance-dependent	Energy consumption & cost (base price + any levies)	Road toll charges and exemptions for zero-emission [c]	Driving distances & mileages
Maintenance & repair	General maintenance	Tyres	Wash, etc.
Technology-independent	Wage expenses	Admin & Insurance	Annual weight fee [d]

a *Subsidies are granted only in a limited number of cases, and one of the project's objectives is to illustrate when alternative propulsion vehicles can be competitive on their own.*
b *Residual values for electric vehicles are set to increase with market maturity; low in early stages.*
c *Ferry costs and exemptions not included. Limited data available and very dependent on use location.*
d *The environmental component of the annual weight fee is only marginal.*

Based on the inputs above, we assess four scenarios to illustrate how cost-competitiveness may change with technology maturity and consequent reductions in investment cost premiums[3]: (1) Today's early market phase for battery- and hydrogen-electric vehicles, (2) Small-scale serial production, (3) Small-scale serial production & lower hydrogen prices[4], and (4) Mass production. For all scenarios, we present a decomposed analysis to illustrate the role of different cost components for competitiveness and differences between ICE vehicles and battery- and hydrogen-electric vehicles.

[3] For today's early phase, assumptions on cost premiums of electric vs. ICE vehicles are based on the sources above. For small-scale serial production, battery-electric vehicles are assumed to cost twice as much as corresponding ICE vehicles; hydrogen-electric vehicles three times as much. Under mass production, battery-electric vehicles are assumed to cost 50% more than ICE vehicles; hydrogen vehicles around 95% more. The latter is based on estimates on system cost reductions for MD trucks when production reaches 100k systems a year [15, slide 15].

[4] Today's retail pump price of hydrogen: 90 NOK/kg (~€ 9.25) [16]. Can potentially be halved with self-production (operator interview) or moderate production scale increases [17].

3 Results

3.1 User experiences

3.1.1 The trials

All battery-electric trucks in the sample operate in the South-East of Norway and are used for food distribution, household and business refuse collection, and recycling. At the moment, there are fewer battery-electric trucks in operation in Norway than is the case for electric buses. In addition to higher technological and capacity demands set by freight vehicles, a difference is that the bus market is steered by public tenders (which increasingly include minimum environmental requirements to encourage E-bus trials), while only a small part of the truck market works in this way. Incentives for purchasing electric trucks therefore mainly come from ENOVA-subsidies (which are only available in a limited number of cases cases - not when zero-emission operation already is a public tender requirement - and even then only cover part of the investment cost premium), and advantages such as exemptions from road toll and ferry charges and bus lane access. In some cases, battery-electric trucks have been purchased to (over)fulfill requirements in public tenders.

The battery-electric trucks that operate in Norway vary in power and total weight, and were almost all registered in 2018. All trucks are intended to operate 5 (or even 7) days a week, with 1 to 3 working shifts per day. Expected annual mileages vary from 18 000 to around 120 000 km, depending on the vehicle and typical use patterns in the existing fleet. A summary of the main characteristics of the pilot vehicles in our Norwegian sample is given in Table 2.

Table 2. Electric heavy duty vehicle (E-truck) trials currently ongoing in Norway.

	Operator 1	**Operator 2** [a]	**Operator 3**	**Operator 4**	**Operator 5** [b]
Vehicle type	Truck	Truck	Truck	Truck	Tractor
Manufacturer	MAN/Emoss	Iveco	Dennis Eagle/ PVI (Renault)	MAN/Emoss	MAN/Emoss/ Allison
Expected range (km/y)	50 000 [c]		18 000	80 000 [d]	120 000-130 000
Stated range/charge (km)	180		140	200	178
# of vehicles	1	1	2	1	2
Registration year	2016	2018	2018	2018	2018
Total weight (t)	18.6	5.6	27.0	28.0	50.0
Length (m)	9.0		9.5		
Battery technology			Lithium-ion		Lithium-ion
Battery power (kW)	240	60	240	200	300
Depot charging	2x43 kW chargers		64 A charging at depot	44 kW charger at depot, industry contact	44 kW charger at depot, industry contact
Opportunity charging				150 kW charger planned	2x150 kW fast chargers
Charging time (hrs)	5		8 (overnight)	4.5 [e]. (lunch break/ overnight)	4-6/0.3

a Operator 2 was not available for interview.
b At the time of the interview, operator 5 did not yet have their tractors in regular operation, but had experience from a test-vehicle
c Average value for the fleet, with large variation.
d For a similar (existing) vehicle in the fleet. Source: Autosys Registry and interviews with the operators
e For full charge.

In addition to the vehicles in the table, two primarily light duty battery-electric vehicle (LDV) operators with a mixed fleet were interviewed for comparison. These companies currently do not have regular operations of heavy-duty battery-electric trucks, but one of them had tested a large battery-electric van for 14 days.

3.1.2 Procurement process

Generally, the users of the battery-electric pilot vehicles noted that they wanted to be among the first actors to test new technologies and that a positive environmental profile was important for their firm. In the procurement process of the battery-electric pilot vehicles, one important incentive was formed by financial support from the authorities through ENOVA. ENOVA is financed by an energy fund and can provide support for 40-50% of additional costs of zero-emission trucks, in addition to the full costs of a charging station (depending on the size of the applicant firm). This was the solution taken by several operators. Other operators probed the opportunities for battery-electric vehicles and made a direct offer in a public tender. Here, it was emphasized that it is important that environmental characteristics are weighted more than price.

Although operators found it relatively easy to find potential suppliers (e.g. in Europe or China), long and sometimes uncertain vehicle delivery times, relative to the often limited time between tender results and start of contracts, were identified as a potential risk. Tenders are usually announced around a year before the start of an agreement, and risks are therefore usually related to getting new vehicles delivered on time. Regarding the electric LDV operators interviewed, one operator commented that they have a framework agreement with all major vehicle suppliers, with frequent renewal of the vehicle fleet and leased vehicles in large quantities.

3.1.3 Battery/charger technology

For the larger trucks in the pilots, battery capacities chosen ranged between 200 kWh and 300 kWh, with a corresponding range (on full charge) of between 140-200 km. Where named, the battery-technology itself was lithium-ion (LiB). Regarding charging technology and solutions, most operators reported that vehicles were charged at the depot, due to challenges with establishing fast chargers. A summary of the selected battery capacity (including for vans), associated range on full charge, and charger solution chosen by the operators, is shown in Fig. 1.

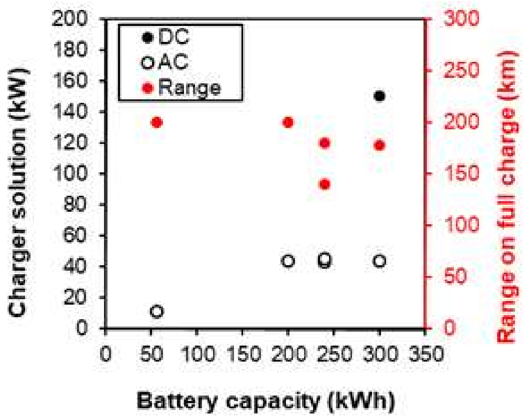

Figure 1. Summary of the battery capacity (kWh) and charging solution (AC or DC, kW) used by the operators. The range on full charge is also shown (in red).

3.1.4 Experience from operation

3.1.4.1 Design

Although the design of the battery-electric trucks did not convey major issues, some user comments were made about a lack of focus on the specific vehicle weight in the bodywork (and associated weight increases due to battery, cooling aggregate, and insulation). Other comments included the limited availability of different vehicle size alternatives. In general, much of the design knowledge for battery-electric trucks has been transferred from buses, with the most important difference being battery dimensioning due to different possibilities for opportunity charging.

3.1.4.1 Vehicle owners/drivers

Despite initial reservations, both managers and drivers are generally pleased with the trucks. Several operators commented that the trucks contribute to a good working environment, and when working properly, are pleasant and fun to drive. The main challenge has been to trust the technology and to overcome range anxiety. Some operators chose to select a few dedicated drivers, to create a sense of 'ownership' of the vehicles (amongst other reasons).

3.1.4.2 Energy use

The energy use of the battery-electric trucks under real-life conditions (per km) proves significantly lower than for ICE vehicles (~1-1.5 kWh/km vs. ~3-8 kWh with ICE, based on fuel use). This has been received positively by the operators, and the same goes for the ability to generate energy when decelerating. However, comments were also made relating to the fact that energy used for waste compressors was sourced directly from the battery and could reduce driving ranges. Also for heating and cooling the cargo and driver's cabin, energy sourced from the battery had an impact on driving ranges. This can particularly be an issue when transporting freight that requires temperature control, and has in some cases been solved using an external HVO-based cooling aggregate. Issues were also reported due to the lack of soft start functions of cooling units.

3.1.4.3 Range/route

Both the vehicle depot locations and daily routes have proven critical in the vehicle trials. Most of the battery-electric vehicles were originally intended to directly replace routes of other ICE vehicles, but in practice, this was not always feasible. In effect, some vehicles were therefore put in operation in central areas, where topographical differences are small and they are deemed most useful (due to low noise and reduction of local emissions). Other operators used careful planning to optimize routes for charging during pick-ups/delivery or breaks.

One operator noted that they avoided starting points at a large distance from the first customers, to avoid too much full-loaded driving and consequent battery-drains. Comments also addressed that when driving patterns vary from day to day, electric vehicles are particularly vulnerable to longer assignments late in the day.

A number of operators further reported that driving ranges did not live up to their expectations, and that ranges used for planning had to be significantly lower than was specified by suppliers. Such issues were also reported for LDVs; this was assumed to be due to the number of stops *en route*, relatively low speed driving, cargo, and route topography.

Different operators also experienced large discrepancies in range between display readings and practice, both positively and negatively. Range differences between summer/winter have so far not been apparent, but there has been little experience with operation during cold days as of yet.

3.1.4.4 Sound/vibrations

In general, the pilot trucks are reported to produce less noise and vibrations than regular ICE vehicles, although in some cases, mechanical noise became more noticeable. Reduced noise/vibrations were received positively, both for the work environment of the drivers/refuse collectors, but also because operators recognized a potential for operation during times of day where noise restrictions preclude ICE operation.

3.1.4.5 Technical/general performance

Experience with the technical/general performance of the trucks has been mixed. One operator reported major technical issues and a lot of downtime. In some cases, troubleshooting/diagnostics and actual repairs took a long time, in part because a service agent was not yet available in Norway. For LDVs and the refuse collection trucks, operators were generally happy with technical performance, and most of the issues reported were relatively minor and attributed to the conversion from diesel to electric powertrains, and teething problems. Examples included warning lights that turned on unexpectedly or a vehicle that stopped several times after washing because of a component that did not withstand water.

Other noteworthy comments included mixed experiences with vehicle traction (good vs. insufficient power under challenging conditions) and a challenge with braking capacity when starting from high terrain. The latter also posed a challenge when batteries were fully charged at the start of a trip, and as such did not have capacity to receive regenerative braking current (this was solved by slightly undercharging the vehicle at the depot).

3.1.4.6 Vehicle capacity

Most operators reported a lower freight capacity for the E-trucks than equivalent ICE vehicles. Reasons given were significant battery weight and in some cases, battery position in the vehicle. In a few cases, reported capacity reductions were so significant that they were considered a bigger issue than range limitations, for example because some heavy goods types could not be transported. In other cases, slight capacity reductions were reported, and in one case, it was the volume, rather than the load weight that limited capacity based on current use. Several policy measures [e.g. 18] and proposals aim to counter capacity reduction challenges by increasing maximum authorized weights for zero-emission vehicles.

3.1.4.7 Charging

Some operators considered the availability and possibility of daytime charging and the number of stops on the route as the most restrictive factor. In addition, various technical issues were also reported relating to charging problems and/or lack of experience. Examples include difficulties with distinguishing whether problems originate in the vehicle or charging point, and (previously unclear) charging restrictions during a 'run-in' period before putting the vehicle in operation. Some issues were also related to the cold Norwegian winter climate, when one of the vehicles sometimes refused to charge outdoors, necessitating indoor facilities. A number of other, more minor technical issues, were mostly resolved quickly.

For battery-electric LDVs, the operators interviewed mentioned challenging power peaks when charging many vehicles simultaneously. Challenges also occurred relating to the availability of grid power when building new terminals, and incentives for the development of charging infrastructure at rented locations. Some operators called for a form of central coordination for smarter charging for the business sector, and load distribution/capacity utilization.

3.1.4.8 Ownership costs

The interviews provided us with detailed information on different cost components, such as battery, chassis, energy, maintenance, chargers, and operation. For reasons of confidentiality, these are not explicitly discussed here, but were an important input for the cost comparisons in section 3.3. In general, however, the interviews suggested that at current cost levels, battery-electric vehicles were between ~1.5-4x the price of corresponding ICE-vehicles, depending on vehicle classes, and that for battery-electric vehicles to be chosen, environmental performance has to be emphasized actively (either through weighting in tenders or by including environmental minimum requirements). Operator expectations on vehicle lifetimes vary. In some cases, this is reflected in how the vehicles are depreciated (either the same or slightly longer write-off periods than ICE trucks).

Operators agree that battery-electric vehicles have significantly lower costs of operation than ICE vehicles. This is particularly due to savings on energy costs and road toll charges (although savings on energy costs are relatively lower compared to passenger cars because of VAT deductions on fuel expenses). Maintenance costs, too, are found to be lower than for ICE vehicles, although savings estimates vary between the operators. It was commented that maintenance expenses are highest when they involve damage to the vehicles, and that in this respect, repair costs between ICE and battery-electric vehicles are similar. Other than this, the largest maintenance costs usually occur after 4-5 years. Battery changes were not expected to be required during the effective vehicle lifetime, but it was commented that this could be relatively expensive, both due to battery costs itself and due to complications from impractical placement within the vehicle.

Overall (and despite the lower maintenance and operating costs), some operators still expect that the battery-electric trucks will be more expensive over a time horizon of 8 years compared to corresponding ICE trucks.

3.1.4.9 Public interest

Several operators reported that public interest is high, and that this extends to both customers and media. One of the operators further commented that both they and their client felt a sense of pride and were happy with the chosen vehicle solution.

3.2 Electrification potential given typical vehicle user patterns

Of the pilot vehicles discussed in our sample, operator 1's battery-electric light distribution truck has a total weight of 18 tonnes, with a 240 kWh battery and 5.5 tonnes cargo capacity. Under optimal conditions, the driving range on a full charge is specified as 180 km. Allowing for 20-25% derating of range in real traffic in winter and a 20 km range buffer at the end of the working day (i.e. ca. 120 km all-year practical range), and provided that daily usage patterns are relatively uniform, the vehicles' potential annual driving distance will thus be about 30 000 km without daytime charging of the battery.

From the Autosys registry and periodic vehicle controls, we obtained a selection of 1 988 ICE distribution trucks in the 12-18t segment[5]. Based on these data, we found that annual mileages decrease with age, with an average mileage for newer trucks of ca. 43 000 km/year. With 50 working weeks and 5 operating days per week, this implies an average of about 172 km/day. In this respect, the effective range of the battery-electric pilot truck appears rather short, even with significant daytime charging during stops. When also looking at maximum annual mileages in this segment, rather than just the average, it becomes clear that many, particularly newer trucks in this segment, far exceed the potential annual range of the battery-electric vehicle.

Looking at trucks of up to 3 years of age, we find that 37% have an annual mileage of up to 30 000 km. Provided relatively uniform daily driving patterns and no daytime charging, this provides an indication of the share of newer distribution trucks that could possibly be replaced by a battery-electric alternative. If significant daytime charging is possible and an annual mileage of 40 000 km could be achieved, this would increase the electrification potential to a maximum of around 55% of newer vehicles.

Because daily usage is not necessarily uniform, we focused further on daily driving, based on a sample of 135 vehicles in the 12-18t segment from Statistic's Norway survey of trucks. Here, we find that trips/ distribution routes[6] of light distribution trucks are on average 108 km long, with a median of 78 km. Although both the median and mean fall within the effective range of the battery-electric pilot truck, the 75th percentile (148 km) suggests that a considerable share of individual trips/routes exceed the electric truck's effective range. Moreover, typical days include multiple trips or routes (in most cases 2 or more per day, with an average of 2.5), implying that in most cases, battery-electric operation still seems ambitious, particularly if daytime charging possibilities are limited.

Finally, Fig. 2. illustrates how average trip lengths vary with the number of trips made per day. It can be seen that distribution trucks with a larger number of trips, on average have relatively short distances per trip. Although this still can amount to sizable daily driving distances, the many stops could potentially allow for significant fast charging, in which case an argument can be made that this sub-segment might be easiest to electrify.

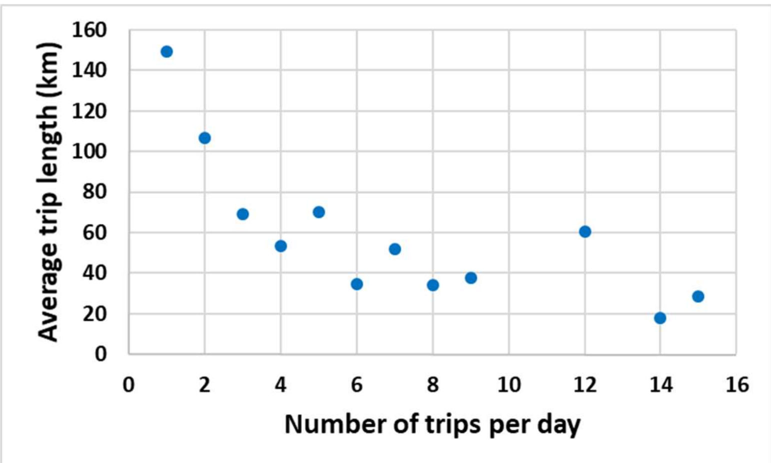

Figure 2. Average trip length (km) vs. number of trips per day per distribution truck in 12-18t total authorized weight class. Source: Statistics Norway's survey of trucks.

[5] Segment defined based on comparability (# of axles) and reduced cargo capacity of battery-electric vs. ICE trucks.
[6] Due to simplified reporting of distribution routes in this survey, distribution routes are recorded as one trip.

3.3 Cost competitiveness of electric vs. ICE operation

Fig. 3. presents results from our Norwegian cost-comparison model for light distribution trucks, at different stages of maturity for battery- and hydrogen-electric technology, including a fall of hydrogen fuel prices (H2 low). For readability, several smaller cost components have been aggregated. Components that differ significantly between technologies or might be used to create policy incentives, however, are presented separately.

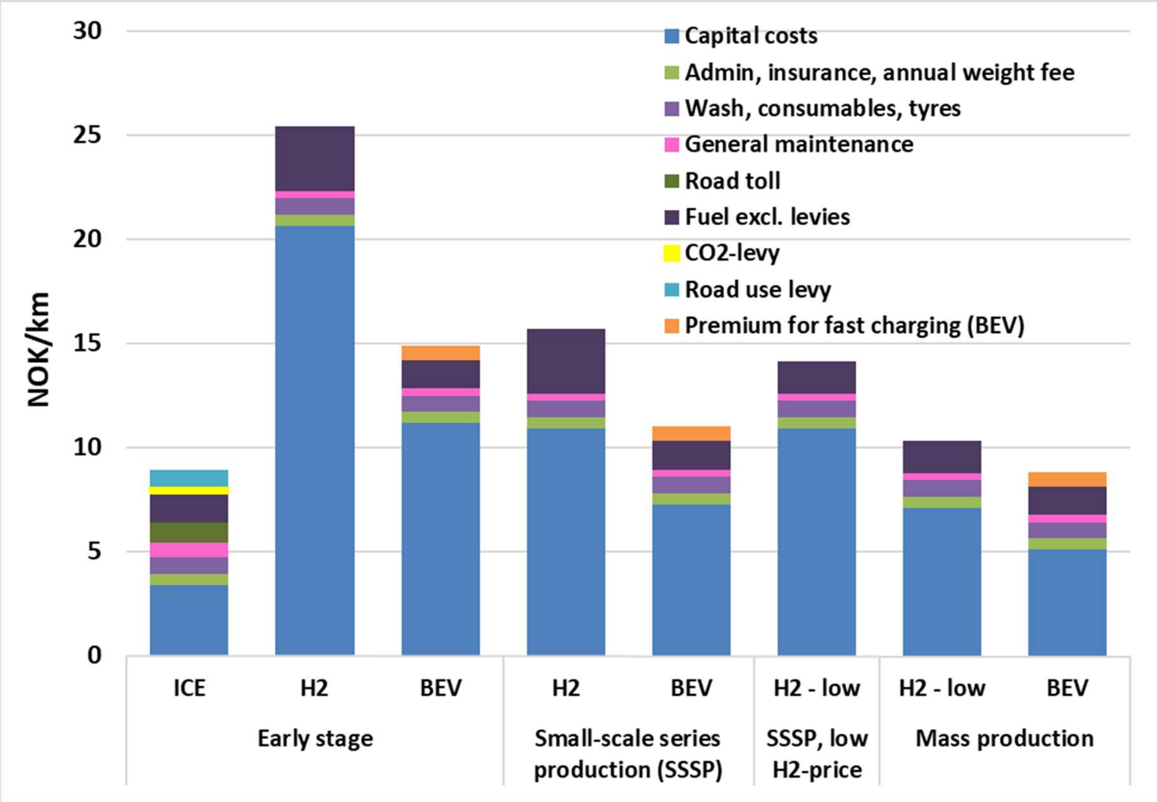

Figure 3. Ownership cost decomposition for light distribution trucks (ICE, BEV (battery-electric) and H2 (hydrogen-electric) in four technological maturity scenarios. Figures in NOK/km.

It can be seen that in today's early stage, ownership costs for light distribution trucks vary from ca. 9 NOK/km with ICE, to ~15 and ~25 NOK/km for battery- and hydrogen-electric vehicles respectively. Although small-scale serial production is seen to considerably reduce these ownership costs, ICE-vehicles still show a significant cost advantantage, even if the price of hydrogen falls by half. It is only in a scenario of mass production that the ownership costs for battery-electric vehicles fall below those of ICE-vehicles. At this point, hydrogen-vehicles are still more expensive at typical annual mileages (45 000 km), but have some potential, particularly within long-haul transport.

When focusing on the individual cost components, we see that capital costs, albeit decreasing with technological maturity stage, remain the main cost driver for electric trucks in the foreseeable future. Administration and insurance costs and the annual weight fee are only minor costs drivers. Even though the weight fee has an environmental component, this component plays such a small role that its effects are marginal at best.

Costs for washing, consumables, and tyres, too, are only a moderate cost driver, and not expected to differ between technologies. Costs for general maintenance, in turn, are expected to be lower for electric vehicles than for ICE, but it can be seen that in the bigger picture, savings are relatively minor.

Looking at energy-related expenses, however, we find some differences. For ICE-vehicles, in addition to fuel costs, operators pay a CO_2-levy and road use levy (together equalling ~2.5 NOK/km). On top of this come road toll charges of around 1 NOK/km. Energy costs for battery-electric vehicles, in turn, are much lower, at under 1.4 NOK/km (or around 2 NOK/km with only fast charging). For hydrogen vehicles, energy costs at current prices are still relatively high, but could fall towards 1.6 NOK/km. These results show that savings on operation costs increase with annual mileage.

Table 3 summarizes at what annual mileages battery- and hydrogen-electric light distribution trucks may become cost competitive with corresponding ICE trucks.

Table 3. Annual mileages (km) required for battery-electric and hydrogen-electric light distribution trucks, respectively, to achieve costs of ownership lower than for ICE. Different stages of technological maturity.

	Early stage	Small-scale serial production (SSSP)	SSSP with low H2-prices	Mass production
Battery-electric	>180 000	>86 000 (regular charging) > 160 000 (given fast charging)		>20 000 (reg. charging) > 38 000 (fast charging)
Hydrogen-electric	Not competitive		>225 000	>93 000

Given typical annual mileages of 45 000 years, it can be seen that battery-electric light distribution trucks cannot cost compete with ICE-vehicles before the stage of mass production is reached, or the vehicle is used very intensively or over long periods. Given mass production, however, battery-electric light distribution trucks may be competitive already with below-average mileages. Hydrogen-electric trucks, in turn, are unlikely to be able to compete on costs in the foreseeable future, even with reduced hydrogen prices. In some cases (e.g. intensive use, long-haul unsuitable for battery-electric trucks, or if technology improves further), hydrogen-electric operation may have some potential.

4 Discussion and conclusions

Currently, the adoption of zero-emission commercial vehicles in Norway is limited, in light of the ambitious targets in Norway's National Transport Plan (for 2025 and 2030), and the contribution that is expected from road transport to CO_2-reduction objectives by 2030.

Experiences from the few pilots in Norway with battery-electric trucks have been promising (especially for waste and recycling trucks), but not in all respects. Although operators are positive about energy savings and lower operation costs, they have generally had to perform considerably tailoring of route/location choices. A number of issues have also been experienced, varying from minor teething problems to a couple of major issues requiring battery/part changes. A number of challenges were, for example, indicated with regard to charging, range, and vehicle capacity reductions. Experience with use in (cold) winter periods has so far been limited, but could bring to light additional challenges.

Looking at typical user patterns for light distribution trucks with internal combustion engines, we found that the majority of newer trucks have annual mileages that considerably exceed the current capability of a battery-electric alternative. Nonetheless, there is also a sub-segment where there is potential for electrification, if daily driving patterns are relatively uniform. Looking at day-to-day variation, however, indicates that in many cases, battery-electric operation using current technology levels will require considerable route tailoring and daytime charging.

If a transition to electric heavy duty transport is to be made, charging infrastructure must be further developed. Although most operators currently use depot charging, an emphasis is increasingly being placed on fast charging. One operator for example suggested that the Norwegian Public Roads Administration should establish fast chargers for HDVs at all its vehicle control stations (weighing stations).

Further, it is important to keep incentives to foster further diffusion of zero-emission trucks, such as ENOVA-support and exemptions of road toll charges (as well as access to bus lanes). The same applies to emphasis on environmental characteristics in public (and private) tenders, as electric solutions might otherwise not be selected due to their current high cost.

Incentives are also important to create demand, in order to speed up the manufacturers' start-up of series productions. Our analysis of ownership costs illustrated that reductions in investment premiums of electric vehicles, through cheaper series and mass production, go a long way to improving the cost-competitiveness of zero-emission solutions compared to ICE-trucks.

In the short term, several of the operators interviewed for this study intend to expand the use of battery-electric vehicles. Driven by tender requirements for zero-emission operation, a number of battery-electric refuse collection vehicles have for example been ordered, as well as several battery-electric tractors with delivery in 2019 (rebuilt from ICE). In addition, multiple operators have placed pre-orders for Tesla tractor units, but emphasize that these are very preliminary given a number of yet unanswered questions on specifications and (tracking) capacity.

All in all, findings in this paper suggest that there might be a growing potential for electrification of commercial vehicles in Norway. Nevertheless, in the years to come incentive schemes, charging solutions, policy facilitation, and technological developments will remain important aspects for zero-emission adoptions.

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.

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