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BEV or FCEV?

The complementary roles of Battery and Fuel Cell electric Trucks

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Contents

Executive Summary

We are witnessing a concerted push towards decarbonization cutting across all industries and geographies. This is very evident in the road transport sector where we are witnessing a rapid increase in the adoption of electric vehicles, especially in the bus and light vehicle segments. Heavy duty vehicles sector, on the other hand, has been a bit behind the curve given the significant challenges in transitioning them towards efficient, cost-competitive, and dependable zero emission alternatives. Though they account for only a small share of all vehicles in operation, they are responsible for a much higher share of the emissions from all road transport. Stringent emission reduction targets coupled with the pressure from end customers to address emissions across their entire value chain is now providing a much-needed impetus for the transformation of the vehicles in this segment.

Battery electric trucks (BETs) and fuel cell electric trucks (FCETs) are emerging as the leading zero emission technology alternatives. Battery electric technology, especially, has seen a lot of advancements across sectors like transportation and energy storage, and this provides a strong tailwind for BETs. Further, BETs have a clear edge over FCETs in terms of energy efficiency. It is simply more efficient to store electricity directly into a battery and then use it for vehicle propulsion than using it to produce hydrogen and then generating electricity from the hydrogen in a fuel cell. This is also reflected in the vehicle operating costs, especially considering current energy and hydrogen prices.

However, BETs also have some associated challenges, and these have tempered the initial enthusiasm among the end customers who were early adopters. For example, BETs are generally much heavier than corresponding FCETs or conventional diesel-powered trucks, especially if they are to be used in applications that require more onboard energy – be it for having a greater driving range per charge, or for negotiating more demanding driving conditions (e.g., cargo weight, topography, or extreme weather). This requires BETs to carry much larger and heavier batteries. Beyond this, it is also important to consider the components and supply chains for BETs and FCETs. In these aspects, FCETs currently have an edge, both in terms of geopolitical considerations and long-term cost reduction potentials, which can help sustainably scale the technology solutions.

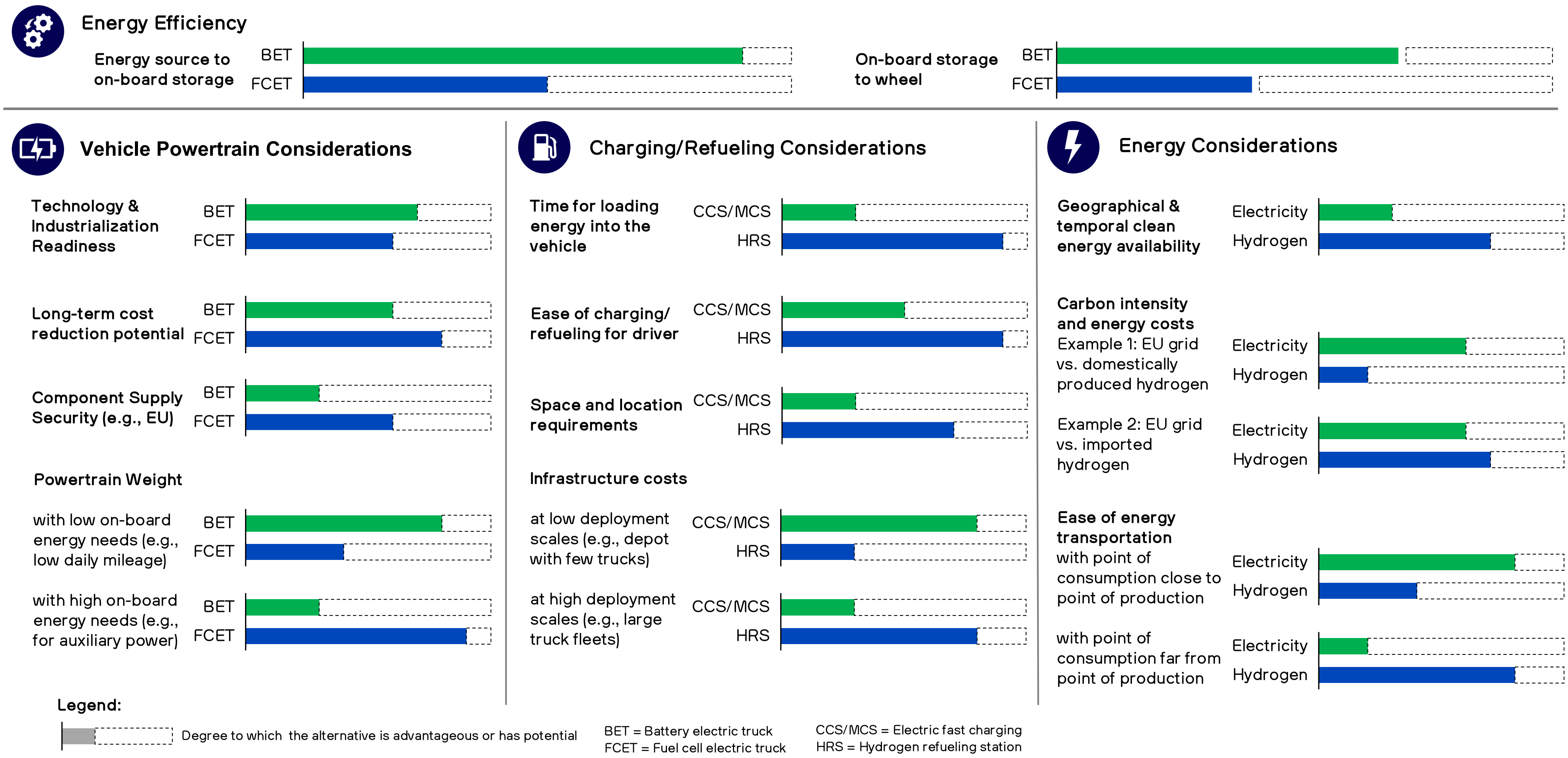
Another challenge is the time required for recharging BETs. While considerable progress is being made in fast charging electric vehicles, BETs require an adaptation of driver behavior and regulations to allow for recharging the truck potentially during the mandatory rest period. Further, significant investments are necessary in terms of infrastructure and grid upgrades to enable multiple BETs to charge in parallel, even in remote locations, in addition to space requirements at truck stops. On the other hand, FCETs typically require much lesser times for refueling the trucks, comparable to conventional diesel-powered trucks. On the other hand, the cost of the charging/refueling infrastructure for these vehicles is contingent on scales.

At low volume adoption, the infrastructure costs for BETs are much lower than the cost of setting up even a small hydrogen refueling station (HRS). However, a HRS has the advantage of being able to refuel much more trucks in a day, leading to a better utilization rate and amortization. In other words, with larger volume adoption, the infrastructure costs tip in favor of FCETs. That said, the reliability and robustness of both chargers and hydrogen refueling networks needs to be standardized and improved as the technologies mature.

In addition to vehicle powertrain and charging/refueling considerations, it is also critical to examine the energy dimension. While BETs have a higher energy efficiency, there are certain challenges associated with electricity. Currently, the electricity mix is itself quite carbon intensive in many parts of Europe and North America, so charging a zero-emission vehicle with such electricity simply shifts tailpipe emissions upstream. Therefore, it is critical to scale up electricity from renewables, tapping sources like solar, wind, hydro and geothermal power. Even then, the electricity produced from these renewable sources is constrained geographically and temporally, and difficult to transport over longer distances to the point of consumption. On the other hand, hydrogen is a promising energy carrier since it can be produced in a variety of ways at locations which have favorable energy economics, and then be transported more easily to the point of consumption. It may be produced locally from on-shore wind or solar installations to improve their utilization during non-peak hours, decentralized at waste-to-hydrogen facilities, or at locations with much higher wind/solar energy availability and transported over pipelines or maritime ships. Further, demand and supply side factors coupled with the impetus being provided by various institutions is expected to help lower the cost of hydrogen as a fuel over the long term, which would also provide a fillip to lowering the operating costs of FCETs.

Taking all these factors into consideration, it becomes clear that decarbonizing the heavy-duty trucks sector is not an either/or choice between BETs and FCETs. Instead, it is important to understand and accept that the two technologies are complementary solutions for end customers looking to rapidly sink their emissions footprint. Which technology is a better alternative is determined by the specific use cases and operating conditions of the vehicles. For example, with limited loads and daily range requirements, a BET would be a favored solution. On the other hand, for a heavy goods long-haul transport use case, FCETs could be a more optimal solution from a system perspective. It is therefore crucial to consider the various dimensions together with the end customers on a case-by-case basis. Finally, given the respective challenges that both technologies still face, building and orchestrating an ecosystem of strong partners, including energy players, vehicle manufacturers, equipment providers, logistics providers, and financial institutions would be critical for enabling their adoption at scale.

Multitude of factors need to be considered and there is no silver bullet solution in decarbonizing HDTs



Introduction

Heavy duty trucks (HDTs)[1] are a backbone of the global economy and supply chains. In the US for example, trucks haul over 10.5 billion tons of goods, making up 70% of the country's freight. Similarly in Europe, road tractors and semi-trailers accounted for 77.8% of EU road freight transport measured in ton-kilometers and for nearly two thirds in vehicle-kilometers in 2021. Each year, over 2 million new HDTs are sold worldwide[2]. As of 2020, this segment of vehicles accounted for 12% of all vehicles in operation in the world. However according to the IEA, in the same year, they accounted for 1.2 billion metric tons of CO_2 emissions globally. This represents 41% of global road freight emissions, which in turn accounted for 9% of global greenhouse gas emissions in 2020.

Greenhouse Gas Emissions from Commercial Vehicles

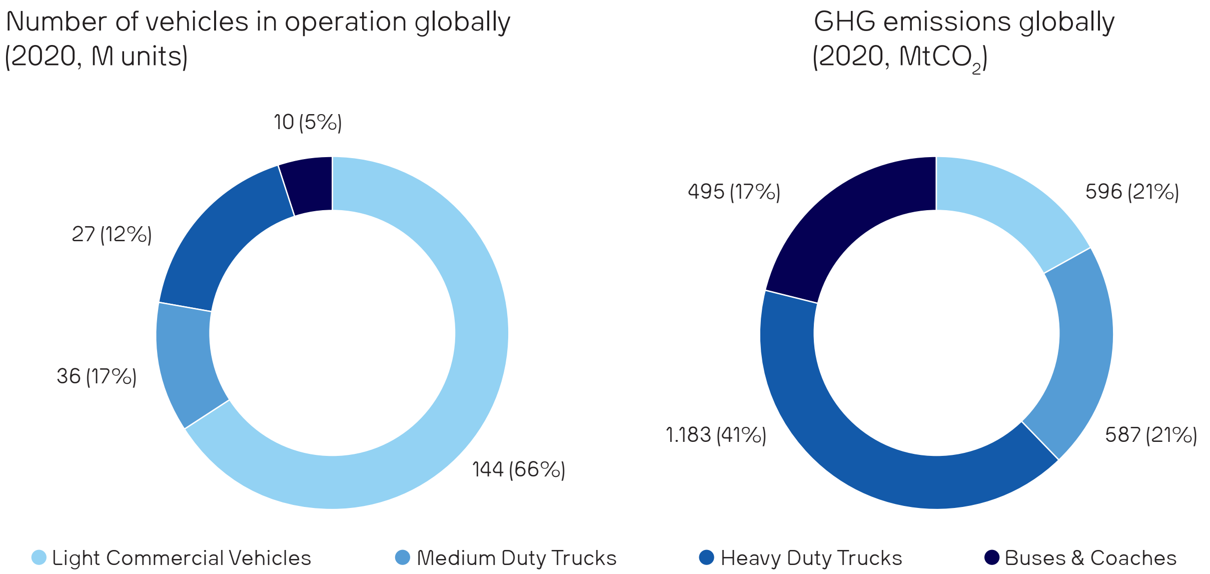


Figure 1

There is an increasing focus on achieving ambitious climate goals and reducing carbon emissions across industries. This is perceived critically especially in heavily polluting industries, including the transportation sector. Companies are not only striving to reduce their direct emissions (Scope 1 and Scope 2) but also the indirect emissions arising from their complete

1. Trucks with gross vehicle weight over 16 tons.
2. Based on data from S&P IHS Markit data from May 2022.
3. Greenhouse gas (GHG) Protocol Corporate Standards divide a company's emissions into three. Scope 1 refers to direct emissions from owned or controlled sources. Scope 2 refers to indirect emissions from the generation of purchased energy. Scope 3 emissions are all indirect emissions which are not included in Scope 2 that occur along the entire value chain of the reporting company, including upstream emissions (e.g., along the supply chain) and downstream emissions (e.g., when the vehicles are being driven in use).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value chain including Scope 3[3]. Such companies are being intensively scrutinized by the society at large, regulatory bodies, investors, and other stakeholders. Consequently, they are pressuring major fleet operators globally to aggressively transition towards rapidly adopting zero-emission transportation solutions.

Dovetailing with these trends, regulators are not only introducing entry restrictions and low emission zones within cities, binding phase out targets for combustion engine powered vehicles, and other carbon taxes, but also simultaneously rolling out significant incentive and support packages to accelerate this transition. This also includes targets for establishing the supply chains to address the inputs needed for manufacturing such vehicles and the infrastructure for supporting their usage. Against this background, it is clear that we urgently need zero-emission trucks as early as possible to help fleet operators master this transition.

However, it is important to recognize that HDTs in the road freight transport sector are hard to decarbonize given the range of their applications. HDTs can have a gross vehicle weight ranging from 15 tons to over 65 tons and are used under a variety of operating conditions - from urban/regional distribution to line-/long-haul, and milk runs (regular routes with high predictability) to unpredictable and varying routes[4]. Concurrently, since they are capital intensive goods, fleet operators typically have high uptime requirements from such vehicles. Therefore, reliability, performance, and efficiency play a key role, in addition to total cost of ownership considerations. Zero-emission transportation solution for HDTs must help address their carbon footprint without adversely impacting any of these operational considerations.

In recent years, various ideas have been under exploration to address this challenge, including electric powertrains, use of synthetic fuels or hydrogen in combustion engines, and dynamic on-route charging through overhead lines or along the road surface. Each of these alternatives has its own advantages and associated challenges. However, from a long-term perspective, electric powertrains are emerging as the strongest contenders for decarbonizing HDTs.

Significant progress is especially being made in the development of battery electric trucks (BETs), benefitting in the slipstream generated by the rapid electrification in the light passenger vehicle segment. Battery electric vehicles have some distinct advantages which make them a very attractive solution for many vehicle segments. These advantages, such as their energy efficiency, are well documented.

4. Urban distribution comprises use cases, especially within cities, with a daily mileage up to 150km, while regional distribution comprises use cases in cities and surrounding suburbs with a daily mileage up to 250-300 km but with a return to base at the end of the day. Line-haul use cases are typically along regular and predictable routes with a daily mileage up to 500 km. Long-haul routes are typically longer with a daily mileage exceeding 500km in ad-hoc settings with limited predictability.

5. Hydrogen can also be used in internal combustion engines. However, the energy efficiency of such powertrains is only comparable to diesel powertrains, and they also require expensive exhaust gas aftertreatment systems to address their NOx emissions. They could yet find application in certain niches where their advantage of easier powertrain thermal management could play in their favor.

However, in case of HDTs, the tough and varied operating conditions have drawn a deeper attention to some of their drawbacks. As in the case of other hard-to-abate industry sectors, the use of hydrogen is showing promise in decarbonizing such use cases through the application of fuel cell electric trucks (FCETs)[5]. It is therefore crucial to understand and evaluate the BET and FCET powertrain and component technologies and their respective advantages and challenges.

Concurrently, such alternative powertrain solutions also engender a shift away from an existing ubiquitous diesel fuel infrastructure. Apart from the higher acquisition costs, a major barrier in the adoption of BETs and FCETs is the current lack of recharging and hydrogen refueling infrastructure respectively. In its absence, HDT operators have been hesitant to purchase and incorporate such vehicles into their fleet mix. Therefore, it is not only essential to examine the vehicle and powertrain technology itself, but also the outlook for the supporting energy infrastructure.

The powertrain technologies needed for clean future mobility are at various stages of their development and have differing levels of technological and industrialization maturity. For example, the currently announced production volumes of BETs and FCETs represents less than 5% of the global annual truck sales. Consequently, there is a lot of debate around their suitability towards being leveraged for decarbonizing the transport and energy sectors. Given this background, this paper takes a nuanced view of the intricacies involved in adopting them for zero-emission trucks. Broadly, it explores energy and vehicle powertrains aspects of BETs and FCETs. On this basis, the role of BETs and FCETs to enable a rapid decarbonization of road freight transportation are discussed.

Factors promoting the adoption of zero emission commercial vehicles

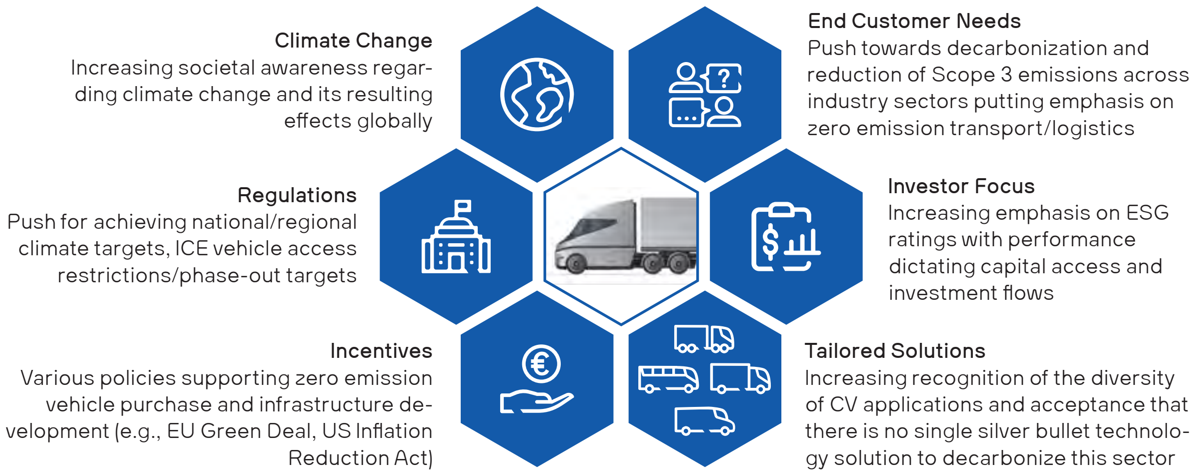


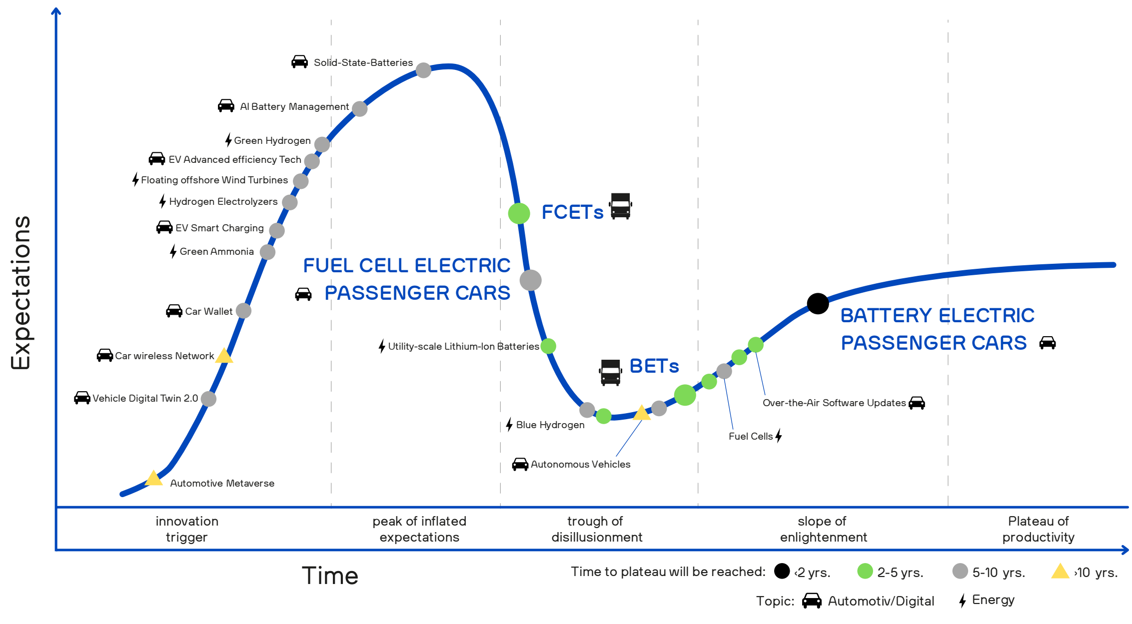
Figure 2

The Energy Efficiency Argument

An indisputable and much touted advantage of BETs is their energy efficiency. A battery electric powertrain has the highest efficiency in converting the energy input into energy at the wheel. In BETs, the energy for operating the vehicle is stored in batteries, with lithium-ion batteries being the dominant and entrenched technology in the foreseeable future. This electrical energy is transferred into mechanical energy at the driven wheels through the on-board power electronics, electric motor, and transmission.

On the other hand, the energy for operating the vehicle in FCETs is stored as hydrogen in compressed gaseous or liquid state in tanks. Inside the fuel cell, the hydrogen is fed into the anode while air is fed into the cathode. A catalyst at the anode separates the hydrogen molecules into protons and electrons which flow to the cathode separately. Electricity is a result of the electrons flowing through the external circuit. This electrical energy is transferred into mechanical energy at the driven wheels like in the case of BETs. Additionally, FCETs also have a

Relative technology and industrialization readiness of BETs and FCETs



Inspired by hype cycles from Gartner, Inc.
Figure 3

lithium-ion battery on board to for additional/backup power requirements, though it is much smaller than in case of a BET.

From a "tank-to-wheel" efficiency perspective (i.e., the efficiency of converting the energy from the storage to the energy available at the driven wheel), battery electric powertrains are a clear winner with over 70% of the energy efficiency. In comparison, fuel cell powertrains typically have over 40% energy efficiency, while internal combustion engines have less than 35%. Another way of viewing this is by measuring how much energy (in kWh) is consumed to drive each kilometer. A recent study by The International Council for Clean Transportation (ICCT) calculated that while FCETs consume 10-12% lower energy than diesel powered trucks in long-haul applications, BETs consume about 50% lesser energy than FCETs. Similarly, they calculated that in regional delivery use cases, FCETs consume 20-24% lesser energy than diesel trucks, but again, BETs require only half the energy in comparison to FCETs.

Key dimensions for evaluating BETs and FCETs

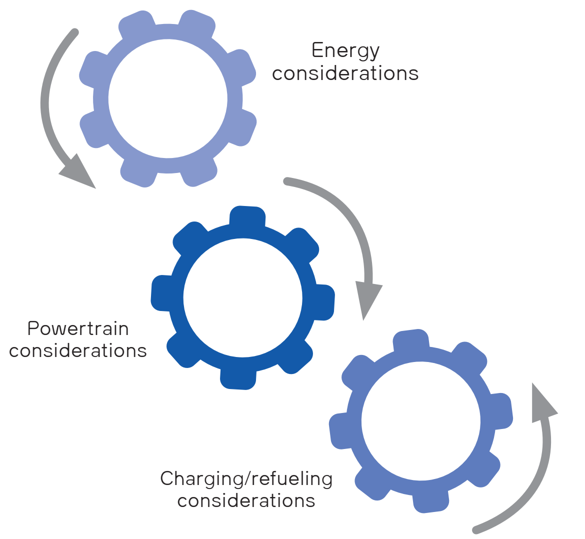


Figure 4

Similarly, from a "well-to-tank" perspective (i.e., the efficiency of energy production, transport, and distribution), it is more efficient to store energy directly into a battery – this has an efficiency of about 85-90% after accounting for potential losses in transmission and vehicle battery charging. On the other hand, green hydrogen[6] is produced through electrolysis, which can have up to 20% efficiency loss. The hydrogen thus produced must be compressed/liquified for transportation through ships or pipelines[7], and then made available at the refueling station. This process could account for another 24% efficiency loss, as estimated by the Hydrogen Council.

However, decisions for adoption of zero-emission HDTs in fleets are not made purely based on the energy efficiency of the vehicles. From a real-world perspective, it is insufficient and one-dimensional to look at the energy costs or efficiencies in isolation, albeit one would expect the most efficient solution to also be the most cost effective one. The challenge of decarbonizing the HDT sector needs to be viewed at a system level through a multidimensional lens. It is necessary to juxtapose supply-side factors such as the maturity of the technologies, green energy production and supply, and availability of supporting charging/refueling infrastructure against demand-side factors such as the cost, operational efficiency, and uptime requirements of transport operators.

6. Depending on how it is produced, hydrogen is labelled with various colors. Green hydrogen is the one produced without any GHG emissions, typically by using clean electricity from renewable sources like solar or wind power to electrolyze water. Sometimes, the hydrogen produced by using solar energy is also labelled as yellow. Another option is to use nuclear energy, in which case the hydrogen produced is labelled as pink, purple, or red. However, the most common method of hydrogen production currently is through steam methane reforming process – this has a large GHG emission associated with it and is labelled as gray hydrogen. If the emitted carbon dioxide is captured and stored in this process, it is labelled as blue hydrogen. However, it is important to note that blue hydrogen may not necessarily be zero carbon, since not all carbon is captured and any methane leakages during its production can sizably contribute to global warming.

7. Hydrogen may also be converted into derivatives like ammonia and transported. This would have additional associated costs and efficiency losses, especially if the derivative must be reconverted into gaseous or liquid hydrogen. However, this makes sense for end applications where there is a need for that derivative, e.g., for chemical or fertilizer industries.

Powertrain Considerations

The biggest cost component of a BET is the battery. For an FCET on the other hand, the major cost component currently are the fuel cell systems and hydrogen tanks. Other components like e-axles, electronics, and motors, are not as significant differentiators between BETs and FCETs. Therefore, we focus on the technology, supply chain, and cost aspects of batteries and fuel cell systems in this section.

A lot of progress has been made in the last decade in battery technology, especially for passenger cars. As a result, significant investments are flowing into establishing battery gigafactories globally to cater to the demand for battery electric passenger vehicles. Despite this progress, it is important to closely examine battery technology and supply chains in the context of heavy-duty trucks. Recent studies from global consulting firms indicate that beyond the battery demand from passenger vehicles, the additional demand from BETs would amount to 275-300 GWh of batteries by 2030. While a lot of battery gigafactory investments and announcements have been made in Europe and North America in the last few years, the challenges in setting up, operationalizing, and scaling them are now also becoming evident.

Lithium-ion batteries are the dominant technology currently in battery electric vehicles, specifically with two major cathode chemistries finding main application. The first is with Nickel-Manganese-Cobalt (NMC) cathodes. These have witnessed rapid advances in the last decade with battery manufacturers striving to decrease the Cobalt content (for supply chain reasons) and increasing the Nickel content (to increase energy density). In the last two years, material price volatility, especially in batteries with Nickel-Cobalt-Manganese (NMC) cathodes, has seen a renewed interest in comparatively lower cost battery chemistries like Lithium Iron Phosphate (LFP) cathodes. In comparison to NMC, LFP is a more mature technology, though they are comparatively heavier and have a lower energy density. LFP is especially entrenched as a technology choice in the bus sector and is also being evaluated as an option for mass market battery electric passenger vehicle segment, light commercial vehicles and HDTs with lighter cargo carrying requirements with return-to-base use cases. Technology advancements like chemistries using even higher Nickel content, silicon anodes, and solid-state batteries are seen as potential solutions to increase their energy density and range of BETs. However, these technologies are still in their nascency and lack of industrial readiness, thus likely having much higher cost levels in the foreseeable future.

Concurrently, despite the progress being made in battery technologies in general, there is insufficient understanding on a cell level impact of vehicle use cases. As a result, there is a lot of work being done leveraging advanced

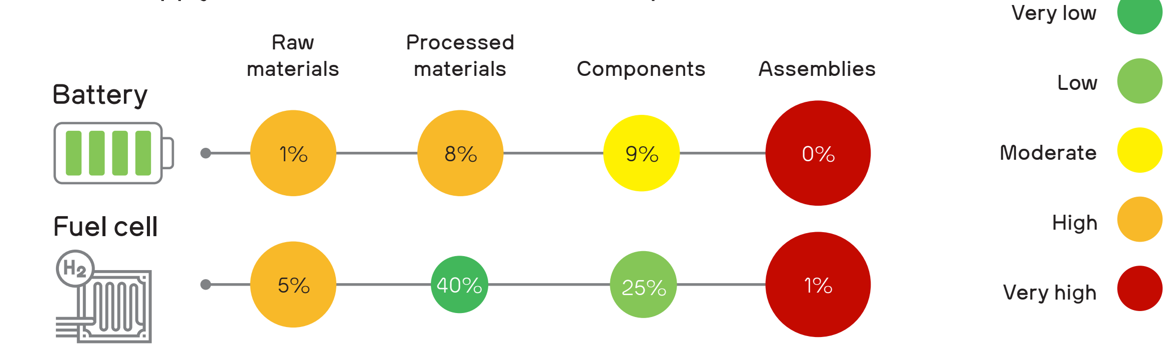
data processing and artificial intelligence approaches to better model and evaluate batteries in terms of their charging and discharging behaviors, state of health (SoH), degradation over lifetime, residual values, and recyclability.

On the other hand, technology for fuel cells as well as for hydrogen generation has been available for years. Indeed, there are some associated technical challenges with adapting the systems to HDT applications like managing the high-pressure hydrogen gas (at 700 or even 1000 bar pressure) without corrosion or leakages to decrease fuel consumption, ensuring robustness and safety, and overall performance at higher power ratings. These are seen as surmountable though since there is already a widespread knowledge of and familiarity with fuel cell components in the automotive industry. Through these advancements, the hydrogen fuel consumption as well as required hydrogen tank sizes are expected to decline in the future.

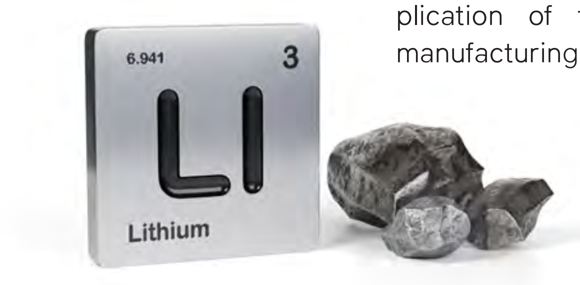
The major challenge now for fuel cell systems is scaling them and reducing costs, which can only come when there is a higher penetration of fuel cell vehicles. This is the proverbial chicken-and-egg issue, as it has also been the case with battery electric vehicles in the last few years. The technical know-how and familiarity with the technology is expected to be instrumental in achieving cost decreases through economies of scale as large volume production lines are set up and standardized. Taking fuel cell buses as an example, the vehicle prices are now one-third of what they were a decade ago, thanks to technological and product innovations. Leading fuel cell manufacturers have already launched eighth generation fuel cells now, with over 30% cost reductions between successive fuel cell module generations. Similarly, the industry is also witnessing price reductions in hydrogen storage tanks and fuel cell electric powertrains at a system level. Even with an annual production of about 10,000 FCETs, over 60% cost reductions in fuel cells are expected. This would be in line with the targets from the US Department of Energy of achieving less than US$100/kW for an annual production of 150,000 systems a year. Factoring in these aspects, an FCET is expected to reach cost parity with a BET within the next few years.

Similarly, as mentioned earlier, larger scale production of BETs would entail a corresponding scaling of battery production. A direct implication of the large-scale manufacturing of lithium-ion batteries would be on the supply of raw materials for meeting the demand accruing from it. Be it lithium, nickel, or cobalt, the process of identifying sites, building new mines, and scaling their production output can take many years. However, current investments into this sector are lagging. As a result, mid-term bottlenecks are expected to lead to a demand-supply imbalance[8]. Industry experts especially highlight that lithium is likely to be the most critical raw material between 2025 to 2035 given that technological options for substituting it are limited, current recycling technologies have limited recovery rates, and new Lithium mine development takes up to ten years. The lithium supply bottlenecks are already manifesting in price increases for the material. Forecasts from Bloomberg New Energy Finance earlier in 2022 suggested that for the first time since 2010, there could be a year-on-year increase in battery prices this year amid rising raw material and component costs. It stands to reason however that battery prices will definitely fall over the long term as their supply chains scale up.

Identified supply risks for the EU and EU shares of production



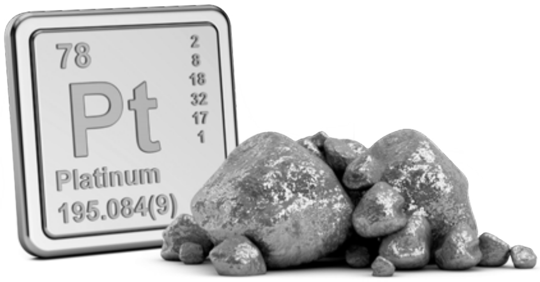
Source: European Commission, Joint Research Centre: „Critical Raw Materials for Strategic Technologies and Sectors in the EU - A Foresight Study“
Figure 5



8. Sodium-ion batteries are still in a nascent stage of development but could potentially play a role in applications like energy storage devices. However, it does not have the energy density and performance required for much more demanding HDT applications. Other alternatives being investigated and developed, such as metal-air batteries, are further away from achieving any technological readiness.

At the same time, it is also important to gauge the geopolitical risks in lithium-ion battery supply chains. A recent EU Foresight Study evaluated the risks in the supply chain for batteries and fuel cells. Supply chains for batteries are currently highly concentrated in far east Asia, with both Europe and North America looking to localize strategically important portions of the value chains. Given that current upstream and midstream processing is heavily dominated by Asian players, strategic independence is seen as necessary, but it will take time to achieve. However, with time, the metals mined in the future will not come cheap as resources are likely to get increasingly complicated to exploit due to lower ore grades, depth, and tighter regulations. Recycling of batteries is expected to alleviate at least a part of the metal supply crunch, but these technologies are still in early phase of industrialization and there is limited experience and knowledge on the performance of batteries manufactured with recycled materials.

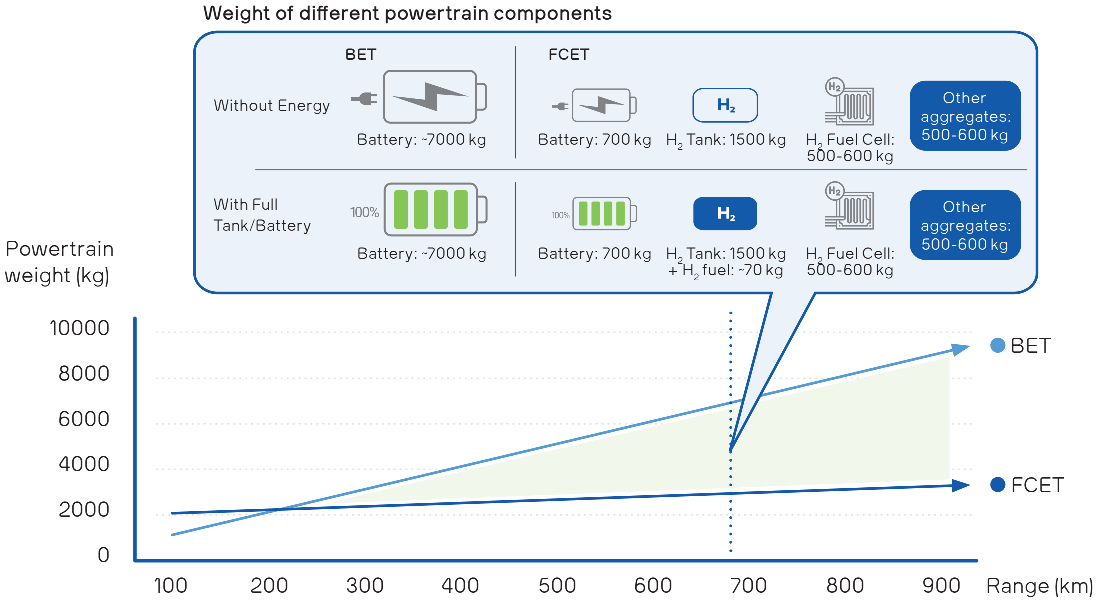
In comparison, FCETs are less dependent on rare or constrained metals and commodities. Instead, these systems are produced mainly from carbon, steel, and aluminum manufactured parts. Further, only a small fraction of the materials is needed for making fuel cell powertrains in comparison to the material required for battery electric powertrains, which gives OEMs more certainty over price fluctuations. Depending on the powertrain and vehicle, the material requirement in an FCET could be 15-20% of the corresponding requirement in a BET. Proton exchange membrane (PEM) fuel cells are currently the dominant technology used in automotive applications. While these use platinum as a catalyst, no shortages of this expensive metal are expected in the foreseeable future even if fuel cell production scales are ramped up. At the same time, fuel cells have very high levels of reusability and recyclability. Since the platinum in the fuel cell does not react in a way that makes it hard to recover or reuse, it is much easier to recycle them at the end of their lifecycle. For example, already today, the platinum used in the catalytic converters in vehicles with internal combustion engines are being recycled easily.



Another major advantage of FCETs over BETs is the weight of the powertrain. FCET powertrains have a weight comparable to the powertrains in conventional diesel trucks today. On the other hand, the powertrain of a 44-ton BET can typically weigh over twice as much as a corresponding FCET powertrain in long-haul application requiring a 700 km range. This is because the battery size is directly proportional to the power requirement of the vehicle. Even in case of line-haul application with a 400 km range requirement, a BET battery is expected to weigh 1.5 times as much as a corresponding FCET powertrain. In fact, based on these assumptions, a sensitivity analysis shows that an FCET powertrain is lighter than a BET battery for a 44-ton HDT with ranges over 200 km. In the US where long-haul trucks frequently have a daily mileage exceeding 600 miles[9], this becomes especially critical.

9. The daily mileage is comparatively lower in Europe since there are stricter limitations on drivers' hours of service and maximum permissible speeds.

Variation of BET and FCET powertrain weights for a 44-ton tractor with increasing range on single charge/refueling



Assumptions: Energy consumption of 160 kWh/100km, FCET buffer battery size of 110 kWh, 240 kW fuel cells, battery weight of ~6.3kg/kWh

Figure 6

Heavier batteries in BETs are associated with certain drawbacks, as this weight must be carried in addition to the cargo by the vehicle. And unlike diesel trucks or FCETs where the fuel is consumed while driving, the state of charge of the battery does not affect its battery weight in any significant way. As the range requirements increase, it becomes inefficient to also transport much larger and heavier batteries on the vehicle. This can lead to potential compromises on the payload and space available for the cargo. This may not severely handicap the transportation of lighter or voluminous cargo but is especially relevant for full truck load transportation of heavy freight. In the HDT sector where every kilogram of weight counts towards the revenues and operating margins of transport operators, additional powertrain weight is still seen very critically.

It is also important to recognize that some applications have additional power requirements. As an example, a 44-ton truck with refrigerated trailer will require 20 kWh of energy just for cooling the cargo each hour. For a BET with 400-500 km daily range with limited time for recharging, this poses a lot of additional demand. In a BET with about 500 kWh usable battery capacity, approximately 200 kWh energy would be used just for the cooling. This would penalize the range that could be driven between each charge. Similarly, topography and driving conditions also have an impact on the energy requirements. For example, if a fully loaded truck must drive uphill in cold temperatures against a headwind, the battery electric range could drop to about 50%. In a fuel cell truck, the corresponding drop in range would be much less significant. While adding bigger batteries would increase the energy available on board, this would again lead to additional battery weight, costs, and charging time requirements. In some cases, like in Europe, additional allowances for vehicle length and tractor weight are being considered for zero-emission HDTs which can potentially help mitigate such a handicap. While this may mitigate some of the potential impact on cargo space or weight, the extra weight of the batteries must still be transported by the truck.

On the other hand, these issues are much less severe in case of FCETs. Additional energy or range requirements can be met by storing more hydrogen on board. While costs can accrue for additional hydrogen tanks, this are much lesser than the cost of additional battery capacity on board. This advantage become even more prominent when we evaluate the time needed for loading energy into the vehicle.

Charging/Refueling Considerations

Given the high uptime requirements of fleet operators, it is important for zero-emission HDTs to be reloaded with energy as quickly as possible. In case of BETs, this is the time needed for recharging the battery, while for FCETs, it is the time needed for refilling the hydrogen tank. Currently, depending on its capacity, a hydrogen tank can be filled with gaseous hydrogen at 700 bar pressure in about 20-30 minutes to enable the FCET to have a real driving range of 600 to 700 km. With technical improvements, the refilling time could potentially drop to 10-15 minutes in the future, which is comparable to the refueling time in conventional diesel fueled HDTs. This offers FCETs a significant edge.

In the case of BETs, various charging approaches must be considered depending on the power output of the chargers. In use cases where the trucks return to the base like urban or regional distribution, it would be necessary to have overnight chargers at the fleet hubs. For longer distance applications like line-haul or long-haul use cases, chargers are needed along the public roads. This would include overnight chargers at highway rest stops. Typically, these chargers have a comparatively lower power rating and can recharge the battery with a range of about 400 km over 8 hours, i.e., at about 50 km range per hour of charging.

As discussed earlier, cost and weight considerations imply that BETs cannot carry large enough batteries to allow them to operate longer distances through the day on a single charge. With current European regulations mandate that truck drivers must have a 45-minute break once in every 4 hours of driving, the HDT must carry at least sufficient energy to drive for this period and can be recharged during the break time. Higher power chargers are also necessary at highway rest stops to

Comparison of BET charging and FCET refueling times

Estimated Charging time for ~500 kWh usable energy

*Depending on starting and finishing state of charge (SoC)

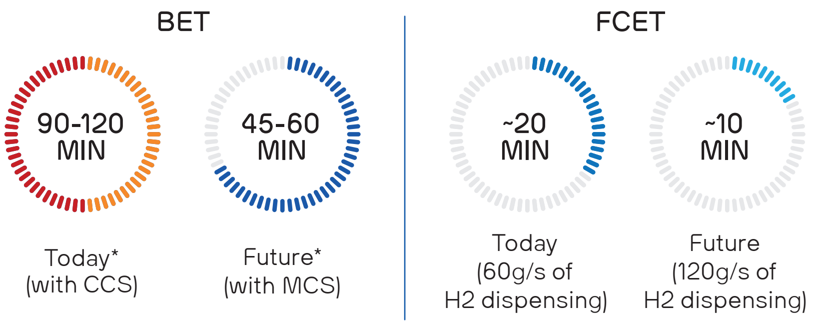


Figure 7

cater to this need. Currently, these chargers can deliver 300-350 kW of power using the Combined Charging System (CCS) standard. In parallel, truck and bus manufacturers are working together to develop the Megawatt Charging System (MCS) which can allow a charging power of over 800 kW[10]. This is expected to become the industry standard after 2025. The EU EV Charging Masterplan outlines how many public and private chargers are necessary in Europe to reach a 30% reduction in CO_2 emissions in HDTs by using BETs. This shows that to support BET adoption, a significant ramp-up of charging infrastructure is necessary.

Despite these superfast charging standards, FCETs retain their comparative advantage in refueling time. A recent study in the US found that due to the longer recharging time and lower range per charge, a BET driving cross-country would have to make more frequent stops and longer stay at each stop. As a result, an FCET undertaking the same journey could take up to 35% lesser time to complete it. Even from a longer-term perspective, if and when fully autonomous trucks gain adoption, there would be no need for driver service breaks or mandatory rest times, leading to a higher daily mileage. In such cases too, FCETs will gain attractiveness with fewer stops needed and faster refueling times.

Theoretically, combining faster charging speeds with the mandatory break time could provide a solution for recharging BETs. However, this could be difficult to achieve in the real world. A truck arriving at a highway rest station must be able to find a parking bay with a functioning charger available exactly at the time it arrives for this approach to function seamlessly. In addition to charger density and availability, the quality and reliability of the chargers also needs to be ensured by learning from the teething issues being experienced currently in the rollout of the charging network for passenger cars. Further, customer acceptance of such operating approaches is still untested and not proven in the HDT sector. For example,

10. The impact of such superfast charging on batteries is currently not sufficiently investigated. Experience in passenger vehicles and consumer devices shows that frequent fast charging leads to quick degradation of the battery's SoH. This can severely impact the lifetime of the battery, as well as the residual value of the battery and the vehicle at the end of its useful life. This also introduces significant complexity and uncertainty in the capability of OEMs and their partners to tailor financial packages for customers looking to rent, lease, or subscribe to zero-emission vehicles, since there are no models to help evaluate and calculate these effects currently.

driver unions in Europe have expressed concerns and are seeking clarification on the need for the drivers to keep a track on the charging progress of their BETs, since strictly speaking, this should be treated as working hours and not as rest time for them.

In addition to that, there are two factors which need to be considered. The first is the number of charging locations needed. Taking North America as an example, estimations from the US Clean Air Task Force indicate that due to the longer charging times of BETs, if all HDTs were switched purely to BETs, more than eight times as many locations would be needed for fast charging than the number of hydrogen refueling stations (HRS) for a fully FCET network. Further, not all highway rest stops have the space on offer for multiple BETs to be parked and charged simultaneously. Similarly in Europe, though some experts have estimated that having 3-4 MCS 800 kW chargers per highway rest station[11] might be sufficient to deploy BETs, grid connections and space for the vehicles are not available at many of them. Multiple parking bays are also needed for vehicles which are waiting for the next available charging opportunity.

The second factor which needs to be considered is the impact of BET chargers on the electricity grids. It is a fact that currently grids are not equipped to cope with the sheer amount of electricity required to fast-charge multiple battery trucks at the same time. For example, if twenty BETs were to a simultaneously use 1 MW MCS chargers at a highway truck stop, the demand would be greater than the power requirement of a town with about 25,000 inhabitants. From the point of view of the network operators, MCS is not possible in all locations since significant grid upgrades would be necessary to deploy BETs at scale. In other words, regional grid transmission including cabling and capacities in the substations need to be upgraded to meet these demands, even in relatively remote locations along highways. If these upgrades are not taken up, there would be a risk of blackouts from the collapse of the grid. There are already instances of power generation companies and grid operators, especially in the US, struggling to cope with the demand stemming from the adoption of small fleets of commercial electric vehicles at depots[12]. In a country like Germany moreover, current estimates suggest that the upgrade

11. In addition to lower power overnight chargers.

12. Given rapid additions in renewable energy generation, the additional power requirement from electric vehicles is expected to be manageable. BloombergNEF expects this to not add more than 15% over the estimated global electricity consumption in 2040. The challenge, however, is that high speed chargers will draw a lot of electricity very quickly at a single place and time, which will impact the grid.

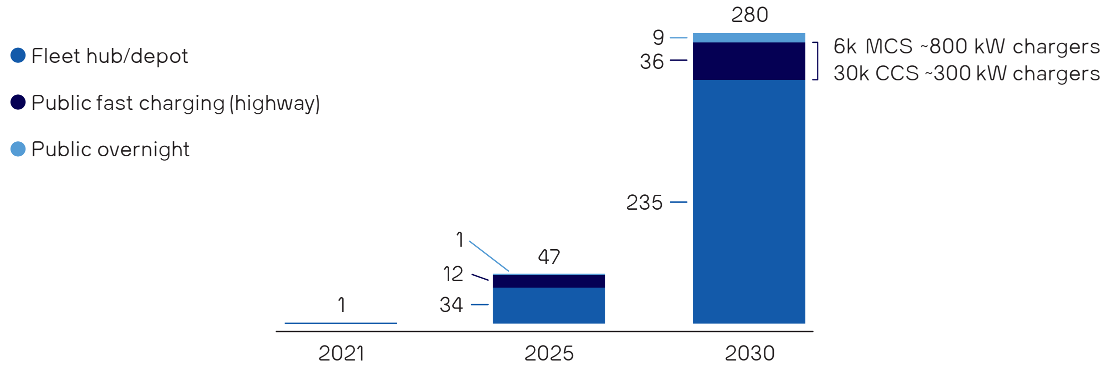
and approval process for establishing a high voltage connection to the grid could take as long as ten years due to administrative and bureaucratic hurdles. A recent study estimated that also in the US, a grid connection that can handle over 5 MW can take up to eight years to build and costs tens of millions of dollars.

Substantial infrastructure investments are a requirement for both BET and FCET solutions. However, the cost of setting up the charging infrastructure at one location is comparatively lower in case of BETs than in case of FCETs. A recent study by Strategy& estimated that for a medium-sized logistics company with a fleet of ten trucks, about €450,000 investment would be needed for a depot charging system with three 250kW chargers. They also estimated that for a highway charging park with six fast chargers of 1.5 MW rating and 28 overnight chargers of 150kW rating would require a €8.5 million investment.

In comparison, the same study estimated that a HRS with five dispensers and 5 kg H2/minute dispensing capacity would require an investment of about €10 million. Despite the higher cost, however, the much faster refueling time of FCETs means that such an HRS would be capable of refueling about 200 FCETs a day, which is indicative of a much higher utilization – even when compared with a MCS charger. This also means that the investment in the HRS can be amortized over a larger number of vehicles, resulting in a lower unit economics. Further, the number of HRS required would also be lower than the number of charging stations needed. For example, the European Fit for 55 Alternative Fuels Infrastructure Regulation mandates one HRS every 150 km along the TEN-T core

Charging infrastructure requirements for BETs in Europe to reach -30% CO2 emissions

Thousands of charging stations required to reach -30% CO2 emissions for trucks in EU-27 Source: EU EV Charging Masterplan



Source: Europe Electric Vehicle Charging Infrastructure Masterplan
Figure 8

highway network by 2030. Further, by setting up of depot HRS, some estimates suggest that it could even suffice to have one HRS at about every 300 km of the TEN-T network in Europe to support the FCETs in operation.

ing up both infrastructures could potentially amount to a waste of public resources. However, a recent analysis by McKinsey & Company found that it would in fact be cheaper to build out an optimal mix of both BET and FCET infra-

Schematic variation in infrastructure costs with increasing BET and FCET adoption

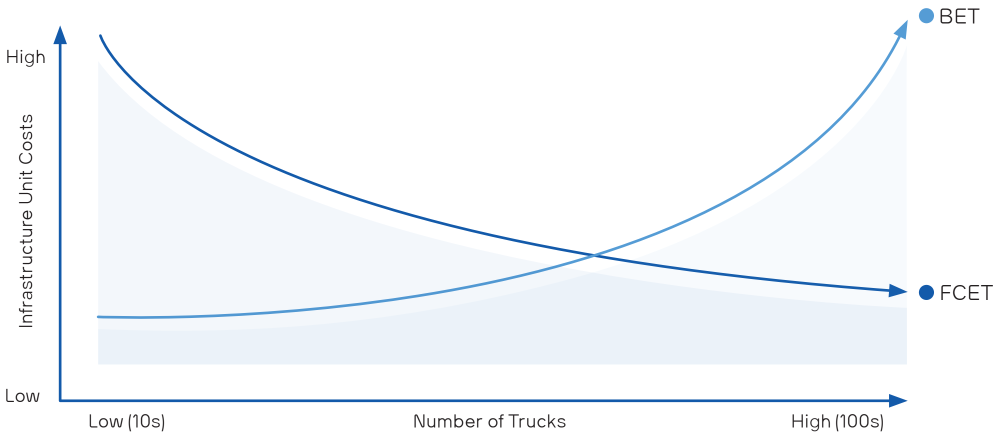


Figure 9

The advantage of hydrogen-powered commercial vehicles is already being seen in case of fuel cell electric buses. Looking at infrastructure costs, the higher vehicle purchase cost can be offset by the lower cost of the HRS infrastructure at scale. In other words, the infrastructure cost for fuel cell buses is seen to decrease as their volume of adoption increases, since the HRS can be shared by over 100 buses at the same depot. On the other hand, as the number of deployed battery electric buses per depot increases, the cost of the infrastructure per vehicle also increases due to the need for more power.

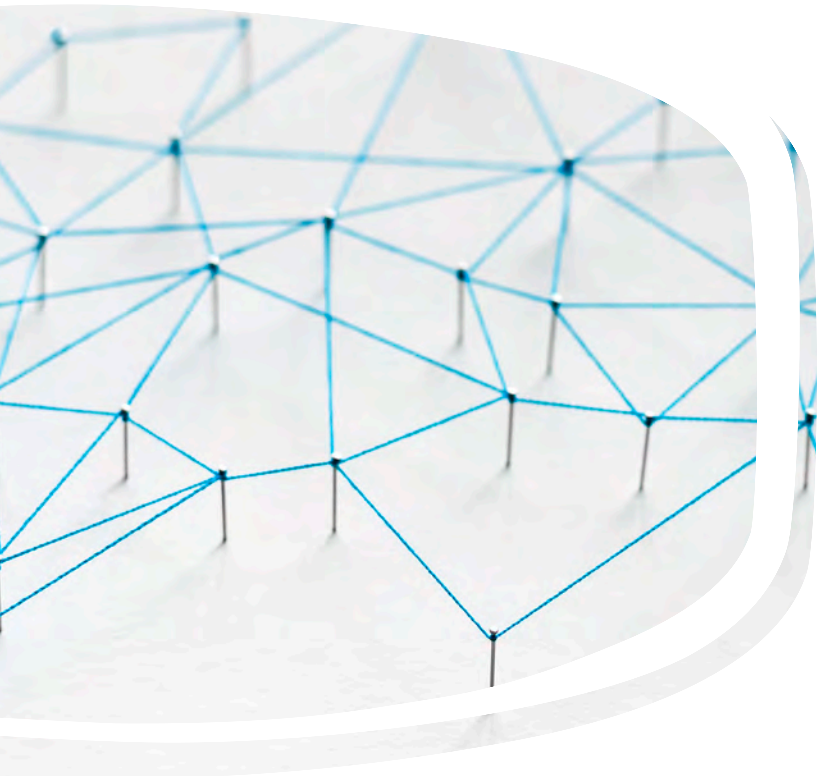
Given the costs associated with setting up the charging or refueling infrastructure at each location, some experts have argued that build-

structure based on use cases and considering system level costs and efficiency, rather than exclusively one of them. This perspective has also been supported by the European Union Clean Hydrogen Joint Undertaking.

Here, it is important to recognize the impact that the scale of BET or FCET adoption plays. At smaller scales, it is cheaper and easier to operationalize a few BETs with a depot charging station costing about €120,000. A single onsite HRS in comparison could cost €2-3 million depending on size, i.e., kilograms of hydrogen delivered and number of dispensers. However, the unit economics can be spread out if there is a minimum base coverage with a substantial number of FCETs using that HRS. At larger scales therefore, HRS infrastructure is less costly to setup than BET charging infrastructure, along with the advantage of lower demands on grid upgrades. According to McKinsey & Company estimates, the cost of charging infrastructure for BETs would amount to 0.11 USD/kWh, while in case of refueling infrastructure for FCETs would only amount to 0.03 USD/kWh. Nevertheless, both infrastructures need to be robustly designed to be high-capacity HDT stations with in-built redundancy of key elements to ensure that they are reliable and dependable.

Energy Considerations

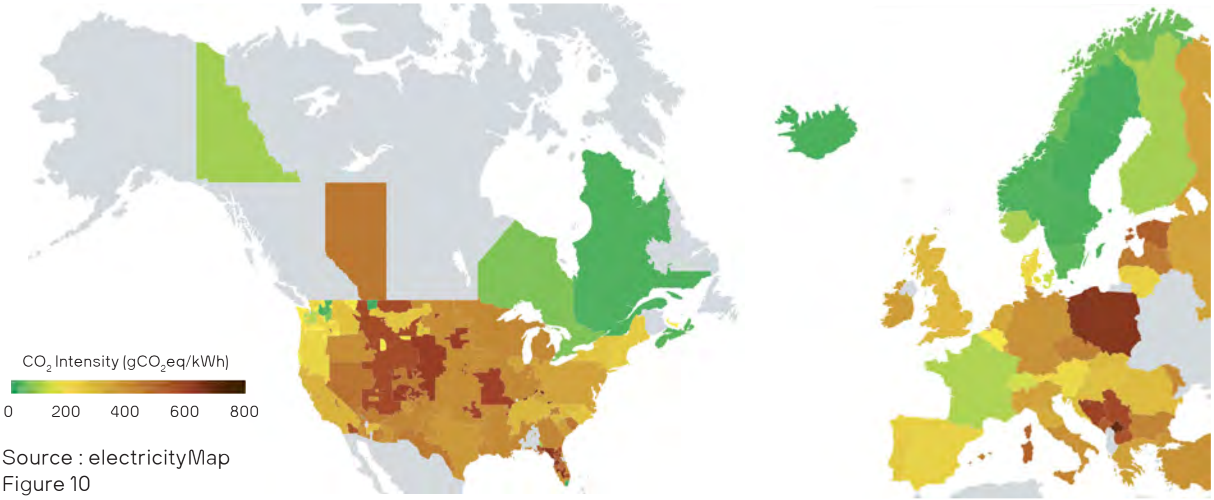
The energy used to power the zero-emission vehicles is another dimension which needs to be examined in the context of decarbonizing road freight transport. One of the significant triggers for this decarbonization is the increasing scrutiny on the Scope 3 emissions of vehicles when they are in use, i.e., the deployment of zero-emission vehicles must help abate the CO_2 emissions from their use phase. In this context, both BET and FCET are zero-emission solutions since they have no tailpipe emissions and have, therefore, no downstream Scope 3 emissions. However, it is also equally important to mitigate the upstream Scope 3 emissions. This places the emphasis on how clean the energy used for manufacturing the vehicle components as well as for operating the vehicles is.



For example, battery manufacturing is an energy intensive process, with about 50 kWh of energy currently needed to produce 1 kWh of batteries. By factoring in the current carbon intensity of the energy mix in Europe, it can be estimated that a battery produced in France today has roughly a tenth of the carbon intensity of a battery produced in Poland. If potential carbon taxes are factored in at an average value of 30 USD/tonCO_2, then this would be equivalent to a price difference of roughly 1 €/kWh of battery capacity between a battery produced in these locations. In fact, battery manufacturers in Norway and Sweden take pride in being able to manufacture the cleanest batteries compared to other European battery gigafactory locations, given the abundance of clean energy available there.

The same argument also applies for the energy used to charge electric vehicles. If the vehicles are recharged with electricity produced from coal or gas, then it effectively means that though the tailpipe emissions are nullified, they are simply shifted further upstream in the value chain. For achieving climate goals, it is essential to decarbonize the entire value chain, including manufacturing of zero-emission vehicles/components (upstream) and the vehicle use (downstream). This highlights the importance of decarbonizing energy supply, given that there is a rapid increase in the adoption of battery electric vehicles (especially in the passenger car and other small vehicle segments

Electricity carbon intensity in Europe and US in the Last 12 Months



Source : electricityMap
Figure 10

globally) and thus a proportional hike in the energy demands stemming from the operation of these vehicles. Currently, the electricity supply both in continental Europe and in the US is quite carbon intensive.

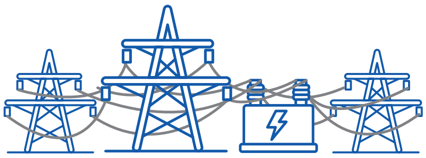
Similarly, the process of electrolysis to generate green hydrogen is also energy intensive. To generate 1 kWh of green hydrogen, about 1.2-1.4 kWh of electricity is needed. The carbon footprint of the hydrogen can only be minimal if it is produced with clean electricity produced from renewable sources. At a system level, this also means that if the power used for electrolysis is drawn from the grid, it should not be replaced by fossil-fuel based electricity to cater to other demand sectors. A recent study by Oliver Wyman estimated that if this were to be the case and electricity generated from natural gas was used as the source, then producing 1 MWh of green hydrogen could have twice the CO2 emission at system level than producing the same amount of gray hydrogen by steam methane reforming.

Consequently, questions are often raised about the economic efficiency of locally produced green hydrogen in regions like western Europe, since it is a lower-value product produced by using electricity, a higher-value product. Hydrogen prices are a function of where it is produced and with what energy prices. Juxtaposed with the rapidly growing demand for clean electricity, the economics for local green hydrogen production become unfavorable in such regions. Here, it is already difficult to meet the (peak) demands purely with clean energy, given that the availability of electricity generated from renewable sources like wind or sun is geographically and temporally constrained. For example, northern Europe or northern USA are roughly 2.5 times less efficient in capturing and utilizing solar energy than sun-rich areas to their geographic south. Taking Germany as a case example, the onshore wind and solar energy load factors are estimated to be 25% and 12% respectively. Given the capital expenditure that electrolysers entail, they need to be operated at high utilization rates to be cost-efficient.

Transportation of green electricity and green hydrogen

Green Electricity

Energy carrier: Electrons



Electricity grid
harder to transport over long distances

Green Hydrogen

Energy carrier: Hydrogen molecules

Tankers, pipelines:
easier to transport as molecule, only non-carbon molecule option for green energy transport

Figure 11

Consequently, hydrogen prices are much currently rather expensive, driven by both capital and operating expenses. The resulting higher energy costs for FCETs in comparison to BETs can effectively erode any advantage gained from the FCET refueling infrastructure costing lesser than the corresponding BET charging infrastructure.

However, a major differentiator between green electricity and green hydrogen is the effort needed to bring them from their point of generation to their point of consumption (i.e., charging station or HRS respectively). It is difficult to transmit electricity over long distances since it can incur significant transmission losses[13]. Therefore, the electricity used for charging BETs needs to be produced relatively close to the point of consumption. Further, this energy is priced at spot rates. In comparison, it is much easier to transport hydrogen molecules over long distances than electricity transmission (i.e., transporting electrons). Large volumes of hydrogen can easily be transported over much longer distances as gaseous or liquified hydrogen or derivatives like ammonia, through new pipelines, repurposing existing pipelines, or on maritime ships/tankers[14].

This means that hydrogen can be produced at sun or wind-rich locations where the load factors or utilization rates are much more favorable economically[15] and transported to the point of consumption. As an example, the same solar installation in the Middle East would have more than twice the annual output of energy than if it were installed in Germany. Consequently, even after accounting for higher losses from a sun-to-wheel perspective for FCETs, the system-level energy output would be comparable to using locally produced solar energy to charge a BET. Further, producing hydrogen at renewable energy rich locations also has a much lower carbon footprint than in using carbon intensive local electricity supplies. Depending on location, this can be comparable or

13. Transmission losses estimated to be between 6 to 10 percent per 1,000 km in high-voltage alternating-current grids and about 4 percent per 1,000 km in high-voltage direct-current grids (which are subject only to ohmic losses).

14. For low volumes and across short distances, it could be cheaper to produce hydrogen locally, potentially with imported renewable electricity. However, for distances of over 500 kilometers, pipelines are better suited to import hydrogen economically and with larger volumes. Repurposing existing natural gas pipelines can decrease the infrastructure investment costs to as low as one-third of building new dedicated pipelines. This mode is well suited for moving hydrogen within Europe or for importing from neighboring regions with pre-existing infrastructure. For import routes across much long distances (3,500 km or more), maritime shipping is emerging as the preferred option when hydrogen pipelines may not be possible.

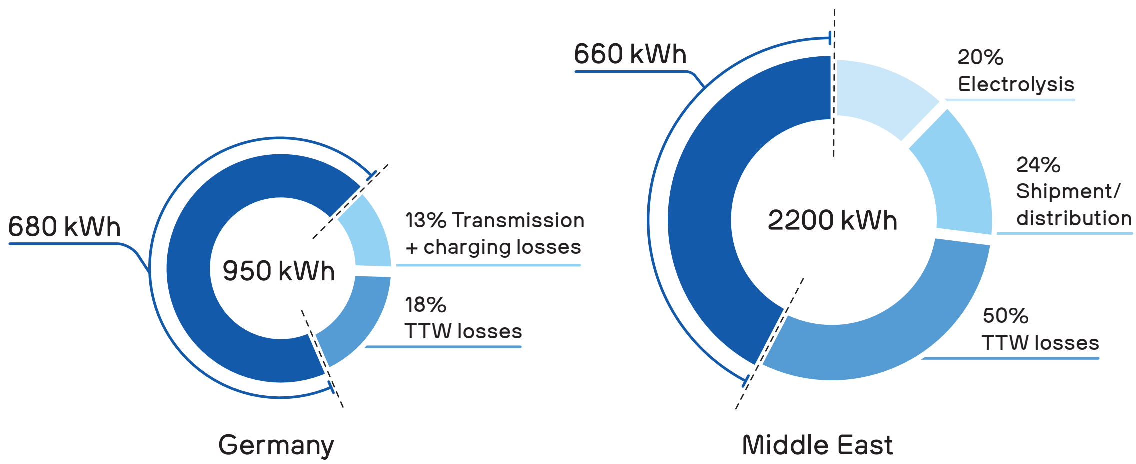
15. Current forecasts suggest that green electricity prices in the Middle East and North Africa region could drop to as low as 0.045 €/kWh by 2030 and further to 0.015 €/kWh by 2050.

even lower than the carbon footprint of battery electric vehicles, according to a recent study published by the Hydrogen Council. Similarly, there is a lot of potential to tap into hydropower is the Nordic region or geothermal energy in countries like Iceland and using it to produce green hydrogen for consumption in Europe.

Though green hydrogen supply is a quite constrained today, there are both demand and supply side effects which support its scaling. Unlike earlier generations of fuel cell vehicles which had a lot of hype but could not reach any significant market penetration, the development of hydrogen solutions is not happening in isolation but rather as part of an overall energy transition and shift to renewable energy sources now. Hydrogen is necessary to decarbonize many hard-to-abate industry sectors like steel, chemicals, and fertilizers. In fact, it is estimated that in 2030, the hydrogen demand in non-transport sectors would account for over 80% of the total global hydrogen demand. This causes scale effects from a demand side, which in turn helps lower midstream infrastructure investment costs.

An increasing number of investors, governments, and energy players have been announcing plans for ramping up green hydrogen production. The US Inflation Reduction Act 2022 makes significant provisions for supporting the building up of local hydrogen value chains, for example. The US DOE National Clean Hydrogen Strategy and Roadmap draft sets a target of 10 million metric tons (MT) of domestically produced clean hydrogen by tapping various energy sources. Similarly in Europe, multiple projects have been identified and supported with public funding from the European Commission as Important Projects of Common European Interest (IPCEI), covering

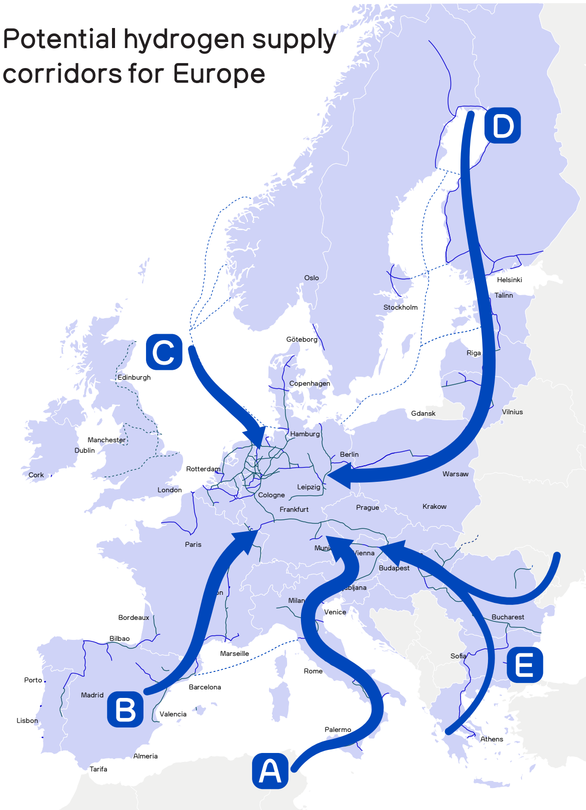
Sun-to-wheel efficiency: Germany vs Middle East



Source: Hydrogen Council, McKinsey & Co.
Figure 12

hydrogen technology and infrastructure development along its entire value chain. Additional emphasis on Europe's hydrogen strategy has also come from the recent geopolitical developments and the need to have greater energy security. The REPowerEU plan was announced three weeks after the war in Ukraine started to increase the ambition for renewable hydrogen from 5.6 million MT to 20 million MT in 2030.

Potential hydrogen supply corridors for Europe



The five hydrogen supply corridors could be:

- Corridor A: North Africa & Southern Europe
- Corridor B: Southwest Europe & North Africa
- Corridor C: North Sea
- Corridor D: Nordic and Baltic regions
- Corridor E: East and South-East Europe

Source: European Hydrogen Backbone initiative
Figure 13.

This includes 10 million MT of domestically produced hydrogen supply, complemented with another 10 million MT imported from outside the EU.

Given the scale of the hydrogen demand, there is a recognition that Europe will have to import clean energy from other regions or partners. From this perspective as well, hydrogen is the best solution if the imports must be limited to non-carbon molecules. The European Hydrogen Backbone initiative has identified 5 potential pipeline supply corridors to deliver access to sufficient and low-cost hydrogen supplies. The vision is to initially connect local supply and demand within Europe, and then expanding and connecting the continent with neighboring regions exhibiting an export potential. Additional supply could be secured through maritime shipping, with the German Canadian Hydrogen Partnership being one such example[16].

In addition to the imported hydrogen, there are also additional opportunities in the mid-term to produce hydrogen locally, taking both centralized and decentralized approaches. Centralized production could be deployed at larger scales by leveraging not only offshore wind, but also using geothermal or hydropower sources. On a regional level, generating hydrogen from waste is also seen as a promising opportunity with the potential to use agricultural and forestry waste, municipal solid waste, and landfill gas. Further, there is also potential to tap into excess onshore wind energy at a local level. For example, it has been estimated that over 6 million kWh of green electricity went untapped in 2020 in Germany, simply because windmills were stopped at times when there was an excess supply in the grid. In such cases, the cur-

16. The US is currently expected to have access to sufficient regionally produced clean hydrogen to meet its demand.

17. It should be noted that also in energy storage and grid balancing applications, lithium-ion batteries offer a far more energy efficient solution to store excess renewable energy than green hydrogen production, especially in cases where the oversupply is only for short periods. They have only about a 15% efficiency loss and a lower capital cost per megawatt than electrolysers. However, the supply chain constraints discussed earlier also apply to batteries in this application. Further, a temporal dimension must also be considered. While lithium-ion batteries are better suited for short-term storage and there is a future potential for sodium-ion batteries, longer term energy storage is a field where nascent alternatives like flow batteries could potentially compete with hydrogen in the future.

tailment of renewable energy production due to demand or grid throughput shortage is effectively energy that is lost. This excess energy could have been harvested and converted into hydrogen with smaller-sized electrolysers, thereby increasing the systemic output. Further, some experts have even suggested that such local hydrogen generation can aid under peak load conditions and reduce the scale of grid upgrades necessary.

These advancements are also expected to provide sufficient momentum to address the issue of high green hydrogen costs by leveraging the falling costs of renewable energy and improvements in electrolyser technology. In fact, the cost of green hydrogen has fallen by 60% from between USD $10-$15/kg in 2010 to as low as USD $4-$6/kg today in some locations. According to industry reports, forecasts suggest that they will continue to fall, with offshore wind-based electrolysis having another 60% cost reduction potential between now and 2030. Similarly, large scale manufacturing of electrolysers are being set up, supported by initiatives like IPCEI in Europe, adding up to 45 GW of annual manufacturing capacity by 2025. Experts at McKinsey & Company estimate that such a shift to large scale production facilities and distribution networks would help decrease hydrogen prices by close to 70% by 2040 compared to today's levels. Taken together, these factors are expected to help address the current challenges with hydrogen application in the transport sector, and specifically in the case of FCETs.

Complementary Roles of BETs and FCETs

With regulators, investors, end customers, and the society at large seeking a rapid transition to zero-emission transport solutions today, we are at the beginning of the transition towards decarbonized transport. BETs and FCETs are the leading options to master this transformation, but they are still at early phases of technological and industrialization readiness. Taking a system-level view, it is evident that each technology alternative has its respective strengths but also associated challenges.

BETs have benefitted from the advancements in battery electric vehicles in general and are closer than FCETs to customer adoption today. Their advantages like their energy efficiency and ease of deployment in smaller fleets makes them very attractive for certain use cases, especially when limited range or lower auxiliary energy requirements are sufficient. The industry is seeing an increasing number of BET models being launched with incremental innovations in product specifications, performance attributes, and overall reliability and durability.

Concurrently, early adopters of BETs have also become sensitized to their limitations. This has provided a fillip to the development of FCETs, which may not have the same energy efficiency but have potentially significant advantages over BETs in terms of charging times and experience, range, operational efficiency, and uptime. There is an increasing recognition that FCETs have a crucial role to play in use cases where BETs are severely challenged, such as line-haul and long-haul sectors. In such cases, FCETs also have the advantage of not penalizing the cargo space and weight limitations. Similarly, in use cases where time is a constraint, either at highway rest stations or while cargo handling at hubs/depots, it would be insufficient for recharging BETs but FCETs would be better suited.

Convenience and flexibility are key customer needs in the HDT space which give FCETs an edge. Though a 100% BET fleet could be capable of handling many urban or regional distribution loads by operating along a spoke to and from a hub, an FCET could handle regional delivery routes but also longer routes with little time needed for refueling. A more flexible fleet is one that may earn more for the business,

BET and FCET favorability by use case

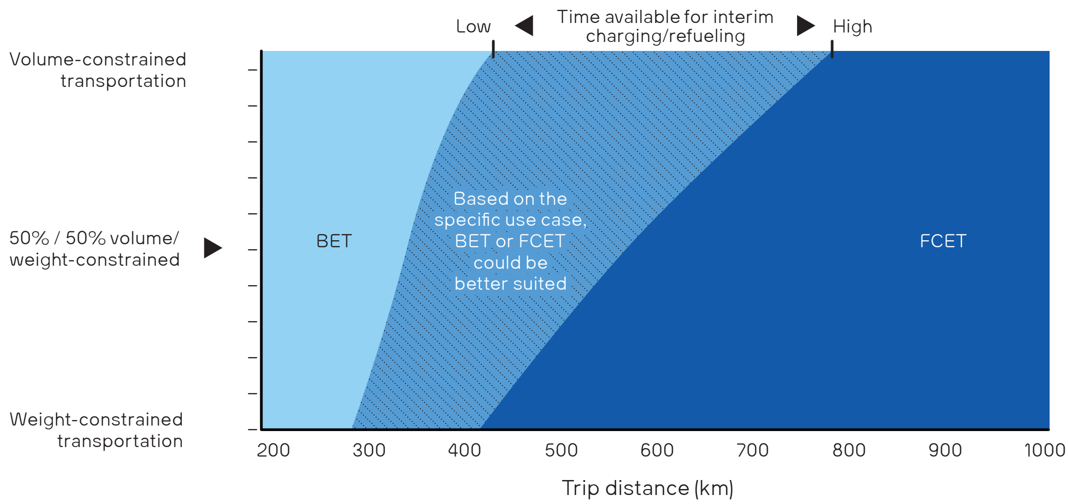


Figure 14

and this is also likely to influence the purchasing decisions, especially of big fleet customers who would be able to better amortize the infrastructure costs associated with hydrogen fuel.

Beyond this, the system-level effects like the impact on electricity grids, temporal and geographic limitations of renewable energy, and relative ease of transporting energy to the point of consumption are also important factors influencing the adoption of BETs and FCETs. Depending on the availability and nature of renewable energy, electricity versus hydrogen fuel costs could skew heavily to favor one or the other powertrain type. Quicker road freight decarbonization can be achieved by combining it with a low-carbon clean energy system which is independent of the electricity mix. Especially in regions with limited or constrained grid capabilities and limited local green energy production, FCETs can become the preferred technology option that fosters greater resilience, cost-efficiency, and optimization at a system level.

A pragmatic first evaluation of these multiple dimensions can be achieved by using established tools like balance scorecards. One such version, developed through interactions with a selection of our customers and industry experts, is shared here. Drawing on the system-level effects evaluated in this whitepaper, a set of criteria were selected, provided weightings, and evaluated on a scale of 1 to 5 in three different use cases, namely urban distribution, regional distribution, and long-haul heavy load transport. Summing the weighted ratings, it is again evident that while BETs are clearly favorable in some cases, there are others where FCETs have an edge. In other words, this emphasizes that BETs and FCETs are complementary solutions towards the decarbonization of heavy-duty transport. Ultimately, the penetration rates of BETs and FCETs will be determined by the most relevant factors for fleet customers or drivers, which will also influence the total cost of ownership.

Taking all these factors into consideration, the complementary roles of BETs and FCETs in decarbonizing HDT transport sector, depending on use cases and contextual conditions, becomes very clear. Hedging bets with two technology pathways helps de-risk the most significant transition in the automotive industry's history. The two technologies and their supporting ecosystems need to be jointly accelerated and scaled. This not only includes building the charging infrastructure in key regions and along key routes, including high power charging stations that can support BETs that allow for fast charging to reduce dwell times, but also achieving cost reductions in hydrogen technologies such as electrolysers and HRS through scale effects and leveraging experience curves. Finally, to achieve a competitive total cost of ownership, the right policy measures, incentives, and business model approaches are necessary for both BETs and FCETs. Given the respective challenges in powertrain, charging/refueling, and energy dimensions discussed earlier, it will be essential to build and orchestrate an ecosystem of strong partners, including energy players, vehicle manufacturers, equipment providers, logistics providers, and financial backers.

We are only just starting on a long and winding path towards large scale adoption of zero-emission HDTs globally. Despite the challenges and the scale of transformation required across multiple industries in achieving

Examples of use cases and favored powertrain option

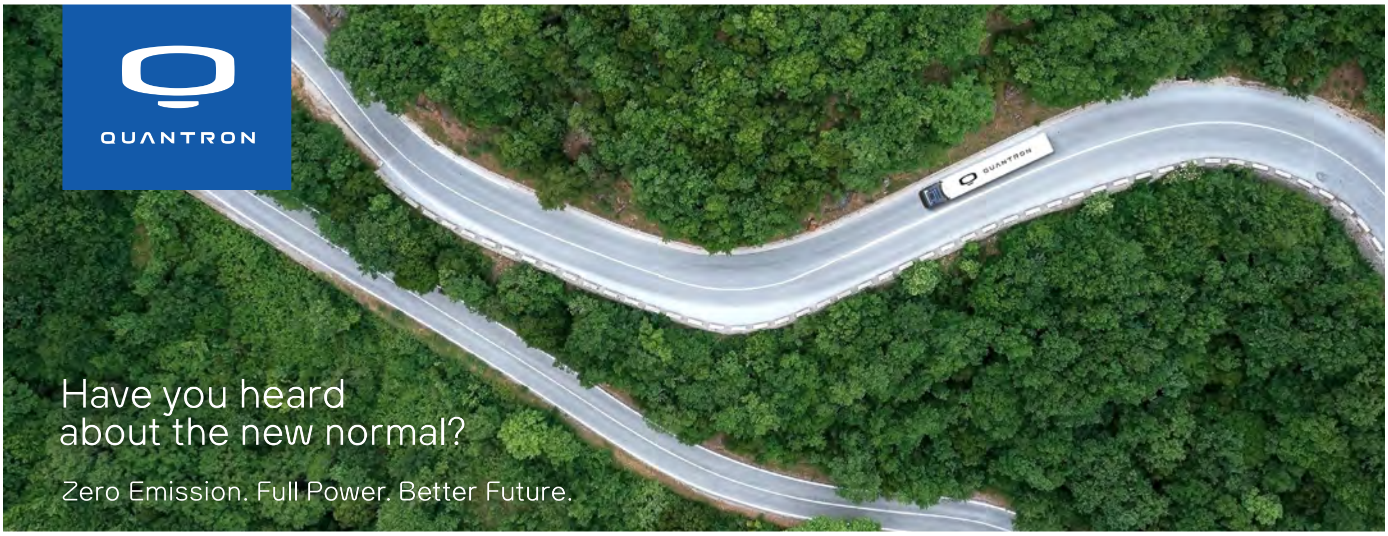
Use Case	E-commerce platform	Food logistics	Heavy goods transport
Description	Multiple small-sized packages distributed from a suburban warehouse (depot) to end customers across a city	Regional distribution of meat, fish, vegetable, and dairy products with refrigerated/ chiller body	Long-haul transport of goods with heavy duty tonnage
Cargo description	Small payload but higher volumes	Mixed focus on volume and weight	Focus on weight (GVW 40-65 tons)
Daily mileage	150 - 200 kilometer range	150 - 250 kilometer range	700+ kilometer range
Additional power requirements	Tail-lift	For maintaining cargo at required temperature	Depending on superstructure, trailer, and type of goods transported
Favored powertrain solutions	✔ BET	✔ BET or FCET	✔ FCET

Figure 15

this goal, it can be reached through concerted efforts by all stakeholders involved. This starts with a nuanced understanding of the solutions available and how and where each of them is a suitable fit. Equipped with that knowledge, the right strategies and business models can be developed and deployed towards decarbonizing road freight transports. We remain convinced that this is not an either-or choice between BETs and FCETs, but rather, a matter of creating synergies and an optimal mix between the two technology solutions.

Use Case:

Dimension	Sub-Dimension	Weight
Equivalent energy efficiency	"Well-to-tank"	2%
	"Tank-to-wheel"	10%
Vehicle powertrain & technology	Vehicle acquisition & operating costs	15%
	Technology & industrialization readiness	4%
	Supply security	2%
	Powertrain weight (vs. energy need)	8%
	Kilometers of range per charge/ refueling	10%
Charging/refueling experience	Time for recharging/refueling	10%
	Ease of charging/ refueling for driver	5%
Infrastructure costs & availability	#Charger / #HRS dispensers	5%
	Infrastructure costs	10%
	Infrastructure robustness(e.g., grid stability)	4%
Energy considerations	Geographical/ temporal availability of clean energy	3%
	Carbon intensity	2%
	Energy price	10%
Total (Scale: 1 = bad, 5 = good)		100%



Last Mile distribution GVW ‹18t, 150 km mileage				Regional distribution GVW 27t, 200 km mileage				Long-haul distribution GVW 44t, 700 km mileage			
BET		FCET		BET		FCET		BET		FCET	
Rating	**Score**	Rating	**Score**	Rating	**Score**	Rating	**Score**	Rating	**Score**	Rating	**Score**
4,50	**0,09**	2,50	**0,05**	4,50	**0,09**	2,50	**0,05**	4,50	**0,09**	2,50	**0,05**
3,50	**0,35**	2,00	**0,20**	3,50	**0,35**	2,00	**0,20**	3,50	**0,35**	2,00	**0,20**
4,00	**0,60**	1,50	**0,23**	3,50	**0,53**	2,00	**0,30**	3,50	**0,53**	3,00	**0,45**
4,50	**0,18**	2,00	**0,08**	4,00	**0,16**	2,00	**0,08**	4,00	**0,16**	2,00	**0,08**
1,50	**0,03**	2,50	**0,05**	1,50	**0,03**	2,50	**0,05**	1,50	**0,03**	2,50	**0,05**
4,50	**0,36**	1,50	**0,12**	4,00	**0,32**	2,00	**0,16**	1,50	**0,12**	4,50	**0,36**
2,50	**0,25**	3,00	**0,30**	1,50	**0,15**	3,00	**0,30**	1,50	**0,15**	3,00	**0,30**
3,00	**0,30**	4,50	**0,45**	1,50	**0,15**	4,50	**0,45**	1,50	**0,15**	4,50	**0,45**
3,50	**0,18**	3,50	**0,18**	2,50	**0,13**	3,50	**0,18**	1,50	**0,08**	3,50	**0,18**
2,00	**0,10**	3,00	**0,15**	1,50	**0,08**	3,00	**0,15**	1,50	**0,08**	3,00	**0,15**
3,00	**0,30**	2,00	**0,20**	2,50	**0,25**	2,00	**0,20**	2,50	**0,25**	2,00	**0,20**
1,50	**0,06**	3,00	**0,12**	1,50	**0,06**	3,00	**0,12**	1,50	**0,06**	3,00	**0,12**
1,50	**0,05**	3,50	**0,11**	1,50	**0,05**	3,50	**0,11**	1,50	**0,05**	3,50	**0,11**
3,00	**0,06**	3,50	**0,07**	3,00	**0,06**	3,50	**0,07**	3,00	**0,06**	3,50	**0,07**
3,50	**0,35**	3,00	**0,30**	3,50	**0,35**	3,00	**0,30**	3,50	**0,35**	3,00	**0,30**
	3,25		**2,60**		**2,74**		**2,71**		**2,49**		**3,06**

3,25	2,74	3,06
QLI BEV	QHM BEV	QHM FCEV

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