Total costs of ownership

Contents

Abbreviations

The following is a list of abbreviations and associated definitions for terms appearing throughout this document:

Abbreviation	Definition
BET/V	Battery Electric Truck/Vehicle
ERS	Electric Road System
FCET/V	(Hydrogen) Fuel Cell Electric Truck/Vehicle
Fuel Cell	A device that reacts stored hydrogen with oxygen from the air to provide electrical power
ICE	Internal Combustion Engine
HDV	Heavy Duty Vehicle – road vehicle over 3.5T, e.g. HGV, buses, coaches and ‘vocational’ vehicles such as gritters, refuse collection vehicles
HGV	Heavy Goods Vehicle
LCF	Low Carbon Fuels
LCOC	Levelised Cost of Charge
OEM	Original Equipment Manufacturer
RCV	Refuse Collection Vehicle
RTFO	Renewable Transport Fuel Obligation
TCO	Total Cost of Ownership
UK	United Kingdom
US	United States
ZET/V	Zero Emission Truck/Vehicle

1 Introduction

1.1 Purpose of this paper

The purpose of this paper is to provide the Taskforce with an understanding of the Total Cost of Ownership (TCO) of zero emsision decarbonisation technologies compared to diesel, and the factors which influence this financial metric.

1.2 Definitions and assumptions

Zero-emission HGVs or trucks (ZETs) are defined as HGVs that have zero tailpipe (pump to wheel) greenhouse gas emissions at point of use. Embodied emissions associated with the creation, maintenance and disposal of vehicles or infrastructure and production and distribution of energy (well to pump) are recognised as being important but are outside the scope of the Taskforce.

This paper focuses on HGVs and covers the Total Cost of Ownership (TCO) of Battery Electric Trucks (BET) and Hydrogen Fuel Cell Trucks (FCET), a brief reference to Electric Road Systems (ERS) and a comparison with ICE vehicles. Low Carbon Fuels are not covered in this paper.

Other Heavy Duty Vehicles such as buses and refuse collection vehicles are outside the scope of the Zero Emission Truck Taskforce and TCO information for these vehicles is not reported here.

While the cost of financing different capital cost components of TCO and the mechanisms for doing so are important for investment decisions, these are not the focus of this paper and financial models are covered in a separate paper. However, in some instances the cost of financing has been included in the reported TCO calculations. Where this is the case, this has been highlighted.

1.3 Methodology

A mixed methods approach has been used to generate the evidence base for this paper. An initial review of published reports was supplemented by a small number of stakeholder interviews. Information relevant to TCO from interviews undertaken on previous papers has also been used. Information from interview respondents has been anonymised unless also in the public domain.

2 Overview of existing TCO approaches

Total Cost of Ownership (TCO) is a financial metric used to calculate the costs associated with purchasing, running and disposing of HGVs. The method is often used to compare different vehicles on the market and subsequently informs purchasing, leasing, or investment decisions. Different components of the TCO may be relevant to different stakeholders, such as OEMs, financers, leasing companies, energy and infrastructure providers, fleet operators and hauliers, and policy makers. TCO has traditionally been considered to comprise three elements:

- Capital costs (including vehicle cost, taxes and subsidies)
- Operational costs (fuel costs, labour costs, maintenance costs, taxes and subsidies)
- End of life costs

These costs may depend on the economies of scale in production, the use case and driving conditions of the vehicles, the financial models available and the regulatory regime. External factors that influence the availability of materials or fuel prices will also play a role.

TCO is calculated and presented in different ways which impacts on the comparability of calculations and makes agreement on any particular set of TCO values difficult. Key parameters that need to be defined are:

- The period over which the costs are calculated. This can be, for example, the 1st ownership period or the total lifetime, and could be expressed in vehicle-km or years.
- The discount rate (if any) applied. This enables costs that are incurred at different points in time to be combined and compared in terms of their present value in the TCO.

  Note: Inflation can be taken account of by using nominal interest rates with nominal costs or real (deflated) interest rates with real costs.

3 TCO Comparison

3.1 Overview

The ICE HGV market is mature. The production and end of life costs of vehicles are well understood and the operational costs associated with the range of use cases required by Scottish operators are also well known.

The comparison of TCO for alternative technologies is complex as many cost elements of TCO for new technologies are currently uncertain and their future trajectory is not well understood. New costs and potential income streams are also introduced. Moreover, the future values of costs for ICE vehicles may become less certain during the transition to ZEVs (Heavy-Duty's High Performance Green Solution). These will not only be influenced by new costs that may be introduced, such as carbon taxes or road user charges, but also by external factors, such as volatility in energy prices.

There is significant uncertainty regarding many of the components of TCO calculations. This uncertainty is acknowledged in several literature sources which identify the need for greater clarity to enable industry to have the confidence to invest. In particular, evidence specific to the UK is limited, with many UK studies using data from European studies or the US, which may not be directly comparable.

In addition, studies are undertaken for a variety of purposes and may differ in key aspects that have implications for their comparability and transferability to the Scottish context. These differences are discussed in more detail in Section 4 of this report.

However, despite these caveats, observations and common conclusions across the studies can be summarised as:

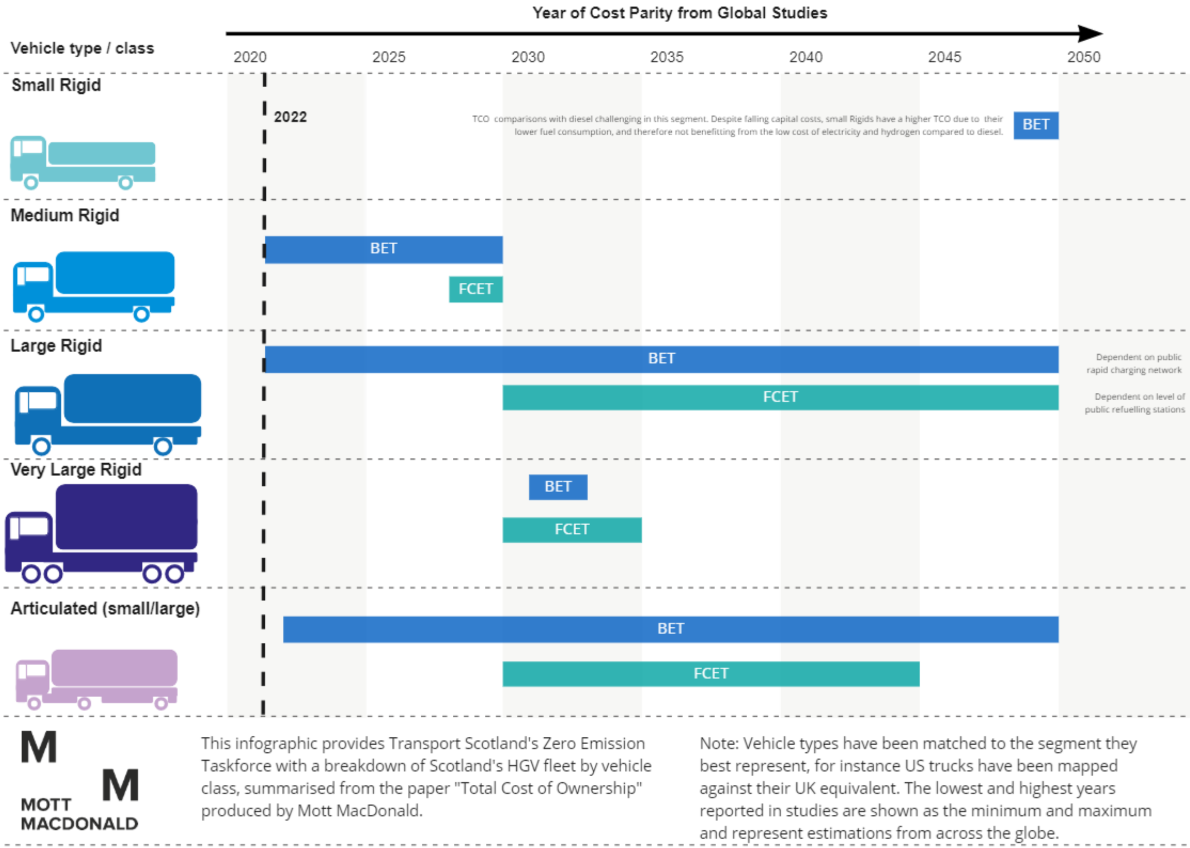
- TCO is a useful metric for comparing ZET and ICE vehicles because the relative contribution of capital, operational and other costs differ across technologies.
- More information is available on TCO for BET than FCET, reflecting the maturity of the technology.
- The capital cost of alternative technologies including BET and FCET are currently higher than their ICE counterparts. The capital costs of FCET are currently higher than BET.
- Capital costs of both BET and FCET are forecasted to drop significantly, with most studies predicting BET to drop more rapidly than FCET. However, this is not a universal conclusion, with some studies predicting BET and FCET will have similar TCOs in the future.
- Operational costs for ZETs are highly dependent on the type of charging or refuelling infrastructure.
- BET are reported as having lower maintenance costs than both ICE and FCET trucks, both now and in the future.
- The end of life value of vehicles is a potentially significant component of TCO but there is very limited information on what future values might be across all technologies or on the contribution of new income streams.

3.2 Cost Parity with ICE Vehicles

The point at which the TCO of different technologies reaches cost parity (cost the same in TCO terms) with ICE trucks is a critical consideration for stakeholders and is the most common analysis included within the studies reviewed.

In the figure below, the range of years over which different studies forecast that ZETs reach cost parity with ICE for different vehicle types are presented. As shown, there is a wide range of forecasts for time to cost parity (and corresponding TCOs) across the studies analysed.

Figure 1: Predicted Year of Cost Parity with ICE Trucks for different vehicle types from global studies



In summary:

- BET and FCET are not currently considered to be cost-competitive with ICE by most studies (and all UK studies). However, several studies from the EU and US report current cost parity for BET (European Federation for T&E, Battery-Electric Truck Users in Norway (2019), ICCT, 2017).
- Futures studies vary in the reported time to cost parity for BET and FCET and the use cases over which each might predominate. Some of these differences can be explained by the underlying assumptions in the TCO calculations. These are discussed further in the following sections of this paper.
- Most studies predict that BET will reach cost parity with ICE vehicles before FCET does. However, this is dependent on vehicle type and use cases. TCO for larger trucks with longer range requirements are more uncertain due to the

limited maturity of technology options.

4 Implications of zero-emissions technologies for TCO

4.1 Introduction

TCO studies are undertaken for a variety of purposes and many differ in key aspects that have implications for their comparability and transferability to the Scottish context, namely:

- Vehicles and use cases
- Costs (and revenues) covered in the TCO
- Methodological and presentational differences
- Regulatory framework

These are summarised in the following sections. A table with additional data on individual studies is provided in Appendix 1.

4.2 Vehicle type and use class

Vehicle type and use cases are key determinants of TCO as they influence vehicle costs, powertrain requirements, infrastructure charging needs and operational costs.

Most studies on TCO compare ICE, BET and FCET technologies as a minimum, although there is more published data on BET and only a small number of studies also consider ERS.

Across these studies, TCO data is only available for a limited set of vehicle types and use cases. These predominantly cover average use cases for three vehicle types: small rigid- urban, large rigid-regional and artic- long haul. A small number of studies focus on large (40t+) trucks (European Federation for T&E, Battery-Electric Truck Users in Norway, Zero-Emission Vehicles Cost Analysis, Hydrogen Council). Vehicles using auxillary equipment such as tail lifts or refrigeration units are not explicitly included in the TCO calculations.

Evidence specific to the UK is limited, with studies providing data for other countries or regions, including the US (A total cost of ownership analysis in Europe, ICCT, 2017), Europe (Feasibility of Heavy Battery Electric Trucks) or using data inputs from outside the UK. Studies from outside the UK, particularly the US, have different vehicle design, duty cycles and driving conditions.

There are differences in the approach taken to vehicle weight and payload. While some studies fix the gross vehicle weight across technologies (European Federation for T&E, Feasibility of Heavy Battery Electric Trucks) and may assume changes in vehicle regulation to enable this (Final report for the committee on climate change (2021)), others include a weight penalty for batteries (Zero-Emission Vehicles Cost Analysis, Hydrogen Council), or fixed vehicle power requirements (Battery-Electric Truck Users, Norway). Battery weight penalties may reduce over time as batteries become more efficient or more rapid charging is available (Final report on climate change, Hydrogen Council).

Energy consumption is a key element in the calculation of fuel/ recharging costs and is influenced by vehicle weight (Feasibility of Heavy Battery Electric Trucks) and vehicle aerodynamics (European Federation for T&E) as well as driving conditions. ICE vehicles are assumed to become more efficient in the future (European Federation for T&E, Battery-Electric Truck Users in Norway) in some studies.

Although data is not often reported in directly comparable units, BET are considered to be more fuel efficient than both ICE and FCET, with most additional gains expected to occur by 2030 (Battery-Electric Truck Users, Norway, Zero-Emission Vehicles Cost Analysis). Current energy consumption in the range 1-1.44kWH/km currently, improving to 0.99 to 1.15kWh/km are reported. Values from US studies (reported in ICCT, 2017) and converting from miles to km are not dissimilar and suggest that diesel trucks use three times more energy than BET, although there is a wider current range. Less data is available for FCET but further efficiency increases beyond 2030 are assumed (Zero-Emission Vehicles Cost Analysis, A total cost of ownership analysis in Europe).

4.3 Cost and revenue components covered in TCO

The transition to ZETs has implications for the traditional cost elements of TCO, such as vehicle capital costs and end of life costs but also introduces potential new revenue streams.

Charging infrastructure, in particular, can influence TCO in several ways. The type and availability of infrastructure has implication for vehicle costs. Charging infrastructure costs for ZETs are often incorporated into operational costs via the refuelling/ charging costs to the end user for both public and private charging infrastructure. However, depot charging infrastructure may have a capital cost element, depending on the model used to finance it. The factors affecting these infrastructure costs are considered in Section 4.3.6. A more detailed analysis of infrastructure is available in a separate paper.

A key caveat in comparing data from studies from different geographical markets is that the prices in these markets may not be directly comparable in addition to being presented in different currencies. In this paper cost information is presented in the currency used in the published study and have not been converted to Sterling to avoid introducing further assumptions.

4.3.1 Vehicle capital costs

In this section the factors influencing vehicle capital costs are considered. The impact of taxes and subsidies on vehicle costs are discussed separately in Section 4.4

There are several new requirements that will need to be considered in the vehicle purchase cost for ZETs that previously were either not considered for ICE trucks or are more uncertain in the future, including energy storage (e.g. battery or hydrogen fuel tank on the vehicle) and powertrain components. There are also assumptions around vehicle design, which may be constrained by regulation; if the vehicle is new or retrofit; battery life; and the type and availability of charging infrastructure, which can affect the energy storage (e.g. battery size) needed to achieve the required range between charges.

Further assumptions that are common to most studies is that cost reductions will occur over time as production is scaled and there are technology improvements. While one interviewee indicated that large OEMs may prefer to focus on production of BET for all use cases, OEMs interviewed for the supply chain paper were developing FCET production capability.

The capital cost of alternative technologies including BET and FCET are currently higher than their ICE counterparts (Decarbonising Road Freight, Total Cost of Ownership for Tractor (2021)). Current estimates for BET range from 110,000 to 450,000 euros, depending on vehicle size, compared to 70,000-150,000 euros for ICE trucks. FCET are also estimated to cost 225,000 to 325,000 euros or three times ICE costs. Current estimates for BET in the US exceed $750,000 in some cases.

While the capital costs of ICE trucks are assumed to increase slightly in the future (ICCT, 2017) or are held constant (A total cost of ownership analysis in Europe), costs for BET and FCET are forecast to drop significantly, although one interviewee indicated that ZET capital costs would always remain higher than ICE at around 100,000 euros). BET costs may decrease more rapidly: one study suggesting a vehicle purchase cost of £140,000 by 2030 for a BET, and a comparable FCET cost by 2050 (Zero-Emission Vehicles Cost Analysis (2022)).

ZET cost reductions are primarily driven by improvements in powertrain and energy storage. It is expected that battery costs will reduce significantly between 2020-2030 by around 50-60% European Federation for T&E, Battery-Electric Truck Users in Norway (2019), ICCT, 2017, Fuel cell electric tractor-trailers (2022)). However, current values used in cost calculations range from 75/kwH to £500/kWh. There is also uncertainty surrounding the cost of replacing batteries in vehicles (European Federation for T&E). Interviewees indicated that OEMs could offer a warranty that would typically cover the first ownership period and half the second. One bus manufacturer has verbally confirmed that bus batteries no longer need to be replaced over the vehicle lifetime, although it is not clear whether this will apply to HGVs in time.

Less information is available on powertrain and energy storage costs for FCET. Fuel cell stacks are currently estimated to be in the range of 250 euros/kWh (A total cost of ownership analysis in Europe, The Feasibility of Heavy Battery Electric Trucks). According to the Hydrogen Council (Electrifying Heavy Duty Vehicles), the cost of hydrogen storage on the vehicle will reduce from 25% of vehicle costs to 15% by 2030 and fuel cell costs will fall by over 60% in the same period, depending on the scale of production.

4.3.2 Operational costs

The cost of energy in the TCO is determined by energy production and distribution costs, infrastructure costs and any taxes and subsidies applied. Comparing energy costs across studies is not straightforward as it is not always clear whether the costs include infrastructure or taxes.

For public charging infrastructure, these costs are included in the end-user (£/kWh) price. How private charging infrastructure costs are included in the TCO will depend on the financial model and could be considered a capital or an operational cost. Several studies use a Levelised Cost of Charge (LCOC) approach to include the cost of infrastructure with the energy cost. Assumptions are made about share of public and private charging and the nature of the charging infrastructure, with the LCOC not only reflecting infrastructure costs but also the potential for fleet owners to negotiate tariffs with charging operators (Zero-Emission Vehicles Cost Analysis (2022), The

Feasibility of Heavy Battery Electric Trucks). Infrastructure costs are considered in more detail in Section 4.3.6.

Taxation is also a key determinant of fuel cost that may be applied differently across technologies, geographies and over time.

None of the studies reviewed for this paper included the effect of energy shocks in their calculations. Reported values for diesel indicated that these were expected to remain constant or increase from 2020 to 2050 (Battery-Electric Truck Users in Norway (2019), Zero-Emission Vehicles Cost Analysis (2022), ICCT, 2017) and that electricity would become cheaper. According to interviews, production costs are the largest component of tanked hydrogen, with transport costs about 25%. Production costs are estimated to account for over 60% of TCO currently but are expected to reduce significantly from $8-10/kg to $4/kg by 2030-35 (A total cost of ownership analysis in Europe, Electrifying Heavy Duty Vehicles). One interviewee did not expect that hydrogen will become cheaper than €3-4 per kg and therefore not be as competitive as BET.

4.3.3 Maintenance costs

Maintenance costs are reported as both annual and per-km values. Most studies suggest that maintenance costs for BEVs are lower than for ICE trucks both now and in the future. For studies reporting annual values, these are in the range 6,000 to 13,000 £/year (European Federation for T&E, Battery electric vehicle diffusion (2016), Zero-Emission Vehicles Cost Analysis (2022)). FCET maintenance costs are assumed to be similar to ICE trucks (Zero-Emission Vehicles Cost Analysis (2022), A total cost of ownership analysis in Europe). More detailed calculations are provided across all technologies by Kleiner et al (8). According to Wang (ICCT, 2017), small differences in costs per mile are sufficient to have a significant impact on TCO cost competitiveness.

4.3.4 Other costs

Labour costs are generally excluded from TCO calculations. There is a general assumption that BET will be charged when truck drivers stop for breaks - fast charging in 45min breaks or overnight charging. A time penalty is imposed in some cases for BET charging time (A total cost of ownership analysis in Europe, Electrifying Heavy Duty Vehicles) , however, any cost of additional driving time to reach refuelling/ recharging stations does not appear to have been explicitly included. Payload limitations due to battery weight and size also add to operational costs (Zero-Emission Vehicles Cost Analysis (2022)). Insurance costs are also typically assumed to be proportionate to vehicle purchase cost.

4.3.5 End of life costs

For the purposes of this paper, end of life costs encompass the residual value of the vehicle at the end of TCO calculation period, which varies across studies.

Currently, ICE trucks can be sold for half their purchase price after around six years, however this could be lower for alternative technologies (Decarbonising Road Freight). One study estimates the resale value of a 40t tractor-trailer BEV (excluding the battery, which is covered separately below) to be around 3% of the initial purchase price, whilst also indicating there will no resale value for FCEV (Decarbonising Road Freight). Whilst the second hand market for ZET is currently unknown, if there is resale value this will have a positive impact on TCO (Battery electric vehicle diffusion (2016)).

There is currently large uncertainty on the residual value of alternative technologies compared to ICE (Decarbonising Road Freight). However, the market and subsequently the residual values of all trucks will also change in the future. According to one interviewee, by the end of the decade, there will be more certainty on the residual value of ZET and less on ICE trucks, which will become more difficult to sell. Wang et al (ICCT, 2017), for example have higher resale values for BET than ICE by 2030. To take account of this uncertainty, most studies either exclude the resale value from the TCO calculations (European Federation for T&E, Battery electric vehicle diffusion (2016)), treat the ZETs in the same way as ICE (JRC Technical Report, Final report for the committee on climate change (2021)) or assume a fixed value for all technologies (Battery-Electric Truck Users in Norway (2019), A total cost of ownership analysis in Europe, Electrifying Heavy Duty Vehicles, The Feasibility of Heavy Battery Electric Trucks).

4.3.6 Infrastructure costs

As noted in Section **Error! Reference source not found.**, the costs of infrastructure often enter the TCO through the refuelling/ recharging costs. For BET and FCET, it is often assumed in these calculations that charging infrastructure (along with vehicle supply) can grow with demand and costs decrease over time with increased utilisation and improved vehicle efficiencies reducing demand (Zero-Emission Vehicles Cost Analysis (2022)). ERS on the other hand requires infrastructure to be built up front (around 800km) and cannot be adapted to levels of utilisation. It requires high frequencies of traffic to be cost competitive (in terms of the infrastructure costs recovered through (per km) user charges) .

Cost calculations for BET and FCET make various assumptions about the different types of charging infrastructure used – depot charging, high power public charging on the road network, public overnight charging and charging at the place of loading/ unloading – each of which have different end user costs associated with them. Interviewees also noted the opportunity for charging at third party sites, where other vehicles (HGV, coach, public sector fleet) can charge at a depot.

Infrastructure costs also depend on the type of infrastructure. Tanked hydrogen has higher distribution costs than onsite electrolysis but lower equipment costs. Fast charging could enable BET to be more competitive for larger trucks but add to infrastructure costs (Hydrogen Council (2020), Electrifying Heavy Duty Vehicles)

One study that tested various infrastructure scenarios found that BEV will be more cost-effective than FCEV by 2050 due to depot and public refuelling options, however as infrastructure for FCEVs will have already been installed by this point in time they will still be used for some operations (Final report for the committee on climate change (2021)).

4.3.7 New revenue streams

Published TCO studies do not consider the impact of new revenue streams, presumably because these are currently too uncertain. There were mixed views on Vehicle-to-Grid (V2G) charging from interviewees, which theoretically enables a vehicle owner to sell electricity from batteries back to the Grid at times of high demand. While vehicle utilisation might not make this as popular as with passenger cars, which are not utilised for long periods, there could still be cost incentives for HGV operators to do this on a case by case basis.

Repurposing of batteries for other purposes, as is currently being done by firms such as Zenobe, is another potential revenue stream; another is recycling materials from lithium-ion batteries. Much of the available evidence focuses on the car market (e.g. Shahjalal et al., 2022). Currently only 5% of EV batteries are recycled, although OEMs are taking action (Where will all the dead cars go?), potentially in response to EU proposals. One study, also focusing on cars, suggests that a huge opportunity exists for recycling in the UK (Automotive Li Battery Recycling), with end of life values of £3.3/kg for BEV batteries and £2.2/kg for PHEV batteries. These represent almost a third of costs for recycling plants with transport costs making up a similar proportion.

The majority of studies present TCO as a fixed amount over a period of time (Final report for the committee on climate change (2021), FREVUE Factsheet, Battery electric vehicle diffusion (2016), Battery-Electric Truck Users in Norway (2019), Zero-Emission Vehicles Cost Analysis (2022), ICCT, 2017) but the time period over which the costs are allocated differ, ranging from a first life of 5 years to vehicle lifetimes of 12 years. Studies reporting TCO per vehicle-km (European Federation for T&E, The Feasibility of Heavy Battery Electric Trucks, Hydrogen Council (2020)) should be comparable to lifetime cost calculations if the total lifetime kilometres are known. A small number of studies also present TCO results per tonne or tonne-km (FREVUE Factsheet, Hydrogen Council (2020), Electrifying Heavy Duty Vehicles)

In addition to the reporting units, studies also differ with respect to the years for which calculations are made and reported. Data is available from studies that only compare current (at the time of publication) costs of ICE trucks and ZET (European Federation for T&E, JRC Technical Report, The Feasibility of Heavy Battery Electric Trucks). In other studies, although TCO may be calculated over a forecast period (commonly to 2030 or 2050), TCO values are not typically reported for every year. The future year for which data is reported may reflect when cost parity is reached or an example future year is selected: TCO data is most commonly available for 2030 (Final report for the committee on climate change (2021), FREVUE Factsheet, Battery-Electric Truck Users in Norway (2019) Battery-Electric Truck Users in Norway (2019), Zero-Emission Vehicles Cost Analysis (2022), Final Report for Transport Scotland (2021)).

It is not clear for all studies what, if any, discount rate has been applied. This affects how the capital and operational costs are combined in the TCO and whether the totals are directly comparable.

4.4 Subsidies and Financial Incentives

The regulatory framework has a strong influence on TCO costs. Subsidies available in the US can reduce BET costs by approximately 50% (ICCT, 2017), whereas the maximum plug-in grant in the UK is £8,000. Fuel taxes also differ. In the UK diesel fuel duty rate has been frozen since 2011 at 57.90p/L and there is a Climate Change Levy on electricity (£-pence 0.81/kWh since April 2020). Subsidies are also available for hydrogen under the RTFO scheme.

The UK implements a time based HGV road charge (£900-1200 pa depending on vehicle type), while EU countries are moving to a distance based road toll (on average 0.15€/km) that could be significantly higher, and are implementing lower costs for ZEV which will impact TCO between ZET and ICE. Vehicle design is also controlled by regulation (see Section 4.3.1).

5 Key findings on TCO and implications for Scottish context

5.1 Key findings on TCO

There are mixed findings on TCO and time to cost parity with ICE for the zero-emission technologies across published studies:

- While BET and FCET are not currently considered to be cost-competitive with ICE by most studies, several studies from the EU and US report current cost parity for BET (European Federation for T&E, Battery-Electric Truck Users in Norway (2019), ICCT, 2017). Interviewees highlighted the lack of TCO parity in the UK and linked it to the lack of fiscal incentives available, suggesting that corporate sustainability policies were currently the main driver of ZET uptake in the UK.
- Futures studies vary in the reported time to cost parity for BET and FCET and the use cases over which each might predominate. Some of these differences can be explained by the underlying assumptions in the TCO calculations.
- Regulatory framework has a strong impact on cost-competitiveness. According to Basma (Battery-Electric Truck Users in Norway (2019)), BET long-haul trucks are already at TCO cost parity with ICE trucks in some European nations due to the adopted policy measures in those countries. Some US studies also show BET are at cost parity now and in future due to subsidies (ICCT, 2017).
- Powertrain and energy costs (influenced by infrastructure) are key drivers of TCO and time to cost parity for ZET is influenced by future assumptions made for these, particularly in relation to how quickly reductions in these costs occur. These may strongly depend on supply side assumptions, such as costs reducing as vehicle and energy production scale
- For the UK, according to one study (Zero-Emission Vehicles Cost Analysis (2022)), without any additional subsidies, BEV could reach price parity with ICE in the late 2030s and FCEVs in the mid 2040s, while another (Final report for the committee on climate change (2021)) suggest that from 2025-2035, despite the high-cost of fuel cells and H2 fuel, BEV and FCEV are relatively cost competitive on a TCO basis as BEV require much larger batteries to meet the needs of long-range vehicle that are also costly. TCO decreases between 2020 and 2030 for BET are reported as being driven by the decrease in the truck purchase price due to battery cost reduction, and by the reduction in the truck operating costs due to truck efficiency and improvement resulting in lower energy costs (Battery-Electric Truck Users in Norway (2019)).
- One EU study (Battery-Electric Truck Users in Norway (2019)), for example, that reported for UK separately found cost parity ranges for 42t BET from 2024-2030, following sensitivity analysis (+-3%) on diesel/electric energy costs. Another from the US (15) found that for long haul, FCEVs dominate even for low electricity prices if hydrogen prices are below $4-5 / kg.
- Infrastructure rollout is a key component of TCO, influencing the end user refuelling/recharging costs; other operating costs if additional time is required for recharging; and BET vehicle costs if larger batteries are needed to achieve sufficient range. In their scenario study for the UK, Element Energy (Final report

for the committee on climate change (2021)) find that from 2035, the rapid expansion of the public mega-charger network makes it possible for HDV with smaller batteries to be a viable option with en-route refuelling, displacing FCET sales.

- There are mixed results in terms of the use cases that BET and FCET are cost effective in. Several studies assume that improvements in powertrain technology and energy that reduce costs occur more slowly for FCET and that FCET are more cost-competitive in long haul segments due to battery size constraints (Final report for the committee on climate change (2021), A total cost of ownership analysis in Europe, Electrifying Heavy Duty Vehicles). However, FCET are also reported to have lower TCO than BET across all segments (FREVUE Factsheet) and BET are also being promoted as suitable for long haul trips (The current and future performance and costs of battery electric trucks and interviews).
- While some studies do undertake sensitivity analysis around their assumptions, published studies do not take account of external shocks that could have a significant impact on TCO cost elements, such as recent energy price volatility.

5.2 Implications for the Scottish Context

- The size of the HGV market in Scotland and the cross-border nature of freight means that other markets may largely determine some of the TCO costs faced by Scottish firms.
- The Scottish freight market is characterised by a mix of vehicle types, daily mileage and driving conditions. While information on TCO for different average use case and the assumptions underpinning them is useful, transferring findings to the Scottish context is challenging, particularly when the limited information available is based on markets outside the UK and there is a large degree of uncertainty.
- Subsidies have been shown to be a key factor in achieving cost parity for ZETs in some countries. Scotland has some powers to provide financial incentives to support ZET deployment but these may be limited in some cases.
- There are a large number of SMEs operating the road haulage sector in Scotland and many operate on tight margins making clear information on TCO even more critical.
- The availability of public infrastructure significantly influences the TCO of zero emission technologies. Certainty around infrastructure plans will help inform TCO information.
- Studies show that powertrain and energy costs are key drivers of TCO. There are opportunities within Scotland to influence these costs through the supply side and to diffuse them using new financial models.
- Maintenance costs can play a significant role in cost-competitiveness, according to some studies. There are opportunities to influence these costs in Scotland through the development of skills.

- There is little evidence on the contribution of income streams that improve the end of life value of ZETs to TCO but there could be local opportunities for Scottish firms, minimising transport costs

Appendix 1 - Key assumptions and findings from selected studies on TCO

								Capital				Operational				Residual		
Ref	**Cost included in TCO**	**Reporting Period**	**Calculation Period and Discount / Interest Rate**	**Technology**	**Vehicle type and distance**	**Fuel efficiency / energy consumption**	**Payload / weight**	**Vehicle purchase**	**Powertrain (if separate)**	**Charging infrastructure**	**Taxes / subsidies**	**Maintenance**	**Fuel / recharge costs (monetary)**	**Other – Labour, insurance, time costs for recharging**	**Taxes / subsidies**	**End of life and other income streams**	**TCO Cost parity results**	**Time to cost parity (years)**
1	Vehicle, personnel, insurance, M&R, fuel, supercharging cost (excluding charging infrastructure)	Not clear. Some elements seem to be current (2018) prices but some data from earlier reports	5 year ownership period Lifetime 150000km per year except ICE average at 110000km	ICE / BET	Type - 40t, for BET class 8 – Tesla Semi, BYD Q3M. one of each type of vehicle but average EU use Distance - ICE operational, best in class. BET 800km, 400km, 160km	Energy efficiency depends on aerodynamics converts ICE L/km to kwH/km (needs kwH/L factor?) 90% battery utilisation rate	All trucks assumed to have same GVW. Lack of data on weight of body and powertrain	Tesla €170,000 (with EU assembly to avoid import tax), 2018 prices BYD €110,000 assumed ICE (best) €110,000 ICE average €80,000	N/A	Not included in calculations although data provided. Based on SDG report but assumptions not explicit. Considers options for overnight charging, opportunity charging, uncontrolled charging but relative costs not considered Estimate charging infrastructure costs at 1-5-2 x vehicle price (initial stage), 60% of vehicle price as tech matures	N/A	€12 500 per year for the ICE (EU data) 50% Ice costs for BET assumed (no battery replacement in first 5 years)	Diesel €1/litre, of which €0.45/litre in excise duty – noted with high confidence Noted uncertainty about electricity costs. Values used not clearly stated in text but notes EU industry average €0.12/kWh (Eurostat non-household use) and Teslad supercharger for car €0.24/kWh	Labour - €50000/year Insurance - proportional to upfront vehicle cost	Diesel €0.45/litr e in excise duty	No resale assumed Grid balancing discussed but not included - suggests benefits limited	Ball park estimates from Fig 2 (€/km) ICE (Average) - 1.09 ICE(best) - 1.01 BET (800km) - 1.05 BET (400km) - 0.99 BET (160km) - 0.98	N/A
3	N/A	Data for publication year	5 year ownership period	ICE, BET, FCET, ERS (CET)	FCET – rigid / artic 6x4 and 4x2. 350-1250km BET – rigid / artic 6x4. 120-400km CET artic 6x2 and 4x2. 65-160km (See Table 2)	See Table 2 FCET: 168-302 kwH/100km BET: 100-140 kwH/100km CET(ERS): 88-147 kwH/100km	Range of GVW (26-40)	See Table 2 BET: €140-180k CET: €158-188k FCET not available	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Assumed same as existing diesel, depending on mileage (see Kleiner)	N/A	N/A
6	Fuel, maintenance, capital cost, depreciation (vehicle purchase – end of life), incentives	2020-2050 forecast period. TCO calc for 2020 to 2035 compared, provided some costs at 5 yearly intervals but mainly reports 2035	6 year ownership period Lifetime small rigid 42000km annual, artic 116000km annual 5% interest on capital	ICE, BET, FCET, ERS	Average vehicle in terms of mileage, payload for each vehicle size (<18t rigid, >18t rigid, up to 44t artic (presumably weighted by expected share of each in fleet). Range 400km by 2035 with depot refuelling	N/A	Allowable mass for diesel + ZET 2t weight allowance and 1m length allowance for artic	Example of rigid BEV in 2035: 70£k glider, 80£k battery + other components=> 172£k Depreciation= capex-residual=£k113 Depreciation (from Fig 61): ICE - 30£k (2020) to 40£k(2035) BEV - 180£k (2020) to £113 by 2035	Battery packs: 3 scenarios with costs 300-500 £/kWh in 2020 to 50-100£/kWH by 2050 Fuel cells: 3 scenarios with costs 50-850 £/kWh in 2020 to 25-50 £/kWh by 2050	N/A	£8000 plug in fuel grant	N/A	50km interval charging points - assumes public refuelling network by 2045 (based on Ricardo peak build rate) different public/depot refuelling options in scenarios mean different fuel costs (se annex tables) - also present in different units for fuel types lifetime fuel costs (large	Labour - Operators are willing and able to recharge the vehicles twice a day, once during the drivers break	N/A	Treated in same way for all tech - % of purchase price? e.g. large rigid BEV 2035: 58£k residual)	N/A	Table 5 provides cost parity as policies: Public HRS - FCET cost parity 2035 Public mega charge - BET cost parity 2035 ERS - BET (with ERS) cost parity 2035 all charging - BET cost parity 2035

								Capital				Operational				Residual		
								FCET - 130£k (2020) to <100£k by 2035					rigid 53,000km annually) from Fig 62					
9	Capital cost – investment / depreciation, financing cost Operational cost – maintenance, personnel, utilities, road tolls, taxes infrastructure – investment / depreciation + O&M	2023, 2030	Ownership period – 1st life 5 years, 2nd life 10 years	ICE, BET, FCET (350 and 700bar), ERS	3 use cases: 1) 40t 4x2 artic, range 140000km annual mileage 2) 27t 6x2 rigid 95000km, 3) 18t 4x2 rigid 90000km Focus on long haul Most common daily and annual km for each use case modelled	N/A	N/A	22% cost premium for FCET in 2023 cf diesel on per vehicle basis and 19% on per tkm basis use case 1 (eur-ct/tkm): 0.25 diesel, 0.2 FCET, 0.3 BEV (excluding powertrain) 2023 use case 2 (eur-ct/tkm): 0.7 diesel, 0.7 FCET, 0.8 BEV (excluding powertrain) 2023 use case 3 (eur-ct/tkm): 1.7 diesel, 1.5 FCET, 1.7 BEV (excluding powertrain) 2023 These equate to similar costs across all technologies for the three use cases 63k euros, 58k euros, 55k euros,	2023 use case 1(eur-ct/tkm): 0.09 diesel, 0.9 FCET, 2.8 BEV 2023 use case 2(eur-ct/tkm): 0.1 diesel, 2.1 FCET, 4,8 BEV 2023 use case 2(eur-ct/tkm): 0.5 diesel, 4.0 FCET, 4.BEV 2023 use case 1(keur/veh): 24 diesel, 240 FCET, 630 BEV 2023 use case 2(keur/veh): 20 diesel,180 FCET, 360 BEV 2023 use case 2(keur/veh): 18 diesel, 140 FCET, 155 BEV	N/A	use case 1 2023 (eur-ct/tkm): 0.03 diesel, 0.1 FCET, 0.2 BEV use case 2 2023 (eur-ct/tkm): 0.1 diesel, 0.3 FCET, 0.4 BEV use case 3 2023 (eur-ct/tkm): 0.2 diesel, 0.5 FCET, 0.6 BEV	Maintenance and insurance use case 1 2023 (eur-ct/tkm): 0.68 diesel, 0.6 FCET, 0.6 BEV use case 2 2023 (eur-ct/tkm): 1.4 diesel,1.4 FCET, 1.5 BEV use case 3 2023 (eur-ct/tkm): 2.3 diesel,2.1 FCET, 2.2 BEV	use case 1 2023 (eur-ct/tkm): 2.4 diesel, 2.4 FCET, 2.0 BEV use case 2 2023 (eur-ct/tkm): 4.5 diesel, 4.1-4.5 FCET,3.6 BEV use case 3 2023 (eur-ct/tkm): 6.7 diesel, 5.9-6.4 FCET,4.9 BEV use case 1 2023 (keur/veh): 600 diesel, 600 FCET, 455 BEV use case 2 2023 (keur/veh): 380 diesel, 380 FCET,270 BEV use case 3 2023 (keur/veh): 220 diesel,230 FCET,160 BEV	N/A	road toll use case 1 2023 (eur-ct/tkm): 0.93 diesel, 0.9 FCET, 1.1 BEV use case 2 2023 (eur-ct/tkm): 2.0 diesel, 1.9 FCET, 2.1 BEV use case 3 2023 (eur-ct/tkm): 3.1 diesel, 2.9 FCET, 3.2BEV	Battery 2nd life - BEV 2023 (eur-ct/tkm): 1) 0.3 2)1.4, 3)1.5 use case 1 2023 (eur-ct/tkm): 0.01 diesel, 0.1 FCET powertrains use case 2 2023 (eur-ct/tkm): 0.1 diesel, 0.8 FCET powertrains use case 3 2023 (eur-ct/tkm): 0.3 diesel, 2.4 FCET powertrains	Total costs keuro (1st+2nd lifetime) Use case 1 illustrative example (Tractor 4x2, 140,000 km annual mileage) Diesel: 1,116(2023), 1,098 (2030) FCET: 1,320(2023), 1,031 (2030) BET: 1,516(2023), 1,173 (2030) Use case 2 illustrative example (Rigid 6x2,95,000 km annual mileage) Diesel: 731(2023), 721(2030) FCET: 838(2023), 672 (2030) BET: 878(2023), 702 (2030) Use case 3 illustrative example (Rigid 4x2 60,000 km annual mileage) Diesel: 468(2023), 463(2030) FCET: 520(2023), 429 (2030) BET: 512(2023), 415 (2030) Use case 1 illustrative example (Tractor 4x2, 140,000 km annual mileage) Diesel: 8.8 €-ct/tkm FCET: 9.5 €-ct/tkm in 2023, 8.1 €-ct/tkm	FCET/dieselCost parity 2027 in illustrative example

								Capital				Operational				Residual		
																	2027, 7.5€-ct/tkm 2030 BET: 11.7 €-ct/tkm in 2023, 9.7 €-ct/tkm 2027, 8.2€-ct/tkm 2030 Use case 2 illustrative example (Rigid 6x2,95,000 km annual mileage) Diesel: 4.4 €-ct/tkm FCET: 5.2 €-ct/tkm in 2023, 4.4 €-ct/tkm 2027, 4.0€-ct/tkm 2030 BET: 6.7 €-ct/tkm in 2023, 5.4 €-ct/tkm 2027, 4,9€-ct/tkm 2030 Use case 3 illustrative example (Rigid 4x2 60,000 km annual mileage) Diesel: 14.0 €-ct/tkm FCET: 14.4 €-ct/tkm in 2023, 12.4 €-ct/tkm 2027,11.7€-ct/tkm 2030 BET: 15.9 €-ct/tkm in 2023, 13.3 €-ct/tkm 2027, 12.1€-ct/tkm 2030	
10	vehicle costs incl. conversion if retrofitted) and battery, charging infrastructure, insurance, maintenance & tyres, taxes, fuel/electricity, subsidies for vehicle price and charging infrastructure	Yearly, 5 years, 10 years but start date (year 0) is not clear	Lifetime - 120km/day (small) 180km/day (medium)+ battery lifetime 10 years	Diesel, BET	Small rigid (12/13 tonne) medium (18/19 tonne) large BET only retrofitted CFV - conventional freight vehicle	N/A	N/A	€70k (CFV) €250k (small)	Not separate	Circa €5k (small)	purchase subsidy (small) €50k infrastructure subsidy (small) €5k taxes CFV circa 2k	BET (small) circa €13k CFV circa €15k	BET (small) circa €13k CFV circa €60k	Insurance - BET (small) circa €13k CFV circa €13k	N/A	Excluded	Estimates from fig 2 (5 year cross section) small BET €250k (incl subs), 300k (excl) CFV (ICE) €155k	Medium rigid almost cost parity after 10 years By driving the maximum number of kilometres the battery allows, about 180km per day, and a purchase subsidy together can almost result in a cost-neutral business case in 10 years, assuming that the lifetime of the EFV and its battery lasts at least 10 years.

								Capital				Operational				Residual		
12	Excludes VAT, includes road tolls	2020-2030 yearly	Lifetime – uses annual VKT by age from EU TRACCS 9.5% discount rate 2% interest rate 5yr loan period	Diesel. BET	Diesel 40t, BET 42t 4x2 (tractor-trailer => artic) 2t additional weight allowance for BET assumed 500km range	Powertrain 350kW (both) presents fuel consumption (kWh/km) for diesel and BET, 2020 and 2030, for 3 payloads - based on simulations uses diesel 30.7l/100km 2020 with 25% reduction in 2030. (Again how converted?) BET 1.38kWh/km in 2020 and 0.99 in 2030.	22.5 to 27.3 tonnes	diesel €133,000 in 2020 (of which 33k trailer) and €145,000 in 2030 BET: over 450k in 2020 to 200k in 2030 (incl battery). Non-powertrain costs 85 k euros (2020) Not clear how get to total values from powertrain and base costs.	250 eur/kWh (2020) decreasing to 60-100 eur/kWh in 2030 Use multipliers but not clear how this is done.	N/A	VAT excluded as pass through cost that can be reclaimed registration and ownership taxes vary by country	N/A	Baseline analysis assumes fixed diesel and electric prices 2020-2030 Sensitivity analysis +/- 3%. For UK find TCO parity ranges from 2024 to 2030.	N/A	Eurovignette - UK time based euro 1000/year. Many EU already distance based - average 0.15 eur/km	Resale value 30% of original after 5yrs	N/A	N/A
14	TCO defined as: system costs (vehicle production costs, fuel production costs, infrastructure costs) but all taxes and levies (AND subsidies?) excluded to focus on economic costs Other taxes on vehicle ownership and use included part of user costs) User costs - operation Labour costs excluded as considered same across all technologies. Cost of electricity grid connection and network and distribution costs included	Reported data for 2020, 2025, 2030. Scenarios to 2050 for decarbonisation	First ownership period used but not specified Lifetime 120000km / yr (480km per day for 250 days)	ICE - diesel but also PtL and dual fuel BET, FCEV and OC-BEV (ERS - overhead catenary) Assumes BEV only for <26t GVW	long haul artic 44t (UK spec). ICE >1900km BEV/FCET 800km	BET efficiency 95%, FCET 76% improving to 85% by 2050. ICE <50% BEV: 1.44 kWh/km 2020, 1.15kWh/km 2030 and then constant FCEt: 2.53 kWH/km 2020, 1.95 2030 and 1.79 by 2050	Max 29.6t (includes calc for payload loss from Bet to 2030) Assumes 50% vehicles have weight limitation.	Vehicle costs mainly from Kuhnel et al (bottom-up calc). Factor of 1.4 for retail margin. Plus BEV penalty for payload. Assume manufacturing capacity at scale for all components ICE: £95k 2020 to £105k 2030 - then constant BEV: £300k 2020 to £140k 2030 - then constant (separate battery pack costs provided - are these included in total cost?) FCET: £225k 2020 to £170k 2030, £144k 2050	BEV: Bloomberg NEF's 2019 forecast for battery packs with 1.4 retail margin. Assumes 1,022kWh battery in 2030 Ricardo low assumptions for battery pack density for technological improvement. Costs £163/kWh in 2020, £69 in 2030 and thereafter constant) FCET: 47kg/70kWH in 2030 Assumes scale production. e.g. for FCET: 1,000 units in 2020, 10,000 units in 2025 and 50,000 units in 2030 based on the U.S. Department of Energy and Moultak et al.	Estimated infrastructure costs are also based on Kühnel et al. They take into account the size and power of the refuelling and charging stations, a high utilisation rate, service life, capital expenditure, operational expenses and the number of supplied vehicles per refuelling or recharging station. Cost reductions to 2030 and then constant Cost calcs based on service life of 15 years: BEV - mix of 1.2MW charger (30 mins for 400km range) and 150kW charger (8 hours for 800km overnight). Both with 15 year lifetime and increasing	UK plug-in grant up to 20% vehicle price or £8000. Assumed 8000 through 2020s •vehicles are the same across all technologies and years £861 p.a.	ICE: circa £16k p.a. BEV: circa £11k p.a. FCET: £21k 2020, decreasing to £15k from 2025	Fuel production costs: Agora PtG/PtL calculator was used to calculate the levelised cost of electricity (LCOE) and the cost of electricity-based fuels produced from it. Renewable source assumed. includes UK-specific network and operating costs as the equivalent to fuel transportation and distribution costs based on cost estimates by the Office of Gas and Electricity Markets (Ofgem). Additional costs if from overseas. PLus grid connection fees. End user prices (incl taxes) ICE: 10.80 £-pence/kWh 2020, 12.60 2030, 17.41 2050	No penalty for BEV - assume charging does not affect operation	Diesel fuel duty rate has been frozen since 2011 57.90p/L (assume no future inflation) Climate Change Levy on electricity(£-pence 0.81/kWh since April 2020) Time based HGV road charge (£900-1200 pa depending on vehicle type)	N/A	2020: ICE 340£k, BET 500£k, FCET 600£k 2025: ICE 330£k, BET 500£k, FCET 470£k 2030: ICE 320£k, BET 325£k, FCET 400£k	N/A

								Capital				Operational				Residual		
										utilisation 2020-30 H2 - fixed refuelling capacity but reducing need per vehicle over time and increased utilisation BEV:£9.5k per veh/per year 2020 to £6.2k er veh/per year 2030 (and then cost) FCET: £4.4k per veh/per year 2020 to £2.3k er veh/per year 2030 (and then cost) Assume these costs are included in end user price for fuel through levelized cost of fuel production Also includes costs for ERS £4.8k pv/pa but no incremental rollout and scaling poss.			electricity: £-pence 19.67/kWh in 2020, 17.87 2030, 15.96 2050 H2 (renewable) £ 5.92/kg to £ 7.17/kg in 2020 OR H2: £-pence 21.50/kWh in 2020, 15.84 2030, 11.09 2050					
15	Vehicle cost, fuel costs (fuel price and fuel economy), maintenance, charging time cost for BEVs Excludes insurance and driver costs	2020-2050	Uses 3-5 yr financial horizon depending on vehicle type. 2-10yr financial horizons may delay or increase parity by up to 6yrs Lifetime - provide annual VMT equivalent for distance bins (graphically) vehicle age modelled but 11 years for HD and 12 years for MD in 201	ICE, BET, FCET, HEV	3 types: class 3, 4-6 (medium) and 7-8 (heavy) Plus 8 different distance/use cases US wide TEMPO model of truck demand BEV: 150, 300,500 miles	ICE fuel economy improves by 32-37% by 2050 fuel economies presented as $/GGE so difficult to work out cost/VMT Improvement for 2020 to 2050($/GGE): ICE - 5 to 8, FCEV 7-15, BEV500 14-26	N/A	($/vehicle) ICE - 120,000 - assumed constant 2020-2050 BEV-500 drop from 500,000 in 2020 to <200,000 in 2035 FCEV: drops from 250,000 in 2020 to parity with diesel in 2035	Batteries: $80/kWh (pack level) in 2035 and $50/kWh in 2050 (330$/kWh 2020) Fuel Cells: $80/kW in 2035 and $60/kW in 2050 (200 $/kWh 2020)	N/A	N/A	Assumed constant over time: class 4-6: ($/mile) 0.118 (ICE), 0.076 (BEV), 0.118 (FCEV) class7-8: ($/mile) 0.152 (ICE), 0.098 (BEV), 0.153 (FCEV)	BEV:$0.18/kWh by 2030 and is held constant through 2050 FCEV : $4/kg by 2035 and is held constant through 2050 BEV charging progressively available, FCEV charging fully available by 2040 More conservative electricity pricing means longer range BEVs do not reach cost parity	BEV are penalized if trucks need to add an intraday stop to recharge: value of time added to charging costs ($75/h). Only applies to long-haul if exceeds range, short haul (<500 miles) overnight charging assumed Labour and insurance assumed constant across all technologies	Assume d constant across all technolo gies	N/A	N/A	2035 - all ZEV medium and heavy duty (without incentives) BEV cost parity before 2030 for short range, 2032 for long haul, FCEV by 2035

								Capital				Operational				Residual		
16	initial purchase costs or CAPEX (powertrain, energy storage, rest of truck), purchase subsidies, scrappage value, operating costs (tolls, fuel, labour, O&M, insurance)	2021 values	8 years HDTAnnual km 156,000 HDT 7% discount rate	ICE, ICE-NG (natural gas truck), HET (hybrid) , BET, FCET	3 road freight vehicle segments Weight/distance combinations): LDT-Urban, MDT-Regional and HDT-Long-haul. Assumes fixed daily range across all tech: 600km	Energy requirements for technologies based on fixed power requirement. Fuel consumption (/km) depends on weight, using log profile	Fixed assumptions across all tech for payload, weight and utilisation	A gross margin of 24.3% (sum of OEM margin, dealer margin, and logistics margin) is assumed for all drive-technologies Truck (excluding powertrain and energy storage) - eur/vehicle (2019 prices): HDT 58,000 Combined data (from figures) indicate: HDT: ICE 150keuro, BET 390keuro, FCET 325keuro	Energy storage (eur/kWh): Battery 140, diesel fuel tank 0.21, H2 fuel tank (700bar) 25. H2 prices also per vehicle up to 42,000 eur. Powertrain: range of components incl power electronics with separate costs. Diesel engine 40 euro/kW, electric motor 32 eur/kW, fuel cell stack 250 eur/kW Energy storage sig proportion of vehicle costs for BET. Powertrain more significant for FCET.	Infrastructure costs for ICE-D, HET, FCET, and ICE-NG vehicles are included in the fuel cost of diesel, hydrogen and natural gas, as use pump prices that include margins which cover the cost of the petrol station. For electricity, cost of charging infrastructure included, Levelised cost of charging (LCOC) covers equipment, installation, O&M discounted over infrastructure lifetime and electricity cost itself. Cost used are based on 150kW charging for 5 units per site, 12 hours a day. 250keuro equipment and installation costs. Not clear if assumptions made about how much depot and public recharging used.	None Insurance fees are assumed to be 2% of the CAPEX	Uses Kleiner Baseline O&M for ICE and % scaling for other tech	Probabilistic approach for price projections based on historical data to 2019. For electricity based this on commercial sector annual consumption level of 500-2000MWh (Eurostat) Assume a symmetric PERT distribution with a most likely value of ~8 €/kg-H2, and +/− 1 €/kg-H2 range. This is the 2021 average hydrogen pump price in Germany (VAT exclusive)	N/A	Tolls - county specific: zero for UK	N/A	N/A	N/A
17	capital, salary, insurance, time	Looks at effect of battery cost on ability to be competitive with ICE as a function of tkm (and vkm), not over time	N/A	BET - consider 3 different battery cost, cycle life and specific energy combinations	Range of GVW (10 to 100t) 40t used for most cost comparisons presented average use case: 290km 75% free flow (80km/hr) and 25% congested (20km/hr)	PS1: 125WH/kg (1000 cycles) PS2: 175 WH/kg, 5000 cycles) PS3: 150WH/kg (3000 cycles) higher efficiency of electric powertrain: 2.5 times (4.2 congestion)	Assume batteries take up share of load capacity relative to ICE of same weight. share of load capacity taken up by battery decreases with weight of truck.	Results hinge on vehicles being redesigned for batteries or use of rigids Price weight dependent	Energy costs are where main gain occurs for BET or ICE Powertrain costs/km depend on cost/kWh and cycle life and vehicle weight as larger vehicle needs bigger pack PS1 : 300 USD/kWH	Possible to use multiple parallel 150 or 350kW chargers already used for cars. Fast charging network assumed to expanded as needed	N/A	40% lower maintenance cost for battery electric trucks (cost is function of truck purchase price)	global average diesel and electricity costs are approximately the same per kWh Costs sensitive to fuel cost assumptions for both diesel and electric.	Fast charging during 40 min after 4.5 hrs (half shift) to 80% but this adds additional 15% to delivery of ICE (not included in costs except for driver costs)	N/A	N/A	N/A	Modelling shows competitive when battery costs 200USD/kWh and cycle life of 3000

								Capital				Operational				Residual		
							Load capacity increases faster than energy consumption and vehicle costs with increasing GVW		PS2: 100 USD/kWH PS3: 200 USD/kWH									
18	vehicle, fuel, refuelling time	2020-2050. Some results for 2030. Trajectories to 2050.	N/A	FCET but compares to BET and ICE	3 cases considered: 7.5t, 300km range (urban) 13t 500km range (regional) 22.5t, 600km range (long-haul) Calculations based on annual sales volumes of 150,000 by 2030 Range expected to reduce by 60% by 2030.	N/A	N/A	2020: FCET 3x ICE cost (incl tanks and powertrain) 2030: FCET 1.2x ICE 22% TCO 2030 for MDT (of which 20% non-powertrain and 2% assembly) H2 tank 25% of HDT vehicle cost (not sure if this vehicle cost includes/excludes powertrain). Expected to be 15% of cost by 2030. Multiple options for tanks exist (350 or 700 bar pressure) or in future hydrogen at atmospheric pressure (less space and weight)	Fuel cell powertrain 20% TCO (2020?) all segments 13% TCO for MDT (2030) 70-80% reductions in cost by 2030 for volume sales. (60-5% even for 10,000) For BET - MDT/HDT batteries 600-900kWh	BET: fast chargers could reduce battery size but add to infrastructure costs Current chargers 200-250kw) FCET: Assumes scale up to match projected sales	N/A	N/A	Hydrogen production (40%) and distribution (25%) >60% of TCO in 2020. Expected to reduce by 60% by 2030. Will account for 80% Tco reduction MDT/LDT and 60% for LDT 4-5 USD/kg H2 for break even (dependent on diesel cost) cf 8-10$/kg 2020. Occurs by 2030 assuming large scale up Commercial mobility applications viable around 3$/kg	Longer charging times for BET	N/A	N/A	TCO for FCET (HD) expected to reduce by 50% by 2030 By 2040 (from graph): LDT - FCET (and BEV) 0.11 USD/tkm, ICE 0.17 USD/tkm MDT - FCET 0.05 USD/tkm, ICE 0.07 USD/tkm (BET 0.06 USD/tkm) HDT - FCET (and BEV) 0.03 USD/tkm, ICE 0.05 USD/tkm	Lower cost than BEV for HDT by 2025, parity with ICE before 2030 (in some regions and dependent on diesel cost)
19	use, production, maintenance, recovery	N/A	N/A	ICE, BET, FCET	Suggests valid for range of use cases including refuse, mixer, lifter	FCEVs more fuel efficient that ICEs and also recover energy braking or downhill.	N/A	N/A	N/A	Provides 2035 split across charging locations: LH 50-55% depot, 10-15% destination, 30-35% public regional: 60% depot, 20% destination, 20% public urban 75-85% depot, 10% destination, 10% public => 90GW EU depot capacity, 10% public	N/A	5% TCO MDt 2030	cf 8-10$/kg 2020	N/A	N/A	N/A	N/A	N/A
20	Depends on paper but as minimum vehicle, fuel and O&R. Comparison	Mainly current (usually 2020) to 2030, some also 2035 and 2040	Ownership period 5-15 yrs	ICE, BET, FCET	Various US most studies appear to cover standard use	Reported in kWh/miles long haul: BEV: 1.3 to 3.8 (current),	N/A	Most studies show small increase in ICE price and decrease in BET over time (except	Most studies show 50% or greater reduction in	Mostly provided separately from fuel costs (charger and infrastructure	LCFS credits make significant difference to TCO, reducing	Long haul: ICE 0.16-0.44$/mile	Most studies show increase in both diesel and electricity	N/A	N/A	Residual value around $30,000-50,000 for diesel and	Results presented as mixture of /mile and total. For NREL, lifetime	N/A

								Capital				Operational				Residual		
	table shows that different studies differ in whether include (and/or report) residual value in vehicle costs, how infrastructure costs included in fuel, what subsidies/taxes are in place. Not clear if labour costs in O&R		2-10% discount rate		case for each vehicle type Long haul - 85-170,000 miles annually short haul 30-80,000 miles annually delivery trucks up to 30,000 miles annually	1.3 to 2 (future), ICE around 6-8mpg current but increasing to >10mpg in future in some studies		CALSTART constant) long haul: ICE $100k to $250 (current) BET: $250k-850k (current) and $150k-300k (future)	battery cost to 2030. Battery size variation from 500kWh to 2000kWh Long haul - current cost: $150/kWh to $375/kWH Future cost: 60-160 $/kWh (2030)	together) - UCLA study includes in fuel costs	lifetime costs by approx 50%. HVIP and charger incentive also available as well as California specific incentives.	BEV 0.06 - 0.23$/mile BEV always less than ICE but difference varies by stud	cost over time (or const) ICE: 3-5 $/gal, BEV 0.1-0.4 $/kWh			$50,000-80,000 for BEV. Exception one study where BEV $206,000	value is 1 million x /mile value long haul: ICE (current) $1.20/mile to $1.64/mile or $400,000 to $2.5 milion/veh lifetime ICE (future) $500,000 to $1.25 milion/veh lifetime BET (current) $1.20/mile to $1.64/mile or $400,000 to $2.5 milion/veh lifetime ICE (future) $500,000 to $1.25 milion/veh lifetime short-haul:	

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