4. COST COMPARISON OF HYDROGEN, BATTERY ELECTRIC AND DIESEL TRUCKS - WHICH DECARBONIZATION PATHWAY IS THE MOST COST EFFECTIVE?

4.1 OVERVIEW

What follows is an in-depth analysis of the total cost of ownership (TCO) where we compare real-world capital costs, fuel costs, maintenance costs and taxation for battery electric trucks (BETs), fuel cell electric trucks (FCETs) and diesel trucks. The analysis that follows shows which decarbonization pathway is the most cost effective.

Where BETs have already reached TCO parity across much of Europe, there is no reasonable time period in which FCETs will achieve such parity due to the capital cost and the cost of the hydrogen fuel. The cost of hydrogen fuel impacts the TCO across all regions as the cost per kg combined with fuel efficiency will considerably add to the capital costs, helping blow hydrogen out of any economical calculation on total cost of ownership.

Using Ti estimates, combined with models from the International Council for Clean Transportation and Transport Environment, we conclude that BETs have already reached cost parity with internal combustion engine diesel trucks. This varies regionally, with different political policies on low emissions transport affecting TCO.

4.2 CAPITAL COSTS FOR DIESEL, BET AND FCET

Figure 4.1 Comparative Capital Costs

	€ per unit
FCET	
Nikola Tre FCEV	825,000
BET	
Tesla Semi	276,000
Diesel	
ICCT Model tractor/trailer unit	133,000

Source: Various sources

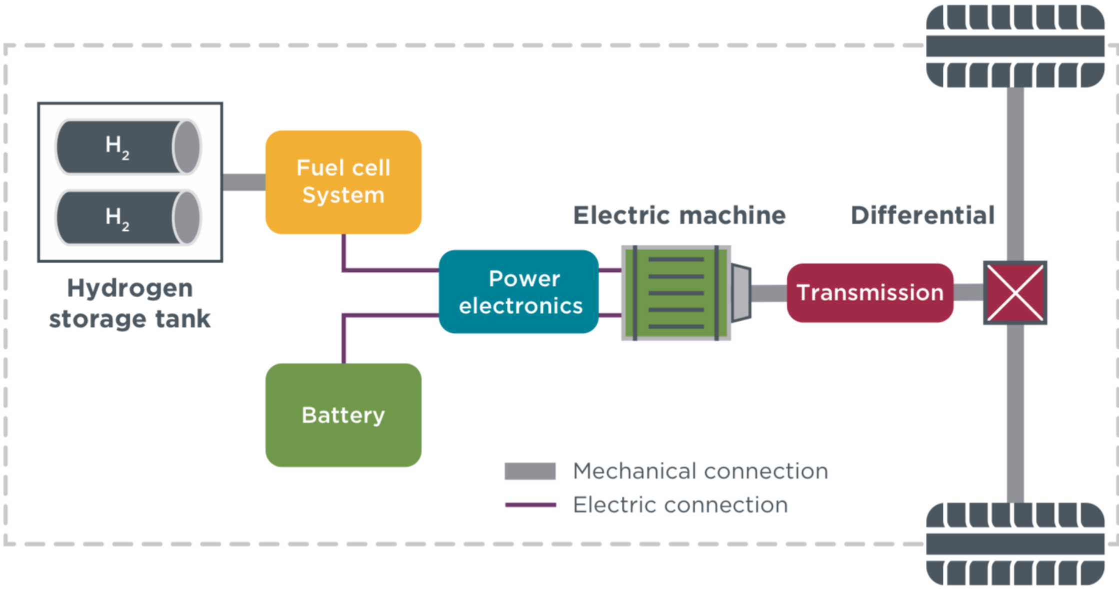
Capital costs have always been the issue that makes purchasers baulk. The Tesla Semi costs double that of a typical diesel truck and trailer unit and the Nikola Tre FCET, excluding government incentives, almost six times that of a diesel equivalent.

Costly components

Put simply, a diesel tank costs less than a battery on a BET that also stores energy. The FCET also has a large battery, though around 75kWh compared to the 450kWh battery of a BET vehicle.

The drive units of the diesel vehicle and the FCET are also very complex - far more complex than that of a BET vehicle whose drivetrain simplicity is a major cost saving. A schematic of a FCET drivetrain can be seen in Figure 2 below.

Figure 4.2 FCET drivetrain schematic



Source: ICCT

Immaturity of technology

In the United States there are just two production FCETs on the market at present, though a number of OEMs are live-trialling FCETs with clients in Europe and the US. One example of the early stage of FCET technology is that rival OEMs such as Nikola and Daimler Benz are pushing two very different hydrogen storage technologies - Nikola are pushing compressed gas while Daimler are trialling a liquid hydrogen unit. This shows just how far away we are from industry standardisation, an important step in the development of such a technology.

With the relatively new technology involved and low volumes of production, FCETs lag far behind BETs in terms of capital cost. The advantage that BET technology has over that of FCET is the large scale consumer level battery electric vehicle (BEV) automobile market. This has given BET technology a head start of over a decade of that of FCET, though still far behind that of the 100+ year head start of diesel!

Volume production

There is no large-scale production of FCETs and this is a very important reason behind the high unit costs of the Nikola Tre FCET.

Several European and US OEMs have released production BETs, but nowhere to the same volumes of that of diesel vehicles. However, with the active support of the Chinese government, a number of large-scale Chinese OEMs have begun volume production of BETs. As with the BEV automobile market, this threatens Western OEMs that have been late to the game.

Government vouchers

The sole reason that Nikola have been able to sell any FCETs has been the generous California state subsidies - California Air Resources Board (CARB) vouchers - that along with the far smaller Federal Tax Credit, can bring the capital cost of an FCET down to the region of US $288,000. This is still significantly above the $250,000 unit cost of a Tesla Semi, that is not eligible for CARB vouchers.

Ultimately, for a vehicle to be financially viable the cost to the buyer should significantly exceed that of the cost to the taxpayer. The Tesla Semi is eligible for a US Federal tax credit of $40,000 per unit, so the majority of the cost exposure is to the buyer and not the government.

EU countries and the UK offer similar, often more generous capital cost incentives than the US for BETs. This is worth researching as part of the buying process.

Without government subsidy, the capital cost of a BET exceeds that of a diesel but the operational costs will offset this within the first five years of ownership. FCETs by comparison, costing €825,000 per unit, will not come close to BET cost parity for the foreseeable future.

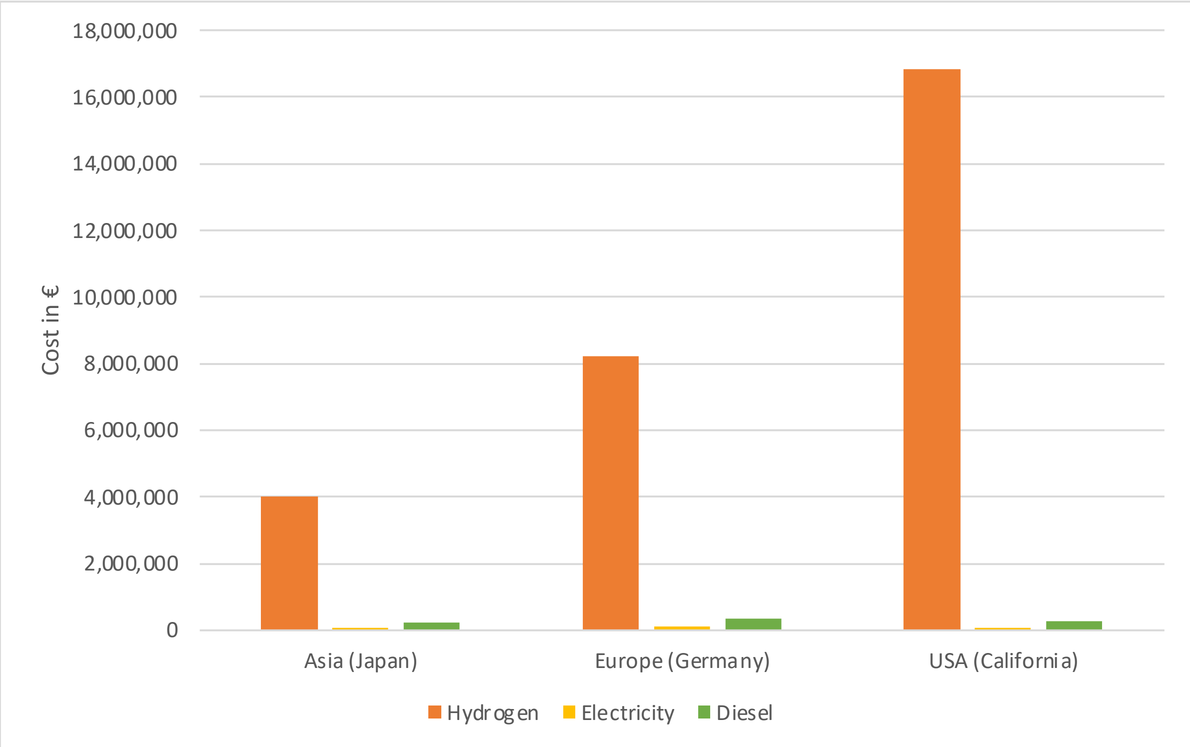
4.3 FUEL COSTS

We open this section with two charts. Figure 3 shows the very large difference between fuel costs for the first five years of ownership for a long-haul truck of all three fuels, and Figure 4 shows the comparative costs of diesel and electricity. Where there is a significant difference in costs between FCET and BET/diesel, the difference between diesel and BET is much smaller.

As one can see, it could cost:

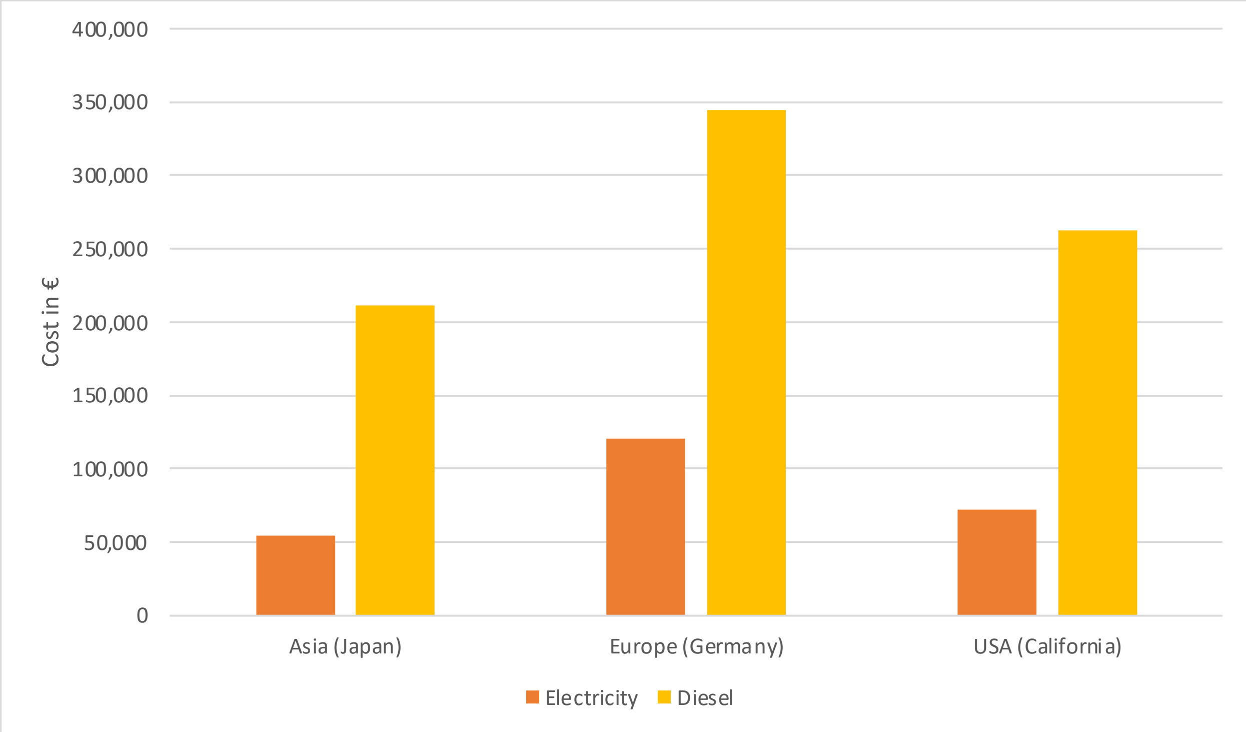
- €16.8m to fuel a long-haul truck with hydrogen in California for five years
- €262,000 to fuel a long-haul diesel truck in the US for five years
- €72,600 to fuel a long-haul BET in the US for five years

Figure 4.3 Hydrogen, electricity and diesel costs per long-haul truck over first 5 years of ownership



Source: Various, Ti estimates

Figure 4.4 Electricity vs Diesel costs per long-haul truck over first 5 years of ownership



Source: Various, Ti estimates

With regards to the fuelling costs of BET, there are significant regional variations in Europe, with the UK notably not subject to European law and therefore an anomaly due to Brexit. Even with Brexit factored in, there is no particularly centralised fossil fuel taxation policy within Europe and it is also very much subject to the vagaries of the market. As can be seen with the war in Ukraine affecting global energy prices, global markets are volatile and few countries barring major oil producers can weather such storms.

Europe, with the UK included, has taken major measures to tackle energy insecurity with the redoubling of efforts to build out renewable energy production to better unhook itself from Russian fossil fuels. With the planned changes to the UK domestic grid energy purchasing markets (again, ostensibly to remove natural gas prices from the formula), overall end user energy prices could fall again as the market reflects the costs of (often cheaper) renewables.

Hydrogen blown out again

Hydrogen fuel costs add to the already high capital costs of the vehicle, and are one of the largest factors in making FCETs far too expensive to operate by comparison to diesel/BET.

A comprehensive hydrogen fuelling infrastructure needs to be in place in order for a large fleet of FCETs to operate. With the exception of Japan, this simply does not exist. Even with government support, the fuelling networks that do exist have been shrinking in recent years as fuel station operators have withdrawn from the market due to lack of demand and the high costs of supply.

At every stage of the FCET development process from design of the vehicles, to sale and roll out, large sums of government money are required. The fuelling station network is another aspect where considerable sums of government money will be required for the fuelling stations, and also for the middle-mile storage depots from which tankers take the hydrogen to the fuelling stations. Given the maturity and TCO of BET technology even without such high levels of government support, on a purely cost basis, questions may be asked as to the viability of setting up such a fuelling network.

BET fuel economy pays for high capital cost

Where the high cost per km of hydrogen adds to the economic woes of using a FCET, the very low cost per mile of electricity offsets the capital cost and sets BETs on the road to TCO parity with diesel.

In the US, the cost of BET fuel per km is 27.6% that of a diesel truck. Over the 600,000km model ownership period for a long-haul truck, that would translate to a €190,200,400 saving per unit. Given the capital cost difference of €143,000 between BET and diesel units, this is the most important cost saving for BETs over diesel vehicles.

A word on 'dwell time'

There is some debate on the question of 'dwell time' where a vehicle will be sat fuelling/charging with the driver costing the company money when they should be driving the vehicle.

With current technologies it takes typically:

5 minutes to put enough diesel into a truck to go 625km
20 minutes to put enough hydrogen into a truck to go around 500km
45 minutes to put enough electricity into a truck to go around 250km on an ultra-rapid CCS charger

Where there is marginally smaller dwell time between FCET and diesel, one of the biggest questions levelled at BET is the considerably higher dwell time.

If a BET driver was lucky they would arrive at the charger at the beginning of their 45 minute rest break, plug in, sit in a cafe and return to unplug at the end of the rest break. But what if another BET arrived at the charger a minute before? That would mean 45 minutes of rest outside the rest break while the truck in front is charging, then 45 minutes plugged in. The company would lose in excess of €40 in driver wages (including taxes) during this 'dwell time'.

For now, this is a valid argument that could impact the overall costs of running a BET. In the future it could be possible that clients' warehouses could charge the BET when it is loading and unloading as part of a long-term contract between businesses. Truck charging infrastructure would be put in place at motorway service stations to allow for redundancy and to help avoid such dwell time.

One technology quite close to adoption is the Megawatt Charging Standard (MCS) which will be rolled out from 2025 onwards. Instead of a maximum of 350kW of energy on a Combined Charging Standard (CCS) charger being put into a truck, anything up to 2MW of energy will be available on MCS. This could reduce the dwell time to 9 minutes for the same 250km added range. Dwell time will be less than hydrogen!

Already the CCS can give as much as 350kWh of energy - roughly 291km of charge on a BET - in an hour. If the BET charging time coincides with the EU legally required rest break of 45 minutes per 4.5 hours of driving, this will already offer 218km of range. With the existing charge left from the overnight charging, that should be ample for the next 4.5 hours at 80km/h before an overnight stop is mandated.

There will be congestion. There isn't adequate HGV resting infrastructure across most of Europe and the UK. Congestion is where the dwell time comes into play. The MCS protocol, due to be launched later this year, will allow as much as ten times the energy to be put into the battery, or 218km of range in just 4.5 minutes. That sort of power is competitive even with diesel refuelling and potentially quicker than that of hydrogen. Dwell time would be a thing of the past.

MCS charging stations at present don't exist and as such are fewer on the ground than hydrogen! Unlike hydrogen the hinterland infrastructure to connect MCS is largely in place already though will require upgrades in its own right. Where the power supply is in place across much of Europe's strategic road network, the hydrogen storage and transport infrastructure isn't.

Given these factors, at a pure economic level, FCET technology may have another longer distance to run to catch up with BET with the next leap in charging technology to come that will be here very soon indeed.

A third technology being seriously considered by various bodies is in-road inductive charging. With a receiving unit under the vehicle, it would take electricity from cables beneath the road surface and continuously charge the BET while it is driving. Such technologies can cost as little as €1m per mile to install, and could in theory be rolled out across strategic road networks quite quickly. In-road induction technology is far from ready for mass roll-out, but could ultimately reduce the size of BETs' batteries and increase their potential payload weights as the vehicles will not have to stop to charge.

Conclusions

FCET fuelling costs considerably add to the high capital cost of the vehicles and it is unlikely at any near-term stage for the price of hydrogen to fall to a competitive level with electric.

Electricity is of low enough cost to pay off the difference in capital costs between these units and diesel units, well within the five year initial ownership period.

4.4 MAINTENANCE COSTS

Another thing to consider with regards to operational costs is the complexity of the FCET drivetrain. Conversely to that of BETs, FCETs are very complex machines and therefore have more to maintain or to go wrong.

Figure 4.5 Maintenance costs for FCET, BET and diesel vehicles

	€/km	5 Years, € Regional	5 Years, € Long-Haul
FCET	0.58900	235,600	353,400
BET USA	0.11400	45,600	68,400
BET EU	0.07800	31,200	46,800
Diesel USA	0.16500	66,000	99,000
Diesel EU	0.10200	40,800	61,200

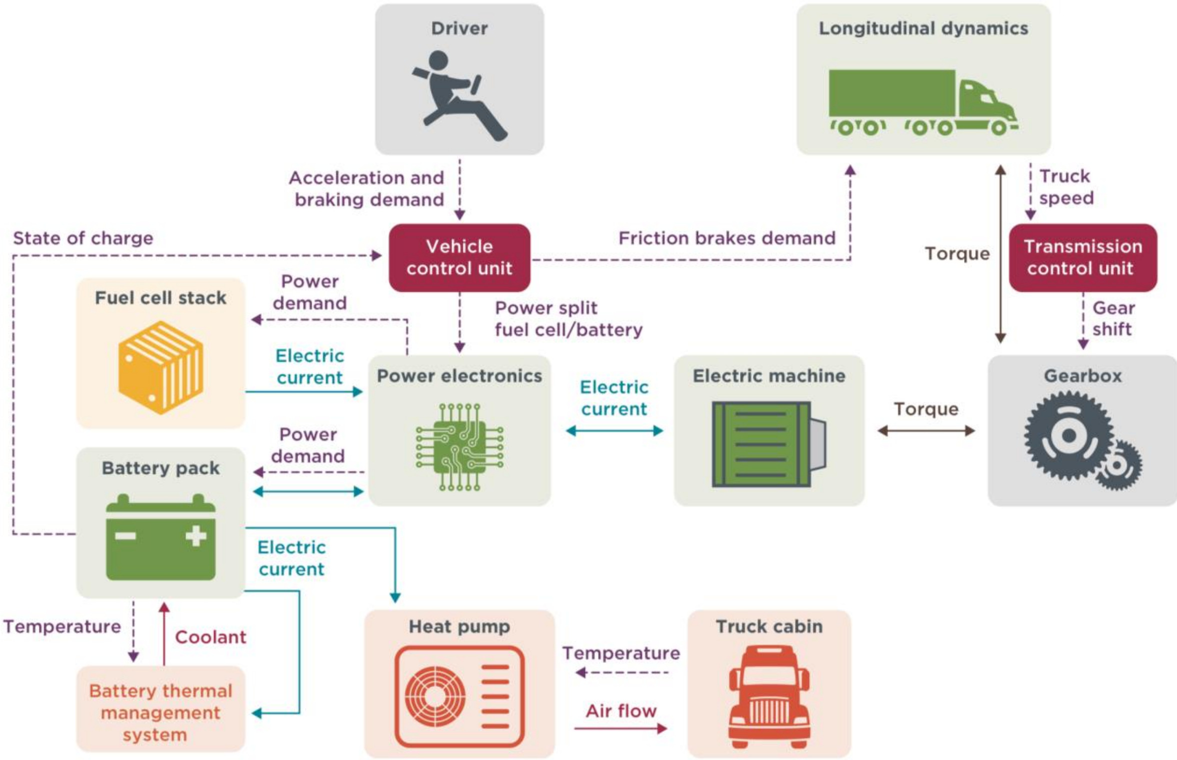
Source: Various, Ti estimates

FCET blown away again

FCETs are once again blown up by the cost. There have been a large number of municipal bus trials of fuel cell buses and study after study has shown that the complexity of such technology leads to a lot of things going wrong across their systems.

The ICCT makes a lower estimate of FCET maintenance costs than we do, but nonetheless has published a very good schematic of the control system of the FCET that we publish below.

Figure 4.6 ICCT schematic for FCET control system



Source: ICCT

Thanks to the complexity of this system, we estimate that an FCET will cost over 86% more to maintain than a BET in the EU, and an 83% more than a diesel truck.

BET - simpler system and cheaper

In both Europe and the US, BET maintenance costs are considerably less than that of diesel. Per km, a BET will cost 31% less than a diesel unit to maintain in the US and 23% less in the EU. For a long-haul truck, over the first five years of ownership, this translates to a €30,600 saving over diesel in the US and €14,200 in the EU.

Where in theory there is a greater sized workforce available to fix a diesel truck, in reality such vehicles are already so complex that technicians have to be highly trained even to deal with current diesel units. In fact, such is the complexity of modern diesel HGVs that the US and EU both have shortages of skilled technicians to repair and maintain them. As with all labour shortages, this has impacted the cost of maintenance.

Such high-level skill sets mean that the era of the backstreet garage is over. It also means that technicians will have to make no great leap in expertise to move from maintaining a diesel system to a BET. The argument that technicians will have to undergo extensive training to learn the detail of maintaining and servicing a BET is almost without basis as a result - they already have to train to a high standard to tackle the machines on the road at present.

Conclusions

Fuel cell systems are complex and have more things to go wrong than diesel or BET. The costs of service and maintenance add to the problems of economic viability.

BET service and maintenance offers a saving of as much as €30,600 over that of diesel in a five year ownership period, considerably adding to the cost savings of running a BET.

4.5 GOVERNMENT REGULATION – ROAD TOLLS

Figure 4.7 Road tolls by region

Standard Tolls	€/km	€, Regional Truck over 5 years of ownership	€, Long-Haul Truck over 5 years of ownership
USA	0.01900	7,600	11,400
EU	0.22100	88,400	132,600
Asia (Japan)	0.34400	137,600	206,400
ZEV Tolls - EU	0.11050	44,200	66,300

Source: Various, Ti estimates

The EU has moved from flat road taxes to per-mile charging for HGVs. Where the UK government has shown low interest in this, for its neighbouring 28 countries this will be a big factor.

Under new regulations being rolled out across the European Union for both FCET and BET vehicles ('Zero Emission Vehicles', or ZEVs), road tolls will be halved by 2028.

Over 600,000km, this would reduce the TCO of a European FCET to €9,504,700 and a BET to €534,700 as against a diesel truck, which would cost €696,200 in the same period. Preferential tolling reduces a European BET TCO by 11.0%, but such tolling would only reduce the TCO of a FCET by 0.7%.

As can be seen in figure 7 above the effect of per km road toll incentives can be very dramatic on ZEV HGV use.

This regionality of government policy impacts BET TCO. It is also subject to national politics - where the Biden administration has shown a certain commitment to reducing the carbon intensity of the US economy, it is subject to the politics of the Presidency and will of Congress. The European Parliament is also subjected to politics too, with bloc-wide protests taking place against excessive regulation at the time of writing this report that might impact the coming EP elections and ultimately the behaviour of the European Commission in terms of climate regulation.

Taxation

Taxation is complex and varies from country to country. Even if ZEVs were given a zero ownership-tax rating, this wouldn't help with the enormous TCO price differential between FCETs and diesel vehicles.

Regulation

For technological change as acute as the transition from ICET to any low carbon fuel, it is inevitable that there will be a level of government subsidy to fund such a transition. As we discussed in regard BETs, there is road use tax in Europe while in the UK and US there are capital cost incentives.

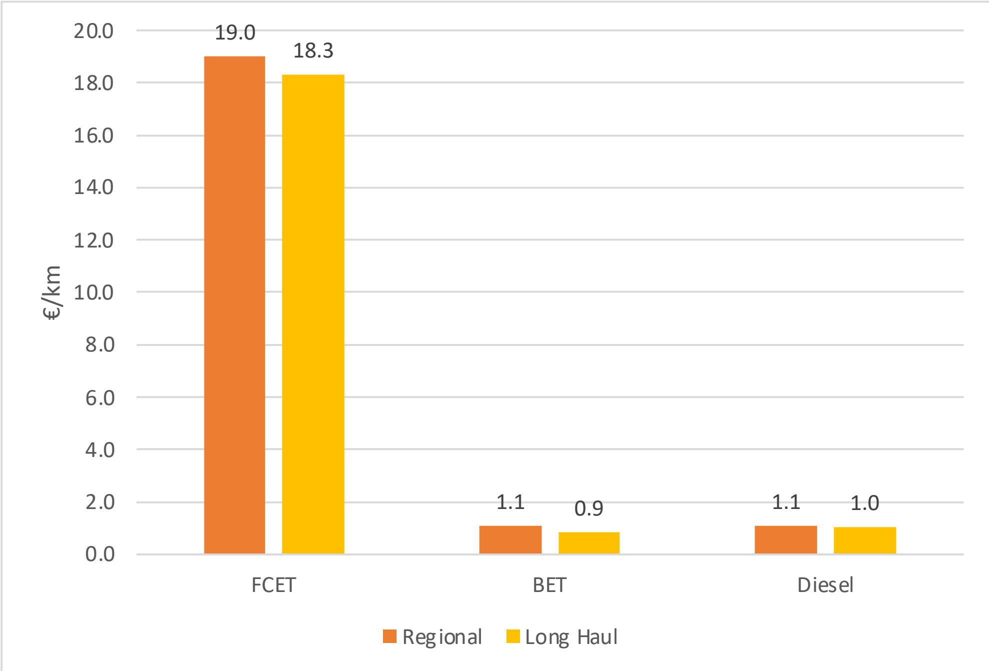
Ongoing regulation in the EU and UK will incentivise the transition to ZEVs.

At the present time there is a debate between stakeholders and the European Commission (EC) as to the detail of the Euro 7 standard that will affect all new combustion engine vehicles in the coming years. It will have the impact of making combustion engine vehicles more expensive to manufacture, though the EC and other stakeholders disagree on just how much.

At the same time, a large number of countries have committed to the ban on combustion engine vehicles being manufactured in the coming decade. This has led to the investment of billions of Euros in developing ZEVs - it started the race between BETs and FCETs.

4.6 TCO COMPARISON FOR DIESEL, BET AND FCET

Figure 4.8 TCO for FCET, BET and Diesel Global Average € per km in 2023



Source: Ti estimates with ICCT model diesel vehicle capital cost

In terms of average TCO across Asia, Europe and the US, FCET TCO is 19 times that of the TCO of a BET. This calls into question of FCET ever achieving cost parity with BETs.

As can be seen in the chart above, in 2023 there was a wide disparity between the TCO of fuel cell electric trucks (FCET), battery electric trucks (BETs) and diesel trucks. This is due to a variety of factors that include:

- Immaturity of FCET technology relative to diesel
- Low volume of BET and FCET vehicles being made
- Complexity of FCET drivetrain and control system impacting maintenance costs
- Immaturity of hydrogen fueling infrastructure
- Inefficiency of hydrogen as an energy store

Driven by the consumer electric vehicle (EV) market, battery electric vehicle technology is coming to maturity. According to the ICCT, at a truck level it is likely that across much of Europe, BETs will become cost comparable with ICETs within the decade.

As can be seen in Figure 9 there are wide regional variations, with Japanese FCETs costing as little as 31.5% to operate of those in California. This is largely down to the very advanced Japanese public hydrogen fueling infrastructure that skews the overall costs. Where it shows the potential for European and US TCO to reach with improved infrastructure, even in Japan the TCO is still in the order of eight times the cost of BET or diesel.

We cannot in any way conclude that hydrogen has any economic advantage over that of battery electric or diesel as of the present time.

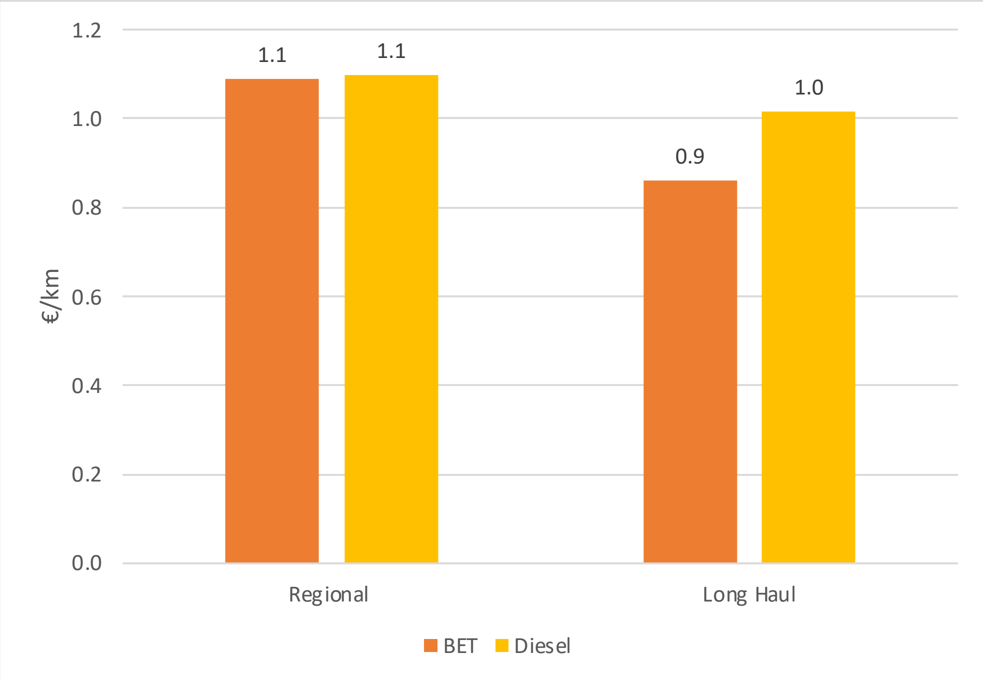
Figure 4.9 TCO for FCET, BET and Diesel By Region

Fuel Cell	€/km Regional Delivery Truck	€/km Long Haul Truck
USA	30.75231	30.05221
EU	16.54950	15.84117
Asia	9.70050	9.01300
Average	19.0	18.3021
Battery Electric	€/km Regional Delivery Truck	€/km Long Haul Truck
USA	0.98181	0.73921
EU	1.14200	0.87347
Asia	1.20300	0.96500
Average	1.1089	0.85923
Diesel	€/km Regional Delivery Truck	€/km Long Haul Truck
USA	0.97971	0.86888
EU	1.18117	1.16033
Asia	1.13050	1.01967
Average	1.09713	1.01629

Source: Various, Ti estimates

BET vs Diesel TCO

Figure 4.10 BET vs Diesel TCO in 2023



Source: Various, Ti estimates

With hydrogen so expensive to operate, how do diesel and BET compare?

Even with BETs being a relatively new technology, already the average global TCO is at parity or below that of diesel. As with FCETs, truck manufacturers are not building at anything like the same volume as those of diesel vehicles but even so with incentives such as European road tolls, they are becoming a worthwhile economic investment even in 2024.

A number of factors will come into play that will make the TCO of BETs far and away better than that of diesel in the coming years:

- Manufacturing economies of scale
- Better battery electric charging infrastructure
- Battery technology improvements achieving greater energy density
- Government incentives to achieve a changeover from diesel to BET
- Maturity of BET technology
- Competition in an open market between manufacturers

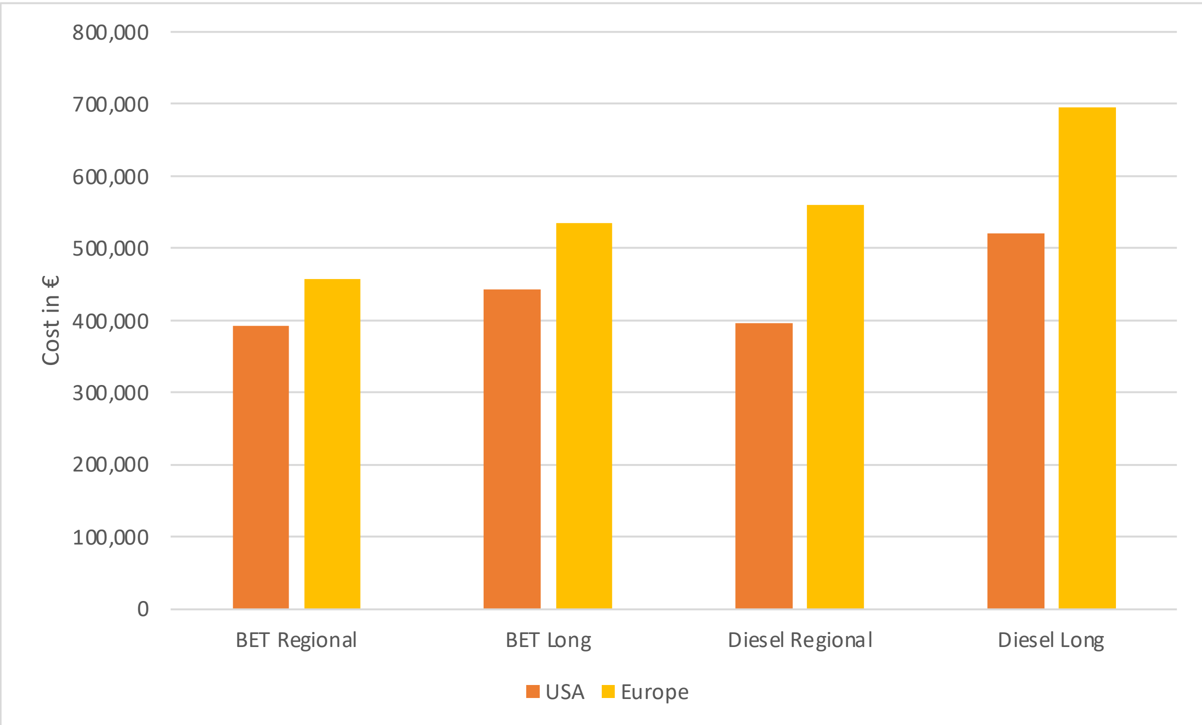
Regional variation

Electricity prices are broadly the same globally and thanks to the recent explosive growth of the EV car market, technology is at a far greater level of maturity than that of fuel cells. Due to the far simpler control system and drivetrain of BETs, they outcompete FCETs on maintenance too.

It is interesting that for long haul trucks, a US Tesla Semi will be more economical to run than a diesel even today, and without road toll incentives that are being introduced to European main roads.

The same data shows that with the incoming European road toll incentives, BETs are more economical to run than diesel for both regional and long-haul routes - though with margins for error, this is closer to the crossover point where BETs are at equal TCO with that of diesel at a regional level. This can be seen in Fig 4 below:

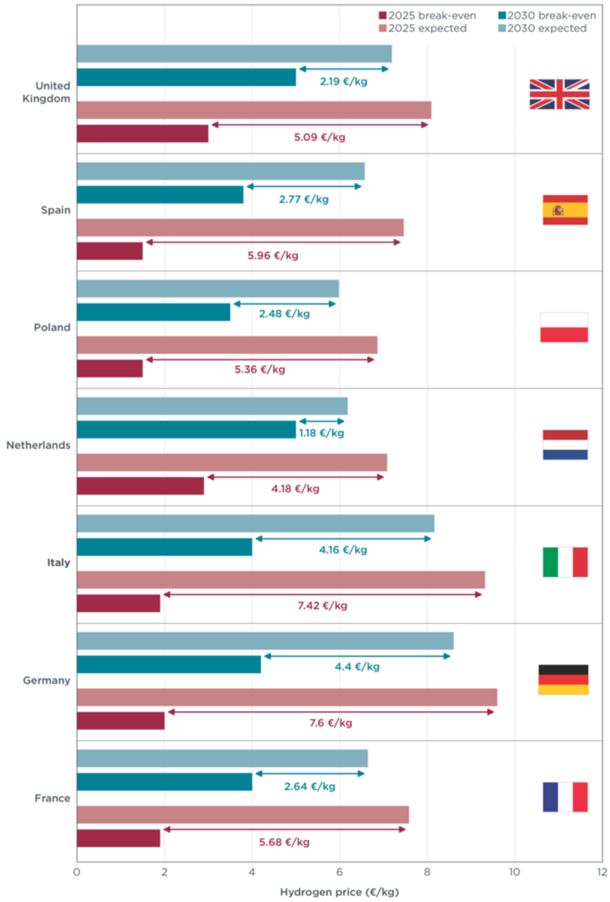
Figure 4.11 BET vs Diesel Trucks TCO over 5 Years of Ownership (Regional: 400,000km, Long- Haul 600,000km)



Source: Various, Ti estimates

As can be seen in Figure 12, cost parity of FCETs and ICETs will only be achieved with vast amounts of subsidy if ever.

Figure 4.12 Subsidy required for hydrogen to achieve cost parity with diesel (Source: ICCT)



As can be seen in the case of Germany above, in 2022 the government subsidy must be €7.60 a kg. Over a million miles that would amount to €638,000 - per FCET. Given the road toll incentives and capital incentives, it would be quite easy to reach €1m in subsidies, or €1 per mile the vehicle travels in its useful life. Given that there are millions of HGVs on the road (500,000 in the UK alone), the costs involved would compete with essential services like health and pensions in terms of cost to the taxpayer. 30,000 FCET HGVs would cost in the region of €30 billion to taxpayers, on top of the capital and operational costs incurred by the logistics provider.

We can conclude that the time is right for significant scale fleet purchases of BETs even today.

4.7 CONCLUSION

In our opinion, there is no way that FCETs will even get an honourable second in this race given the hurdles in technology and infrastructure to achieve anything like cost parity between the two ZEV technologies.

In the rules of capitalism, the bottom line is always an important factor and we can see no way that FCETs will ever fall in cost sufficiently to compete with diesel, short of subsidy that would compete with a country's national health budget in terms of size.

Postscript by Thomas Cullen, Chief Analyst at Transport Intelligence

Hydrogen

From the economic logic articulated above, it would seem reasonable to assert that electric propulsion is the only alternative to the internal combustion engine. Even with existing Lithium-Ion technology batteries are more economically viable than any other non-carbon option both in-terms of running costs and capital expenditure.

However, this is a complex question which is organically linked to the issue of wider energy generation. There is one core issue which injects an important variable into any calculation around energy for the vehicles and that is the production-driven utility of hydrogen.

Hydrogen is viewed within State-driven energy strategies[1][2][3][4] as a key mechanism for the management of energy. Non-hydrocarbon energy sources tend to be inflexible in terms of the timing of energy supply. In contrast to hydro-carbon powered electricity whose output can be varied even within a 24 hour period, many non-hydro-carbon based power sources are either inflexible or unpredictable. For example:

- Wind power is characterised by variable and unpredictable electricity generation.
- Nuclear power has a very stable but inflexible electricity output.
- Solar power generates only during the day and even then, the level of output can be unpredictable.

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[1] *https://www.wasserstoffrat.de/fileadmin/wasserstoffrat/media/Dokumente/EN/2023/2023-07-24_NWR-Statement_Updated_NWS.pdf*

[2] *https://www.bundesregierung.de/breg-en/service/hydrogen-technology-2204238*

[3] *https://assets.publishing.service.gov.uk/media/64c7e8bad8b1a70011b05e38/UK-Hydrogen-Strategy_web.pdf*

[4] *https://www.hydrogen.energy.gov/library/roadmaps-vision/clean-hydrogen-strategy-roadmap*