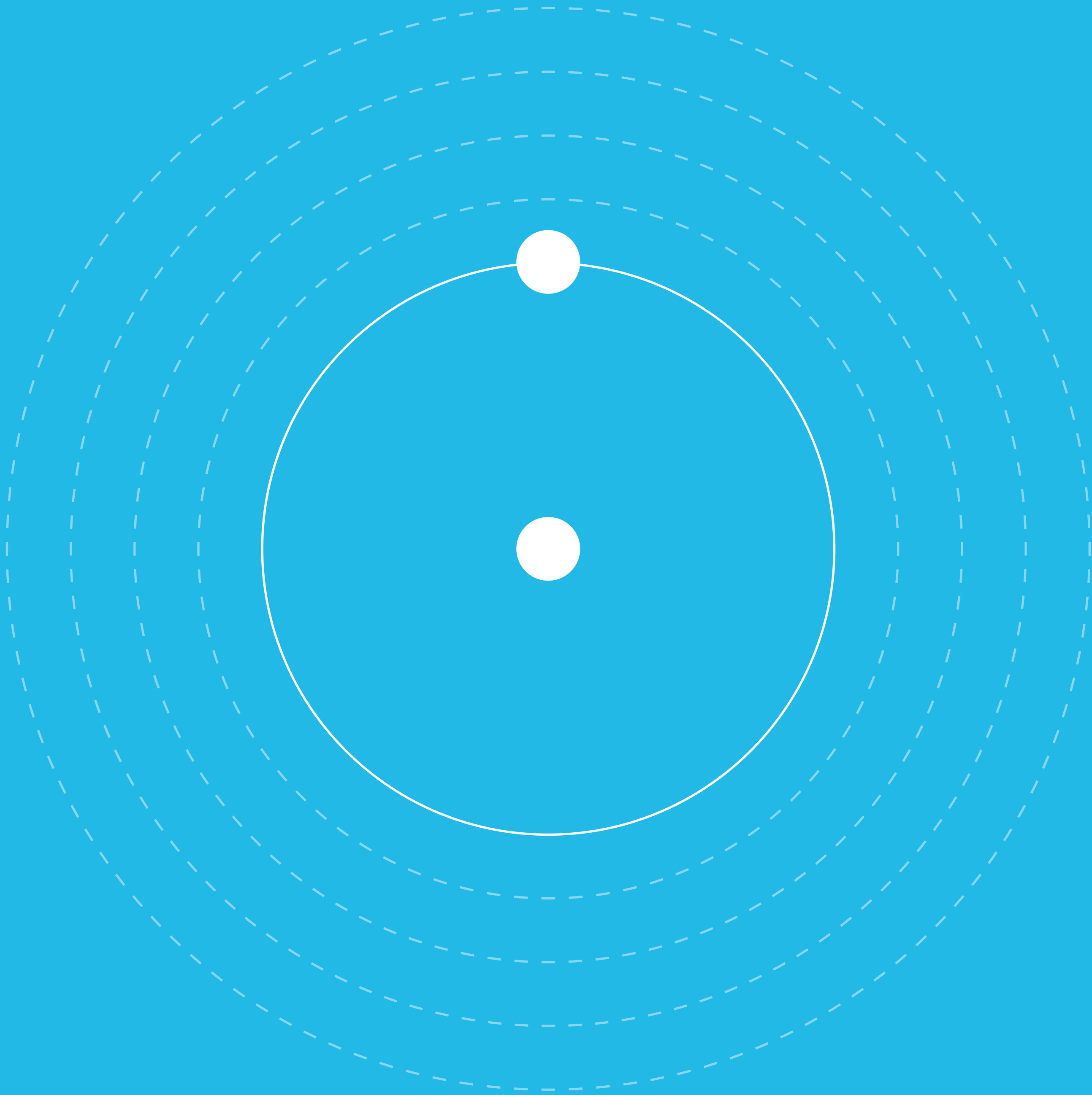


Hydrogen could meet a **significant share of global energy needs** competitively

15%+

Share of global energy demand where hydrogen applications can compete with other low carbon alternatives by 2030

3 | Hydrogen applications

In this chapter, hydrogen's competitiveness is explored within each of the target end-use segments: transportation, heat and power for buildings, heat and power for industry, and industry feedstock.

Road transport

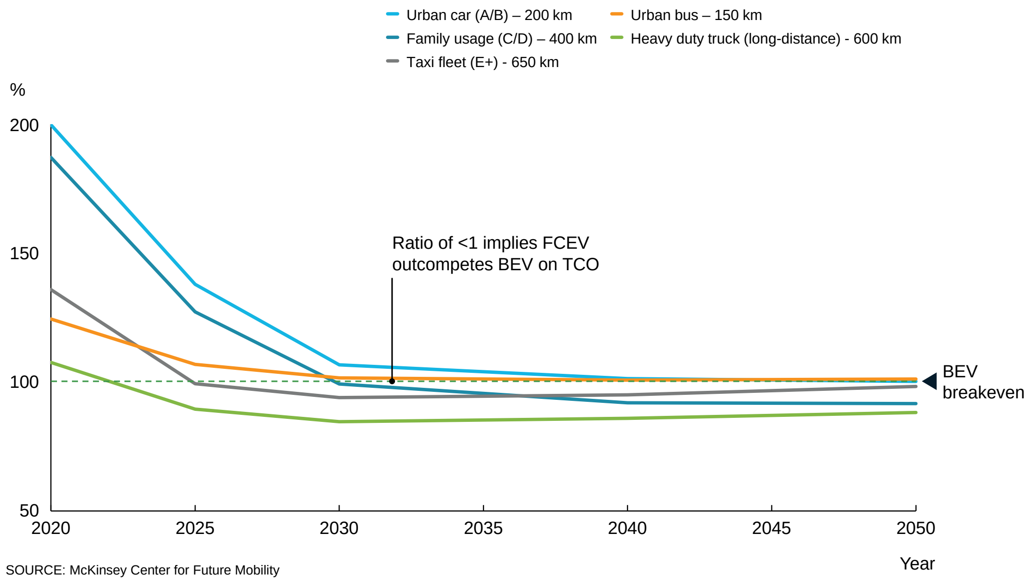
A range of road transport use cases with different types of vehicle and mobility patterns were considered, such as ranges, daily mileage, and payload (for trucks). Each use case was assigned a specific range in terms of tank, total mileage, and size of motor, and the TCO of three main technologies was assessed: fuel cell passenger vehicles, trucks, and buses. They were then compared with BEVs as the low-carbon alternative and internal combustion engines (ICE) as the conventional option.

The findings suggest hydrogen and fuel cell technologies are ideal for the decarbonisation of heavy-duty or long-range transport applications, as shown in Exhibit 17. These segments include use cases such as heavy-duty trucks, large passenger vehicles with long-ranges, and long-distance coaches. Heavy-duty trucks and coaches will likely achieve cost parity prior to 2025, because without breakthroughs in battery technology, the full battery alternative fails to meet commercial vehicle requirements due to the high cost and weight of batteries and relatively long recharging times. Meanwhile, large passenger vehicles with long ranges break even closer to 2030. For segments that require long-range capabilities, hydrogen is the most practical decarbonisation alternative.

For use cases with small vehicles and short ranges, like cars for urban use or short-range urban buses, the story differs. The battery required is relatively small, and as BEV technology becomes more developed it will remain the more competitive alternative, with hydrogen alternatives expected to remain more expensive than comparable BEVs. On the other hand, FCEVs will continue to offer higher range than BEVs. This increased flexibility may be decisive for vehicle purchase decisions that are not purely driven by TCO considerations. Ultimately, it depends on the consumers' willingness to pay for the increased flexibility of an FCEV compared to a BEV.

Exhibit 17 | TCO of road transport applications

TCO ratio between FCEV/BEV vehicles
No. average of 5 car segments ranging from small and low usage to large and high usage



SOURCE: McKinsey Center for Future Mobility

FCEVs are generally better than BEV in use cases that require long tank range due to:

- Lower cost of vehicle due to smaller battery
- Short refueling times made possible by Hydrogen

Longer charging time may imply fleets need to purchase a higher number of vehicles to provide same service.

For fleets developing infrastructure, FC offers additional economies of scale vs. BEV, which scale more linearly.

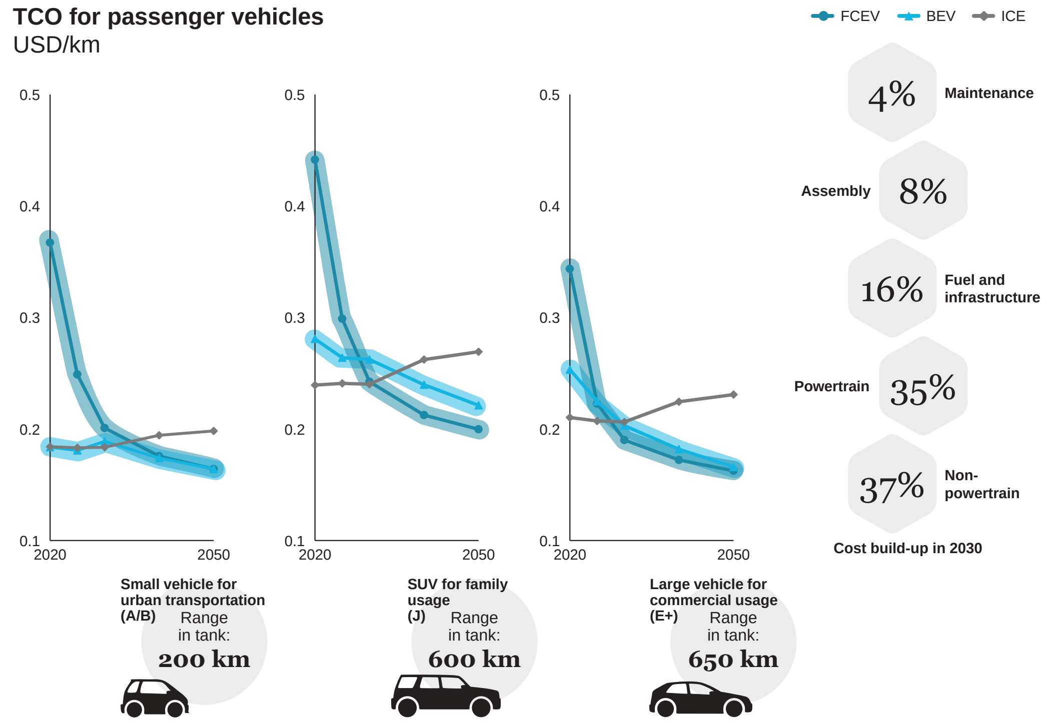
In the following sub-chapters, a more detailed analysis of each of the passenger vehicle, truck, and bus segments is provided. The TCO trajectory is explored in greater depth, including the conditions where hydrogen is most competitive, and the key cost drivers are identified across the value chain.

Fuel cell passenger vehicles

The cost analysis of passenger vehicles shows that the attractiveness of hydrogen applications varies across use cases, with fuel cell vehicles being more competitive in segments with heavier use and longer-range requirements (500 km or more between refuelling), such as large passenger cars, SUVs, or taxi fleets.

That being said, when the consumer considers the choice of vehicle and technology, factors beyond cost often emerge, including range, time to refuel, comfort, fuel efficiency, as well as the impact on the local and global environment. The final choice depends on all these factors, and ultimately comes down to the vehicle's intended use and mobility pattern.

Exhibit 18 | TCO trajectory of passenger vehicles



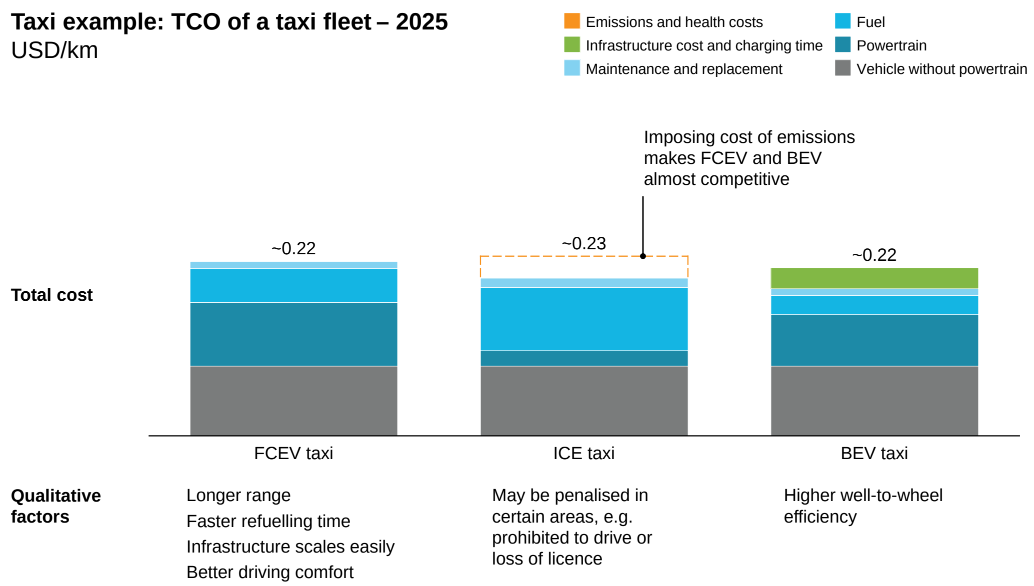
SOURCE: McKinsey Center for Future Mobility

Cost competitiveness. Our analysis suggests that under the assumed scenario of production volume, hydrogen will outcompete BEVs by circa 2025 for taxi fleets where a range of 650 km is required, as shown in Exhibit 18. Sub-segments such as SUVs, large passenger cars and taxi fleets that have range requirements of 500 km or longer will be competitive earlier than smaller vehicles with shorter range requirements. Reaching these cost levels will require an estimated annual production of 600,000 vehicles worldwide, which should generate sufficient economies of scale and create adequate learning effects.

For the mid-size car with a 400 km range requirement, FCEVs will reach cost competitiveness around 2030. Considering a use case with a mid-size vehicle with a shorter range of 300 km, the FCEV reaches cost parity around 3 to 5 years later. This suggests that the BEV is more attractive for use cases with lower mileage and short range requirements in the foreseeable future.

Our findings for small, urban cars with 200 km ranges support this point. FCEV are not expected to reach cost parity in this segment, and only reach similar cost levels to BEV in 2040. Urban usage is a better case for BEVs due to the shorter-range requirement. They can use a smaller battery of 30 kWh, resulting in lower TCO impact. If fuel cells are to be competitive with BEVs, a price of hydrogen of well below USD 3 per kg at dispenser would be required in 2030.

Exhibit 19 | TCO of taxi fleet application



SOURCE: McKinsey Center for Future Mobility

Considering the true cost of emissions to society, including CO_2 emissions and the health impact from local emissions, fuel cell vehicles are already comparing favourably in some cases.

For taxis, FCEVs place a lower total cost on society than combustion vehicles already by 2025, even considering the currently still high hydrogen refuelling costs and low scale of vehicle production.

Fuel cells are most attractive for fleet applications and will break even with BEVs around 2025. In fact, if one includes local regulations penalising polluting vehicles, FCEVs represent the lowest-cost alternative overall in 2025 even when compared with ICE vehicles. However, regulatory support is required, either to make decarbonised alternatives more attractive, or to penalise the conventional polluting alternative.

Fleets differ from personal vehicles in that they typically use centralised, dedicated infrastructure, which ‘guarantees’ high equipment utilisation and thus reduces the cost per refuelling. For BEVs, economies of scale in fleet operations face limits, since one charger can only serve a finite number of vehicles in a given timeframe. Consequently, recharging times impose a potential limit on BEV fleets, meaning they would need a higher number of vehicles compared with FCEVs.

Cost development. Today, components of the fuel cell vehicle, such as the fuel cell, hydrogen tank and battery, account for about half of the vehicle's TCO, while hydrogen fuel accounts for roughly 25 per cent of costs. By 2030, these components are expected to make up approximately 30 per cent of the TCO and hydrogen fuel around 15 per cent, and the overall TCO to drop by up to 50 per cent. The key cost reduction factors include the cost reduction in the fuel cell powertrain and of hydrogen supplied at the pump, accounting for more than 90 per cent of the cost reduction until 2030. In the following, the possibility for costs to decline is discussed for each of these two main cost components.

Manufacturing costs largely drive fuel cell costs, and these are in turn largely determined by production volume. Today, fuel cell manufacturing is manual and small in scale, with less contribution from material cost. By taking advantage of production volume increases, companies can achieve significant cost reductions for several reasons. Firstly, procurement costs will decline as suppliers invest in equipment to deliver larger quantities of fuel cell membrane electrode assemblies (MEAs) and ionomers. Secondly, production line automation will lower production line labor costs, as will the development of advanced manufacturing technology. Thirdly, higher volumes will enable companies (at least initially) to utilise their equipment better; for example, at lower volumes, an automated stacking system routinely runs at less than 10 per cent of full capacity. Fourthly, manufacturers will streamline production at higher volumes, and source cheaper and lighter materials for the fuel cell balance of plant (BoP). With an annual production volume of 200,000 vehicles, a decrease in the cost of the fuel cell system would be estimated at around 45 per cent, rising to as much as 70 per cent with an annual production of 600,000 vehicles.

Another key cost component is the hydrogen tanks. They contribute up to about 15 per cent of total vehicle capex today, declining to only roughly 7 per cent in 2030. A cost decrease of approximately 55 per cent is projected at global production of 600,000 vehicles per year. Three factors will drive the reduction in tank cost. Firstly, the bill of material will go down per tank as production scales up to industrial levels from a few hundred or thousand of tanks at sub-commercial scale, which will allow costs to be amortised across a larger number of units. Cost of procuring parts will also go down as suppliers build new production lines. The carbon fibre is particularly important, as it is the largest share of the materials cost. Secondly, the high costs for certification of components can be amortised across many more units. The cost of production certification will also decline as the process becomes more automated and repeatable, the latter meaning that smaller samples will be required. Thirdly, automated production lines and higher utilisation of existing equipment will directly reduce production costs.

One additional consideration for reducing tank costs is the potential for reducing safety standards. Today the safety factor for 700 bar tanks is 2.25, meaning that the tank must be able to withstand up to 1,575 bar pressure. Reducing this to 2, i.e. ability to withstand 1,400 bar, proportionally reduces the amount of carbon fibre required. This will be possible once the production process is industrialised, automated, and repeatable, and based on a proven track record of safety.

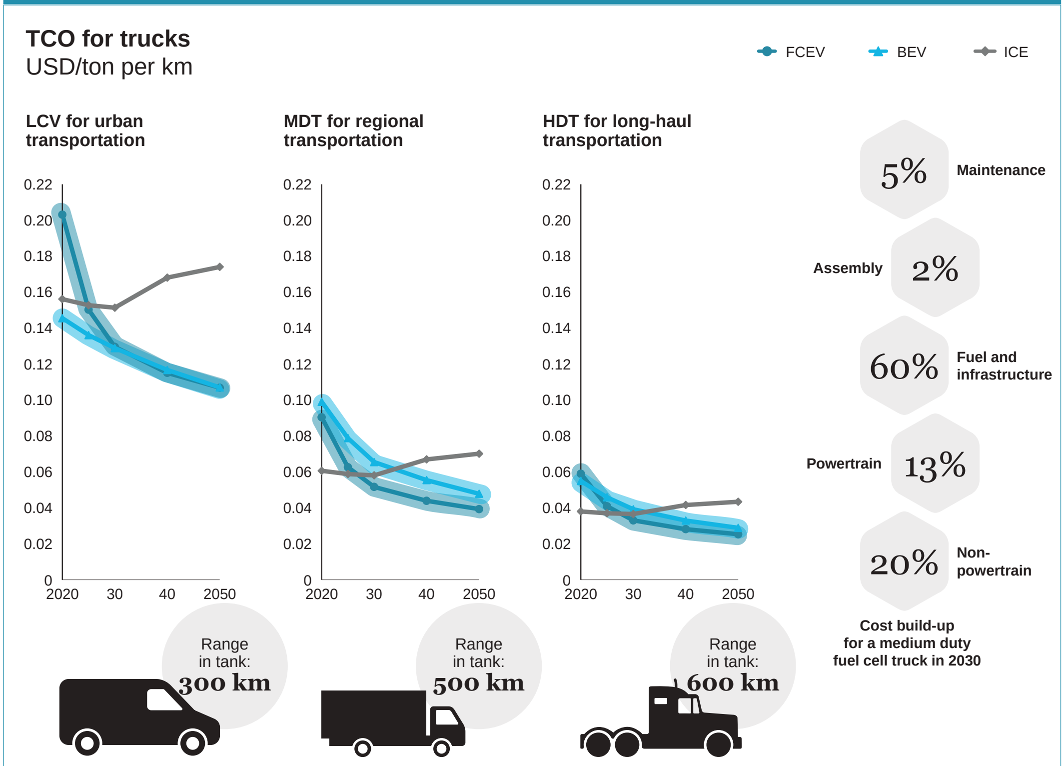
Fuel cost is the second-largest cost contributor for hydrogen passenger vehicles. Today, costs are high at about USD 10 to 12 per kg at the pump. Given the scale-up of vehicle deployment, supply and distribution channels must achieve greater scale to meet demand. For this, the entire value chain will scale up, resulting in a cost reduction at the pump by about 60 per cent, to beween USD 4.50 and 5 per kg. As explored in the prior chapter, three main factors will drive this cost drop: the production of lower-cost hydrogen, a larger and better utilised distribution system, and bigger and better utilised hydrogen refuelling stations. The last factor accounts for the largest share of value chain cost, contributing about USD 5 to 6 per kg of total cost in 2020, declining to roughly USD 1 to 1.50 per kg in 2030.

Fuel cell trucks

The analysis of fuel cell trucks suggests that this technology is the lowest-cost way to decarbonise both the medium- and heavy-duty segments. The BEV alternative is less attractive for heavy, long-range segments due to the large size (payload penalty), weight penalty, and cost of the batteries required, as well as the long recharging times. Three use cases were considered: 7.5-ton light commercial vehicles with a 300-km range requirement (LCVs), 13-ton medium-duty trucks with a 500-km range requirement (MDTs), and 22.5-ton heavy-duty trucks with a 600 km range requirement (HDTs).

In addition to the upfront cost for the vehicle and the lifetime fuel costs, the end users – most often fleet operators in these use cases – also consider factors such as refuelling time, available payload, operation under different climate conditions, and local regulations. All these effects influence the total cost of operating the fleet, which is ultimately what matters to such operators.

Exhibit 20 | TCO trajectory of trucks



SOURCE: McKinsey Center for Future Mobility; CARB Advanced clean truck; ICCT

Cost competitiveness. As discussed in Chapter 1, fuel costs are a significant component of the cost for trucks, particularly for HDTs and MDTs, accounting for about 60 per cent of TCO. For LCVs, fuel accounts for roughly 45 per cent of TCO. The fuel cell powertrain accounts for about 20 per cent of the cost for all segments.

Fuel cell MDTs and HDTs could become lower-cost alternatives to comparable BEVs as soon as 2025. The need for long-range capabilities mainly drives this assertion, which for the MDT and HDT segments likely translates to very large 600 to 960 kWh batteries. Batteries of this size are expensive and heavy and reduce the payload of the vehicle – particularly for HDTs with the largest batteries. Batteries this big also require long charging times, even with high-capacity fast-chargers (200 to 250 kW today, possibly more in the future). These fast chargers would potentially lower battery size requirements but would result in higher grid infrastructure costs.

Conversely, LCVs have a shorter range requirement and size, and correspondingly, smaller batteries of around 130 kWh. The BEV alternative therefore remains competitive in this case.

What may be more surprising is that fuel cell trucks may break even with conventional technology before 2030 in some regions, given a hydrogen cost at the pump of between USD 4 to 5 per kg (the exact break-even point depends primarily on the cost of diesel). FCEVs are more fuel efficient than ICE-powered vehicles and have the added benefit of recovering energy when braking or driving downhill, to some extent compensating for the higher cost of fuel.

Cost development. Cost reductions are possible because of the savings potential of two main cost components: the price of hydrogen at the pump, and the cost of equipment including fuel cells and on-board hydrogen tanks. Given annual sales volumes of 150,000 a year projected for 2030, the TCO trajectories shown in Exhibit 20 are feasible.

The majority of the cost drop from 2020 to 2030 will result mainly from cuts in hydrogen fuel cost, which will account for about 80 per cent of the TCO reduction for MDT and HDT, and roughly 60 per cent for the LCV. This follows a cost reduction of about 50 per cent for hydrogen delivered – from approximately USD 8 to 10 per kg in 2020 to about USD 4 to 5 in 2030, assuming the large scale-up envisioned.

Approximately 30 per cent of this reduction will result from the lower cost of hydrogen production, and the remainder from the lower cost of distribution. Distribution costs will decline due to lower-cost retail hydrogen, driven by increasing station size and utilisation, which should generate a 70 per cent lower cost allocated to hydrogen refuelling stations. There are additional improvements expected for compression and trucking of hydrogen.

The cost of fuel delivered to FCEV trucks is lower than for passenger vehicles because these trucks are typically served by larger stations with higher utilisation. This is due to two factors: firstly, trucks require larger volumes for each vehicle, e.g. an HDT has a tank that is about ten times larger than an SUV's. Secondly, trucks operate in fleets, which in many cases enables high utilisation of dedicated refuelling infrastructure.

The second major cost-reduction driver for hydrogen fuel cell trucks is equipment costs. The high cost of fuel cells and hydrogen tanks will primarily drive the cost of the powertrain in 2020, at which point the fuel cell truck will be about three times the cost of a comparable diesel vehicle. By 2030, scale manufacturing of fuel cells and hydrogen tanks could compress this gap by about 1.2 times.