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Hydrogen Council

Roadmap towards zero emissions

The complementary role of BEVs and FCEVs

Summary document

September 2021

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This report was authored by the Hydrogen Council with analytical support from McKinsey & Company.

The report has been compiled both from public sources and proprietary data of the Hydrogen Council and McKinsey & Company. Its messages have been developed in dialogue with the Observatory Group that consists of representatives from government agencies and academia, as well as associations and companies active in sectors like regenerative electricity generation, electricity grid equipment manufacturing, electric vehicle charging, fleet management.

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1. There are no recommendations and/or any measures and/or trajectories within the report that could be interpreted as standards or as any other form of (suggested) coordination between the participants of the study referred to within the report that would infringe EU competition law; and
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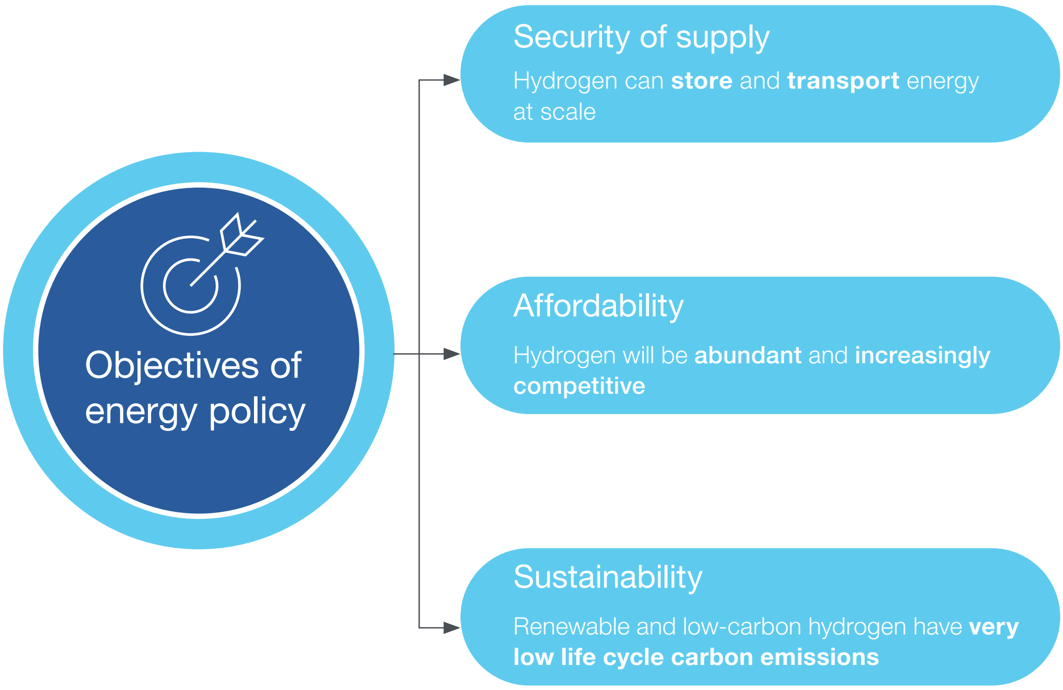
Hydrogen will play a key role in the decarbonised, sector-coupled energy system

Decarbonisation of the energy system is a massive and unprecedented task at an enormous scale. Collectively, we need to replace two-thirds of our energy supply, which is currently sourced from fossil energy sources. This implies 'sector coupling' because different energy consumers, such as those in the electricity generation, home heating and transportation sectors, will all rely on electric energy.

Integrated energy systems need to be reliable, secure, affordable and sustainable.

Hydrogen will play a key role in each of these needs, because it will help support an energy system that is mostly based on renewables.

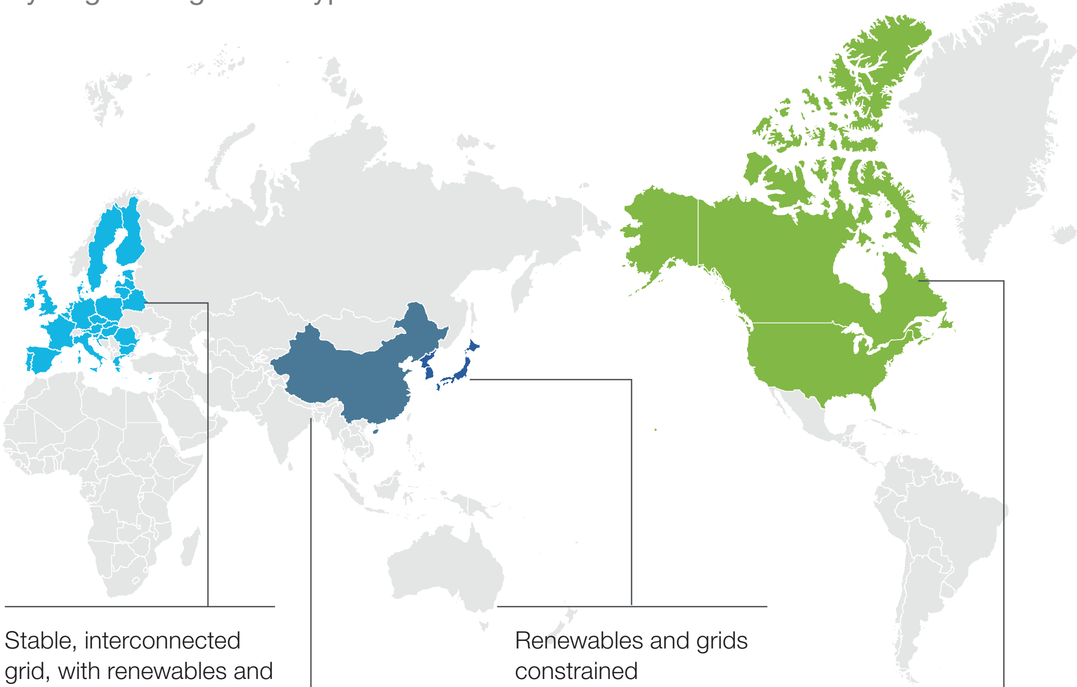
Hydrogen from renewable and low-carbon sources will be complementary to electricity in reaching all objectives of energy policy in the long term



The exact role will depend on the regional situation

While the relevance of hydrogen to decarbonize hard-to-abate sectors is universally accepted, its role will differ between regions. For example, Europe is expected to have a highly seasonal electricity generation, that will need to be buffered over long periods. In contrast, Japan and South Korea are struggling to achieve renewable electricity self-sufficiency and will thus need to import energy over long distances and addition to the domestic supply. Hydrogen could serve as an energy carrier in this situation. On the other hand, in North America and China, it will be necessary to transport energy over vast distances within the countries, which is not always feasible with an electricity grid. Hydrogen could also support intra-country transport of energy.

Hydrogen usage archetypes in a decarbonised world scenario



In road transport, hydrogen can support direct electricity use; both BEVs and FCEVs are needed

The challenge is even more pronounced in road transport. Currently, over 95% of the energy used in this area is fossil fuel based. In many regions, energy demand will be hard to cover with locally available renewable electricity.

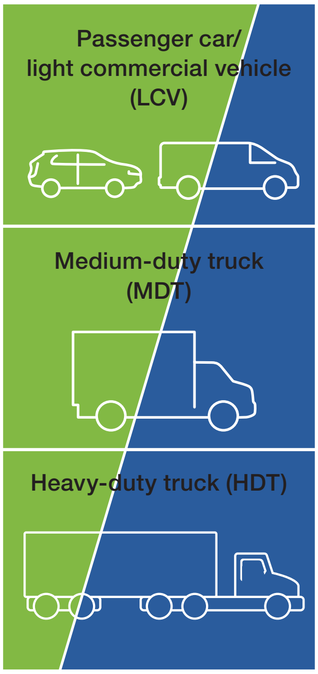
Thus, we expect that zero-emission vehicles (ZEVs) will be powered by a mix of batteries (using electricity) and fuel cells (using hydrogen). BEVs are rapidly becoming more common and are being used in more and more situations. They are the best solution for multiple use cases, especially in passenger transportation.

Hydrogen, however, has some advantages that make it more suitable for certain scenarios. In regions with a structural renewable electricity constraint and the need for imports, it makes sense to keep hydrogen as a molecule for as long as possible instead of converting it into grid electricity. Furthermore, hydrogen is well positioned for wherever large amounts of energy are needed for the vehicle performance due to the higher energy storage density of fuel cell systems. This is why we expect adoption both in passenger vehicles and, at a large scale, in commercial vehicles. Given the broad consensus on the role of hydrogen in heavy duty transportation, the following analyses focus mainly on passenger vehicles.

Battery (BEV)

BEVs are vital for enabling **fast decarbonisation** of transport and will become **mainstream** in **many use cases**

Relevance in segment (illustrative)



Fuel cell (FCEV)

For **important segments** of road transport, **hydrogen** is the **best option.**

- Regions with **constrained renewables** or grid capacity in the mid to long term
- **Vehicle segments with high power** and **energy demands**
- Use cases and customer segments with a preference for **long-range capability and fast refuelling**

12 facts about the complementary role of BEVs and FCEVs

Why a ‘combined world’ will be greener, faster and cheaper

We are convinced that a world where road transportation is fuelled by both batteries and fuel cells is better than one that relies on only a single technology.

This combined world would benefit the environment both from an emissions and a material mining perspective.

It would allow society to achieve a carbon-neutral world more quickly than with one technology. The number of customers who use combustion engines would decrease and the need for cumbersome upgrades of the electricity grid would be reduced.

The combination of these technologies would also be cheaper from an individual and societal perspective.

Greener

1 Comparable systemic efficiency
In a systemic view, BEVs and FCEVs have comparable 'sun/wind-to-wheel' efficiencies

2 Similar CO_2 life cycle
BEVs and FCEVs are similarly beneficial in CO_2 life cycle assessment

3 Storage and import
Hydrogen can store local renewable energy across seasons and enable renewable energy import from optimal production locations

4 Resource demand reduction
Lower total resource demand due to recycled platinum and reduced nickel, cobalt, lithium mining

Faster

5 Independence from electricity mix
One path is not enough; faster decarbonisation can be combined with a low-carbon energy system independent from the electricity mix

6 Additional capacity
Transition towards decarbonised transport just kicking off, BEV and FCEV must jointly accelerate

7 Building momentum
Greater momentum on hydrogen than is visible on the road

8 Convenience and flexibility
Convenience and flexibility are key customer needs, which FCEVs can meet with long range and fast refuelling

9 Situational benefits
Optimal choice is not black and white and varies by location and use

Cheaper

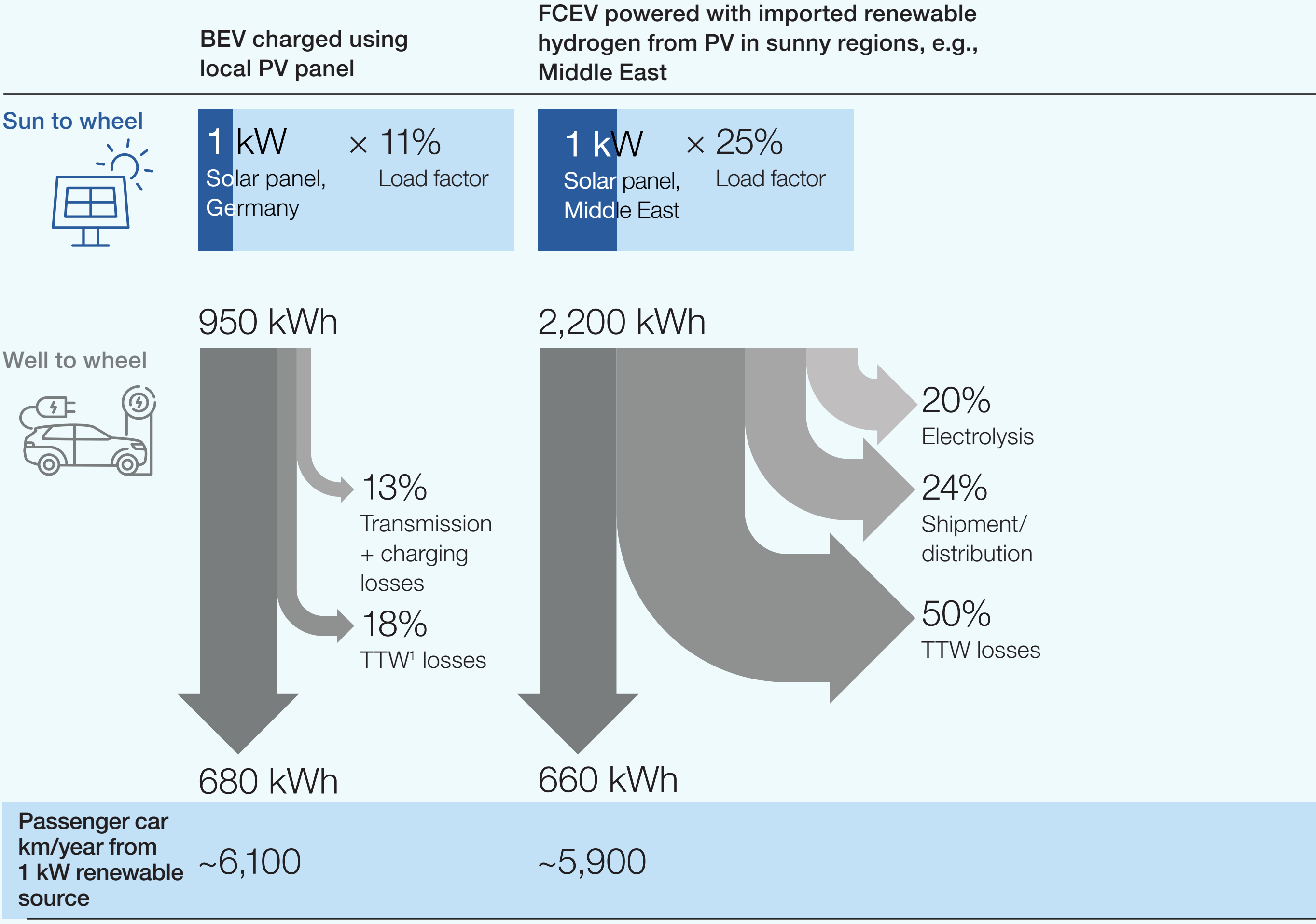
10 Hydrogen is the cheapest option in some segments
Getting from A to B with hydrogen will be the cheapest option in many road transport segments in this decade

11 Infrastructures complement each other
Two infrastructures are cheaper than one: hydrogen supply can reduce peak loads and thus reduce necessary grid upgrades

12 De-risking
Hedging bets with two pathways de-risks the most significant transition in the automotive industry's history

In a systemic view, BEVs and FCEVs have comparable sun-to-wheel efficiencies: case Germany

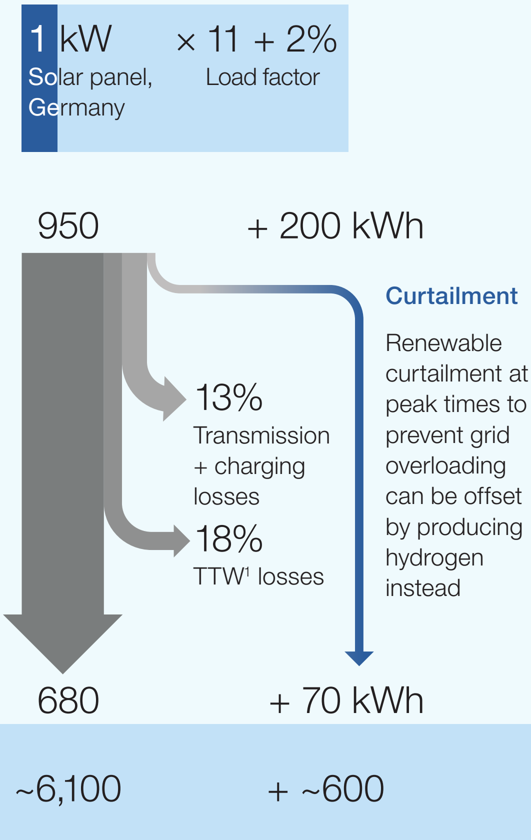
Illustrative pathway example: exact efficiency of each component can vary depending on context



When looking at efficiencies, a full picture should contain not only the view from well to wheel but much rather needs to start at the very source of energy – be it solar or wind. While grid electricity for charging a BEV needs to be produced relatively close to its location of usage, hydrogen can be shipped across long distances. This allows production at ideal locations: e.g., in the Middle East, a solar cell has more than twice the annual output compared to Germany. This results in a comparable total output at the wheel even taking into account the lower TTW efficiency of FCEV compared to BEV.

The case becomes even clearer when taking curtailment into account. If renewable production needs to be curtailed due to demand or grid throughput shortage, this energy is lost. If it is used instead to produce renewable hydrogen, the systemic output is higher than in any single-technology world.

BEV charged using local PV panel; peak supplies renewable hydrogen for FCEV fuelling



- Easy **storage and long-distance shipment** of hydrogen from **optimal regions**
- Renewables can be used more effectively
- **Increased total amount of energy available** from same renewable installation
- Local hydrogen generation not subject to **demand fluctuation or grid constraints,** thus avoiding curtailment

1 TTW losses; 4% battery, 7% power electronics, 4% motor drive electronics, 4% gearbox; FCEV stack 39%; FCEV BoP 10%; FCEV additional recuperation -10%

Note: There are additional effects along the life cycle that can bring further energy balance benefits to FCEV

Assumptions: 11.2 kWh/100 km WLTP consumption at the wheel (Tesla Model 3 standard range); 20% curtailment losses forecasted for a steady-state German renewable electricity scenario

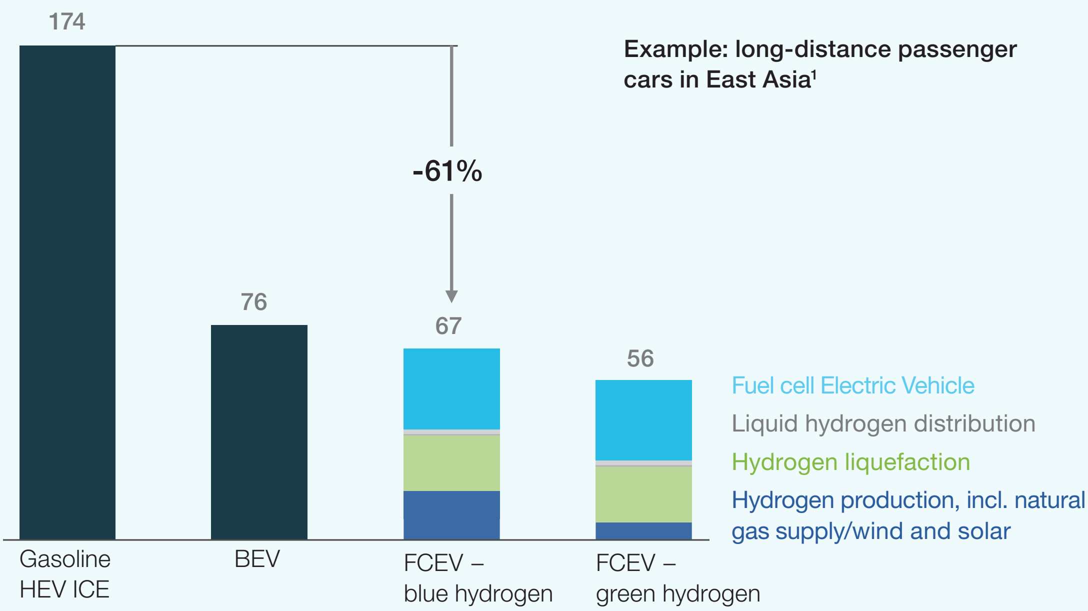
Source: Expert interviews; Kim et al. (2020); Nedstack (2019); Lohse-Busch (2019); NREL; Büchi et al. (2005); Eberle & Helmolt (2012); Sun (2010); Besselink et al. (2010); Hydrogen Council Cost Roadmap

2

In a CO_2 life cycle assessment, BEVs and FCEVs are similarly beneficial

Apart from energy efficiency, CO_2 emissions are obviously a critical factor for technology decisions. BEVs and FCEVs can have similar life cycle emissions (also considering the manufacture of the vehicle and all emissions related to the refuelling/recharging infrastructure). While BEVs are powered by grid electricity, dedicated renewable or low-carbon hydrogen infrastructure produces hydrogen with very low carbon emissions. Furthermore, transporting hydrogen via ship or pipeline results in low emissions, meaning even the conversion steps between production and usage of hydrogen do not impact the carbon balance materially. In renewable-constrained places like East Asia, this may lead to a slight advantage of FCEVs over BEVs in the near future.

LCA GHG emissions, including recycling, 2030, g CO_2eq/km



- BEVs and FCEVs only help decarbonise road transport when produced and operated with renewable or low-carbon energy
- Even when accounting for the additional emissions from long-distance LH2 shipping, FCEV and BEV have similar lifecycle emissions
- **Hydrogen transport via pipelines** incurs lowest emissions

[1] Blue hydrogen (NG+ATR+CCS) and green hydrogen (solar) produced in Australia, liquefaction and liquid hydrogen shipping (9,000 km) to East Asia, trucking to HRS and recycling; BEV using grid electricity forecast for East Asia

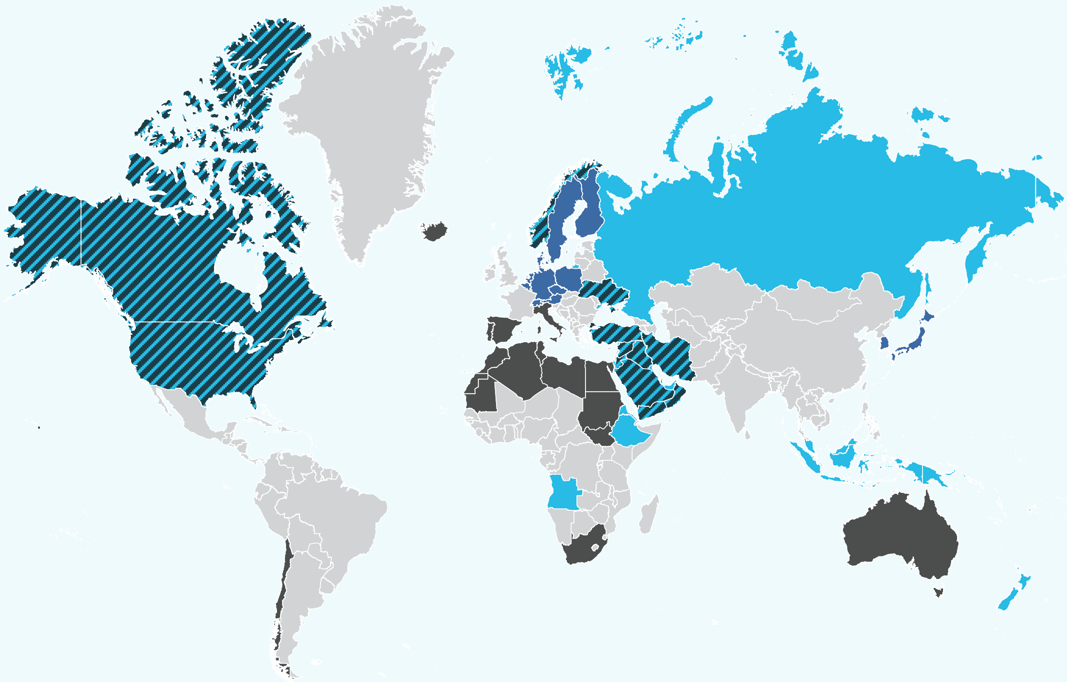
Source: Hydrogen Council, 'Hydrogen Decarbonization Pathways', LBST

3

Hydrogen will be available to store local renewable energy across seasons and to import renewable energy from optimal production locations

In a decarbonised world, some regions will have more readily available renewable energy resources and available land than others. The same holds true for the geological potential to produce low-carbon hydrogen. Consequently, we expect the formation of a global hydrogen market. The volume growth will lead to a ready supply of low-carbon and renewable hydrogen at much lower prices compared to today – either locally produced or imported.

Geography: hydrogen can be exported from locations with ideal conditions



- Net exporter of low-carbon hydrogen
- Net exporter of renewable hydrogen
- Net exporter of both low-carbon and renewable hydrogen
- Net importer
- Self-supplied/not analysed/no consensus

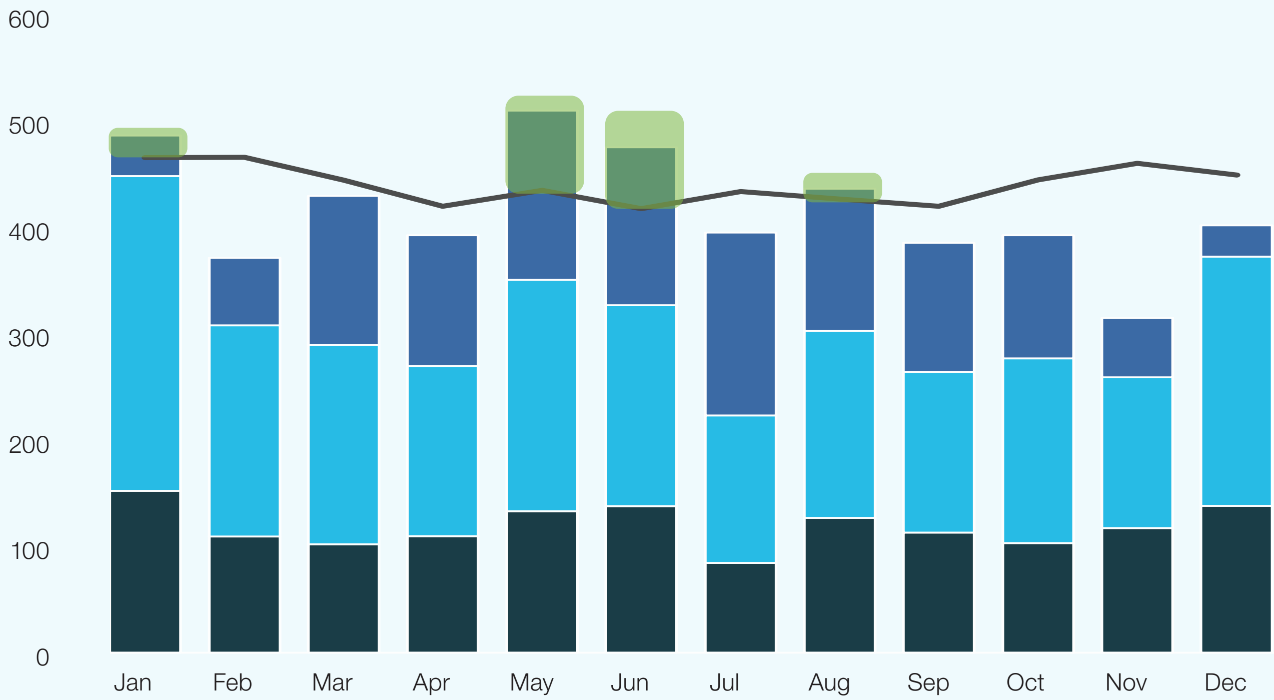
Source: Hydrogen Council; McKinsey

3

Hydrogen can store local renewable energy across seasons and help to import renewable energy from optimal production locations

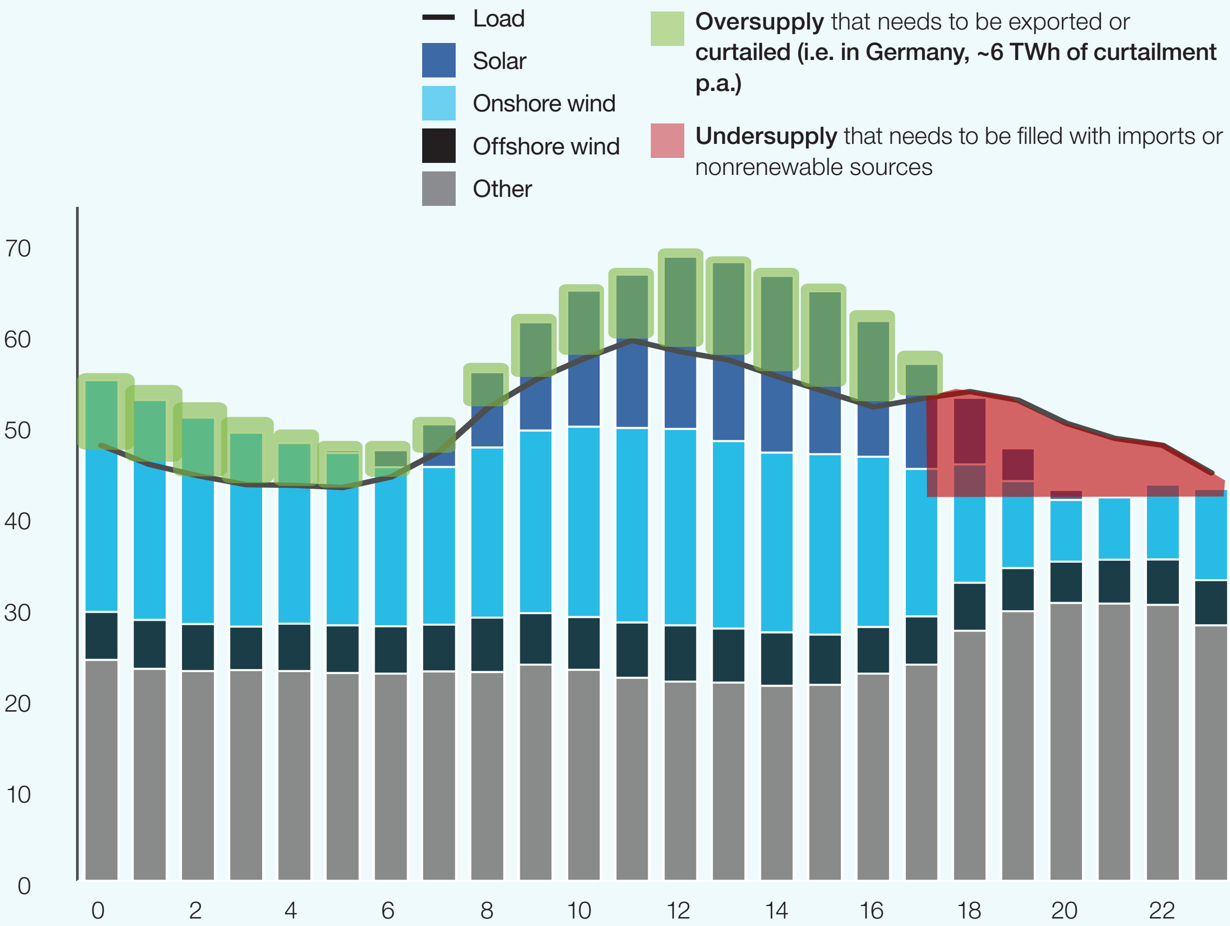
Electricity is difficult to store directly. While this has not been a problem in the fossil fuel world, it puts regions with a high seasonal fluctuation of renewable energy in a complicated position. For instance, forecasts for 2040 see a structural energy undersupply in spring and autumn in Germany and a surplus in winter and summer. The scale of this discrepancy can only be solved through either shipping energy to and from other regions or by storing energy long term. Only hydrogen is, as of

Seasonal forecasted demand and supply
2040 forecast, TWh



Source: Europe Net Zero Report; German grid agency; McKinsey Power Model today, able to scale well enough to balance out these gaps. Once this hydrogen is created, it is more beneficial to use the molecule directly, i.e. in an FCEV, than transforming it back into grid electricity. A similar logic applies to intra-day supply-demand imbalances, although there are also other relevant storing options (hydro, batteries, etc.).

Daily demand and supply (example)
6 June, 2020, GW



4

Reduced need of scarce material mining such as Nickel, Cobalt, and Lithium

Both BEVs and FCEVs need various scarce materials throughout their respective value chains. For batteries, supply shortages of Cobalt and Nickel are forecasted as early as 2030. Furthermore, strengthening the electricity grids will need massive amounts of copper in transformers and transmission lines.

While the increased demand for platinum and iridium in fuel cells and electrolyzers also raises concerns, this can be counteracted with the recycling of combustion engine catalytic converters.

In a combined world, demand peaks can be flattened as there is less dependence on single materials. Especially when replacing some large batteries with fuel cells, the effect becomes most noticeable.

The upcoming materials and mining report of the Hydrogen Council/World Bank will study those implications in detail.

In a combined world, demand for scarce materials can be flattened

Batteries

Lithium, Cobalt and **Nickel** demand expected to increase significantly until 2030

Supply shortages especially expected for Cobalt and Class 1 Nickel

Fuel Cells and Electrolyzer

Platinum and **Iridium** demand expected to increase for fuel cell and electrolyzer applications

In the case of platinum, counteracting effects through reduced catalyst demand for combustion engines and increased recycling

Electricity grid

Copper demand forecasted to rise drastically for transmission lines and transformers

Substitution with aluminum possible in some applications only

Benefits of a combined world

Usage of FCEV especially in high-capacity and high-power applications reduces need for battery minerals as well as grid upgrades.

Detailed implications are studied in upcoming Hydrogen Council/World Bank report on materials and mining.

Source: Europe Net Zero Report; German grid agency; McKinsey Power Model

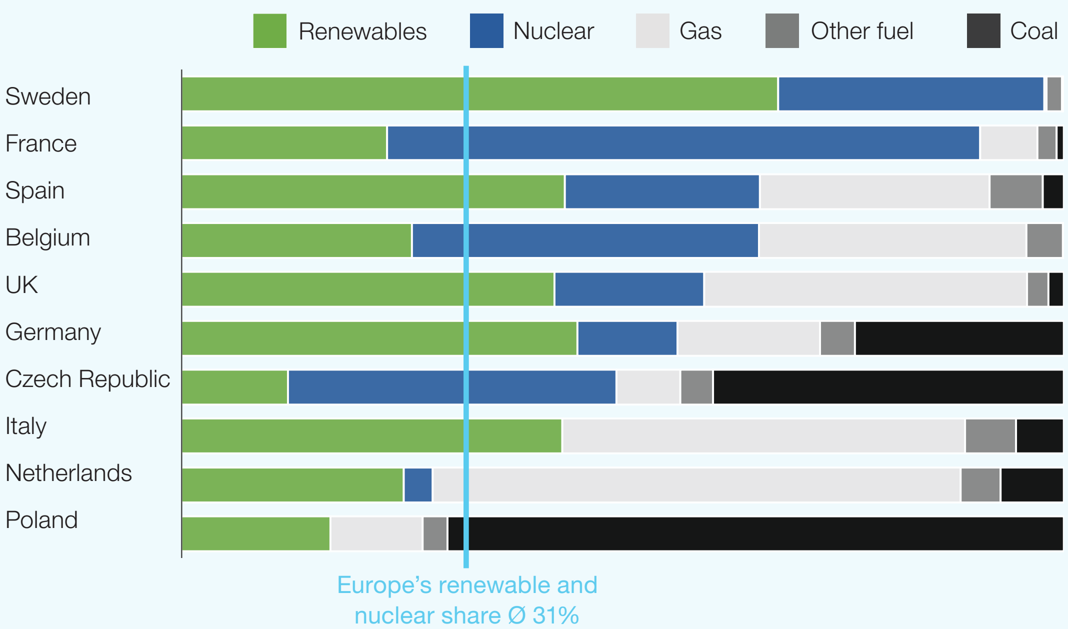
5

One path is not enough: every FCEV can contribute to decarbonisation in addition to the shift in the electricity grid

The decarbonisation of the electricity grid is a massive challenge. While some countries are already covering a high share of their electricity demand with low-carbon renewable or nuclear sources, other countries are relying heavily on fossil fuel energy sources in their power plants.

Thus, every BEV that hits the road challenges a more or less decarbonised energy mix even more. In contrast, imported or stored renewable and low-carbon hydrogen for FCEV can be an additional decarbonised energy source for the transportation sector.

Grid electricity by source in top 10 European countries
Percent of generation, 2020



Source: Hydrogen Council, 'Hydrogen Decarbonization Pathways'; LBST

6

The transition towards decarbonized transport is just kicking off, we need both BEV and FCEV to accelerate

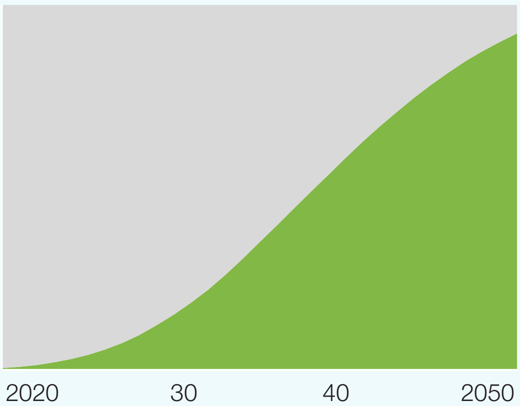
BEVs and FCEVs are often framed as competing technologies. Instead, they are both contributing to the same objective: decarbonizing the fleet of ICE vehicles. Even while sales of BEV have been picking up recently, more than 98% of passenger vehicles and virtually 100% of commercial vehicles on the road are still powered with combustion engines. Each new BEV and FCEV on the road helps to accelerate the transition to decarbonized transportation, which is still in its infancy.

BEV and FCEV together contribute to decarbonization of the the car parc in all segments

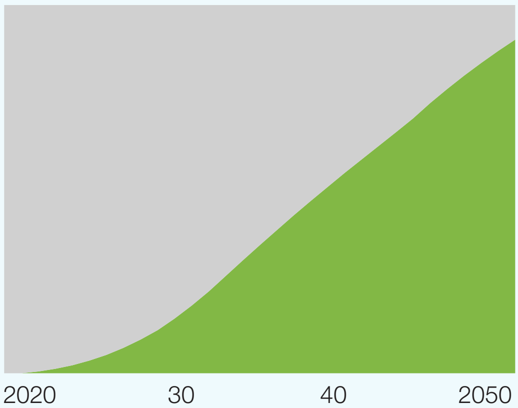
Car parc by powertrain, percent of total car parc

ICE ZEV

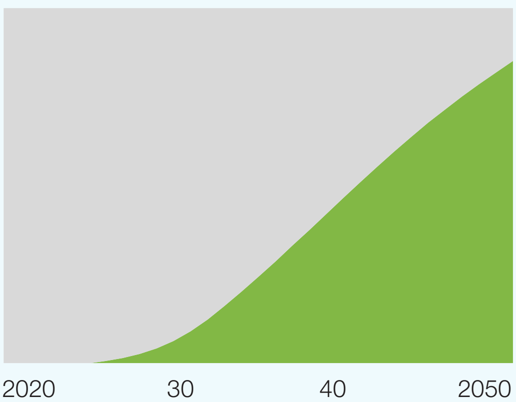
Passenger cars



Light duty trucks



Medium + Heavy duty trucks



BEVs and FCEVs are not competitors, but much rather both replace current gasoline and Diesel ICE

Source: McKinsey Energy Model

7

There is already more and bigger momentum on hydrogen than is visible on the road

The momentum on BEV is clearly visible through model launches and the build-up of charging infrastructure. A similar development is taking place for hydrogen throughout the value chain.

By 2030, 350 TWh annual decarbonized hydrogen production capacity is expected to go live, including 69 GW electrolysis capacity. OEMs develop new FCEV models especially in the commercial vehicle segment. The distribution networks, as well as the refuelling stations, are being built at high speed with all major industrialized regions having ambitious targets. Consequently, the cost of renewable hydrogen is drastically decreasing. As climate change becomes a top political issue, both governments and private sector make decarbonization a top priority with resulting massive investments also in hydrogen technology.

Leveraging momentum now will accelerate the advantages of an FCEV system

+350 TWh low-carbon and renewable Hydrogen supply projects have been announced by 2030, including +69 GW installed electrolyzer capacity

Up to 100 FCEV models (30 PV, 70 CV) will be in production within the next 5 years, today already 5x more models are available compared to 10 years ago[1]

Large-scale infrastructure projects under consideration: e.g. European Hydrogen Backbone proposed to be ready by 2030

250% increase in HRS worldwide in the past 5 years; 2030 targets: 1,000 each in Europe, Japan, China; >4,000 in US

-60% decrease in renewable hydrogen cost in the last 10 years, with forecasts to 1.4-2.3 USD/kg H2 production costs by 2030

Additional announcements and commitments from public and private sector

90
countries announced to become **carbon neutral by 2050**

359
major investments of in total **>250 bn USD** announced into hydrogen technology

[1] Commercial vehicles counted separately all weight classes

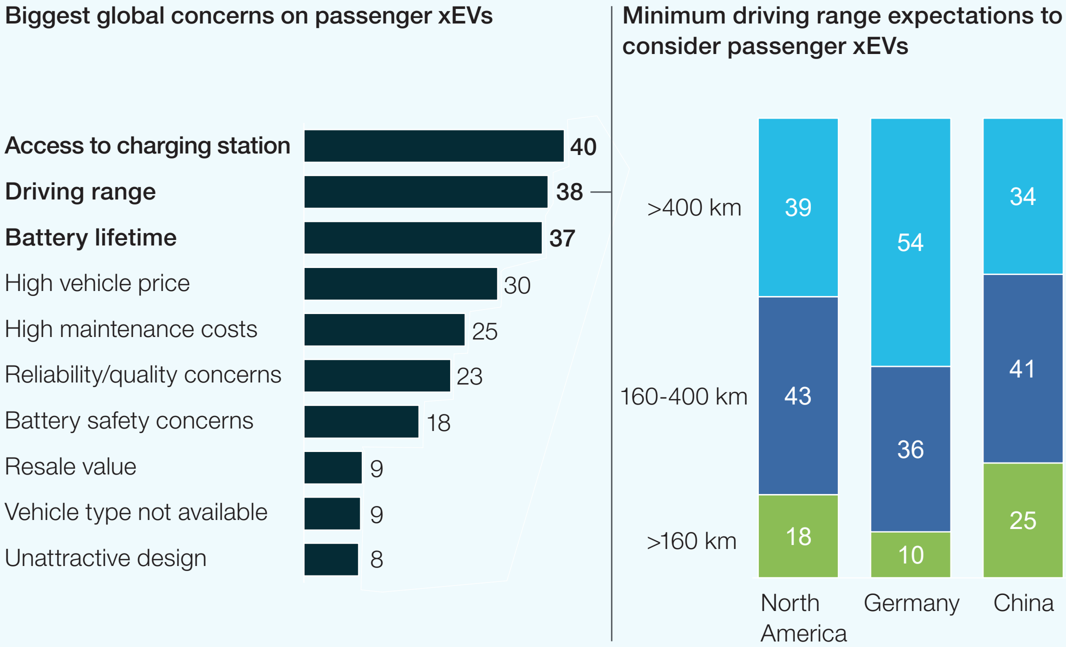
Source: H2 insights, IHS Automotive, Argus Media, Statista

Convenience and flexibility are key customer needs

While the perception of xEVs has improved dramatically, many consumers are still concerned about switching from a conventional vehicle. The most cited reasons are the access to charging, the driving range, and the lifetime of the battery. Depending on the region, one-third up to one-half of consumers demand a driving range of over 400 km.

Convincing those customers to use a BEV will be challenging and will require massive investment on all sides, including improved charging access with corresponding grid upgrades, bigger battery capacities and faster charging, while keeping the lifetime high. However, those demanding customer segments could especially be served well with FCEV technology.

Consumer preferences and concerns on electric vehicles (xEVs), share of respondents, percent



Source: McKinsey ACES Consumer Survey 2020; Dena survey: Alternative drives and acceptance of measures in the transport transition (November 2019)

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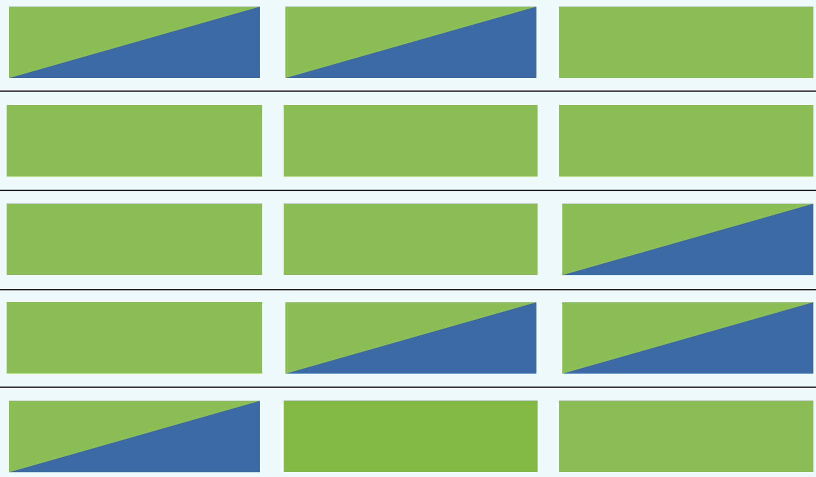
9

The optimal choice is not black and white; it varies according to the location and context of use

	Illustrative example use cases		
	Middle-aged living in the suburbs Small car for medium-distance daily commute to work Home charging possibility	**Parent living in a city home with family[1]** Private and/or shared parking with chargers Short-distance trips	**Environmentally conscious young adult** Cheapest green option Small car for ad hoc trips to friends, university, city, etc.
Powertrain purchase criteria			
Cost			
Range			
Charging access and convenience			
Infrastructure requirements[3]			
Durability			



1 E.g. apartments, detached homes

2 E.g. vocational, public services, courier

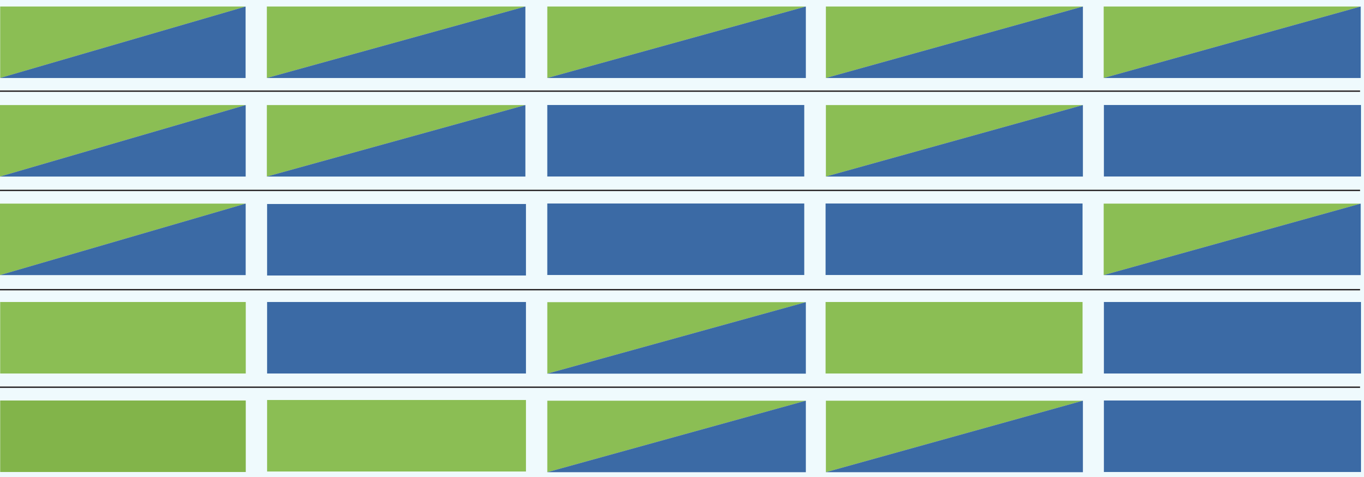
3 Grid upgrades; proliferation of H2 distribution

The powertrain decision does not hinge on a single dimension but rather multiple criteria in the prevailing use case. There are some cases that seem rather clear: e.g. a daily commuter living in a suburban single-family home with parking and ready access to charging would be perfectly served with a BEV. On the other hand, a highly utilised LCV of a craftsperson with changeable, long routes and no reliable charging access would likely favour an FCEV to maximise productivity.

Between these extreme cases, there are many different user types that would favour one technology or the other. For example, a resident of the inner city may drive short distances in a small car (and thus seems like the ideal BEV customer) but may lack reliable charging access due to no home parking or a strained grid that limits fast chargers. Consequently, even people in the same situation will make their decisions differently, depending on their individual preferences. The proliferation of new mobility services will support the flexible, context-dependent choice of vehicles.

Primarily **BEV** **FCEV**

Family going on holidays with their car	**Couple living in a city apartment**	**Executive with busy schedule**	**Taxis, LCV delivery, autonomous mobility**	**Buses and transport with medium and heavy duty CV**[2]
Large vehicle with capacity for the entire family	Small city car adhering to city requirements	Powerful, reliable and long-range car	High utilisation rates and daily mileage, large cars	High mileage and heavy transport
Flexibility and possibility for long trips	No private/limited public charging possibility at home	Minimal patience for refuelling time	Quick on-the-go refuelling necessary	Charging needs dependent on fleet management



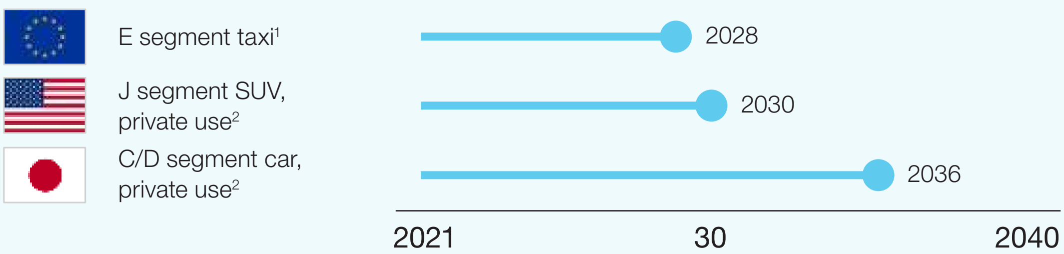
10

BEVs and FCEVs will be TCO optimal in different segments in this decade

Both fuel cell and battery technologies are experiencing drastic cost decreases and are becoming increasingly competitive with combustion engines. Currently, BEVs have a lower TCO than FCEVs in passenger vehicle applications – a trend that will reverse later this decade or in the 2030s in various segments. From there on, FCEVs will have a superior TCO than BEVs in multiple segments, especially in use cases with larger cars or more frequent usage. While we expect significant cost improvements in the fuel cell system, hydrogen supply, and battery systems, the grid and charger infrastructure costs will increase.

Selected passenger vehicle segments

FCEV TCO breakeven with BEV



Key drivers for cost development

Fuel cell system
Steep learning rate from increased manufacturing volumes – costs may fall to <USD 80/kW (stack and BoP)

Fuel costs
Average hydrogen price at refuelling station dispenser expected to go from ~USD 10/kg today to ~USD 4.8/kg by 2030

Battery system
Decrease in battery cost per kWh (USD 144 to 77/kWh, already down from USD 1,160/kWh in 2010)

Grid and charger infrastructure
Technical improvements of chargers as well as production at scale are lowering the cost of chargers, while infrastructure costs are rising

Other components, e.g. tank, power electronics, also contribute to price decreases of either technology to a lesser degree

1 Annual mileage taxi: Germany 56,000 km, includes stack replacement assumption for FCEV taxi

2 Annual mileage private car: Japan 8,000 km, US 17,000 km

Source: Hydrogen Council Cost Roadmap; Enerdata; AutoStack; Tesla; McKinsey Center for Future Mobility

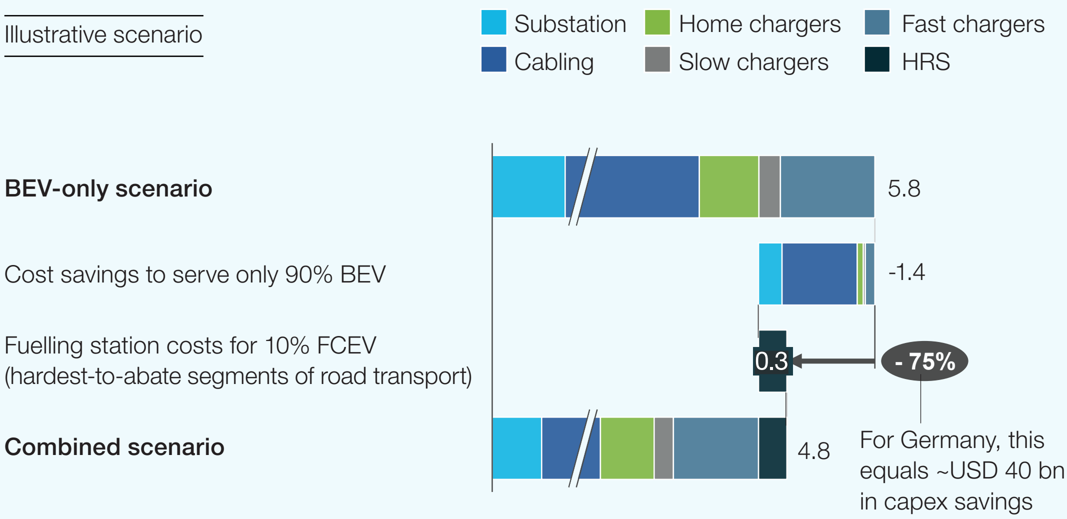
11

Two infrastructures are cheaper than one: hydrogen can reduce peak loads and necessary grid upgrades (1/2)

It may seem counterintuitive: building a hydrogen refuelling network alongside battery charging infrastructure is actually cheaper than building a charging infrastructure that is powerful enough to cover all use cases, including those with high power demands and little charging capacity. Even if only 10% of xEVs are powered with fuel cells, this would already be worth it due to the reduced necessary upgrades of the electricity grid in hard-to-serve and high-demand areas, i.e. remote highway refuelling stations and public fast chargers in cities with high grid loads. The effect will be even more pronounced when including commercial vehicles.

Comparison of incremental recharging vs. refuelling investment

Capex to serve 1,000 passenger vehicles, USD millions, 2050



In a combined world with 90% BEV and 10% FCEV penetration, the cost of additional hydrogen refuelling stations is more than offset by savings in charging equipment and corresponding grid upgrades

Replacing hardest-to-abate passenger BEV use cases that rely heavily on public fast charging with FCEV disproportionately reduces grid upgrade needs

Note: IEA comes to a similar conclusion: "While full electrification of road transport is possible, it could involve additional challenges (...) For example, it could increase pressure on electricity grids, requiring significant additional investment, and increasing the vulnerability..." (Net Zero by 2050, 2021)

Source: Hydrogen Council Cost Roadmap; IEA; expert interviews

11

Two infrastructures are cheaper than one: hydrogen can reduce peak loads and necessary grid upgrades (2/2)

The scale of infrastructure investment for fast charging is most obvious for highway refuelling. HDTs especially have a massive energy consumption that needs to be re-charged during drivers' resting times in order to be commercially viable. We estimate the power consumption of each highway charging station to equal a town of ~25,000 inhabitants – which needs to be provided in relatively remote areas, requiring sufficient cabling and substations to be built.

Example highway rest area

Electricity demand of a highway rest area using superchargers

Illustrative estimate

Cars: load at peak time (holidays, weekends)

Highway refuelling stations are fully utilised

A typical refuelling station has 8 pumps, refuelling takes <10 minutes

100 kW fast charging takes 50 minutes

→ 40x 100 kW chargers are required to serve the demand

Passenger vehicle charging

Trucks: recurring base load

50 HDTs are at a rest area

Each truck needs to refuel 4 hours of driving (300 km) in a 1-hour break

A truck needs ~1 kWh/km

300 kW charging power required

50x 300 kW power demand at steady state

HDT charging

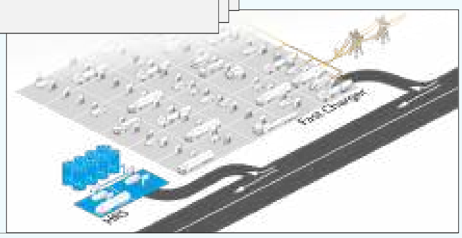
= Demand of a town with ~25,000 inhabitants

Estimate for a single typical highway refuelling station

Germany has ~360 stations

France has >400 stations

The EU addressed highway charging in the Fit for 55 Alternative Fuels Infrastructure Regulation, requiring one HRS every 150 km along the TEN-T core road network by 2030



Source: Hydrogen Council Cost Roadmap; Statista; McKinsey Center for Future Mobility

12

Hedging a bet on two pathways de-risks the most significant transition in the automotive industry's history

Both BEVs and FCEVs are in comparatively early development stages with many challenges remaining unsolved

Electrification is the biggest transition the automotive industry has ever had to face. There are drastic challenges along the entire value chain that need to be resolved in order to reach this goal. Having two pathways to rely on as a society reduces the risk if something does not go as planned. Furthermore, the complementary nature of BEVs and FCEVs increases the technology competition, fostering innovation and progress. During the transition phase, various hybrid options as well as direct hydrogen combustion may play a role.

Energy and raw materials

~60% of electricity and **~95%** of hydrogen are still sourced from fossil fuels

+80% nickel class 1 supply needed by 2030 for battery production

Production

275 BEV, 12 FCEV and 176 PHEV passenger car models are currently available, so there are still **3** times more ICE models available

<45 electric (BEV and FCEV) heavy freight trucks were on the road in 2020

Launching a new vehicle plant takes **2-3 years**

Transmission

+50% power demand due to electrification of heating and transport

The hydrogen distribution network is still in the build-up stage

Vehicle-to-grid technology is still in the pilot phase

Distribution

3.5 mn chargers are currently installed; this would need to grow at least **75x**

The standard recharging time with DC 50 kW fast chargers on the market is **~45 min**

Ultra-fast chargers of **1 MW** would be required for charging long-haul trucks quickly (this equals the peak load of ~100 homes)

Usage and recycling

<1% of the global car parc is electrified

Li-S batteries will have 50-70% of closed loop recycling potential; recycling capacity will have to grow **36x**

Source: IEA. 'Global EV Outlook 2021'; Our World in Data; Hydrogen Council; IHS; WEF; McKinsey

FCEV and BEV: different flavours of the same electric powertrain

Similar to the current variety in ICE powertrains (gasoline and diesel), we see battery and fuel cell as different flavours of the same electric powertrain

BEVs and FCEVs do not make use of two distinct technologies, but only differ in the way energy is stored in the vehicle. The drivetrain from the motor downwards is identical.

High power demand applications, areas with constrained renewable electricity supply and use cases that require long ranges with short refuelling times are most suited to be served with FCEVs. This can be compared to the duality of diesel and gasoline combustion engines, which also complement each other depending on the use case and the regulatory environment.

The case for hydrogen in road transport