A cost reduction of roughly 70 to 80 per cent for the fuel cells would be possible given an annual production volume of 150,000 vehicles; similar reductions could also be reached for the PEM stack and the fuel cell balance of plant. Manufacturers could capture significant fuel cell cost reductions of approximately 60 to 65 per cent with even relatively small annual production volumes of 10,000 trucks per year. The impact is higher for trucks than for passenger vehicles at the same volumes because of the larger fuel cell systems needed (two to four times the size of passenger vehicle systems) and a corresponding higher number of PEM stacks.

The hydrogen tank is a major part of the cost and accounts for 25 per cent of the total HDT investment cost in 2020 – less for MDTs and LCVs – and declines to about to 15 per cent of the cost in 2030. This results from achieving manufacturing scale in hydrogen tanks, which should enable a reduction of 60 per cent with an annual production of 150,000 trucks per year. With an annual production of only 10,000 vehicles, cost reductions of roughly 50 per cent should occur.

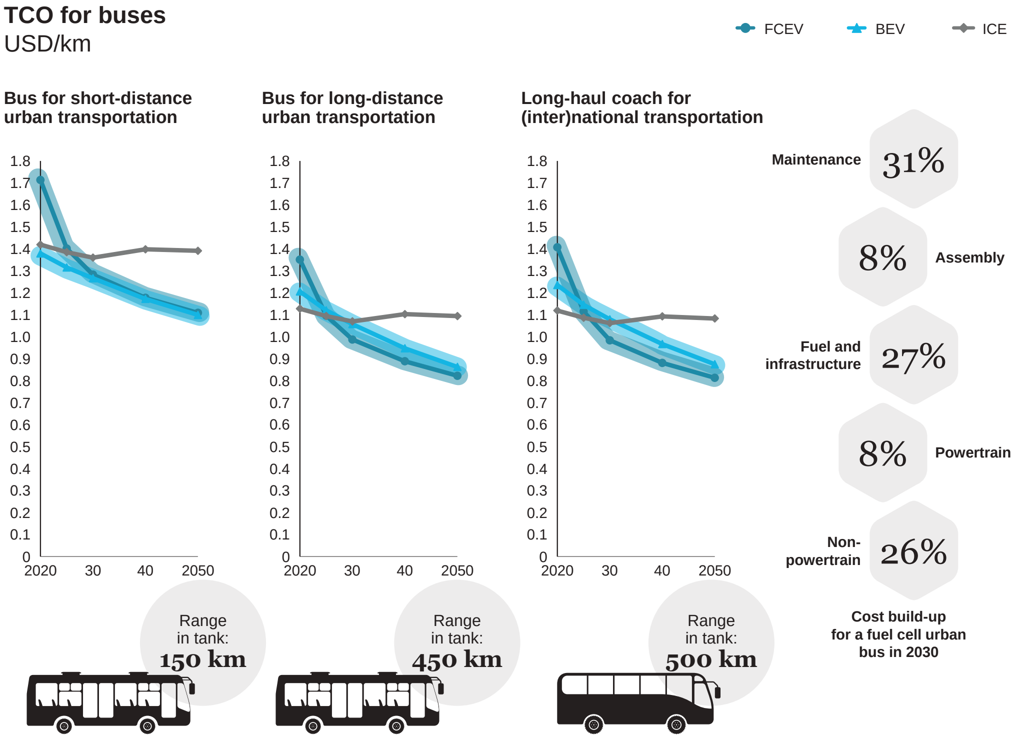
It should be noted that multiple options exist for truck hydrogen tank systems, which could feature on-board tanks with 350 or 700 bar pressure. The 700 bar specification allows for smaller tanks due to 70 per cent higher hydrogen density. Cryogenic tanks, which carry liquid hydrogen at atmospheric pressure, are also a possibility, with 90 per cent higher density than the 700 bar tanks. Although these tanks are not yet commercially available, they have the benefit of taking up less space and weight, allowing for more volume and weight for carrying goods, ultimately with further potential improvements for TCO.

Fuel cell buses

The cost analysis of fuel cell buses (FCEBs) shows that hydrogen is the most cost-efficient way to decarbonise long-range bus segments in the medium term, but it will not cost less than a comparable battery bus (BEB) for short-range urban use. The analysis considers three specific use cases for fuel cell buses: short-distance urban buses with a 150-km range per refuelling, long-distance urban transportation with a 450-km range, and coaches for long-distance travel with a range of 500 km. As for other road transport applications, this analysis compares fuel cell buses with BEBs and conventional diesel buses.

The key decision criteria for a bus operator is the cost of acquiring buses and operating them, in addition to a range of other important parameters like refuelling time, comfort and space requirements, operations in hot or cold climates where relevant, flexibility across line requirements, and the cost of infrastructure required to refuel. All these factors influence the choice of technology, but cost is ultimately what matters most to bus fleet operators. However, given that many urban bus fleets are subsidised today, this may be a segment where policy decisions could drive early uptake.

Exhibit 21 | TCO trajectory of buses



SOURCE: McKinsey Center for Future Mobility

Cost competitiveness. The analysis reveals that fuel cell buses outcompete full battery buses when the range required exceeds 400 km, due to the BEB's large, heavy battery and long charging times. For coaches, the full battery alternative is challenging today due to its size, weight, and recharging time. For buses with shorter ranges, e.g. urban buses, BEBs remain more competitive, as the battery required is much smaller and therefore less expensive.

Both fuel cell long-distance urban buses and coaches could outcompete BEBs in 2025, and even ICE buses before 2030, as shown in Exhibit 23. By 2030, urban short-range fuel cell and electric buses reach cost parity and remain so until 2050. This implies that the lowest-cost application will be highly sensitive to local conditions such as costs of electricity or hydrogen fuel, available infrastructure for refuelling, range required, and mileage. For example, longer mileage will benefit the BEB due to its higher efficiency and lower fuel consumption. The FCEB competitiveness, on the other hand, would benefit from higher grid electricity cost or requirements for longer range and flexibility. Ultimately, the optimal technology choice will depend on the fleet operator preferences for flexibility, operational constraints and infrastructure costs.

FCEBs have the benefit of providing higher flexibility and longer ranges for less additional investment than BEBs, and no impact on refuelling time. BEBs can take advantage of 'opportunity charging' (charging during stops to prolong driving range), and thus can ultimately have a smaller, cheaper battery. However, this strategy is expensive from a network perspective, as fleets must install more fast chargers and associated infrastructure.

Cost development. For FCEBs, roughly 10 per cent of TCO is contributed by the fuel cell powertrain and 25 per cent by fuel, as shown in Exhibit 21. For the coach, the cost is divided differently due to the larger motor and higher total fuel usage: the powertrain accounts for about 12 per cent and fuel approximately 40 per cent.

Achieving cost parity will require a scale-up in both the manufacturing of FCEB components and the hydrogen value chain. Companies will likely reach parity for coaches and long-range urban buses when annual production volumes reach 2,500 buses, while a production volume of 20,000 buses per year is required for the short-range urban bus to be competitive with the BEB.

Reducing fuel costs represents the largest cost-cutting opportunity for FCEBs, accounting for about 70 per cent of the TCO reduction for long-range urban buses and coaches, and somewhat less for short-range urban buses. By achieving annual production volumes of about 20,000 buses per year, the industry can already begin to achieve enough scale in the supply and distribution value chains to make a difference. This can potentially lead to fuel cost reductions of about 50 per cent, reaching costs of approximately USD 4 to 5 per kg, as market demand would drive down costs. Hydrogen costs for buses, as for trucks, are lower than those for passenger vehicles due to the high utilisation of dedicated refuelling stations for fleets and larger-scale stations. For instance, a coach carries more than ten times more hydrogen than a mid-size vehicle with a range of 400 km.

The lower cost of equipment is the other major cost-reduction driver. Reaching 2,500 vehicles per year will cause fuel cell costs to decline by roughly 65 per cent to about USD 100 to 110 per kW. A further production increase to 20,000 vehicles annually will yield additional cost improvements of around 30 per cent. This will lead to a total fuel cell cost reduction of about 80 per cent in total compared to 2020 levels.

Cost reductions for hydrogen tanks are slightly lower, with a roughly 50 per cent reduction achieved with a production scale of 2,500 units per year, and approximately 60 to 65 per cent with 20,000 units per year. Because tanks are similar across multiple types of vehicles, the knock-on effects caused by greater scale will probably emerge in passenger vehicles, trucks, and buses.

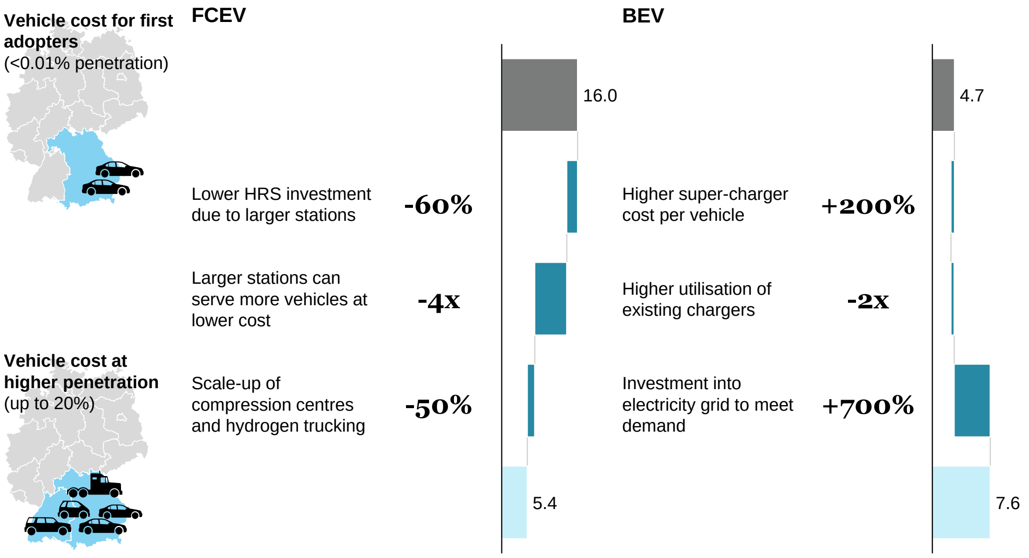
Buses can potentially use tanks with different pressures or even liquid on-board storage. Higher-pressure tanks or liquid tanks require less space but are more expensive, which may be acceptable if long ranges and enough space for passengers are required. Ultimately, it comes down to a question of consumer need and what type of value chain yields the lowest total costs, since a higher-pressure tank value chain is about 5 to 10 per cent more expensive due to greater compression specifications and the higher-pressure storage required.

Road transport infrastructure cost

When assessing and comparing TCO across transport application alternatives, the most critical competitiveness driver is the cost of infrastructure and how it develops with increasing scale. While a lot of uncertainties remain regarding the future trajectories of infrastructure scale-up, the infrastructure cost of FCEVs initially comes in significantly higher than for BEVs, but swiftly becomes cheaper with increasing market share in a given area. The tipping point appears to occur when FCEV market share reaches approximately 1 per cent, with pockets of higher presence of about 20 per cent, as shown in Exhibit 22.

Exhibit 22 | FCEV and BEV infrastructure and operations cost over lifetime

Cost of refuelling/recharging infrastructure investment and operations over lifetime (Germany use case)
USD/vehicle, thousands



SOURCE: McKinsey Center for Future Mobility

Accordingly, the cost of hydrogen refuelling infrastructure per vehicle is initially three to four times higher than for BEVs but should ultimately drop to below of the cost of BEV recharging infrastructure. It will reach cost parity due to the significant economies of scale available from increasing the size of distribution channels and the introduction of larger retail stations. For example, the cost of investment per kg of pumping capacity from a hydrogen refuelling station (HRS) will decline roughly 70 per cent over time, from about USD 6,000 for a small station in 2020 to an estimated USD 2,000 for a large station in 2030.

From a system perspective, BEV infrastructure costs typically increase with the increased introduction of fast chargers in the system and grid upgrades that may be required to cover the increased load. These costs were assumed to be allocated across all BEVs depending on their lifetime distance driven – a plausible approach, given that the costs of new infrastructure will probably have to be assumed in the electricity charging price. That being said, in a world where slow-charging dominates and there is effective demand management, costs may actually be lower than estimated. In addition, BEVs can initially enter the market with lower infrastructure costs, particularly if customers primarily use low-cost home-charging systems.

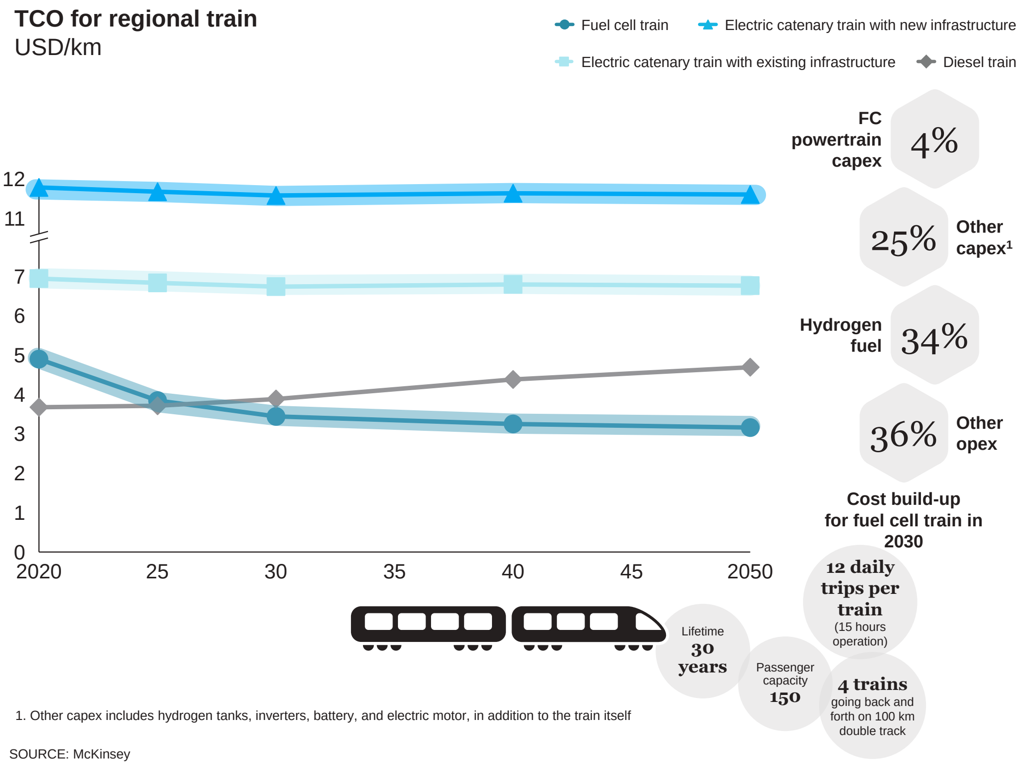
Fuel cell trains

The fuel cell train is a strong alternative for regional trains, outcompeting electric catenary trains in 2020 in areas where there is no existing catenary line in specific use cases. However, to beat diesel trains, it requires a cost of carbon of up to 120 per ton of CO_2e, depending on the region and the comparative cost of hydrogen and diesel fuel.

Our use case for this analysis consisted of four trains travelling a distance of 100 km and conducting a total of 24 return trips per day. We compared the fuel cell train with an electric catenary train both with and without existing overhead catenary lines as the low-carbon alternative, and we used combustion engine trains using diesel as the conventional option. We did not consider battery-driven trains with opportunity charging, which may of course be a possibility, but will require technological development and significant investment in charging infrastructure at multiple locations. The choice of technology depends largely on cost. However, this is influenced by several factors, including the existing rail network and infrastructure, topography, distance, usage frequency, environmental targets, and operating mode, which considers the duration of trips and the amount of downtime.

The hydrogen fuel cell train is best suited for longer, relatively low-frequency routes, with short downtimes and limited time for battery charging, and routes not already electrified. Ongoing projects already exist, and stakeholders have announced several more. For instance, there are already trains operating in Germany, and the East Japan Railway Company has announced it will develop hydrogen fuel cell trains with expected delivery in 2024.

Exhibit 23 | TCO trajectory of regional trains



1. Other capex includes hydrogen tanks, inverters, battery, and electric motor, in addition to the train itself

SOURCE: McKinsey

Cost competitiveness. As shown in Exhibit 23, our analysis suggests that the hydrogen train is already more competitive than electric catenary for a use case with relatively long distance and low frequency. However, as noted above, this conclusion will largely depend on key factors such as travel distance and frequency. In our specific use case, we find that by increasing frequency to 48 round trips per day and reducing the travel distance to 50 km, electric catenary solutions would cost less than the hydrogen alternative.

Cost development. Although the regional fuel cell train is already an attractive alternative today, room for cost cuts also exist to further improve competitiveness for other types of use cases. Cost reductions will likely come from the fuel cell system, on-board hydrogen tanks, and the value chain for hydrogen fuel, with the largest reductions available from the cost of fuel. The cost trajectory of components should be similar to that of heavy-duty vehicles, with some premium segment effects due to the smaller volume of trains compared to trucks.

Today the fuel cell system accounts only for about 3 to 5 per cent of the train TCO, equivalent to 10 to 15 per cent of purchasing cost. Similarly, the hydrogen tank accounts for roughly 3 to 5 per cent of the total cost of ownership. With projected cost improvements, the combined cost share of the fuel cell system and tanks should fall to approximately 2 to 4 per cent: a decline of about 60 per cent.

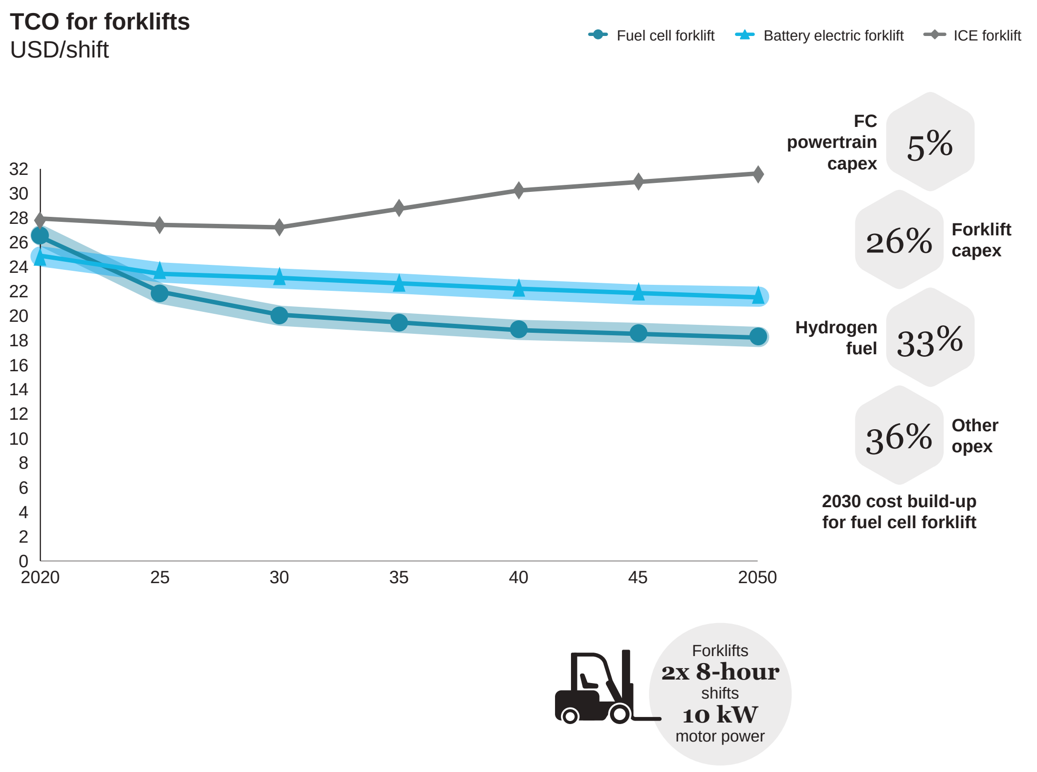
Like trucks and buses, trains will have dedicated infrastructure conducive to high utilisation rates, and they take advantage of a larger supply chain in the short term. Today the fuel probably accounts for about 40 to 50 per cent of a train's total cost of ownership and could decline to around 20 to 30 per cent in 2030. For this to happen, hydrogen cost at the pump must drop below about USD 4.50 per kg in 2030, or about half of today's price. We believe this is possible, given the scale-up of both low-carbon and/or renewable hydrogen production and distribution.

Fuel cell forklifts

Fuel cell forklifts would already be competitive given sufficiently low hydrogen costs of around USD 6 to 7 per kg. The analysis assumes that a forklift operating in a warehouse on two eight-hour shifts per day with one refuelling able to cover both shifts.

Fuel cell forklifts were compared with full battery electric units as the low-carbon alternative, and diesel as the conventional alternative. Even today, both the fuel cell and battery technologies outcompete the diesel in the right conditions.

Exhibit 24 | TCO trajectory of forklifts



Cost competitiveness. As shown in Exhibit 24 the fuel cell forklift breaks even around 2023 compared to the full battery version, even given a hydrogen production cost of approximately USD 3.50 per kg, not including distribution, confirming that fuel cell forklifts are a highly competitive near-term hydrogen application. Compared with diesel, the fuel cell is already the lower-cost option, even when considering the relatively high cost of hydrogen fuel and a very limited penalty for carbon emissions (about USD 30 per ton of CO_2e). Two factors contribute to this situation: higher fuel costs due to lower powertrain efficiency, and the limited cost benefit for the ICE due to the small motive power (10 kW) requirement. This implies that for vehicles with smaller motive power requirements, conventional alternatives offer fewer benefits.

Cost development. The total cost of fuel cell forklift ownership is projected to decline by about 20 per cent through 2030, with a total decline of around 30 per cent by 2050. Like other transport applications, the key cost-reduction drivers include expected declines in the cost of the fuel cell powertrain, particularly the cost of the tank system given the small fuel cell (10 kW), and the cost of hydrogen fuel.

Initially, the fuel cell system's share of capex is roughly 4 per cent, declining to about 2 per cent following the scale-up of fuel cell manufacturing for transport applications. The hydrogen tank represents a notably larger share of the cost, as one refuelling must cover two shifts. In 2020, the share of capex is expected to be about 15 per cent, declining to 10 per cent in 2030 following a reduction of about 30 per cent for the tank itself, and improved powertrain efficiency due to incremental technological improvements.

The hydrogen cost at the pump in 2020 is expected to be relatively low, as users typically operate forklifts constantly. This results in high utilisation for the refuelling infrastructure even at this early stage, although this clearly depends on the size of the fleet, the refuelling station required and forklift fleet operational scheduling.

The cost of hydrogen at the pump is expected to decline by about 45 per cent by 2030 for forklifts, driven by both lower production costs and the scale-up of the distribution value chain – the latter accounting for around 70 per cent of the cost reduction of hydrogen delivered to the user.

Hydrogen in aviation

Today's aircrafts fly on standard jet fuel (kerosene), which emits 3.15 kg of carbon dioxide per kg of fuel. This translates to about 360 tons of carbon for a ten-hour trip with a Boeing 747, and the whole sector emits around 3 per cent of global carbon emissions, or about 0.75 million tons, per year[8].

Kerosene is the ideal fuel for flying: it is both extremely light, measured by its energy content, as well as dense, requiring little volume to store that energy. Conversely, it is extremely difficult to electrify a plane. For short-haul flights in small airplanes (up to 20 passengers), hydrogen and fuel cells are a viable option and are indeed trialled today. Most emissions in aviation, however, stem from long-haul flights.

For the large aircrafts used on these routes, the most realistic decarbonisation option is to replace kerosene from fossil sources with kerosene that does not bring new carbon into the atmosphere. One option is to use biofuels (bio-kerosene); another is to produce synthetic kerosene from hydrogen. Synthetic fuel is a liquid fuel derived from a blend of hydrogen and carbon monoxide, for which hydrogen and a carbon feedstock are needed. Since bio-kerosene and synfuel are chemically similar to conventional kerosene, they can be 'dropped into the fuel pool' and stored, transported and used like conventional kerosene. That makes the transition to these fuels easier, as existing infrastructure and aircrafts can be used.

Compared to kerosene, synfuels and biofuels are more expensive. Today, kerosene costs approximately USD 0.50 per litre, while biofuels cost USD 1.20 to 1.50[9] and hydrogen-based synfuel costs USD 2 to 2.30 per litre, depending on the source of carbon.

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[8] Air Transport Action Group (2018).

[9] Pavlenko, N., Searle, S., and Christensen, A. (2019).

To make synfuel truly carbon neutral requires that carbon is sourced from a carbon-neutral source. This can be achieved by taking carbon directly out of the atmosphere using direct air capture. Carbon can also be sourced from biomass, for instance through CCS of a biomass gasification plant. If the carbon is captured from an industrial process and used to make synfuel, which is the lowest-cost alternative, it is eventually emitted into the atmosphere, adding to the total carbon in the atmosphere. This is the re-use of carbon and, while lowering total emissions, is not a zero-carbon method.

Cost competitiveness. As Exhibit 25 shows, as hydrogen production costs drop, synfuel could become cost competitive with bio-kerosene as early as 2030 when using carbon from an industrial process. Given a biofuel cost of USD 1.50 per litre, hydrogen must reach a cost of USD 2.70 per kg to become competitive with biofuels.

If the synfuel is based on direct air capture of carbon, a hydrogen cost of USD 1.80 per kg is required to outcompete bio-kerosene. This will be feasible by 2030 in regions with good resources for hydrogen production.

Competitiveness with conventional kerosene requires a certain carbon cost. For instance, paying USD 1.50 per litre extra for low-carbon fuel rather than conventional kerosene would add approximately USD 120 per passenger on a flight from London to New York. By 2030, the cost of abating 1 ton of carbon through synfuels will be around USD 300 when using hydrogen from low-cost production sites and direct air capture at around USD 90 per ton.[10] Switching to carbon from industrial processes lowers the cost of abatement to about USD 200 per ton of CO_2. In the long run, with hydrogen costs nearing USD 1 per kg, the abatement costs are reduced to around USD 150 with direct air capture at USD 60 per ton of carbon.[11]

Cost development. There are three main cost drivers of hydrogen-based synfuel. The first and most important cost driver is the cost of hydrogen feedstock, for which the cost trajectory is discussed in Chapter 2. Carbon feedstock is the second important cost driver and the cost depends greatly on the source of carbon. Carbon feedstock from industry processes based on fossil fuels or biomass is estimated to cost USD 30 per ton of carbon. Direct air capture costs are comparatively high as the technology is not fully developed, estimated at USD 160 per ton of CO_2 today. The cost of direct air capture is expected to decline by about 40 per cent until 2030 as the technology matures, reaching USD 90 per ton of carbon. The third important cost element is the fuel synthesis plant itself; a cost-reduction potential of about 40 per cent is estimated for the plant itself from 2020 to 2030 due to scaling up plant capacity.

For small aircrafts, hydrogen can also be used directly in fuel cells instead of converting it into synfuel. This is currently being tested in planes of up to 20 passengers and ranges up to 800 km, as well as VTOLs (vertical take-off and landing) and smaller drones. In small aircrafts, hydrogen is attractive, as the equipment being replaced – turbines – is relatively expensive (a small turbine costs between USD 0.5 million to 1 million) and requires frequent maintenance.

Furthermore, smaller plane operators do not have access to kerosene at the same prices as large airlines, resulting in more expensive fuel. Fuel cell planes theoretically require less maintenance as they do not produce heat and vibration like turbines. They are also significantly less noisy and can offer a better flying experience.

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[10] Fasihi, M., Efimova, O., and Breyer, C. (2019).

[11] IRENA (2019a).