THE ROAD TO NET ZERO

Study on the strategic deployment of battery-electric vehicles and fuel cell-electric vehicles infrastructure

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Executive summary

To fully deliver on the European Green Deal ambition, a concerted effort is needed across all sectors, particularly by the sectors of the economy that contribute the most to greenhouse gas (GHG) emissions. Road transportation is among these sectors, accounting for roughly 20 percent of the European Union's (EU's) overall emissions, predominantly from passenger cars (PCs), light commercial vehicles (LCVs, such as vans), trucks, and buses.[1]

While multiple technologies will be needed to fully decarbonize the road transportation sector, battery-electric vehicles (BEVs) and fuel cell-electric vehicles (FCEVs) have been selected as two promising technologies to investigate in this report. Furthermore, a need remains to assess a future where both technologies coexist as part of a complementary ecosystem. This study represents the first in-depth investigation of a potential combined ecosystem of BEV and FCEV infrastructure throughout Europe.

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[1] *Net-zero Europe: Decarbonization pathways and socioeconomic implications*, McKinsey, November 11, 2020.

State-of-the-art BEV and FCEV technologies

BEV and FCEV technologies are advancing rapidly, and cost-competitiveness is within reach compared to internal combustion engine (ICE) technology. However, BEV and FCEV technologies are at different stages of development, which is reflected in their costs and current adoption rates.

The overall market share and mix of BEVs and FCEVs on the road are expected to progress quickly and shift as the respective technologies evolve and users make decisions based on their needs and the energy realities of their place of residence. The current market share already varies strongly across the different vehicle segments, namely light-duty vehicles (hereafter referred to as LDVs which includes PCs and LCVs) and heavy-duty vehicles (hereafter referred to as HDVs, which includes trucks and buses). Sales penetration of electric power trains (xEVs) in light-duty segments was as high as 30 to 60 percent in the Nordics in 2021, but just 2 to 3 percent in many eastern European countries.[2] Penetration of xEVs in the heavy-duty segments remains lower on average at roughly 10 percent of buses but less than 1 percent of trucks in 2021. Most xEV sales across segments comprised BEV (including plug-in hybrid) models, while FCEVs accounted for less than 1 percent of sales across segments in 2021.[3]

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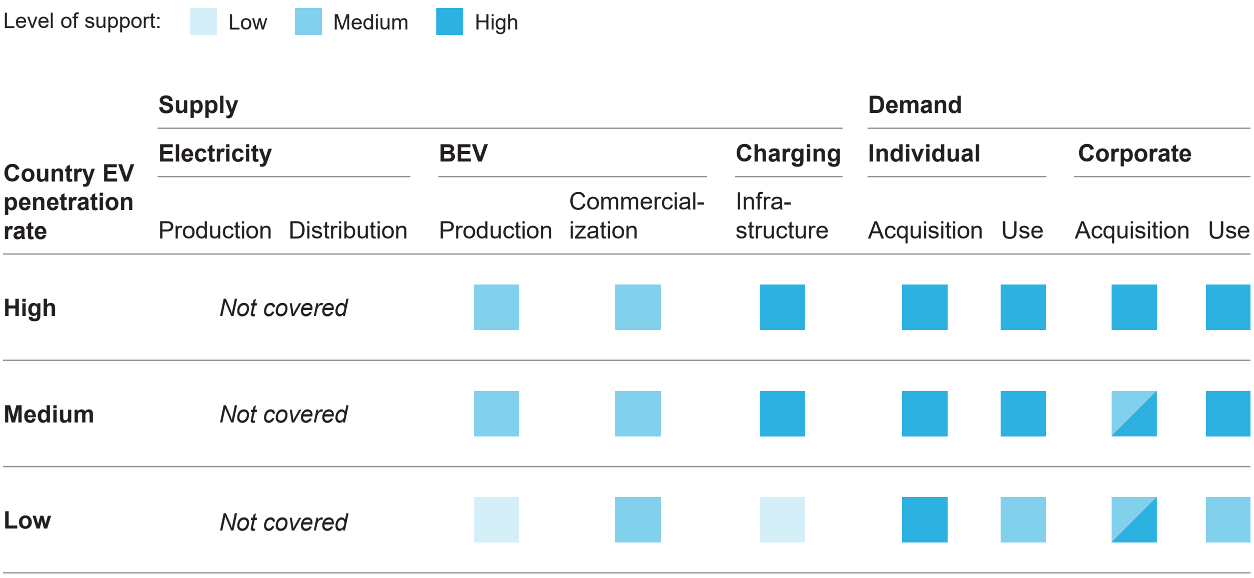
[2] For more information, see McKinsey Center for Future Mobility.

[3] For more information, see McKinsey Center for Future Mobility.

Exhibit E1

BEV regulatory support at a European country level for each step of the value chain



Level of support: ▢ Low ▨ Medium ■ High

	Supply					Demand			
	Electricity		BEV		Charging	Individual		Corporate	
Country EV penetration rate	Production	Distribution	Production	Commercialization	Infrastructure	Acquisition	Use	Acquisition	Use
High	*Not covered*		▨	▨	■	■	■	■	■
Medium	*Not covered*		▨	▨	■	■	■	◪	■
Low	*Not covered*		▢	▨	▢	■	▨	◪	▨

Source: EU regulations; directives and policy brief repository; member-state regulations; press search

Regulation impacting xEV adoption and infrastructure deployment

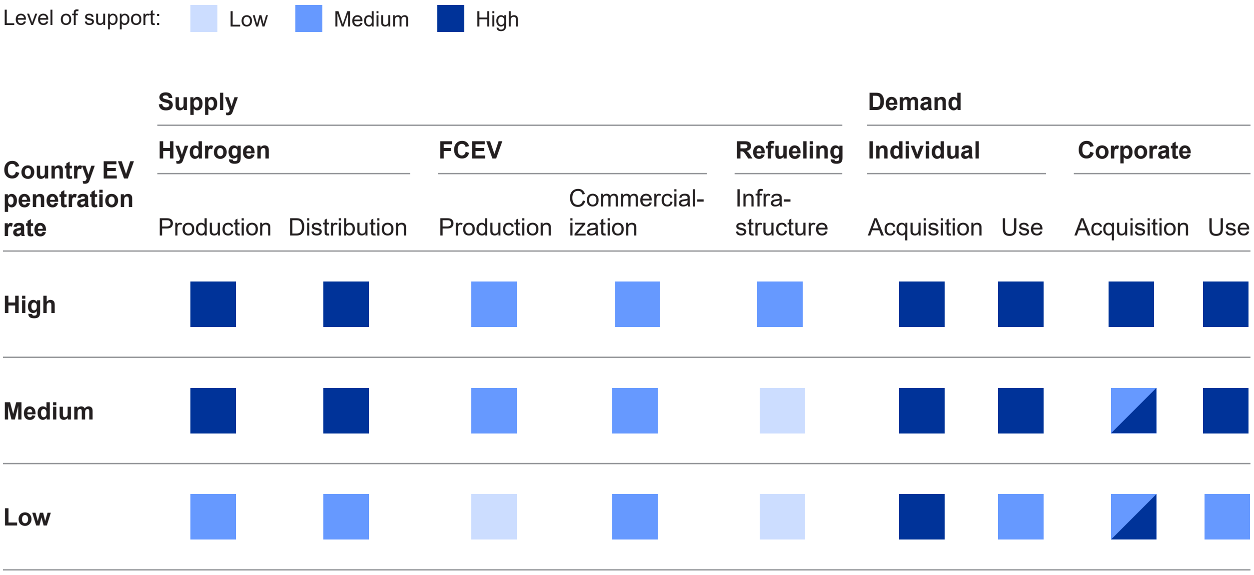
Efforts to rapidly decarbonize the transportation sector have been ramped up to help achieve the objectives of the European Green Deal (including zero emissions by 2050). The EU's efforts to regulate emissions from the transportation sector have intensified in the past five years. The first set of regulations was implemented in 2017 (monitoring and reporting CO_2 emissions from fuel consumption of LDVs and new HDVs). Since then, this first regulatory package has been updated and reinforced through:

- EU-wide ambitious regulation packages on emissions reductions (such as the European Green Deal and Fit for 55)
- Clear and progressive targets with short and long-term milestones (including 2025, 2030, and 2050), notably on infrastructure development at a country level
- New decarbonization regulations focused on road transportation, both on LDVs and HDVs, favoring the use of clean technologies (such as fuel cell electric, battery-electric, and synthetic fuels)

At a country level, there is strong regulatory support for xEV adoption (including corporate and individual subsidies for xEV purchases), energy production (like subsidies for the development of hydrogen technologies), BEV infrastructure development (such as BEV charging station targets), and an opportunity for future support of FCEV infrastructure development. Five of ten of the EU's largest cities have set clear charging station targets by 2023. However, none have set concrete hydrogen refueling station (HRS) development targets (Exhibit E1, Exhibit E2).

Exhibit E2

FCEV regulatory support at a European country level for each step of the value chain



Level of support: ░ Low ▒ Medium █ High

	Supply					Demand			
	Hydrogen		FCEV		Refueling	Individual		Corporate	
Country EV penetration rate	Production	Distribution	Production	Commercialization	Infrastructure	Acquisition	Use	Acquisition	Use
High	█	█	▒	▒	▒	█	█	█	█
Medium	█	█	▒	▒	░	█	█	▒/█	█
Low	▒	▒	░	▒	░	█	▒	▒/█	▒

Source: EU regulations; directives and policy brief repository; member-state regulations; press search

State-of-the-art research on xEVs and their infrastructure

Since BEV and FCEV technologies are considered two important technologies to decarbonize the EU road transportation industry, numerous studies have investigated their development. To establish a more detailed view of the research on these areas, approximately 30 related studies were examined for their coverage of the five key segments of our analysis: xEV penetration scenarios, member state selection, BEV and FCEV infrastructure costs and development, and an optimal blend of both types of infrastructure.

Among the studies examined, none have modeled selected representative member states as archetypes for Europe, and very few have attempted to estimate the optimal mix of BEV and FCEV infrastructure to be deployed. A few studies have, however, investigated FCEV and BEV penetration from an infrastructure cost perspective. Yet, methodological strengths still appeared across the literature review:

- Studies including bottom-up modeling of Electric Vehicle Charging Infrastructure (EVCI), grid infrastructure extension, HRS, and hydrogen supply infrastructure costs provided more detailed cost estimations

- Technology learning curves generated a better understanding of cost structure evolution over time

- Comparing the total cost of ownership (TCO) by including detailed vehicle capital expenditure and operating expenditure breakdowns strengthen the analysis from a consumer perspective

There is a unique opportunity for the current study to make four key contributions to the existing literature and infrastructure modeling:

1. Providing a single picture for a comprehensive set of vehicle segments

2. Developing a high level of detail by geography, user type, location, and technology

3. Determining a combined infrastructure deployment strategy for FCEV and BEV infrastructure

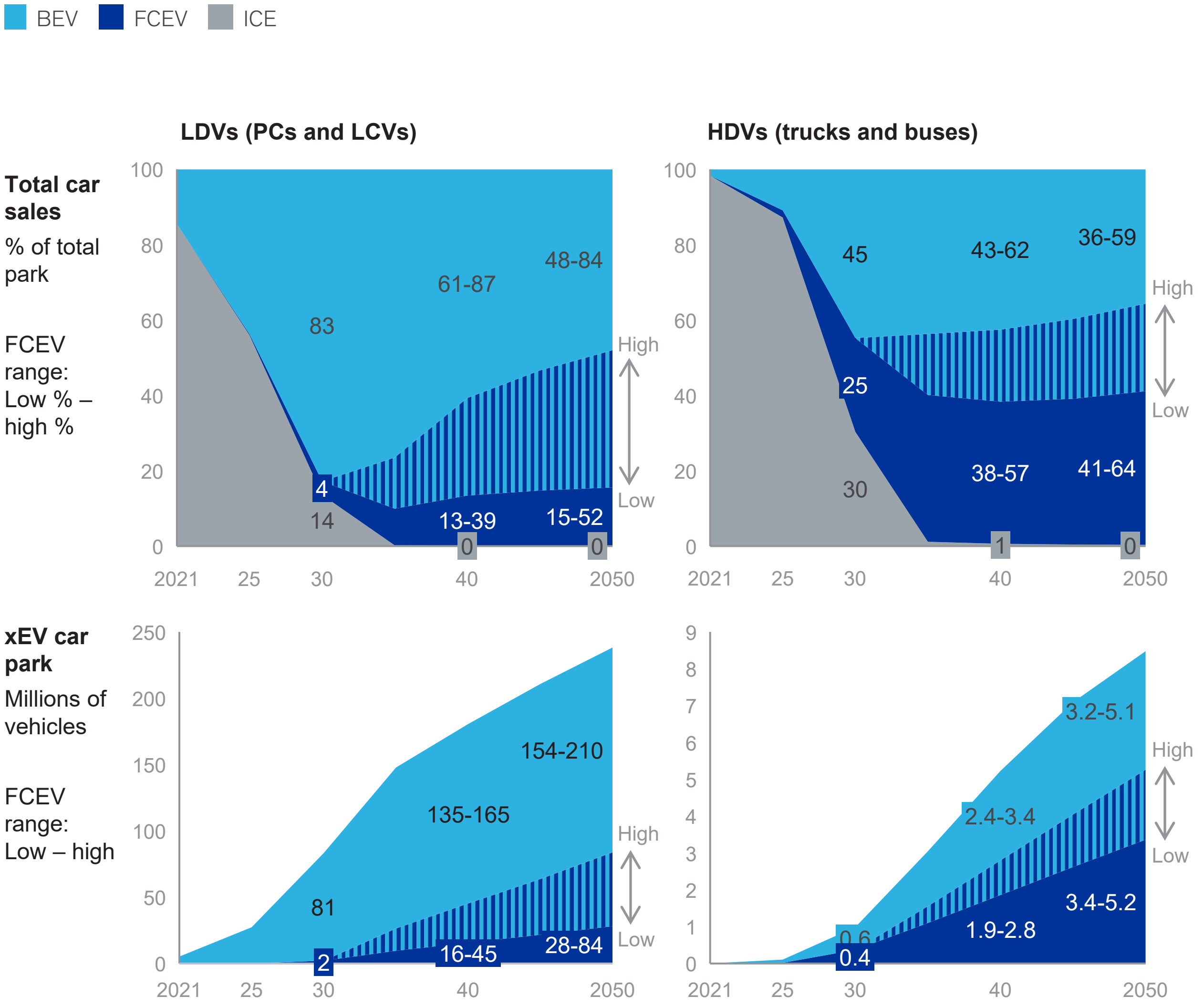
4. Leveraging a careful selection of countries to serve as archetypes for the EU and its different member states

Aligning the “optimal blend” of infrastructure to deploy is a challenge and doing so in a way that allows for the organic development of both BEV and FCEV technologies is even more so. With these goals in mind, we began by looking at a central xEV adoption scenario through 2030 that follows the current trajectory of vehicle adoption, technology development, and regulatory targets. Through 2050, we project overall xEV adoption to be consistent with a net-zero emission-reduction pathway and consider a “range” for the underlying mix of BEVs versus FCEVs in each segment. To model the required infrastructure deployment, we first asked: what would the optimal deployment of infrastructure to support the evolving vehicle fleet look like? We then asked: if the mix of EVs on the road shifts, how would that impact key metrics such as cost, timing, feasibility, and emission reduction?

Exhibit E3

Beyond 2030, the car park is modeled with a range of BEV and FCEV distributions in order to investigate the implication on infrastructure deployment and costs

EU-27+2



Source: McKinsey Center for Future Mobility

Our "net-zero" scenario considers the EU's net-zero ambition, including the 90 percent emission-reduction target for transportation by 2050 (versus 1990 levels) as well as more ambitious near-term targets laid out as part of the EU's Fit for 55 package. This "net-zero" scenario was developed based on projections from McKinsey's proprietary Mobility Electrification Model housed within the McKinsey Center for Future Mobility and considers five key factors: TCO comparison, consumer adoption, production constraints, country targets, and regional targets. Beyond 2030, we represent the mix of xEV power trains as a range to reflect uncertainties around the evolution of relevant technologies and their applications.

In this "net-zero" scenario, xEV sales would reach roughly 87 percent of total sales (or 14 million vehicles per year) in the LDV segment and 70 percent of total sales (or 300,000 vehicles per year) in the HDV segment by 2030. The share of total sales for EVs would grow to reach nearly 100 percent in both LDVs and HDVs (or about 17 million and 500,000 vehicles per year respectively). Sales penetration is expected to vary by vehicle subsegments and use case, given differences in purchasing and energy costs and user requirements (Exhibit E3).

For the definition of LDV and HDV, see report section 2.B.1.

Our methodology for defining xEV infrastructure requirements

Starting from our "ranged" adoption scenario, we project aggregated infrastructure requirements for the EU-27 plus the United Kingdom and Norway, which are included in this analysis. We first project infrastructure requirements and costs to portray the level of near-term mobilization and coordination needed across Europe. Looking toward 2050, the evolving road transportation ecosystem is less certain, particularly with regard to the roles BEVs and FCEVs will play. We depict a range of possible futures, sensitivities, and relative penetrations of BEVs and FCEVs across segments to highlight the cost impact of these changes on the overall xEV ramp-up.

We have chosen to focus this study on downstream and midstream capital expenditures, including HRS, charging stations, and distribution capital expenditures (excluding hydrogen pipeline costs) and excluding hydrogen or electricity production costs and all operating expenditures such as labor and maintenance (Exhibit E4).

Exhibit E4

An estimate of the total infrastructure costs

▨ Included in the overall infrastructure cost estimates

	FCEV	BEV
Downstream	HRS capex: **HRS infrastructure hardware** (e.g., pumps, on-site compressors)	Chargers capex: **home charger hardware and public charger infrastructure and hardware**
Midstream	Trucking capex: **trucks and lorries to carry hydrogen** Compression capex: **infrastructure and hardware for the compression** of hydrogen prior to its transportation	Grid capex: **grid upgrade costs** implied by the road transportation industry
Upstream	All hydrogen **production costs**	All electricity **production costs**
Other	All **opex** (e.g., HRS operators, truck drivers, and electricity needed by the stations)	All **opex** (e.g., maintenance, software, and electricity distribution charges)

Source: McKinsey analysis

We consider four factors as guiding principles to determine the blend of infrastructure for zero-emission mobility:

- **Infrastructure cost.** The capital expenditures required to deploy supporting infrastructure for BEVs and FCEVs as part of the future vehicle fleet. Particular emphasis is placed on this factor.
- **Timing and speed of deployment.** The rate at which infrastructure can be rolled out to support and drive xEV adoption. This factor is also linked to sustainability impact.
- **Feasibility.** The availability of critical resources (such as labor and sustainably sourced raw materials) and adequate funding to deploy the infrastructure.
- **Sustainability impact.** All else being equal, the impact of BEVs and FCEVs is assumed to be equivalent from an emission-reduction perspective. While our assumption here looks at tailpipe emissions only, the overall sustainability impact would be driven by emissions from the full value chain, including hydrogen and electricity production, transportation emissions, and sun-to-wheels efficiency, which are beyond the scope of this study.

We can further view the blend of infrastructure as 1) the mix of the infrastructure deployed for each power train for an existing or projected vehicle park and 2) the ratio of BEV charging versus FCEV refueling infrastructure if deployment choices could be made independent of the existing or projected vehicle park. In this chapter, we will look at both.

- On 1) we'll look at how to deploy infrastructure against our "ranged" adoption scenario in a way that seeks to minimize costs while meeting the remaining optimization criteria.
- On 2) we'll consider several sensitivities to our "ranged" scenario to illustrate how overall system costs might be impacted given changes in overall vehicle uptake or the mix between BEVs and FCEVs on the road.

Results

xEV infrastructure deployment through 2030

An increasing share of xEVs on the road would require BEV and FCEV infrastructure to be rolled out quickly. Through 2030, our scenario would require some 52 million charging points to be installed across Europe and nearly 5,000 HRS. This compares with around 270,000 chargers and around 200 HRS today.[4]

Cumulative investment in Europe's combined recharging and refueling infrastructure would reach €220 billion by 2030, increasing to nearly €30 billion per year between 2026 and 2030 compared to the 2022 to 2025 average of about €18 billion. Roughly 68 percent of the total investment in xEV infrastructure would come after 2025 (Exhibit E5). While the bulk of the investment (around 95 percent) is needed to meet BEV charging infrastructure demand, the amount spent on HRS will help fuel-cell technologies scale up in relevant segments (for example, long-haul trucks).

xEV infrastructure deployment beyond 2030 and sensitivities

Looking beyond 2030, the EU-27 (plus the United Kingdom and Norway) will need to deploy between 99 and 134 million chargers to support BEVs and 20,000 to 34,000 HRS to support FCEVs. Roughly 70 percent of the total investment would be driven by charger deployment (€689 billion to €952 billion total spent on charging infrastructure from 2030 to 2050) including grid upgrades (€7 billion to €14 billion on average annually from 2030 to 2050) related to electric mobility. The remainder of the post-2030 investment (about €65 billion to €117 billion in total through 2050) would go toward the rollout of HRS and the distribution network. These investments may enable up to 247 million xEVs to enter use by 2050.

In the "ranged" scenario, the total costs for the BEV and FCEV infrastructure ecosystem would reach €1.0 trillion to €1.2 trillion. This is a sizeable fraction of the estimated €28 trillion needed for the EU to fully complete its net-zero transition, in all sectors, in the same time frame.[5] Importantly, while the bulk of investment (79 to 82 percent) would be made post-2030, the mobilization of €220 billion in the near term is not trivial, nor is doing so in a coordinated way across member states and their regions (Exhibit E6).

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[4] Source: IEA; FCH Observatory.

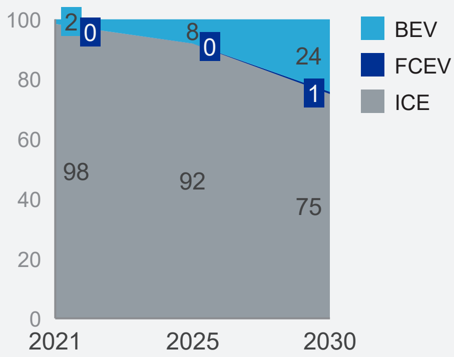
[5] *Net-zero Europe: Decarbonization pathways and socioeconomic implications*, McKinsey, November 11, 2020.

Exhibit E5

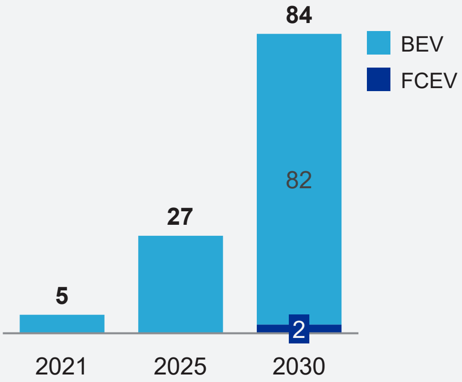
The EU car park is expected to be made up of ~25% xEVs by the end of 2030—mostly BEVs—resulting in an investment need of €220 billion

xEV park

Car park split, % by power train

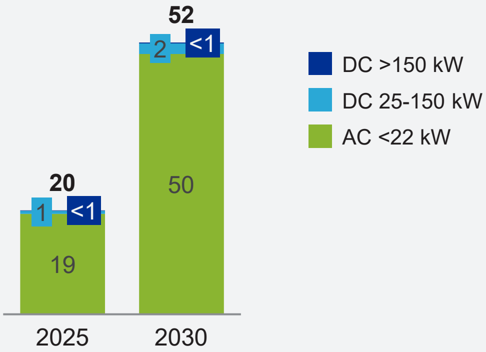


xEV park, million vehicles

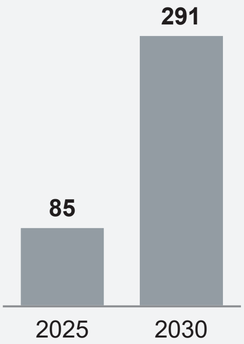


BEV infrastructure

Number of charging points, millions by type

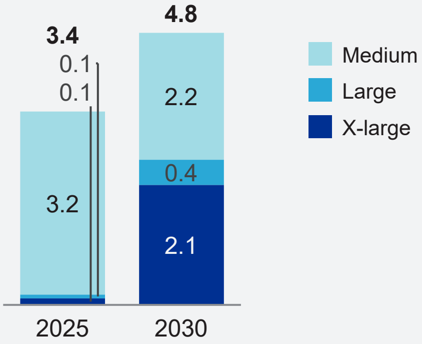


Electricity consumption, TWh

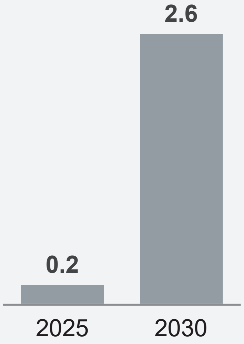


FCEV infrastructure

Number of HRS, thousands by size[1]

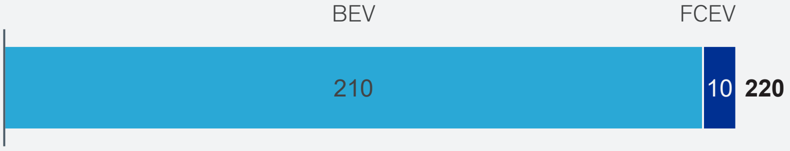


Hydrogen consumption, Mt



Infrastructure costs

Total capex,
2022-30, € billions



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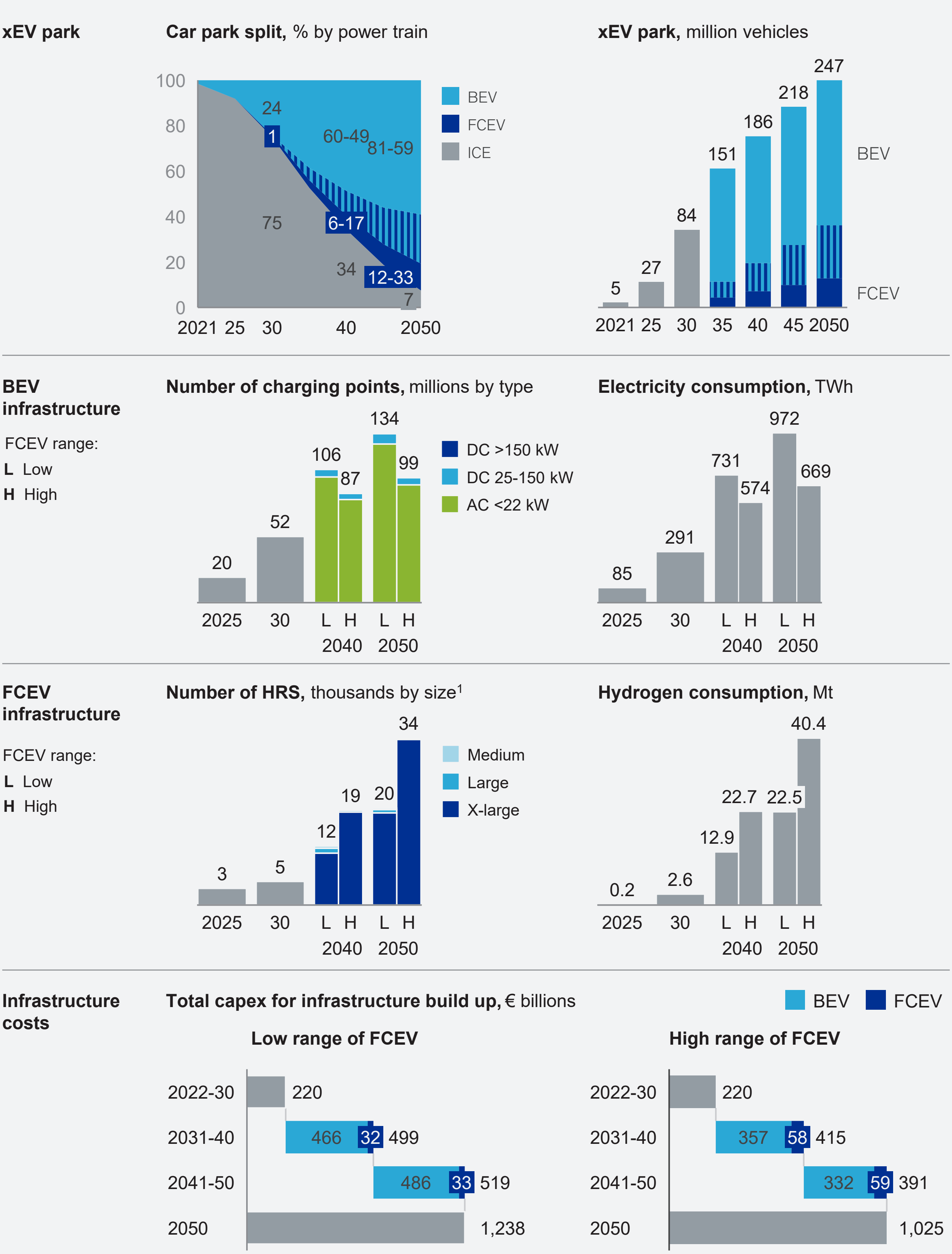
[1] Medium station = 480 kg/day capacity; large station = 1,000 kg/day capacity; x-large = 4,000 kg/day capacity.

Source: McKinsey Center for Future Mobility

Exhibit E6

The EU car park is expected to increase from ~25% to 93% xEVs between 2030 and 2050, triggering a significant infrastructure investment

EU-27+2



xEV park

Car park split, % by power train

xEV park, million vehicles

BEV infrastructure

FCEV range:
L Low
H High

Number of charging points, millions by type

Electricity consumption, TWh

FCEV infrastructure

FCEV range:
L Low
H High

Number of HRS, thousands by size[1]

Hydrogen consumption, Mt

Infrastructure costs

Total capex for infrastructure build up, € billions

Low range of FCEV

High range of FCEV

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[1] Medium station = 480 kg/day capacity; large station = 1,000 kg/day capacity; x-large = 4,000 kg/day capacity.

Source: McKinsey Center for Future Mobility

As cross-border connectivity is critical to Europe's economy, we also explore implications for infrastructure deployment along key transportation corridors in the EU. To do so, we investigated the results of our infrastructure models and implications in the context of Europe's TEN-T corridors.[6] Depending on the upper or lower end of the "ranged" scenario, between 27,000 and 32,000 public fast chargers for LDVs and between 5,500 and 8,200 public fast chargers for HDVs would be located along the TEN-T corridors by 2050.

With several long-term possible futures envisaged, we modeled two extreme sensitivities to our "ranged" scenario to demonstrate the impact on infrastructure costs should the power train mix shift in one direction or the other. These sensitivities are not meant to be forecasts or predictions but provide a theoretical degree of change to infrastructure system requirements should various inputs shift (such as the power train mix).

Exhibit E7 shows infrastructure capital expenditure requirements for both the theoretical 100 percent BEV and FCEV model cases compared with the "ranged" scenario for the whole of Europe.

— **The 100 percent BEV versus a "ranged" combined scenario.** The theoretical scenario in which no FCEV infrastructure is developed and there is no adoption of FCEVs results in higher overall infrastructure costs than our "ranged" scenario. Comparing the two scenarios until 2050, infrastructure costs would increase to cumulative capital expenditures of €1.5 trillion from between €1.0 trillion and €1.2 trillion for the "ranged" scenario, representing a 26 to 52 percent increase. Until 2030, the increase in cumulative capital expenditures is approximately 12 percent or €247 billion, up from €220 billion for the "net-zero" scenario. Looking at the evolution of average annual capital expenditures in line with the cumulative capital expenditures, the difference in cost increases over time from around 16 percent in the 2026 to 2030 period, to 24 to 49 percent in the 2031 to 2040 period, and 35 to 79 percent in the 2041 to 2050 period.

— **The 100 percent FCEV versus a "ranged" combined scenario.** The theoretical scenario in which no (additional) BEV infrastructure is developed and there is no (additional) adoption of BEVs results in lower overall infrastructure costs versus our "ranged" scenario. Comparing the two scenarios until 2050, we see that total infrastructure costs would decrease to €0.3 trillion from between €1.0 trillion and €1.2 trillion for the "ranged" scenario, representing a 69 to 75 percent decrease. Until 2030, the decrease in cumulative capital expenditures is approximately 59 percent to €90 billion, down from €220 billion for the "net-zero" scenario. Looking at the evolution of average annual capital expenditures in line with cumulative capital expenditures, the difference in cost increases over time from 59 percent in the 2026 to 2030 period, to 70 to 75 percent in the 2031 to 2040 period, and 75 to 80 percent in the 2041 to 2050 period.

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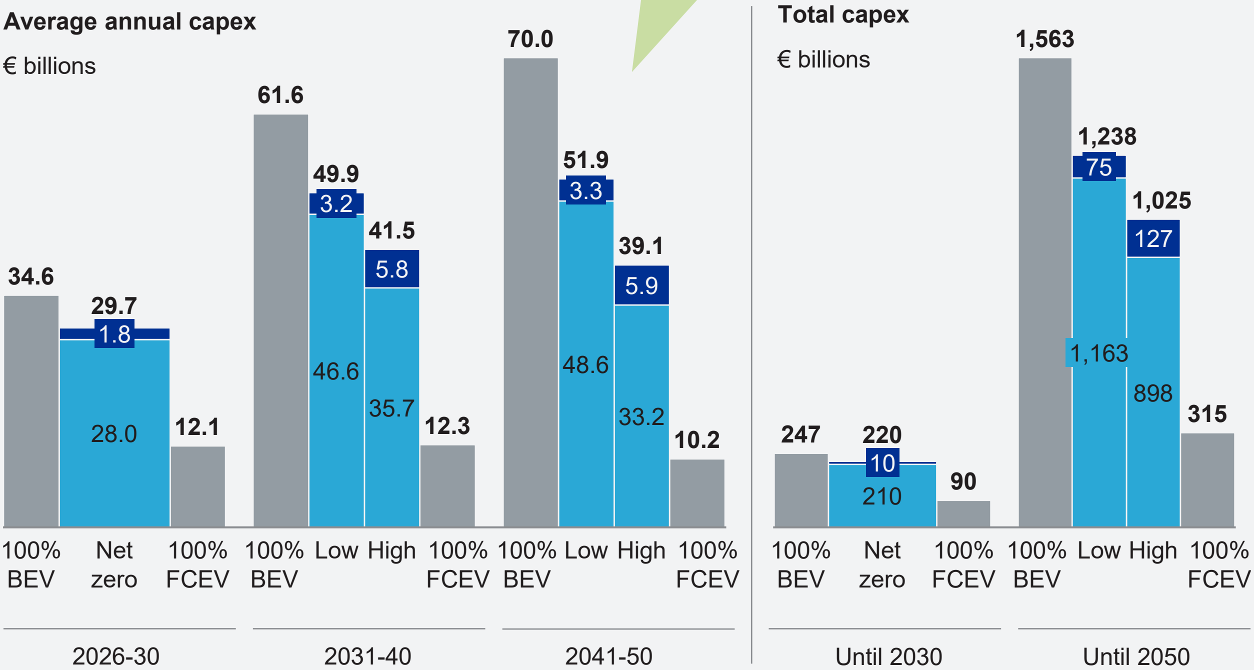
[6] "The Trans-European Transport Network (TEN-T) policy addresses the implementation and development of a Europe-wide network of railway lines, roads, inland waterways, maritime shipping routes, ports, airports and railroad terminals. The ultimate objective is to close gaps, remove bottlenecks and technical barriers, as well as to strengthen social, economic and territorial cohesion in the EU." https://transport.ec.europa.eu/transport-themes/infrastructure-and-investment/trans-european-transport-network-ten-t_nl

Exhibit E7

An infrastructure capex comparison of extreme power train split cases

🟦 BEV ■ FCEV ▨ Extreme scenarios

This chart shows **theoretical 100% BEV and FCEV** model cases compared to the ranged scenario based on the infrastructure capex and gives no indication of the TCO associated with these input fleets. Taking TCO into account, the 100% FCEV model case would show suboptimal TCO for certain user groups and thus be an expensive way of decarbonizing the total fleet.



Source: McKinsey Center for Future Mobility; McKinsey Hydrogen Insights FCEV infrastructure model; McKinsey Hydrogen Insights Hydrogen Demand model; McKinsey Global Energy Perspective

Synergies and limitations to consider in the deployment of BEV and FCEV infrastructure

For FCEVs, the competition around hydrogen supply could be reframed as an opportunity for synergies. As the upstream infrastructure is identical for most use cases, capacities need not be built exclusively for one use case but shared among all. This implies that a critical demand level supporting the build out of green hydrogen supply is reached early on and that cumulative demand across all use cases will rapidly drive down costs through economies of scale.

A similar argument can be made for midstream synergies. While the infrastructure for compression and distribution is only partially shared between road transportation and nonroad transportation or industry, there could still be interoperability between the use cases, leading to shared benefits (such as, increased fixed-cost coverage and economies of scale) for certain applications.

Grey hydrogen: Hydrogen produced from natural gas; carbon dioxide is emitted.

Blue hydrogen: Hydrogen produced from natural gas; carbon dioxide is captured or reused and not emitted.

Green hydrogen: Hydrogen produced by electrolysis of water using renewable energy; no carbon dioxide is emitted.

FCEVs and BEVs share certain upstream and midstream synergies. For example, the large-scale introduction of xEV technology will require an increase in renewable power generation, which—with increased demand for renewables in other sectors—could reduce costs through economies of scale. The overall power capacity will need to satisfy demand even in peak hours. With the ability to smart charge at off-peak hours, BEVs will play a significant role in making the best use of this power capacity by flattening the demand profile throughout the day.[7] With vehicle-to-grid (V2G) functionality, BEVs could further increase the system's stability and alleviate the need to design the system to cope with extreme demand or supply (due to volatile renewable power generation) spikes. Similar benefits can also be realized in more local electricity transmission and distribution.

While there are synergies to capture, there are also multiple limitations that must be overcome with respect to the deployment of xEV infrastructure. We start our analysis of these limitations from a set of key concerns around the deployment of BEV and FCEV infrastructure and develop a fact base tailored to each concern to arrive at a data-driven assessment of potential limitations. In total, we answer ten typical questions raised by xEV experts associated with the development of BEV and FCEV infrastructure. The questions are centered around the topics of energy supply and distribution capacities, raw material availability, labor supply, regulatory support, the attractiveness for private investments, and concerns around efficiency and capacity in distribution, regulation, and vehicles (Exhibit E8).

The availability of green hydrogen (Question 1) is particularly relevant as hydrogen demand for FCEVs is in direct competition with hydrogen demand from other sectors, be it industry, buildings, or other (nonroad) transportation sectors. One potential risk is that grey hydrogen will continue to form a large part of the hydrogen produced, or the technology to capture CO_2 from blue hydrogen will not materialize, preventing the decarbonization of road transportation. A second risk is that green hydrogen produced in a continuous process will compete for the limited renewable energy resources, requiring further grid updates. We consider it likely that the overall hydrogen supply will be able to cover demand from most end-use cases, with the aim of green hydrogen playing an increasing role in hydrogen supply. However, to meet demand, we will likely continue to rely on a share of blue hydrogen.

Another major concern is the availability of skilled labor (Question 4) required to support the envisioned mobility transition. We observe the current shortages based on vacancy rates in three key sectors required for the mobility transition (construction, utilities supply, and transportation and storage) in selected member states. The impact of labor shortages is not limited to the mobility industry, however, and opportunities for large-scale up- or reskilling of the current workforce might exist to meet the demand.

Within our analysis, we assumed a hydrogen distribution network based on the trucking of hydrogen in its gaseous form, rather than the usage of pipelines or trucking of liquid hydrogen (Question 6). This is because the transportation of hydrogen as a gas is the most cost-effective solution given significant costs of liquefaction and uncertainty around the future network of hydrogen pipelines. To capture the impact of some level of hydrogen pipeline development in the future, we have decreased the average trucking distance by 2050. The infrastructure costs for hydrogen distribution we derive in this report thus represent a conservative estimate; however, there are potential operational savings in a more refined and diversified distribution network, leveraging and combining the advantages of each mode of transportation.

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[7] BMW Group Bidirectional Charging Management Consortium, Volkswagen Group We Charge Press Release.

Exhibit E8

We’ve aspired to answer ten top-of-mind questions on the challenges facing the deployment of xEV infrastructure

✔ Yes ✓ Under certain circumstances ✕ No

Energy supply	**1. Will there be enough green hydrogen supply to meet FCEV demand?**	✓	Green hydrogen supply will exceed road transportation demand
	2. Will there be enough green electricity supply to meet BEV demand?	✔	Green electricity supply will exceed road transportation demand, but the total energy mix will still include other sources (e.g., natural gas)
Raw materials	**3. Will there be sufficient raw materials available to support the transition to clean mobility?**	✓	For example, a material like nickel could be in short supply, especially if recycling is not intensified. There is significant ongoing research into using alternative metals
Labor	**4. Will there be enough skilled labor to support the transition to clean mobility?**	✓	There is a need to upskill labor to specific needs to meet demand (e.g., electricity and gas jobs)
Investments	**5. Can the FCEV and BEV industries attract sufficient (early) investors without additional incentives?**	✕	Without supporting incentives, high up-front investments (esp. for FCEV infrastructure) can deter early investors
Distribution	**6. Is trucking the most efficient way of distributing hydrogen?**	✓	Yes, for small quantities and a nascent network, but for large quantities a pipeline is more efficient
	7. Is the grid strong enough to support the energy transition and BEV penetration?	✕	The grid will require additional investments to support the energy transition
Infrastructure and vehicles	**8. Are there local regulatory requirements that impede FCEV development?**	✔	There are some local environmental regulations that require HRS developers to apply for specific permits if capacity surpasses a threshold
	9. Is the FCEV value chain energy efficient compared to BEVs?	✕	FCEVs are less efficient than BEVs due to losses when producing, transporting, and converting hydrogen back to electricity[1]
	10. Are enough FCEV models available to the customers?	✕	Current model announcements place the short-term model availability of FCEVs far below that of BEVs and ICE vehicles. However, FCEV vehicle technology is rapidly developing

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[1] However, green hydrogen may represent renewable energy otherwise not captured entering the energy value chain.

Source: McKinsey Center for Future Mobility; McKinsey Hydrogen Insights FCEV infrastructure model; McKinsey Hydrogen Insights Hydrogen Demand model; McKinsey Global Energy Perspective

Comparing xEV infrastructure deployment across member states

In thinking about Europe's alternative power train infrastructure, there are as many on-the-ground realities as there are countries. At a member-state level, infrastructure requirements will differ in terms of overall investments required, timing of deployment, and investment split between technologies. Somewhere between a futile attempt at a one-size-fits-all infrastructure approach and 29 separate models is the development of archetypes into which multiple countries can be clustered. We use these member-state archetypes to compare and contrast xEV infrastructure deployment with the hopes of better understanding the opportunities and challenges that may be faced at the individual country level.

With all EU member states plus Norway and the United Kingdom distributed across the five archetypes (progressive leaders, large hydrogen and EV leaders, small EV and infrastructure leaders, first followers, and other followers), we sought to highlight a single member state from each archetype. We looked for the most extreme current situations and starting points to ensure our selection included an array of differences in time scenarios, cross-border traffic, and participation in TEN-T across the group of five selected member states.

With these considerations in mind, the following EU member states were selected:

- **Sweden.** Among progressive leaders, Sweden exhibits the highest EV penetration, the most developed EV infrastructure, and the highest level of renewable energy development and penetration.

- **Germany.** Among large EV leaders, Germany's size and the complexity of its road infrastructure system and city networks along with its high TEN-T corridor exposure sets it apart within the archetype.

- **The Netherlands.** Among small EV and infrastructure leaders, the Netherlands are an extreme example of being small in surface area and dense in population.

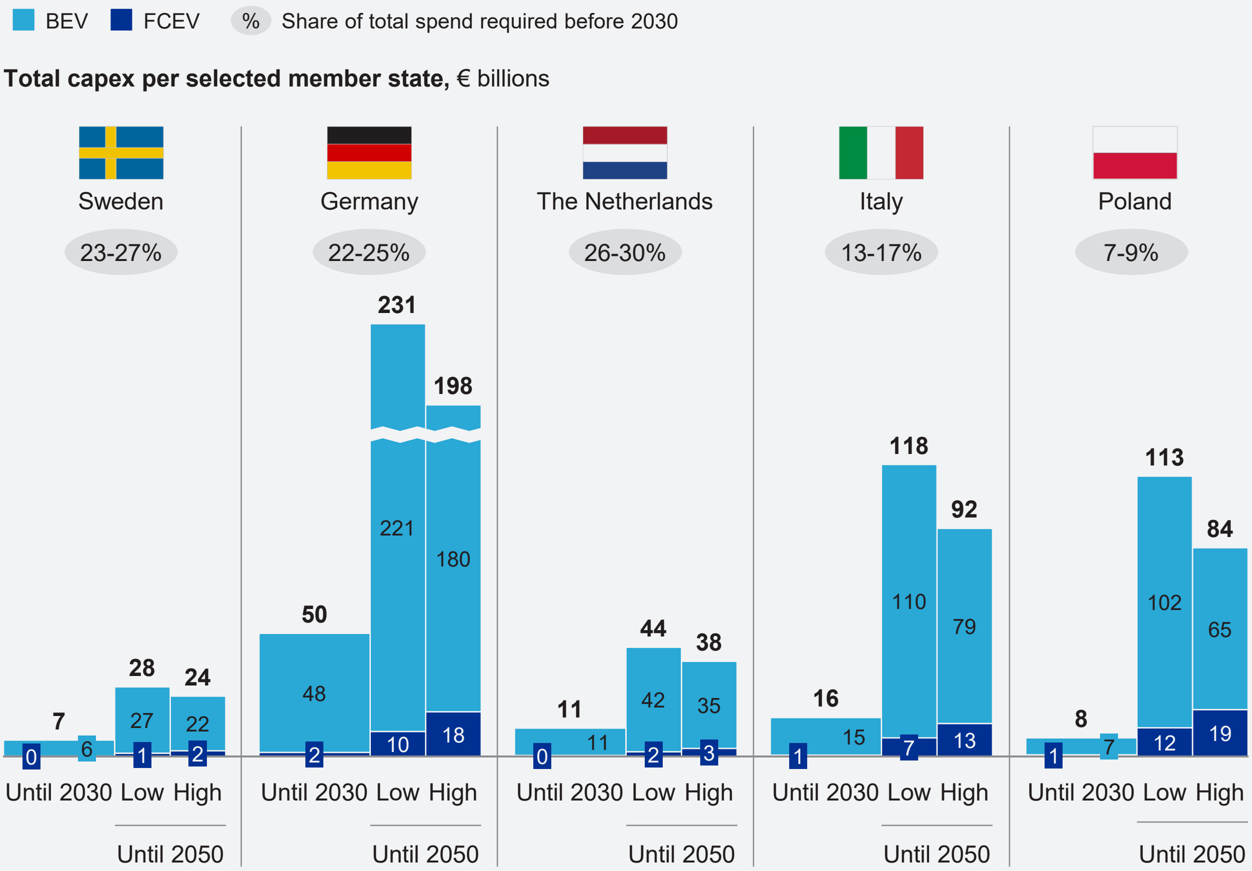
- **Italy.** Among first followers, Italy is remarkable in both its potential to successfully develop renewables and its public announcements regarding plans for hydrogen development.

- **Poland.** Among other followers, Poland has a very high level of cross-border traffic.

When looking specifically at capital expenditures, we see large differences in overall investment required for infrastructure across the five representative member states. In absolute terms, large, densely populated countries like Germany would spend five to ten times more than smaller countries like the Netherlands or Sweden (the higher absolute investment for Germany is primarily driven by a larger vehicle park (along with population) and more kilometers of road on which a viable network would need to be built. Countries like Sweden would spend the least in absolute terms, largely due to their smaller vehicle fleet, sparser road network, and higher existing levels of charger deployment (Exhibit E9).

Exhibit E9

The timing of overall infrastructure investments varies according to member-state specificities



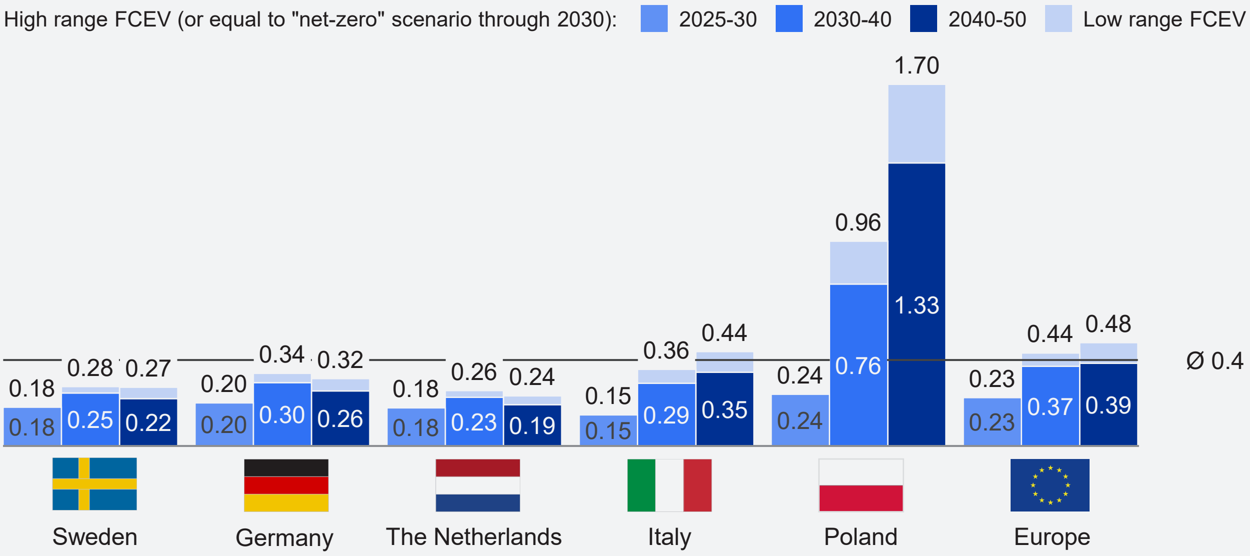
Source: McKinsey Center for Future Mobility; McKinsey Hydrogen Insights FCEV infrastructure model; McKinsey Hydrogen Insights Hydrogen Demand model; McKinsey Global Energy Perspective

By GDP, investment in infrastructure will be higher for some member states (for example, Poland) than for others (like the Netherlands) (Exhibit E10). While there is a correlation between GDP and the overall investment required, member states lagging in xEV penetration versus the EU average will need to spend more to catch up. In addition, the mix of vehicle types is a key determining factor: Poland, for example, has a significantly higher share of HDVs than other countries; the comparatively higher investment required to serve these vehicle segments drives up the total investment required in these countries.

Exhibit E10

The share of infrastructure investments differs per country based on the GDP

Share of average annual capex to the 2020 GDP



Source: McKinsey Center for Future Mobility; McKinsey Hydrogen Insights FCEV infrastructure model; McKinsey Hydrogen Insights Hydrogen Demand model; McKinsey Global Energy Perspective; IMF: World Economic Outlook (WEO) Database – October 2021

Key insights and recommendations for decision makers

Transitioning to a decarbonized mobility system is a critical lever to achieving the EU's net-zero ambition. The shift to xEVs in road transportation will be key to achieving that goal. However, as the European road fleet shifts away from ICE vehicles, so must its vehicle infrastructure. Through our investigation of xEV infrastructure requirements, we arrived at two key insights:

1. **Two infrastructures are better than one.** A future optimal mix of infrastructure would include both BEV and FCEV infrastructures. Decarbonizing the EU road fleet through the deployment of two technologies can reduce risk and is expected to cost less from an infrastructure perspective than if only BEV infrastructure were deployed. Our analysis found that a 100% BEV ecosystem could cost €3 trillion to €5 trillion more through 2050 from an infrastructure perspective than a combined ecosystem. The development of multiple technologies can also reduce the risk of resource exhaustion and alleviate other deployment bottlenecks that might arise should only one technology pathway be pursued. Last, the availability of both technologies could accelerate xEV adoption as users gain the ability to choose between power trains based on their needs.

   Investing in both technologies delivers infrastructure and TCO advantages over investing in only one. Yet, this transition comes at a cost: while some of the xEV demand is driven by an increasingly attractive TCO, mass adoption will only be ensured when every xEV owner has access to a reliable and strategically deployed charging and refueling network. To deploy the 99 million to 134 million chargers and 20,000 to 34,000 HRS needed to support the future European road fleet, a total infrastructure investment of around €1.0 trillion to €1.2 trillion will be required by 2050—of which most will be invested post-2030 (only €220 billion will be invested by 2030).

2. **Uncertainties around FCEV adoption represent a limited investment risk in the near term.** Uncertainties around FCEV penetration will have a limited impact on the number of refueling stations deployed and the overall investment costs through 2030 as the development of a minimum network is required—no matter the FCEV penetration rate—to support the development of the technology. The overall investment required to fund FCEV infrastructure development in the near term is also quite low in relative terms. Until 2030, the investment in FCEV infrastructure would be roughly €10 billion (or about 5 percent of the total investment through 2030).

From our observations on the optimal deployment of BEV and FCEV infrastructure, we derived a number of recommendations to help guide decision makers:

Implement policies to support the development of both BEV and FCEV technologies. A supportive regulatory environment is needed to ensure the uptake in both technologies and the required infrastructure build-out. "Technologically neutral" (or those that do not specifically favor one technology over the other) policies will be needed to support organic development in the geographies and use cases where they are most attractive for user adoption.

Provide financial support to achieve at-scale infrastructure deployment. Satisfying minimum network requirements and providing support for cross-border traffic will be critical in the early stages xEV adoption. While the roll-out of a minimum network for charging is well underway, the deployment of a commensurate HRS minimum network is still quite nascent. As initial utilization for such a network to support FCEVs is low, an intervention by policymakers would be required. It should be targeted at stations with the strongest "network effect," triggering additional private FCEV infrastructure investments. For BEVs, charging infrastructure needs to be deployed even in locations where the business case is not convincing in the short term. In such locations—such as rural areas, where upgrades may be expensive or relatively uncommon—support could be beneficial for the rollout of charging infrastructure and the required grid upgrades.'

Plan infrastructure to accommodate accelerating xEV adoption. Infrastructure should be "upwards-compatible," with standardized technologies and interoperability. Planning for networks, including the power grid, should consider the at-scale scenario, and technology needs to be upgradeable to higher charging and refueling outputs (and potentially different charging technologies such as inductive charging). Fast-charging infrastructure and HRS also need to be developed with the ability to expand over time.

Balance EU-level coordination with tailored member-state support. Collaboration between EU member states is key to achieving highly effective infrastructure for both technologies. Member states would also need to enact different policies to support an "optimal" mix of infrastructure for themselves. The current state of infrastructure development, existing xEV penetration, and recharging and refueling habits vary between member states, which will impact the infrastructure framework outlook, the timing of deployment, and overall investment needs.

Address specific barriers to accelerate xEV uptake and infrastructure development. In addition to the need for targeted support to ensure xEV infrastructure deployment, other key barriers need to be addressed, including upgrades to the EU's complex electricity grid to support electrified road transportation. Our analysis suggests between €200 billion and €260 billion would need to be invested through 2050 specifically in grid upgrades to support BEV charging. Additional FCEV models would also need to be launched to satisfy users' needs.

Capture ecosystem synergies through the deployment of xEV infrastructure. The development of both BEV and FCEV technologies presents synergies with other end uses. Potential synergies exist especially on the upstream and midstream sections of both technologies' respective value chains (notably through the interoperability of infrastructure and the additional capacity developed). Significantly, the development of a hydrogen production and distribution ecosystem can support decarbonization in other sectors whereas improvements to the electrical grid needed to support BEVs would also support increased electrification throughout the EU economy.

Introduction:
The road to net zero

To tackle environmental and societal challenges brought on by climate change, the European Commission unveiled the European Green Deal, a set of policies to make the EU climate neutral by 2050. The European Green Deal, approved by the European Parliament on January 15, 2020, created a blueprint for the transformational changes required in all sectors of the economy. All EU-27 member states are committed to turning the EU into the first climate-neutral continent by 2050. To get there, they have since pledged to reduce CO_2 emissions by at least 55 percent by 2030, compared to 1990 levels.

Yet to fully deliver on the European Green Deal ambition, a concerted effort is needed across all sectors, particularly by the sectors of the economy that contribute the most to GHG emissions. Road transportation is among these sectors and contributes roughly 20 percent of the EU's overall emissions, predominantly from PCs, LCVs (such as vans), trucks, and buses.[8] While transitioning toward net zero would require additional investments in clean technologies and processes, it would ultimately lower operating costs, thus offsetting a large portion of those up-front investments. By 2050, total system savings on operating expenditures in the transition to net zero could reach €260 billion annually or just over 1.5 percent of the EU's current GDP. Most of these savings are predicted to come from transportation.[9] Therefore, a fast and orderly transition is both an environmental and an economic imperative.

The shift from conventional ICE vehicles to vehicles with xEVs will be at the heart of the decarbonization conversation in road transportation by 2050. BEVs and FCEVs are two high-potential technologies to drive this transition, with different states of commercialization, cost-competitiveness, and existing policy support within the EU. As such the development of multiple technologies can be complementary and can help accelerate the transition to decarbonized mobility.

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[8] *Net-zero Europe: Decarbonization pathways and socioeconomic implications*, McKinsey, November 11, 2020.

[9] Ibid.

Several studies have shed light on the parallel deployment of both technologies by analyzing the costs of installing the required recharging and refueling stations and the associated electricity or hydrogen production and distribution infrastructure. However, in most studies, the results are presented so that only one of the two options is favored, depending on the assumptions and modeling of the vehicle adoption. A need remains to assess a future where both technologies coexist as part of a complementary ecosystem. Electric vehicle (EV) users choose BEVs or FCEVs based on economic and environmental considerations (including annual mileage, usage intensity, duty cycles, and emission reduction).

This report is the first in-depth assessment of a combined infrastructure rollout for the mobility transition that considers BEVs and FCEVs. Key questions to be answered include: What is the optimal mix of BEV charging versus FCEV refueling stations? What will the required size and capacity of these stations be? Where should these stations be deployed? The answers to these questions may provide the input necessary for stakeholders to deploy these infrastructures efficiently and take advantage of synergies.

The structure of this report is as follows: First, the landscape in which an xEV infrastructure strategy will be developed will be laid out by looking at the status of certain xEV technologies (including current adoption) and the regulatory environment which will enable their rollout. Second, the methodology and core assumptions of the analyses conducted in this study will be explained. In particular, the central EV adoption case (a "net-zero" scenario) will be laid out, which is a key driver for this analysis. Third, infrastructure deployment and development costs will be assessed by exploring an array of xEV use cases across vehicle segments. By considering various inputs of BEV and FCEV infrastructure, we investigate the resulting technology split, capacity requirements, and location of an optimized xEV infrastructure network. Key challenges and synergies around the deployment of BEV and FCEV technology and infrastructure will also be highlighted to decompartmentalize the dialogues around batteries and fuel cells. Fourth, an assessment of five selected archetypal member states will be provided to illustrate how xEV infrastructure deployment and associated costs might vary across the EU. Finally, we share a set of key insights and recommendations with hopes they might serve decision makers taking near-term action in this space.

Chapter 1

The state of the art

While multiple technologies will be needed to fully decarbonize the road transportation sector (batteries, catenaries, fuel cells, biofuels, and synthetic fuels), BEVs and FCEVs have been selected as two promising technologies to investigate in this report. This chapter aims to depict the current state of the art for BEV and FCEV technologies in the EU from three points of view:

1. **Technology.** An explanation of current power train and infrastructure technology points out key differences between BEVs and FCEVs and the key challenges both technologies face.
2. **Regulation.** A discussion of how strong regulatory support is being implemented at the EU and member-state levels to enable the rollout of BEVs and FCEVs.
3. **Academic research.** An overview of state-of-the-art academic research.

Key takeaways

In the short to medium term, BEVs have certain advantages over FCEVs due to the comparative maturity of battery technology and charging infrastructure.

BEVs have already seen significant uptake across LDV segments with some use cases emerging for HDVs, while FCEV use cases are becoming attractive across LDV and HDV segments as the technology evolves.

Significant regulatory support for xEV development exists across the EU. Both the amount and relative level of support are likely to influence the future mix of BEV and FCEV infrastructure.

This report fills a research gap by providing a thorough understanding of infrastructure that incorporates both FCEV and BEV power trains.

1.A

Technology review: State-of-the-art technologies

BEV and FCEV technologies are advancing rapidly, and cost-competitiveness is within reach compared to ICE technology. However, BEV and FCEV technologies are at different stages of development, which is reflected in their costs and current adoption rates.[10]

The overall market share and mix of BEVs and FCEVs on the road are expected to progress quickly and shift as the respective technologies evolve and users make decisions based on their needs and the energy realities of their place of residence. The current market share already varies strongly across the different vehicle segments, namely LDVs (which includes PCs and LCVs) and HDVs (which includes trucks and buses). Sales penetration of xEVs in light-duty segments was as high as 30 to 60 percent in the Nordics in 2021 but just 2 to 3 percent in many eastern European countries such as Poland and Slovakia.[11] Penetration of xEVs in the heavy-duty segments remains lower on average at roughly 10 percent of buses but less than 1 percent of trucks in 2021. Most xEV sales across segments comprised BEVs (including plug-in hybrid) models, while FCEVs accounted for less than 1 percent of sales across segments in 2021.[12]

BEVs have certain advantages due to the relative maturity of both battery technology and existing infrastructure, with a higher availability of recharging stations in urban areas and highways. BEVs are also quite energy efficient, converting a relatively high percentage of the energy stored in their batteries to kinetic energy driving the vehicle. Additionally, the large number of competing BEV models in the PC segment has led to lower up-front purchasing costs compared to FCEV PC models and are already on par with certain ICE models.

For long-haul HDVs (for example, long-haul trucking), FCEV technology can be beneficial. While the energy efficiency of fuel-cell power trains may be comparatively lower than that of BEVs, high energy density per refueling makes the technology attractive for traveling long distances with heavy payloads. Installing HRS in remote areas may avoid installing electric power lines and thus lead to a lower infrastructure costs. Relatively quick refueling times at HRS allow for a faster turnover (trips per day), which could be critical to maximizing the utilization of HDVs. Finally, batteries in large BEVs can reach hundreds of kilograms in weight, affecting the payload of HDVs.

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[10] Alternative hydrogen vehicle technologies such as hydrogen ICEs are emerging. While these are not analyzed in this report, they would most likely require similar infrastructure.

[11] For more information, see McKinsey Center for Future Mobility.

[12] For more information, see McKinsey Center for Future Mobility.

1.A.1

BEV power trains and infrastructure technology

BEVs already display a satisfactory range per charge (from around 300 km to over 700 km, depending on the model), and battery costs have fallen by roughly 90 percent per kWh in the last decade. It is projected that by 2030—due to continuous advances in battery research in the EU—a new generation of batteries will enable over 800 km real-world range.[13] These developments, considered together with a 95 percent recyclability of batteries,[14] may benefit BEVs in the PC segment. However, BEV technologies still face challenges in the HDV segment as total battery costs remain higher and payload lower than for alternative technologies such as diesel, CNG, or LNG.

Infrastructure

Electric chargers can be installed in private locations (such as home and multihome chargers), provide BEV owners with a full charge every morning, in semiprivate locations (such as workspaces, destinations, and fleet hubs) or in public locations (like on streets and highways). These chargers differ in their charging rates, ranging from less-expensive but slower-charging AC chargers at roughly 22 kW capacity to more expensive but faster-charging DC chargers with 50 and 350 kW (or higher) capacity. AC chargers are better suited to charging BEVs parked for a few hours, like at home, work, or while shopping. Meanwhile, DC fast chargers enable long-distance travel or rapid recharging for city dwellers without access to home charging.[15]

AC charging dominates the current EV infrastructure landscape, but the distribution is rapidly evolving. In Europe (including Norway, Switzerland, Iceland, and the United Kingdom), it is estimated that around 32,000 public fast-charging DC stations and 220,000 public slower-charging AC stations were deployed by late 2021.[16]

In AC charging, the conversion of the electrical current from alternating to direct happens via an onboard charger inside the EV. AC chargers are more common in the EV ecosystem as they are inexpensive to produce, install, and operate. AC charging is further subdivided into (1) slower AC charging (3 to 7 kW) via home sockets and which does not require any infrastructure to be installed, and (2) faster AC charging (7 to 22 kW) via wallbox chargers (at a current cost of €500 to €1,000).[17]

In DC charging, the conversion of the electrical current from alternating to direct happens inside the charger. DC chargers are more expensive than AC chargers but considerably faster, typically ranging from 50 to over 350 kW of charging power. When plugged into a 150 kW DC fast-charging station, a BEV PC can receive an 80 percent charge in as little as 15 to 20 minutes, depending on the vehicle

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[13] *Green Cars*, "Next gen EV batteries will deliver 500-mile range," November 18, 2021.

[14] "Umicore introduces new generation Li-ion battery recycling technologies and announces award with ACC," Umicore, February 11, 2022.

[15] "Do you know the difference between AC and DC Charging?" IES, June 8, 2021.

[16] "Global EV Data Explorer," IEA, April 29, 2021.

[17] "AC vs DC charging," Center for Energy Finance and CEEW, June 30, 2021.

and charging rate.[18, 19] The key challenge in the deployment of electric charging infrastructure is the ramp-up of DC fast-charging stations given constraints in labor, materials, and permits.

BEV HDVs require more time to recharge due to their larger batteries; however, upcoming charging advances may enable HDVs to charge at over 1,000 kW. BEV HDVs may also need to account for reduced payload capacity due to the weight of the onboard battery pack.

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[18] Mark Kane, "Battery electric vs hydrogen fuel cell: Efficiency comparison," Inside EVs, March 28, 2020.
[19] "AC vs DC charging," Center for Energy Finance and CEEW, June 30, 2021.

Exhibit 1

There are >200,000 public charging stations deployed across Europe today; deployment varies by member state

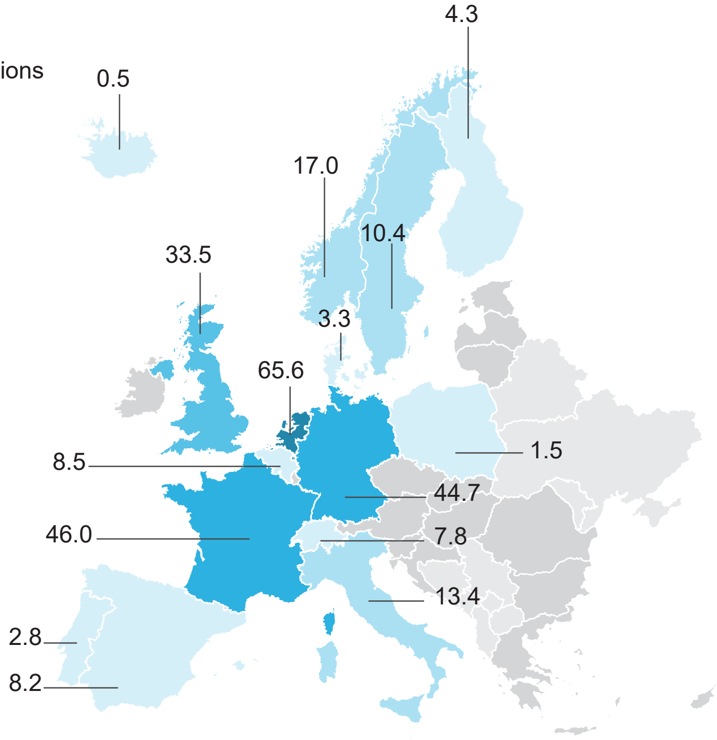
BEV charging stations in Europe, 2020

Total (publicly available) number of charging stations by country,[1] thousands

0 10 20 30 40 50 60

▢ Out of scope

▨ No data available[2]



[1] Includes slow (<22 kW) and fast (>22 kW) charging stations.
[2] There may be BEV public charging stations in countries marked as no data available. This map reflects IEA and FCH Observatory sources as of Q4 2021 only.

Source: IEA; FCH Observatory

1.A.2

FCEV power trains and infrastructure technology

FCEV technology is currently at a nascent stage of development. Depending on the vehicle model, FCEVs have a sufficient range of between 500 and 800 km after each refueling session. Vehicle purchase and refueling costs remain higher for FCEVs than BEVs in the PC and LCV segments. However, fuel-cell prices are primarily driven by manufacturing scale and may drop by up to 45 percent in the long-term as the benefits of scale materialize.[20] In the HDCV segment, FCEVs display some advantages over BEVs. While vehicle costs are high and similar to BEVs, the additional range may be obtained without penalizing the payload.

Infrastructure

HRS for FCEVs can be located in semiprivate locations (like fleet hubs) or public locations (like on streets or highways). HRS differ by the hydrogen output pressure,

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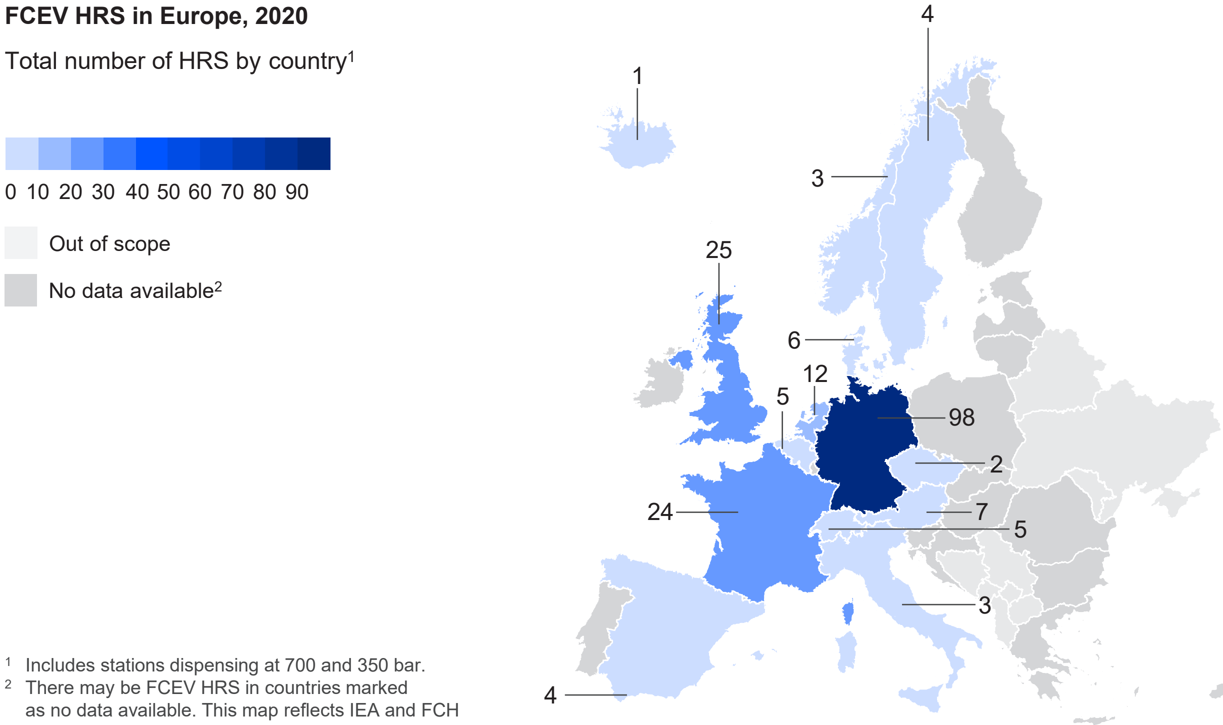
[20] "Hydrogen insights 2021," Hydrogen Council, McKinsey, July 15, 2021.

Exhibit 2

Europe's FCEV refueling network is relatively nascent compared to its BEV charging counterpart; current deployment is concentrated mostly in western Europe

FCEV HRS in Europe, 2020

Total number of HRS by country[1]



[1] Includes stations dispensing at 700 and 350 bar.

[2] There may be FCEV HRS in countries marked as no data available. This map reflects IEA and FCH Observatory sources as of Q4 2021 only.

Source: IEA; FCH Observatory

with certain stations at 350 bar and others at 700 bar. The deployment of refueling infrastructure is comparatively less developed than that of BEVs, with 178 HRS deployed in the EU, United Kingdom, Norway, Switzerland, and Iceland combined.[21] While there is no one-to-one comparison of the number of HRS and number of public charging stations, current FCEV infrastructure is at a lower level of development than that of BEVs in the EU. To date, HRS deployment has been highly concentrated with just over 55 percent of stations within Germany alone owing largely to the policy support received there.

Refueling times of FCEVs are advantageous compared to BEVs. FCEV PCs can refuel in 3 to 5 minutes,[22] while FCEV HDVs used for long-distance transportation may require 20 minutes or more to refuel sufficiently for a range of 1,200 km.[23] This compares with roughly 200 to 300 km range for current BEV HDV models with a similar charging time.[24]

The key challenges for FCEVs span the upstream part of the value chain, from hydrogen production to its distribution and use. Hydrogen is categorized in colors based on the way it is produced, three of which are discussed in this report: grey, blue, and green. The majority of today's hydrogen is grey hydrogen, produced from natural gas, which results in GHG emissions and therefore does not meet the EU goals for a green transition. Blue hydrogen production is based on the grey hydrogen production process with an added carbon storage step, trapping and storing the emitted CO_2. Green hydrogen production is based on electrolyzing water using renewable energy. Green and blue hydrogen production is still nascent and will need to rapidly ramp up (from less than 2 percent of total hydrogen produced in 2020 to 100 percent by 2030) to meet the European Green Deal's goals. Moreover, after being produced, hydrogen needs to be either compressed or cryogenically stored, transported, and recombined with oxygen to form electricity inside a vehicle's fuel cell. These processes are currently less energy efficient, resulting by some estimates in a sun- or wind-to-wheel efficiency of about three to four times lower for an FCEV than for an equivalent BEV. This higher energy requirement may result in the need to build more renewable energy capacity to support the additional energy demanded to produce green hydrogen.

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[21] HRS availability map, European Commission, March 17, 2022.
[22] "Hydrogen fueling overview," California Air Resources Board.
[23] "Battery electric vs hydrogen fuel cell: Efficiency comparison," March 28, 2020.
[24] *Trends and developments in electric vehicles markets*, IEA, 2021.

1.A.3

Differences between BEV and FCEV technologies

While this study considers BEV and FCEV infrastructure as a single ecosystem in which both are required to support the EU's zero-emission mobility future, three fundamental differences between these technologies should be noted:

1. **Maturity.** Fuel cell and battery technologies both represent technologically feasible emission-reduction opportunities but with specific energy efficiencies, cost impacts, and challenges per vehicle segment. LDV BEV technologies are fairly mature, particularly when compared with their FCEV counterparts. In terms of supporting infrastructure, BEVs already have a "minimum network" in place, and development is now focused on expanding the network of chargers and increasing reliability and user convenience. FCEVs are, however, at a nascent stage of development, and the focus is on developing a "minimum network" of infrastructure to foster customer adoption. These differences put the two technologies at different starting points for infrastructure deployment.

2. **Operating models.** The two technologies also differ in how and where they are best suited to operate. BEV infrastructure can provide private, semiprivate (fleet-hub chargers), and public charging (slow street chargers and fast highway chargers). FCEV infrastructure, however, is not suitable for private deployment (such as at homes) and is more likely to proliferate in semiprivate (fleet-hub stations) or public refueling (street and highway station) locations.

3. **Speed options.** Finally, BEV and FCEV infrastructure differ in their charging or refueling speeds. BEV charging technology allows for different kilowatt output options across various types of chargers (from AC to over 500 kW DC chargers)[25] to tailor each charger to the required use conditions. Conversely, HRS speeds are likely to be unique per vehicle segment.

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[25] "Battery electric vs hydrogen fuel cell: Efficiency comparison," March 28, 2020.

1.B

The regulatory landscape impacting zero-emission mobility and xEV refueling and charging

Efforts to rapidly decarbonize the transportation sector have been strengthened to help achieve the objectives of the European Green Deal (including zero emissions by 2050). The EU's efforts to regulate emissions from the transportation sector have intensified in the past five years. The first set of regulations was implemented in 2017 (monitoring and reporting CO_2 emissions from fuel consumption of LDVs and new HDVs). Since then, this first regulatory package has been updated and reinforced through:

- EU-wide ambitious regulation packages on emissions reductions (such as the European Green Deal and Fit for 55)
- Clear and progressive targets with short and long-term milestones (including 2025, 2030, and 2050), notably on infrastructure development at a country level
- New decarbonization regulations focused on road transportation, for LDVs and HDVs, favoring the use of clean technologies (such as fuel cell electric, battery-electric, and synthetic fuels).

1.B.1

Regulatory support for zero-emission mobility in the EU

Establishing a widespread, reliable, and easy-to-use alternative fuel infrastructure network is key to achieving the climate neutrality target by 2050. In 2014, the European Commission communicated the deployment of the Alternative Fuels Infrastructure Directive (AFID) to address issues such as the lack of coordinated deployment of alternative fuel refueling and recharging infrastructure across the EU and improve the long-term security needed for investment in the technology for alternative fuels and alternative fuel vehicles. Among the measures to be taken in light of the communication of the European Green Deal in 2019, the European Commission announced that it would review the AFID in efforts to transform it into a regulation, which is currently underway.

In 2020, the European climate law was amended to increase the 2030 target from a 40 percent net GHG emission reduction to a 55 percent net emission reduction compared to 1990 levels.[26] In December 2020, the European Commission published its sustainable and smart mobility strategy, which included the revision of the AFID in its work plan and important and ambitious milestones for the ramp-up of the production, deployment, and use of sustainable alternative fuels in all modes of transportation by 2030 and 2050.

To secure the 2030 target, the European Commission presented a package of regulatory proposals in July 2021, called the Fit for 55 package. Under the Fit for 55 initiative, the European Commission proposed stricter 2030 emission-reduction targets for cars (-55 percent versus 2021 levels) and vans (-50 percent versus 2021 levels), with a 100 percent reduction target by 2035. Such measures could accelerate EV deployment rapidly since they would mandate that all vehicles sold from 2035 onward have zero tailpipe emissions. Individual European countries are also continuing to deploy subsidies and incentive schemes. Emission-reduction targets still vary by vehicle segment and time horizon. The latest targets are:

- By 2025: a 15 percent emission reduction for HDVs[27] versus the 2019 to 2020 baseline
- By 2030: a 30 percent emission reduction for all vehicles versus the 2019 to 2020 baseline
- By 2030: a 55 percent emission reduction for PCs versus the 2021 baseline
- By 2030: a 50 percent emission reduction for vans versus the 2021 baseline
- By 2035: zero emissions from new PCs versus the 2021 baseline
- By 2050: net zero overall EU emissions and a 90 percent reduction in transportation emissions versus the 1990 baseline

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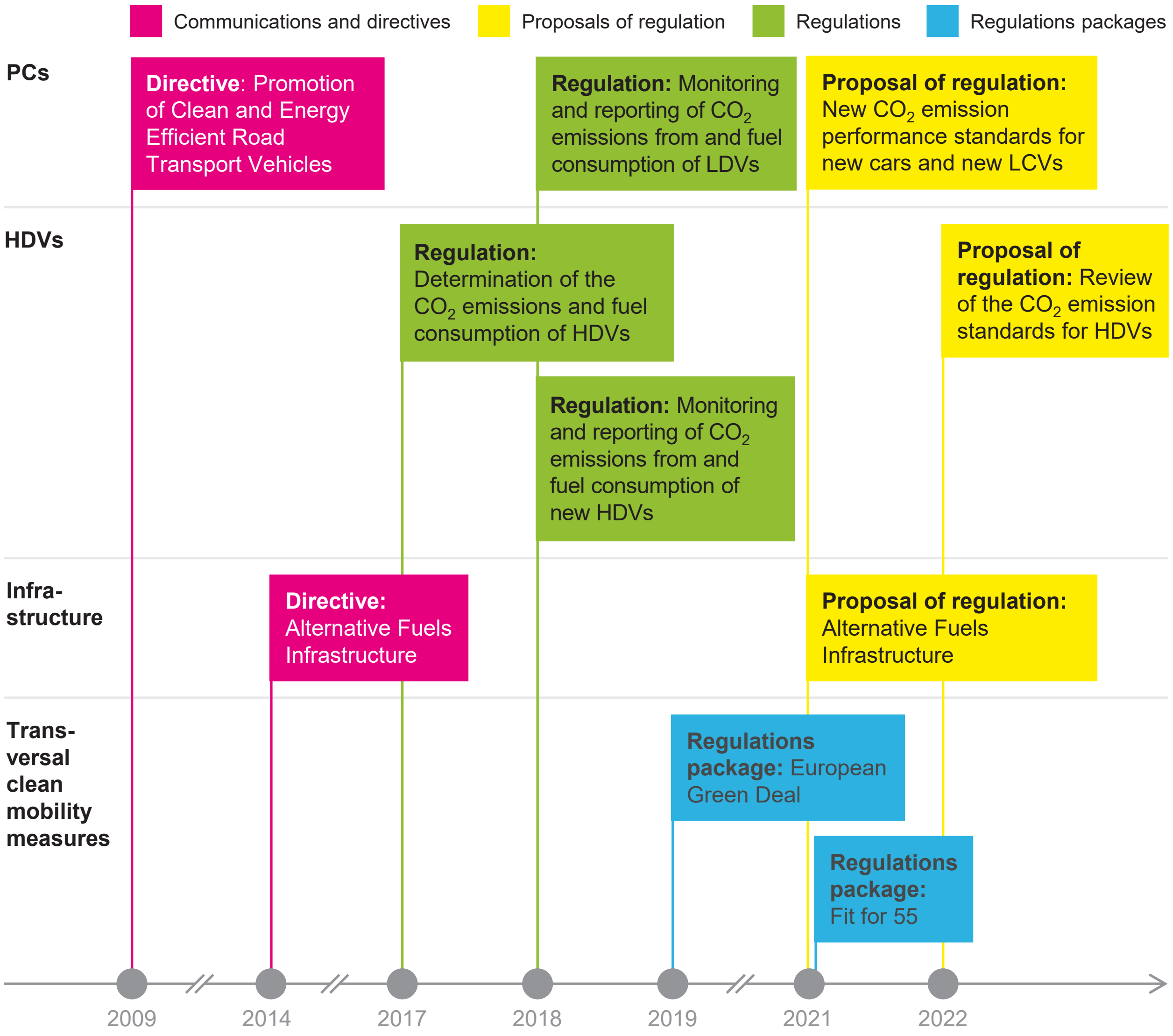
[26] "A European Green Deal: Striving to be the first climate-neutral continent," European Commission.
[27] "Reducing CO_2 emissions from heavy-duty vehicles," European Commission.

In the Fit for 55 package, the European Commission also proposes to repeal the 2014 AFID and replace it with an updated version of the regulation. The proposed regulation sets several mandatory national targets for deploying alternative fuels infrastructure to ensure drivers can charge or fuel their vehicles reliably across Europe. The rules contain provisions for member states to provide minimum coverage of publicly accessible recharging and refueling points dedicated to LDVs and HDVs in their territory, including the Trans-European Transport Network's (TEN-T) core corridors as well as urban networks.

Finally, the Fit for 55 package includes a proposed amendment to the renewable energy directive from 2018 (RED II). The main changes that the European Commission has proposed to its transportation fuels policy in RED II raise the overall ambition of the policy, converting the energy target to a GHG-intensity

Exhibit 3

EU efforts to regulate transportation emissions have intensified in the last five years



Source: EU regulations; directives and policy brief repository; press search target, and introducing a new target for renewable fuels of nonbiological origin (RFNBOs). The proposed RED II revision replaces the 14 percent renewable energy target with a 13 percent GHG-intensity reduction target for transportation for 2030, compared to a liquid fossil fuel baseline GHG intensity. The change to a GHG target represents a significant structural modification to the directive. With the energy target in the 2018 RED II, all fuels are required to pass a GHG-reduction threshold to be considered eligible. These requirements are 50 to 65 percent for biofuels, depending on the date of facility construction, 70 percent for RFNBOs, and yet to be defined for recycled carbon fuels (Exhibit 3).

In parallel with reducing emissions produced by the transportation sector, the EU has intensified its efforts to increase local hydrogen production capacity and consumption. To do so, it launched the Hydrogen Strategy in July 2020. The Hydrogen Strategy is made up of three phases to ensure a gradual increase in clean hydrogen production capacity (for example, by scaling up electrolyzer capacity and decarbonizing existing hydrogen plants), and clean hydrogen demand (for example, by increasing the number of refueling and storage capacities), especially from heavy-emitting sectors like transportation (Exhibit 4). In addition to the Hydrogen Strategy, the REPowerEU Plan announced in May 2022 aims to increase hydrogen supply and accelerate infrastructure development by setting a target of ten million metric tons of domestic renewable hydrogen production and ten million metric tons of renewable hydrogen imports by 2030. The European Commission's Fit for 55 package further supports the development of hydrogen transportation infrastructure through new targets for sustainable fuel use and production for road transport vehicles, including hydrogen fuels.[28]

Other EU policies have also helped spur the uptake of xEV technologies in recent years. The 2020 corporate average CO_2 emission standards in the EU have been a driver of higher EV sales in 2020 despite the pandemic. The EU's COVID-19 stimulus measures in 2020 also favored alternative power trains by offering additional purchase subsidies and more favorable vehicle trade-in schemes.[29]

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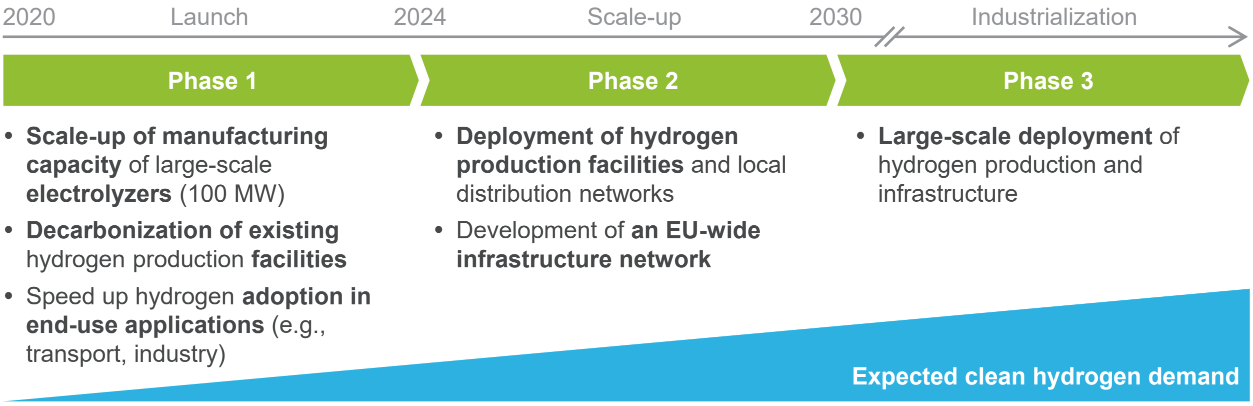
[28] EU REPowerEU Plan, European Commission Fit for 55 Plan.

[29] Sarah McBain and Ekta Bibra, *Electric vehicles*, IEA, November 2021.

Exhibit 4

In 2020, the EU launched its Hydrogen Strategy to accelerate the development of clean hydrogen

Suggested measures per phase



Phase 1

- **Scale-up of manufacturing capacity** of large-scale **electrolyzers** (100 MW)
- **Decarbonization of existing** hydrogen production **facilities**
- Speed up hydrogen **adoption in end-use applications** (e.g., transport, industry)

Phase 2

- **Deployment of hydrogen production facilities** and local distribution networks
- Development of **an EU-wide infrastructure network**

Phase 3

- **Large-scale deployment** of hydrogen production and infrastructure

Source: EU Commission's Hydrogen Strategy communication

1.B.2

Regulatory support for zero-emission mobility in member states

At a country level, there is strong regulatory support for xEV adoption (including corporate and individual subsidies for xEV purchases), energy production (like subsidies for the development of hydrogen technologies), BEV infrastructure development (such as BEV charging station targets), and an opportunity for future support of FCEV infrastructure development. The extent and comparative level of regulatory support for FCEVs and BEVs may influence how the mix of xEV infrastructure develops across Europe. Five of ten of the EU's largest cities have set clear charging station targets by 2023. However, none have set concrete HRS development targets (Exhibit 5, Exhibit 6).

Member state support for xEVs. On the demand side, most European countries offer some xEV purchase subsidies to individual buyers, and nearly half offer xEV purchase subsidies to companies to stimulate EV adoption. Many view the support for xEV adoption in the corporate sector as a key driver of strong xEV adoption, despite the effects of the COVID-19 pandemic. However, regulatory support for vehicle uptake varies between countries: some countries with a high share of xEVs (like Sweden) have started to scale back purchase subsidies, focusing on tax rebates and other benefits instead; in contrast, some countries with a low share of EVs have high subsidies (uptake results depend on infrastructure). Nearly all European

Exhibit 5

BEV regulatory support at a European country level for each step of the value chain

Level of support: ░ Low ▒ Medium █ High

	Supply					Demand			
	Electricity		BEV		Charging	Individual		Corporate	
Country EV penetration rate	Production	Distribution	Production	Commercial-ization	Infra-structure	Acquisition	Use	Acquisition	Use
High	*Not covered*		▒	▒	█	█	█	█	█
Medium	*Not covered*		▒	▒	█	█	█	▒/█	█
Low	*Not covered*		░	▒	░	█	▒	▒/█	▒

Source: EU regulations; directives and policy brief repository; member-state regulations; press search

countries have some form of EV subsidies for new cars, and 17 European countries, including the Netherlands, Greece, Germany, Italy, Norway, and Portugal, offer free or preferential parking for EVs. The most common policy in Europe is grants or subsidies, followed by registration and ownership tax. Furthermore, we see that countries with the highest share of EVs have a strong focus on developing the public infrastructure. Some countries with purchase subsidies for BEVs exclude FCEVs, including Hungary, Ireland, Lithuania, the Netherlands, Norway, Portugal, and Slovakia.

Support for hydrogen production. Most hydrogen policies are still being developed at the member-state level. Nevertheless, many countries are planning pilot projects, especially in the Baltic region, Ireland, and parts of southern Europe, to prove the viability of hydrogen as a fuel and decide whether to push for further adoption.

Support for xEV infrastructure. The AFID issued in 2014 introduced the requirement for EU countries to develop national policy frameworks (NPFs) to implement a sufficient number of recharging and refueling points for certain alternative fuel vehicles and vessels. The directive left it to the member states to decide whether to include HRS infrastructure in their NPFs.

The recently proposed Alternative Fuels Infrastructure Regulation (AFIR) sets a framework for EU-wide and national infrastructure plans by defining an EU-wide approach for TEN-T related to road, rail, aviation, and waterways. It also aims to ensure coherent member-state approaches to manage national, regional, and subregional specificities related to transportation modes via their NPFs. The proposed AFIR would require member states to expand charging capacity in line with zero-emission car sales and install charging and fueling points at regular intervals on major highways: every 60 km for EV charging and every 150 km for hydrogen refueling.[30]

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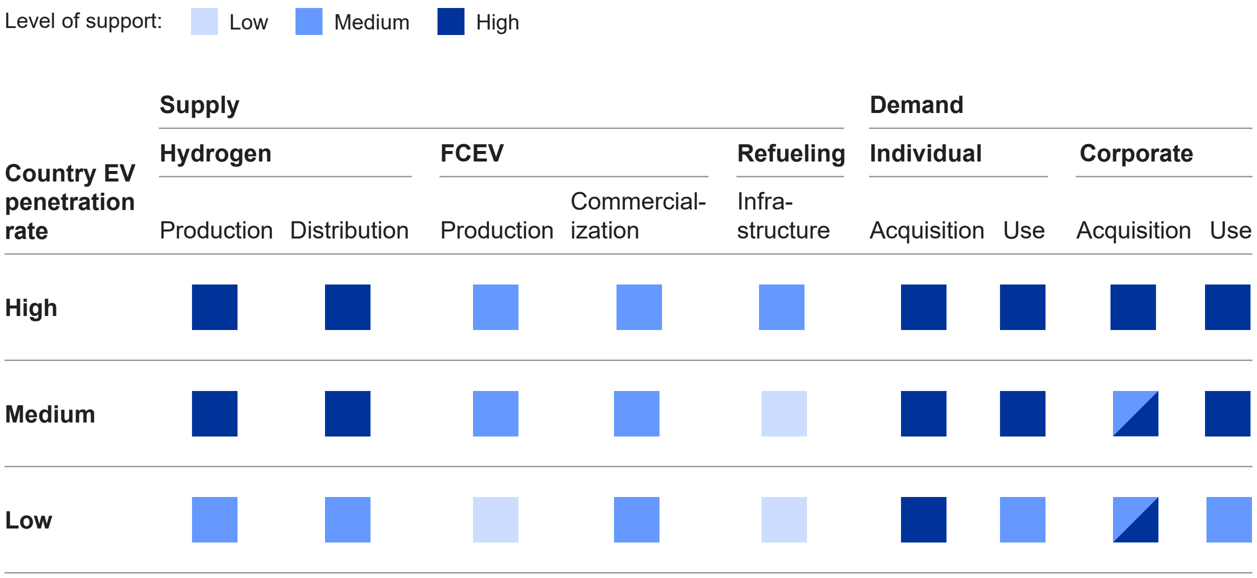
[30] The AFIR text is currently under discussion and subject to change. Our analysis is based on the text in April 2022.

Exhibit 6

FCEV regulatory support at a European country level for each step of the value chain



Level of support: ░ Low ▒ Medium █ High

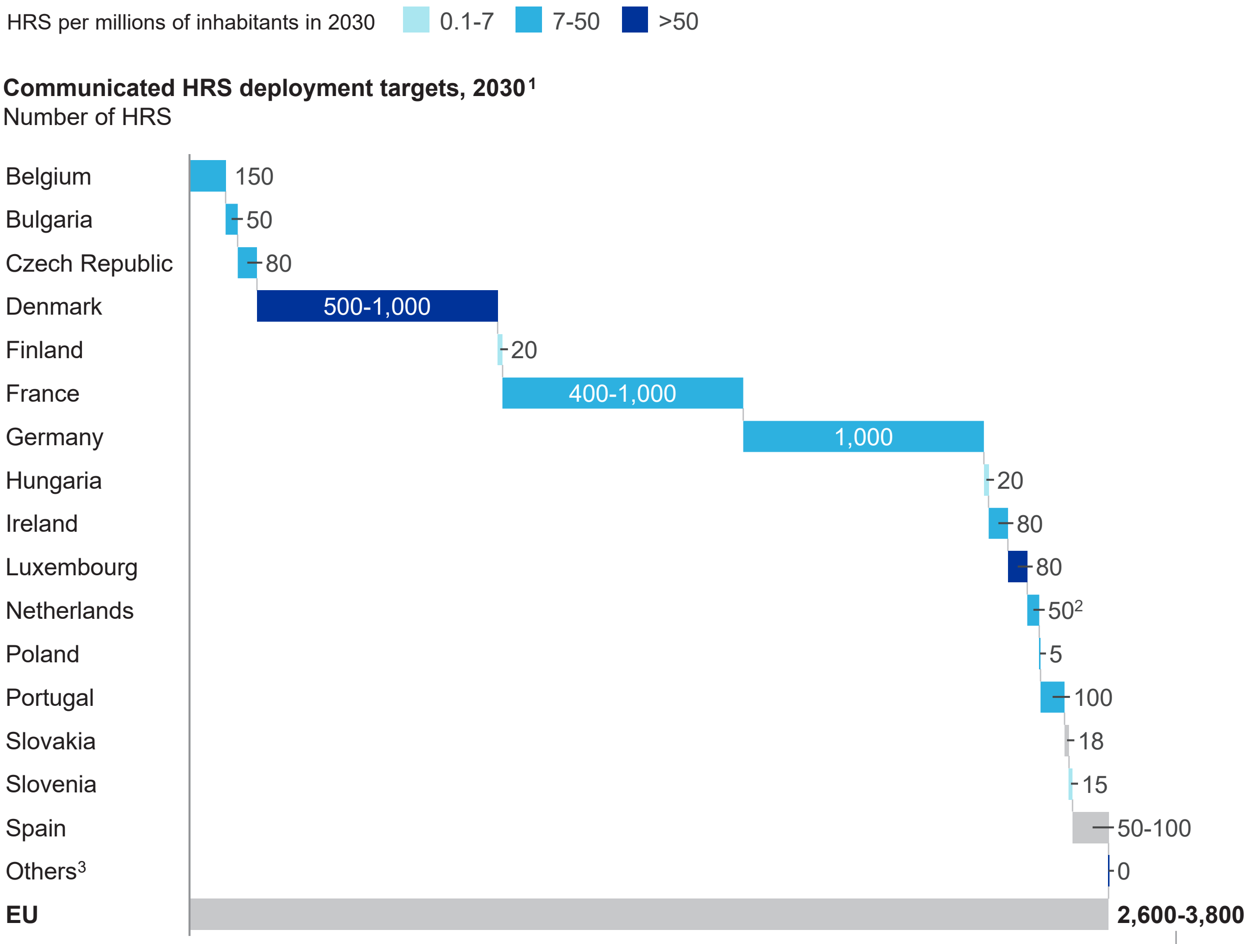
	Supply					**Demand**			
	Hydrogen		**FCEV**		**Refueling**	**Individual**		**Corporate**	
Country EV penetration rate	Production	Distribution	Production	Commercial-ization	Infra-structure	Acquisition	Use	Acquisition	Use
High	█	█	▒	▒	▒	█	█	█	█
Medium	█	█	▒	▒	░	█	█	◩	█
Low	▒	▒	░	▒	░	█	▒	◩	▒

Source: EU regulations; directives and policy brief repository; member-state regulations; press search

At a member-state level, many countries are actively investing in BEV charging infrastructure. However, most investments are supported by private incentives like purchase subsidies, tax exemptions, and parking benefits. FCEV refueling infrastructure sees relatively less support at the country level. The current collective member-state target is for 2,600 to 3,800 HRS to be deployed by 2030. For reference, this compares with more than 110,000 gas stations in the EU in 2020. Large differences also exist between the member states themselves. For example, Denmark, France, and Germany account for 75 to 80 percent of all HRS target installations in the EU through 2030. Some countries have very low or no incentives in place for EV infrastructure, namely, Bulgaria, Croatia, Cyprus, Czech Republic, Estonia, Latvia, Lithuania, and Poland (Exhibit 7).

Exhibit 7

With current member states' targets, 2,600 to 3,800 HRS should be deployed in 2030, but high discrepancies will exist between member states



Vs. ~110,000 fuel and petrol stations in the EU in 2020

[1] HRS deployment targets for 2030 communicated up to Q4 2021. Communicated HRS targets are not used to construct basic network assumptions in our model.

[2] In 2025; no targets for 2030.

[3] Austria, Croatia, Cyprus, Estonia, Greece, Italy, Latvia, Lithuania, Malta, Poland, Romania, and Sweden have not set HRS deployment targets as part of their NEPC or other policy issuing.

Source: Member states NECP; local policy review; press review; Fuels Europe Statistic Report 2021

1.C

Literature review: State-of-the-art research on zero-emission mobility and associated infrastructure

Since BEV and FCEV technologies are considered two important technologies to decarbonize the EU road transportation industry, numerous studies have investigated their development. To establish a more detailed view of the research on these areas, approximately 30 related studies were examined for their coverage of the five key segments of our analysis: xEV penetration scenarios, member state selection, BEV and FCEV infrastructure costs and development, and an optimal blend of both types of infrastructure.

Clean Hydrogen Partnership[31] has already contributed to a number of studies which have attempted to cover key segments of these topics. Studies such as "Fuel cells hydrogen trucks – heavy-duty's high performance green solution" (2020), "Hydrogen roadmap Europe" (2019), and "A portfolio of power-trains for Europe: a fact-based analysis" (2010) cover the xEV penetration scenario, BEV and FCEV infrastructure deployment, and costs, and partially cover the topic of an optimal blend between power trains.

Other studies touch upon key segments of our analysis: "Fuel cell electric buses – potential for sustainable public transport in Europe" (2015) covers xEV penetration and hydrogen and FCEV infrastructure deployment and costs. Similarly, "Opportunities for hydrogen energy technologies considering the national energy & climate plans (2020)" covers xEV penetration, though it does not provide a comprehensive view of the different segments of our analysis.

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[31] The Clean Hydrogen Partnership was formerly known as the Fuel Cells and Hydrogen Joint Undertaking.

Among the studies examined, none have modeled selected representative member states as archetypes for Europe, and very few have attempted to estimate the optimal mix of BEV and FCEV infrastructure to be deployed. A few studies have, however, investigated FCEV and BEV penetration from an infrastructure cost perspective. Yet, methodological strengths still appeared across the literature review:

- Studies including bottom-up modeling of EVCI, grid infrastructure extension, HRS, and hydrogen supply infrastructure costs provided more detailed cost estimations
- Technology learning curves generated a better understanding of cost structure evolution over time
- Comparing the TCO by including detailed vehicle capital expenditure and operating expenditure breakdowns strengthen the analysis from a consumer perspective

There is a unique opportunity for the current study to make four main contributions to the existing literature and infrastructure modeling:

1. Providing a single picture for a comprehensive set of vehicle segments
2. Developing a high level of detail by geography, user type, location, and technology
3. Determining a combined infrastructure deployment strategy for FCEV and BEV infrastructure
4. Leveraging a careful selection of countries to serve as archetypes for the EU and its different member states

1.C.1

Existing perspectives on xEV adoption

A number of industry studies were also explored to understand the existing views on xEV adoption and form the basis of our analysis. Thirteen of the studies considered different vehicle adoption scenarios in the scope of their work. Three of these were selected and are discussed in detail below to show evolving views on xEV adoption across segments.

Study 1: Hydrogen Council, "Roadmap towards zero emissions: BEVs and FCEVs"[32]

This report found that certain transportation solutions have comparable systemic efficiencies and similar CO_2 life cycle intensities under certain conditions. From the user's perspective, FCEVs and BEVs provide flexibility and convenience, meeting their requirements within their specific context of use and geographic locations. Additionally, while not modeled in detail, it was expected that a combined network for FCEVs and BEVs would cheaper than building one alone, primarily due to the reduced peak loads for the electricity grid and avoidance of extending the grid to remote areas. Leveraging two technologies for decarbonization also allows for hedging of risks during the transition (such as raw material supply) and could reduce overall system costs as FCEVs would be cheaper to operate in some segments than BEVs.

Both fuel cell and battery technologies are experiencing cost decreases and becoming increasingly competitive with ICEs. BEVs have a lower TCO than FCEVs in PC applications. In future, FCEVs may have a lower TCO than BEVs in certain segments, especially in use cases with larger vehicles or higher utilization requirements. While significant cost improvements in the fuel cell system, hydrogen supply, and battery systems are expected, grid and charger infrastructure costs will increase with a transition to both technologies to cater to the electricity requirements necessary to either power BEVs directly or produce hydrogen. While the report does not explicitly call out underlying assumptions on vehicle adoption, the overall xEV share appears to be 10 to 20 percent of the light-duty car park by 2030 and about 5 to 10 percent of the heavy-duty car park. By 2050, xEVs would make up between 85 and 95 percent of the total EU car park. A split between BEVs and FCEVs is not provided.

Study 2: Fuel Cells and Hydrogen Joint Undertaking, "A portfolio of power-trains for Europe: a fact-based analysis"[33]

This study included a balanced mix of vehicle sizes (or segments), attempting to avoid bias toward any particular power train and represent most vehicles on the market. While it is possible that breakthrough technologies could provide step changes in current pathways to sustainable mobility, the study only considered

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[32] Roadmap towards zero emissions: BEVS and FCEVS, Hydrogen Council, September 2021.

[33] A portfolio of power-trains for Europe: A fact-based analysis, Fuel Cells and Hydrogen Joint Undertaking, November 8, 2010.

vehicle technologies that are proven at an R&D stage and capable of being scaled up and deployed commercially and meeting the EU's CO_2 reduction goal for 2050.

Concerning vehicle adoption and sales, the study investigated three "future worlds": one where conventional vehicles dominate, one where BEVs dominate, and one where FCEVs dominate. In the "conventional" world (a non-net-zero scenario), xEVs (including plug-in hybrids) would account for 40 percent of the EU vehicle fleet by 2050 with FCEVS accounting for 5 percent of the total. The EV-dominated world (a net-zero scenario) would see a 95 percent share of xEVs by 2050, and FCEVs would account for 25 percent of the total car park. By contrast, the final FCEV-dominated world puts forth the same 95 percent overall adoption rate for xEVs, but FCEVs would comprise 50 percent of the overall EU car park by 2050. The results of the study show that the impact on costs from the various FCEV penetration scenarios is insignificant.

Study 3: Fuel Cells and Hydrogen Joint Undertaking, "Study on Fuel Cells Hydrogen Trucks"[34]

The TCO modeling of trucks with conventional and alternative power trains shows that fuel cell technology can significantly reduce costs if a large ramp-up is achieved, looking at the period from 2023 to 2030. While the results reveal a cost premium of up to 22 percent for FCEV trucks over diesel trucks in 2023, the analysis indicates a clear trend toward cost reduction of FCEV heavy-duty trucks by 2030. Cost competitiveness is possible for several hydrogen storage technologies. Compared to BEV trucks, FCEV trucks show better TCO results for the long- and medium-haul use cases, but not short haul.

The detailed parameter assumptions of the TCO model were developed in close cooperation with the study's Industry Advisory Board to provide the current state of costs and future cost and volume projections. The assumptions can be clustered into three main groups: (1) general input on motor vehicle tax, insurance cost, and road tolls; (2) truck and technology-specific input, such as vehicle configuration and payload considerations, fuel cell and hydrogen tank costs, battery capacity, and costs; and (3) fuel or energy and infrastructure input, such as refueling and charging costs.

The study revealed the FCEV market potential for the use cases discussed above, with sales between 16 and 51 percent in 2030, depending on the uptake scenario. The conservative scenario shows high growth in sales from 2027 to 2030 and a slower overall development for xEVs. The base scenario shows a higher uptake for 2027, with a steep increase until 2030. In this scenario, FCEV sales already surpass BEV sales in 2023, reaching a 16 percent market share by 2030. The optimistic scenario predicts a total sale of over 95,000 FCEV heavy-duty trucks in 2030, representing 51 percent of the market in the considered market segments. It shows a higher uptake rate for 2027, with a steep increase until 2030. BEV truck sales also increase. The market-potential analysis estimates that, following the base scenario, 110,000 heavy-duty FCEV trucks will be deployed on European roads by 2030. This represents a 1.7 percent market share in a 6.6 million medium and heavy-duty truck market in Europe.

Previous studies have systematically been tested for their coverage of the five key segments of our analysis (Exhibit 8).

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[34] Yvonne Ruf, et al., Fuel cells hydrogen trucks: heavy-duty's high performance green solution, Fuel Cells and Hydrogen Joint Undertaking, December 2020.

Exhibit 8

State of the art: More than 27 studies were analyzed for their coverage of the five main segments of our modeling approach

🟩 Our model ✔ Fully covered ✓ Partly covered

	Authors/ countries represented	xEV penetration scenarios	Member state selection	BEV infrastructure deployment and costs	H_2 and FCEV infrastructure deployment and costs	Optimal blend	Comments
Study on the impact of deployment of BEV and FCEV infrastructure	Clean Hydrogen Partnership *EU*	Consideration of different penetration scenarios of the total xEV share	Selection of representative member states as archetypes for Europe	Modeling the infrastructure costs for the deployment of BEV charging infrastructure (incl. grid extensions and EVCI)	Modeling the infrastructure costs for the deployment of FCEV refueling infrastructure (incl. distribution and HRS)	Considering the joint BEV/FCEV charging/refueling infrastructure to determine an optimal BEV/FCEV blend	
Comparison of hydrogen and battery electric trucks (2020)	European Federation for Transport and Environment *France*	✔		✔	✔	✓	
Comparative analysis of infrastructures: Hydrogen fueling and electric charging of vehicles (2018)	Forschungszentrum Jülich *Germany*	✔		✔	✔	✓	Rigorous bottom-up analysis of BEV and FCEV infrastructure; qualitative discussion about BEV and FCEV blend
A portfolio of power train options for Europe (2010)	Clean Hydrogen Partnership *EU*	✔		✔	✔	✓	Qualitative discussion about BEV and FCEV blend
Fueling the future of mobility: Hydrogen and fuel cell solutions for transportation (2020)	Deloitte *US, EU, China, and Japan*			✔	✔	✓	TCO based on high-level assumptions
Hydrogen roadmap Europe (2019)	Clean Hydrogen Partnership *EU*			✔	✔	✓	
Prospective cost and environmental impact assessment of battery and fuel cell electric vehicles in Germany (2019)	International Journal of Life Cycle Assessment *Germany*			✔	✔	✓	
Retail infrastructure costs comparison for hydrogen and electricity for light-duty vehicles (2014)	The National Renewable Energy Laboratory *US*			✔	✔	✓	
How many charge points will Europe and its member states need in the 2020s? (2020)	European Federation for Transport and Environment *France*	✔		✔			

Exhibit 8 (continued)

State of the art: More than 27 studies were analyzed for their coverage of the five main segments of our modeling approach

🟩 Our model ✔ Fully covered ✓ Partly covered

	Authors/ countries represented	**xEV penetration scenarios**	**Member state selection**	**BEV infrastructure deployment and costs**	**H_2 and FCEV infrastructure deployment and costs**	**Optimal blend**	**Comments**
Study on the impact of deployment of BEV and FCEV infrastructure	Clean Hydrogen Partnership *EU*	Consideration of different penetration scenarios of the total xEV share	Selection of representative member states as archetypes for Europe	Modeling the infrastructure costs for the deployment of BEV charging infrastructure (incl. grid extensions and EVCI)	Modeling the infrastructure costs for the deployment of FCEV refueling infrastructure (incl. distribution and HRS)	Considering the joint BEV/FCEV charging/refueling infrastructure to determine an optimal BEV/FCEV blend	
Accelerated electrification and the GB electricity system (2019)	Vivid Economics *UK*	✔		✓			Detailed modeling of existing and required infrastructure
Connecting the dots: Distribution grid investment to power the energy transition (2021)	Deloitte *EU*			✓			Distribution grid infrastructure investment estimation based on DSO data
Scaling EV infrastructure to meet net-zero targets (2021)	McKinsey's Global Infrastructure Initiative *Worldwide*			✓			Mention of cost based on another study
The impact of electric vehicle density on local grid costs: Empirical evidence (2020)	Norwegian University of Life Sciences *Norway*			✓			Distribution grid infrastructure investment estimation based on DSO data
Report on the integration of electric mobility in the public electricity distribution network (2019)	ENEDIS *France*			✓			Distribution grid infrastructure investment estimation based on DSO data
Fuel cells hydrogen trucks: heavy-duty's high performance green solution (2020)	Clean Hydrogen Partnership *EU*	✔			✔	✓	Distribution grid infrastructure investment estimation based on DSO data
Path to hydrogen competitiveness: A cost perspective (2020)	Hydrogen Council *Worldwide*	✔			✔		
Fuel cell electric buses: potential for sustainable public transport in Europe (2015)	Clean Hydrogen Partnership *EU*	✔			✔		Includes cost of ICE replacement buses in TCO during downtimes of FCEV buses during early years of development. Considers labor cost for bus operation.
The great transformation: decarbonising Europe's energy and transport systems (2012)	Bruegel *EU*	✔			✓		

Exhibit 8 (continued)

State of the art: More than 27 studies were analyzed for their coverage of the five main segments of our modeling approach

🟩 Our model ✔ Fully covered ✓ Partly covered

	Authors/ countries represented	xEV penetration scenarios	Member state selection	BEV infra-structure deployment and costs	H$_2$ and FCEV infrastructure deployment and costs	Optimal blend	Comments
Study on the impact of deployment of BEV and FCEV infrastructure	Clean Hydrogen Partnership *EU*	Consideration of different penetration scenarios of the total xEV share	Selection of representative member states as archetypes for Europe	Modeling the infrastructure costs for the deployment of BEV charging infrastructure (incl. grid extensions and EVCI)	Modeling the infrastructure costs for the deployment of FCEV refueling infrastructure (incl. distribution and HRS)	Considering the joint BEV/ FCEV charging/refueling infrastructure to determine an optimal BEV/ FCEV blend	
A roadmap for financing hydrogen refueling networks – Creating prerequisites for H$_2$-based mobility (2013)	Clean Hydrogen Partnership *EU*				✓		
Charging up Europe through binding capacity targets for publicly accessible charging infrastructure and MS action plans (2021)	ChargeUp *EU*	✔					
Electric vehicle outlook 2021	Bloomberg *Worldwide*	✔					
World energy model documentation (2021)	IEA *Worldwide*	✔					
Opportunities for hydrogen energy technologies considering the national energy & climate plans (2020)	Clean Hydrogen Partnership *EU*	✔					
Ladeinfrastruktur nach 2025/2030: Szenarien für den Markthochlauf (2020)	Nationale Leitstelle Ladeinfrastruktur *Germany*	✓					Single penetration scenario as median of different data points
Roadmap towards zero emissions (2021)	Hydrogen Council *Worldwide*					✓	Qualitative discussion about BEV and FCEV blend
Challenges and perspectives of deployment of BEV and FCEV (2020)	Asia Pacific Energy Research Centre *APEC*					✓	Qualitative discussion about BEV and FCEV blend
On the electrification path: Europe's progress toward clean transportation (2021)	European Alternative Fuels Observatory *EU*						Qualitative discussion of historical data
Study on the use of fuel cells and hydrogen in the railway environment (2019)	Clean Hydrogen Partnership *EU*						

Chapter 2

Methodology to calculate xEV infrastructure requirements

To reach its emission-reduction target in road transportation, the EU will not only have to support the acceleration of xEV adoption but also the deployment of associated infrastructure—namely charging and hydrogen refueling—to support the evolving vehicle fleet.

Agreeing on the “optimal blend” of infrastructure to deploy is a challenge and doing so in a way that allows for the organic development of both BEV and FCEV technologies is even more so. With these goals in mind, we began by looking at a central xEV adoption scenario through 2030 that follows the current trajectory of vehicle adoption, technology development, and regulatory targets. Through 2050, we project overall xEV adoption to be consistent with a net-zero emission-reduction pathway and consider a “range” for the underlying mix of BEVs versus FCEVs across each segment. To model the required infrastructure deployment, we first asked: what would the optimal deployment of infrastructure to support the evolving vehicle fleet look like? We then asked: if the mix of electric vehicles on the road shifts, how would that impact outcomes on key metrics such as cost, timing, feasibility, and emissions reduction?

In this chapter, we look at the methodology and key assumptions that drive our analysis starting from the central net-zero vehicle adoption scenario, then deriving energy demand (electricity and hydrogen) for xEVs, and finally infrastructure requirements to support the vehicles in questions and deliver that energy. This chapter explains the general approach, key assumptions taken, and technologies considered throughout the analysis.

Key takeaways

The cost of FCEV and BEV infrastructure is linked to the expected rate of market penetration of xEVs.

Our expected xEV market penetration considers five factors: a comparison of TCO between xEV types, consumer adoption rates, xEV production constraints, and national and regional regulatory environments.

To estimate infrastructure needs and associated costs, our methodology uses the size of the parking lot of xEVs, the energy demand of xEVs, charging and refueling behaviors, and location-specific charging and refueling requirements.

2.A

xEV adoption and the “net-zero” adoption scenario

The adoption of zero-emission vehicles is critical for infrastructure deployment throughout the EU. The shift toward these vehicles and the speed at which it occurs is driven by many purchase and energy costs, customer preferences, regulation, and the availability of supporting infrastructure, such as charging and refueling stations.

As a starting point for the projection of infrastructure needs across the EU, an xEV adoption scenario was developed, aligning with the EU’s ambition of achieving climate-neutrality by 2050. It considers the EU’s net-zero ambition, including the 90 percent emission-reduction target for transportation by 2050 (versus 1990 levels) as well as more ambitious near-term targets laid out as part of the EU’s Fit for 55 package. This “net-zero” scenario was developed based on projections from McKinsey’s proprietary Mobility Electrification Model housed within the McKinsey Center for Future Mobility and considers five key factors: TCO comparison, consumer adoption, production constraints, country targets, and regional targets (Exhibit 9).

The “net-zero” adoption scenario indicates that, directionally, it is reasonable to expect both FCEV and BEV power trains to be used in Europe. The precise share for each power train is difficult to identify because, while this scenario is based on current trends and data, significant challenges and uncertainties exist. There may also be constraints on the supply side, for instance, as the production chains of certain technologies are still nascent. The TCO for the respective power trains is also expected to evolve quickly as technologies progress and may impact the uptake of zero-emission vehicles over ICE ones. Beyond 2030, we represent the mix of xEV power trains in our “net-zero” scenario as a range to reflect uncertainties around the evolution of relevant technologies and their applications.

In this “net-zero” scenario, xEV sales would reach roughly 87 percent of total sales (or 14 million vehicles per year) in the LDV segment and 70 percent of total sales (or 300,000 vehicles per year) in the HDV segment by 2030. The share of total sales for electric vehicles would grow to reach nearly 100 percent in both LDVs and HDVs (or about 17 million and 500,000 vehicles per year respectively). Sales penetration is expected to vary by vehicle subsegment and use case, given differences in purchasing and energy costs and user requirements (Exhibit 10).

Exhibit 9

The McKinsey electrification forecast considers consumer pull and regulatory push of EV

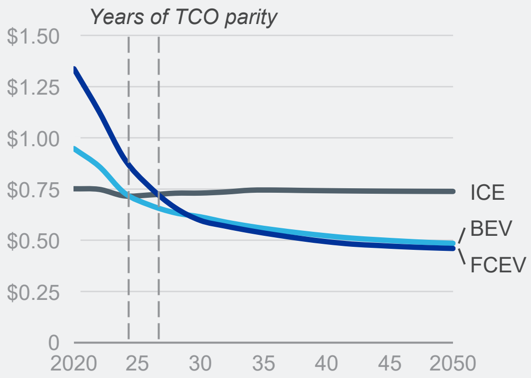
McKinsey EV insights

Consumer pull

1 Comparison of TCO

TCO, $/km

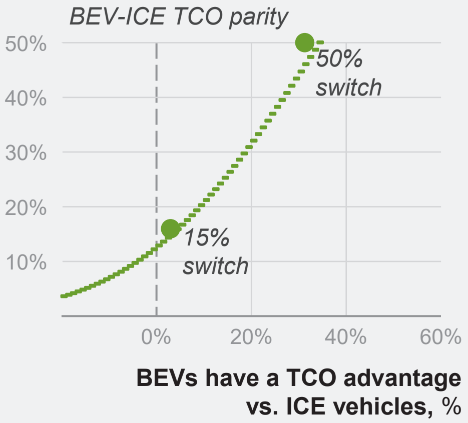
Exemplar TCO curve, Indicative of HDV long-haul truck in Europe



Computed based on manufacturers' suggested retail price (MSRP), residual value, fuel/electricity and maintenance costs. TCO varies by power train, region, and vehicle segment

2 Consumer adoption

BEV/FCEV adoption, % of sales



Models consumer adoption based on TCO price delta of xEV vs. ICE engines, consumer pull varies by region

3 Production constraints

Production constraints

	2020	2021
BEV	3%	9%
PHEV	10%	16%
FCEV	*Short-term: limited model availability*	

Considers short-term EV production constraints of OEMs or on a regional level. Measured in % reduction of theoretical maximum production capacity

Regulatory push

4 Country targets

ICE sales ban (non-exhaustive)

2025: Norway

2030: Germany, Sweden, and the United Kingdom

2035: China, Italy, and Japan

2040: France, Spain, and Canada

Models country-level EV ramp-up based on country targets

5 Regional targets

2030 reduction targets (vs. 2020/21 emissions)

-55%	-36%	-30%
🇪🇺	🇨🇳	🇺🇸

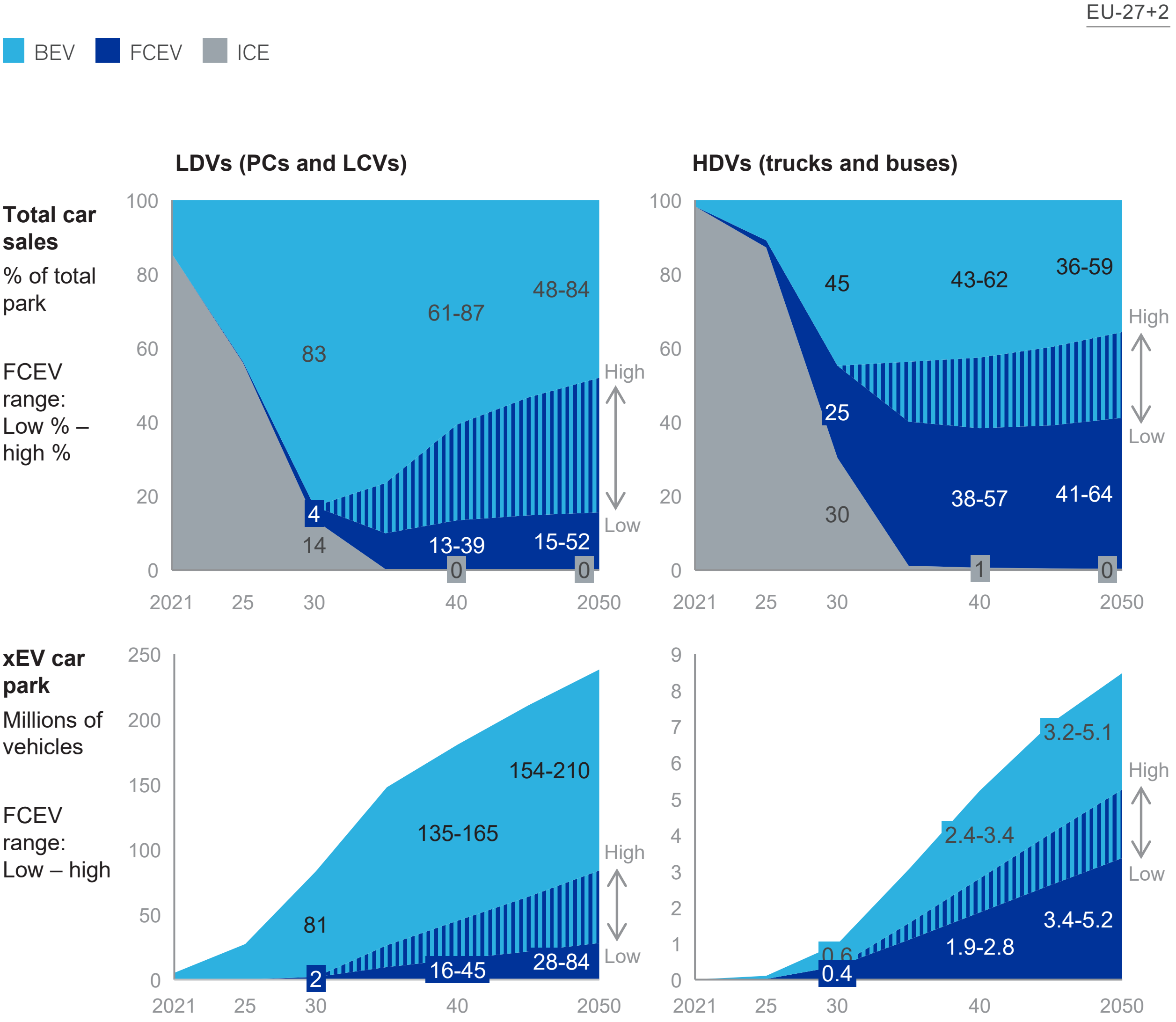
Incorporates regional regulatory targets and computes the power train mix required to meet regulatory targets

Source: McKinsey Center for Future Mobility; MCFM Electrification Model, May 2022

The EV park share is expected to lag behind the uptick in sales since the typical vehicle lifetime is long (16 to 18 years on average in the EU), and thus most ICE vehicles in today's car park will still be on the road in 2030. Additionally, while TCO parity between xEVs and ICE PCs will occur for most EU customers before 2030 (first by BEVs and later by certain FCEVs), a lack of variety in available models and infrastructure to support the growth of the xEV park, may inhibit their uptake. As a result, achieving the ambitious Fit for 55 proposals—or 55 percent overall emission-reduction compared to 1990 levels by 2030—could require more stringent regulations concerning current vehicle parks and new technologies that reduce emissions and mileage compared to existing ICE vehicles.

Exhibit 10

Beyond 2030, the car park is modeled with a range of BEV and FCEV distributions in order to investigate the implication on infrastructure deployment and costs



Source: McKinsey Center for Future Mobility

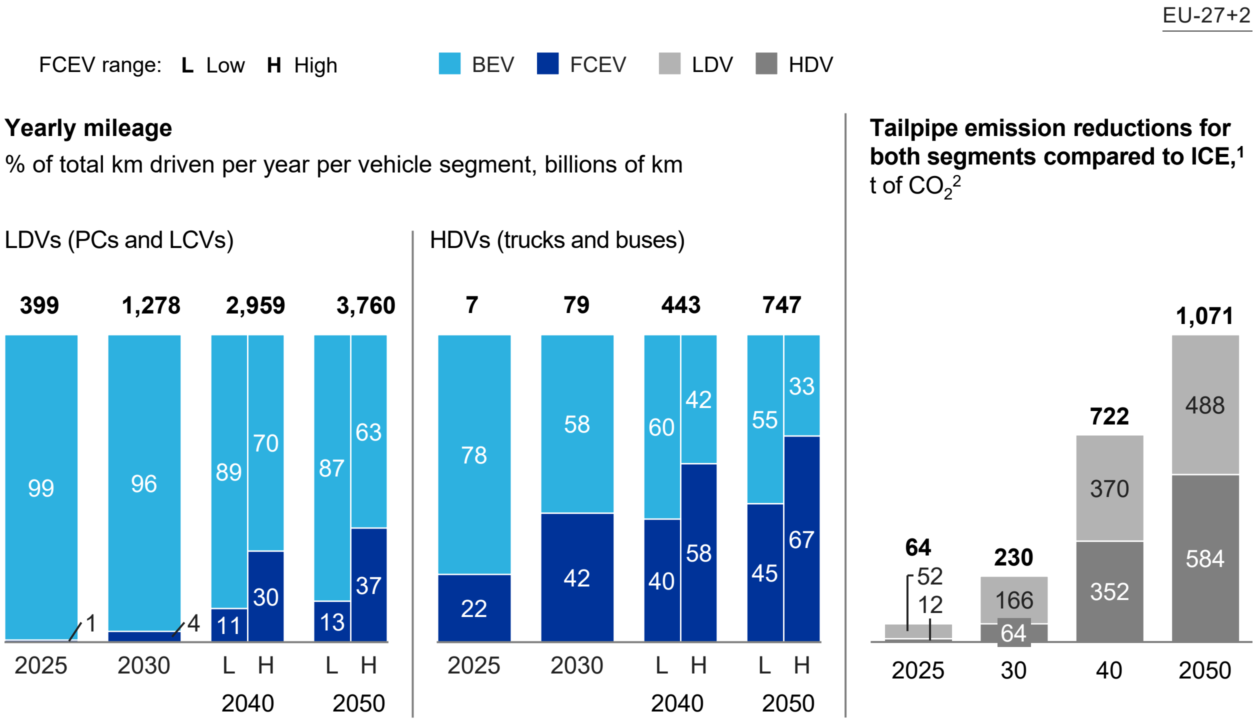
The “net-zero” scenario projects around 85 million and 245 million EVs on the road in 2030 and 2050, respectively. In 2050, HDVs, including trucks and buses, would comprise only about 3 percent of xEVs on the road but represent approximately 17 percent of yearly kilometers driven. Therefore, the solutions deployed to reduce emissions in HDV segments would have a significant impact on decarbonizing Europe’s road transportation system (Exhibit 11).

Given existing customer adoption trends, TCO advantages (including purchase, energy, and maintenance costs), and regulatory support, the “net-zero” scenario projects BEVs to comprise a larger share of the EU’s future LDV park through 2030 when compared with FCEVs. Among other factors, the adoption of xEVs in the PC segment has been supported by subsidies that—in certain jurisdictions and for certain use cases—have already resulted in TCO parity between BEVs and ICE vehicles. Adoption has been so high that certain price-based subsidies have been downwards adjusted. Despite similar subsidies in most EU countries, the adoption of FCEVs has been lower and costs higher, remaining 40 to 60 percent above their BEV peers (excluding subsidies in both cases).

Beyond 2030, we have chosen to represent the mix of BEVs versus FCEVs as a range, to reflect the degree of uncertainty that exists around the longer-term evolution of these technologies. In our chosen adoption scenario, BEVs in the EU LDV park would grow to 154 million to 210 million versus 28 million to 84 million for their FCEV counterparts in 2050.

Exhibit 11

HDVs would account for a lower proportion of overall mileage but are expected to contribute ~50% of emissions reductions



[1] Assuming by 2050 both the energy and the hydrogen needs are green.
[2] LDV average of ~136 g/km; HDV average of ~808 g/km.

Source: McKinsey Center for Future Mobility

In HDV segments, FCEV models may have more of an edge. For example, FCEV HDVs may start to become cost-competitive compared to ICE vehicles and BEVs from 2027 for long-distance coaches and from 2028 for long-haul, heavy-duty trucks.[35] FCEVs are therefore expected to play a larger role in heavy-duty segments (namely, medium- and heavy-duty trucks and buses). In our "net-zero" adoption scenario, the FCEV HDV park would grow to between 3.4 million and 5.2 million vehicles versus between 3.2 million and 5.1 million BEV HDVs in 2050. Here again, we express the share of BEVs and FCEVs as ranges to reflect the uncertainty around power train technology development.

It is important to note the many uncertainties and interdependencies that will drive vehicle adoption over the next 30 years. Energy prices, including the future price of hydrogen, the development of technology, and the successful scale-up of supply chains and manufacturing capabilities, are only some of the factors that will drive overall xEV adoption together with the combination of BEVs and FCEVs in the future vehicle fleet. As these technologies and their associated costs evolve, consumers will make choices based on the quality of the available products and their purchasing power. The goal then for policymakers is to create an ecosystem where multiple technologies that will help meet the EU's net-zero goals can flourish.

The "net-zero" scenario and ranges in the power train mix presented above are not forecasts or predictions but starting points for further discussion. While there is a higher level of certainty around 2030 projections, the limitations in articulating outcomes for 2050 are recognized. In this report, we model outcomes, including infrastructure requirements and costs and represent a range of possible outcomes for the 2030 to 2050 period. The goal is not to predict with absolute certainty the infrastructure needs of the future road transportation system but to indicate the direction and magnitude of action needed and provide a fact base around which policymakers and business leaders can make decisions.

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[35] Based on analysis by the McKinsey Center for Future Mobility (MCFM) and the Hydrogen Council.

2.B

Key assumptions driving infrastructure requirements and costs

Beyond xEV adoption, we looked at numerous drivers of infrastructure requirements and costs. This section covers the technologies considered in our scope, their costs, the minimum network requirements, and refueling and utilization behaviors and assumptions.

2.B.1

Technologies in scope and their costs

For vehicles, we looked at the full range of road transportation from LDVs (like PCs and LCVs) to HDVs (including trucks and buses). The definitions of the vehicle segments can be found in Exhibit 12.

Exhibit 12

Vehicle categorization

Categories	Vehicle types		Description
LDVs	PCs		Private cars, taxis, corporate, and government cars
	LCVs		Commercial vehicles <3.5 metric tons (e.g., delivery, utility vehicles, and passenger transportation)
HDVs	Trucks	Light and medium duty	Regional and urban trucks <7.5 metric tons
		Heavy duty	Long-haul trucks >7.5 metric tons
	Buses		Municipal, regional, and school buses

Source: EU Commission, vehicle categories

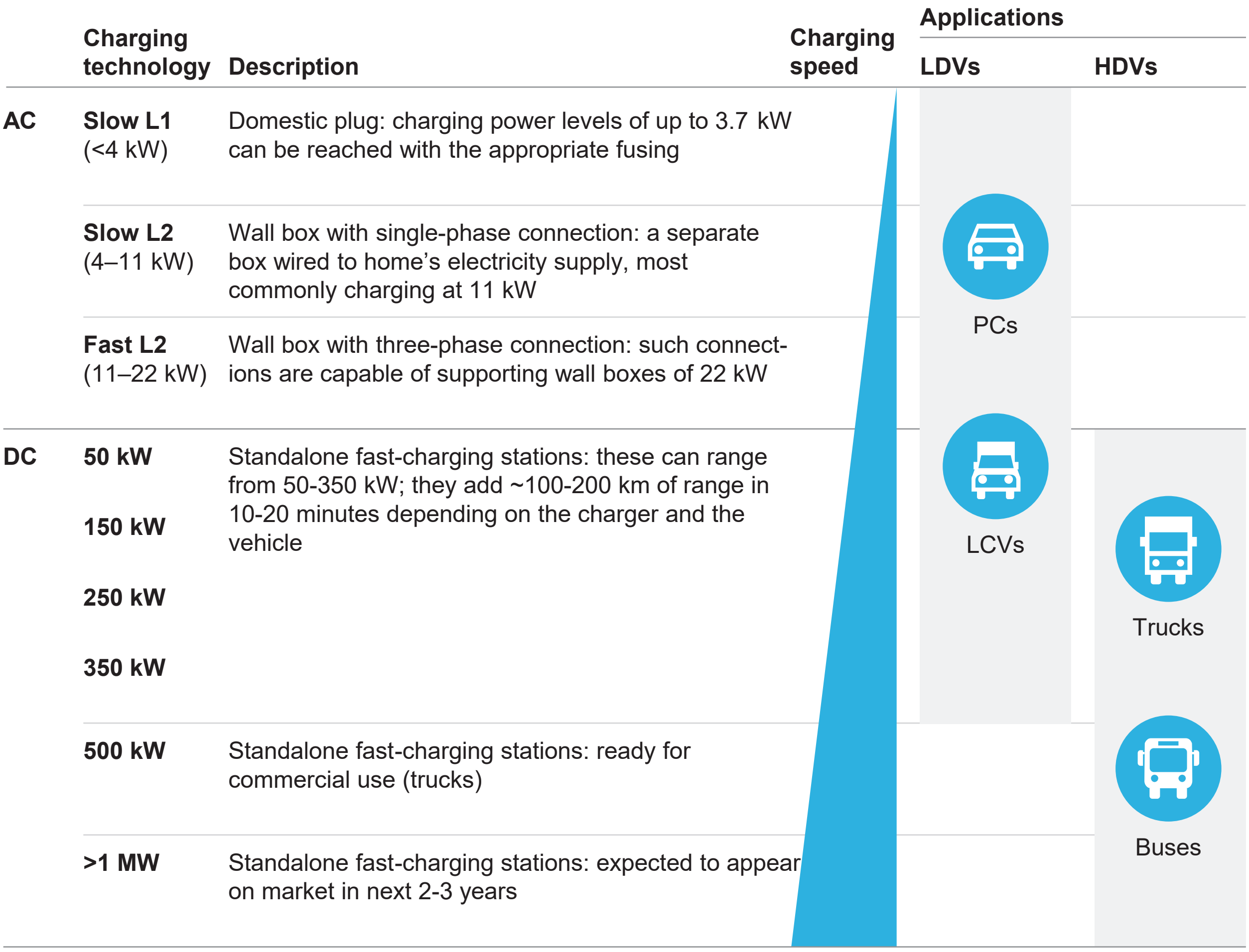
BEV infrastructure technologies and their costs

For BEV charging, we considered:

- **Less than 22 kW AC chargers.** “Slow” chargers that are primarily used in private settings (for example, home domestic plug charging or installed wall boxes connected to the home’s electricity supply) appropriate for longer-duration and overnight charging. Costs per charger: between €500 and €1,000.
- **50 to 150 kW Dc chargers.** Standalone charging stations—faster than AC slow chargers—that are often deployed at private or semiprivate locations such as fleet hubs where multiple vehicles are charged. Costs per charger: between €20,000 and €70,000.
- **Greater than 150 kW DC chargers.** Standalone “fast” charging stations that are typically deployed in public locations such as streets and highways and enable LDVs to achieve near-full charge in 15 to 20 minutes. Costs per charger: between €70,000 and €150,000 (chargers up to 1 MW) (Exhibit 13).

Exhibit 13

Charging technologies in scope



	Charging technology	Description	Charging speed	Applications	
				LDVs	HDVs
AC	**Slow L1** (<4 kW)	Domestic plug: charging power levels of up to 3.7 kW can be reached with the appropriate fusing		PCs LCVs	
	Slow L2 (4–11 kW)	Wall box with single-phase connection: a separate box wired to home’s electricity supply, most commonly charging at 11 kW			
	Fast L2 (11–22 kW)	Wall box with three-phase connection: such connections are capable of supporting wall boxes of 22 kW			
DC	**50 kW** **150 kW** **250 kW** **350 kW**	Standalone fast-charging stations: these can range from 50-350 kW; they add ~100-200 km of range in 10-20 minutes depending on the charger and the vehicle			Trucks Buses
	500 kW	Standalone fast-charging stations: ready for commercial use (trucks)			
	>1 MW	Standalone fast-charging stations: expected to appear on market in next 2-3 years			

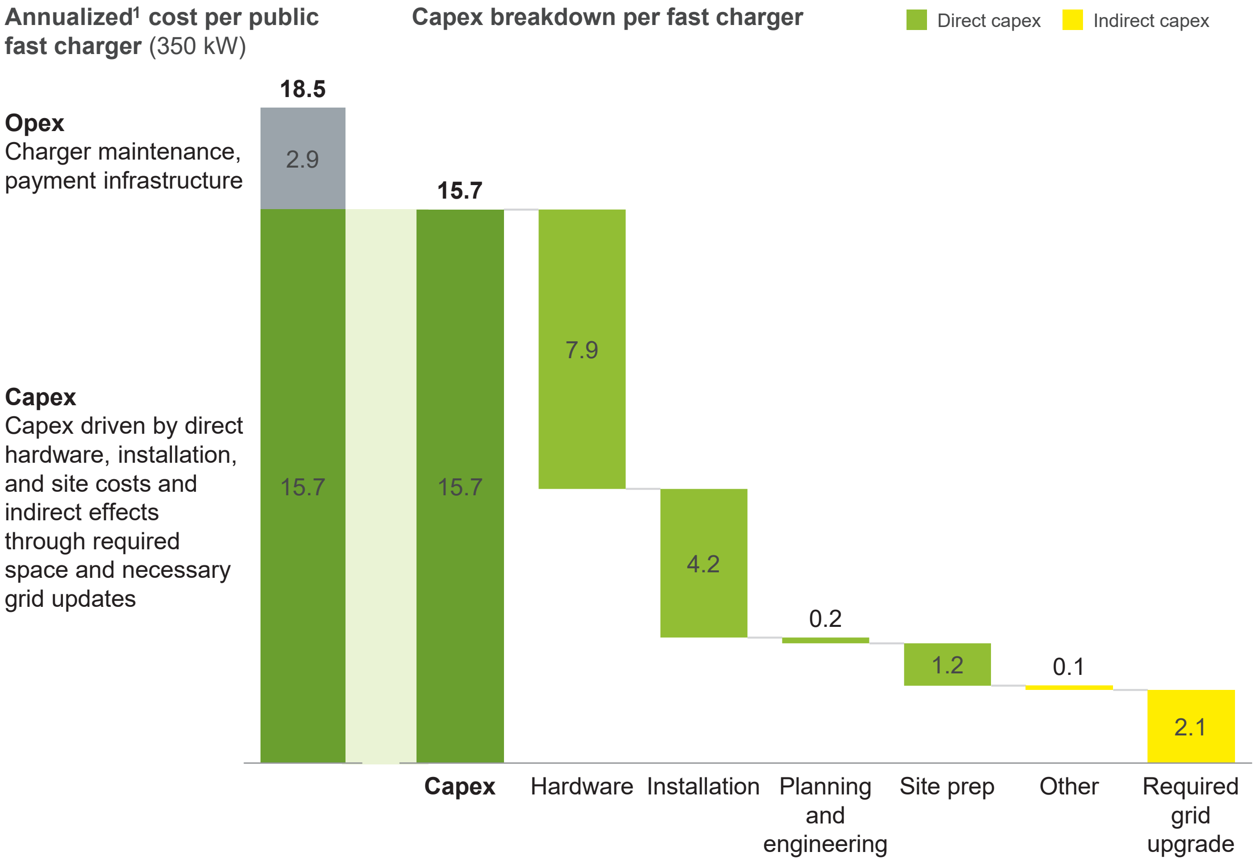
Source: EU Commission, vehicle categories

Charging infrastructure costs are driven by multiple factors. This report considers the full scope of capital expenditures related to charger deployment and grid upgrades to support zero-emission mobility. While charger costs vary by type of technology, hardware and installation costs vary by country. Differences can be driven by labor costs in members states impacting everything from site preparation and planning to installation costs. Charger costs are annualized based on the charger lifetime; in the case of a 350 kW DC charger, eight years (Exhibit 14). (For a more detailed breakdown of assumptions and what is included in our infrastructure analysis, please see the Methodology Box in Chapter 3).

Exhibit 14

2030 BEV infrastructure investment

2030, European average, thousand €/year



[1] Assuming 8 years of lifetime.

Source: McKinsey Center for Future Mobility

FCEV infrastructure technologies in scope and their costs

For FCEV refueling, we limited our focus to gaseous hydrogen dispensed at either 350 or 700 bar. We also considered a range of station sizes ranging from “small” with a capacity of 200 kg of hydrogen dispensed per day to “extra-large” stations with a capacity of 4,000 kg of hydrogen dispensed per day (Exhibit 15). Our model for future deployment excludes “small” stations as these have limited economic viability.

We focus our modeling on gaseous hydrogen distributed in trucks as analyses found that liquid hydrogen is more expensive due to higher up-front compression capital expenditures. We also chose to exclude pipeline distribution in favor of trucking, given significant uncertainty surrounding the level of pipeline development in the short to medium term. As a result, our model considers trucking as the primary mode of distribution; however, it assumes that over time the availability of some hydrogen pipelines will reduce the trucking distance between production sites and HRS from 300 km in 2020 to 50 km in 2050, resulting in cost reductions as the network evolves.

Exhibit 15

A variety of hydrogen technologies are available; the solution space shows selected supply chain options

Overview of steps and technologies along the supply chain

			HRS,[1] bar of fueling pressure[2]			
Type of HRS	**Compression**	**Distribution**	**Small** 200 kg/day	**Medium** 480 kg/day	**Large** 1,000 kg/day	**X-large** 4,000 kg/day
Gaseous hydrogen	To 300 bar →	300 bar, 950 kg capacity →	Limited economic viability	350 bar		
	To 500 bar →	500 bar, 1,100 kg capacity →		700 bar		
On-site production	To 350 bar →	→		350 bar		
	To 700 bar →	→		700 bar		

[1] Standard HRS sizes used, utilization per location and country will vary based on actual demand.
[2] Final compression to refueling bars on HRS site.

Source: McKinsey Hydrogen Cost Model: Supply and Distribution

This report only considers infrastructure costs, specifically the capital expenditures related to postproduction compression and distribution by trucks and the capital expenditures related to the construction and upgrade of HRS (Exhibit 16).

HRS costs are annualized based on predicted station lifetime. Costs vary based on the set of technologies chosen, the level of hydrogen pressurization, and location.

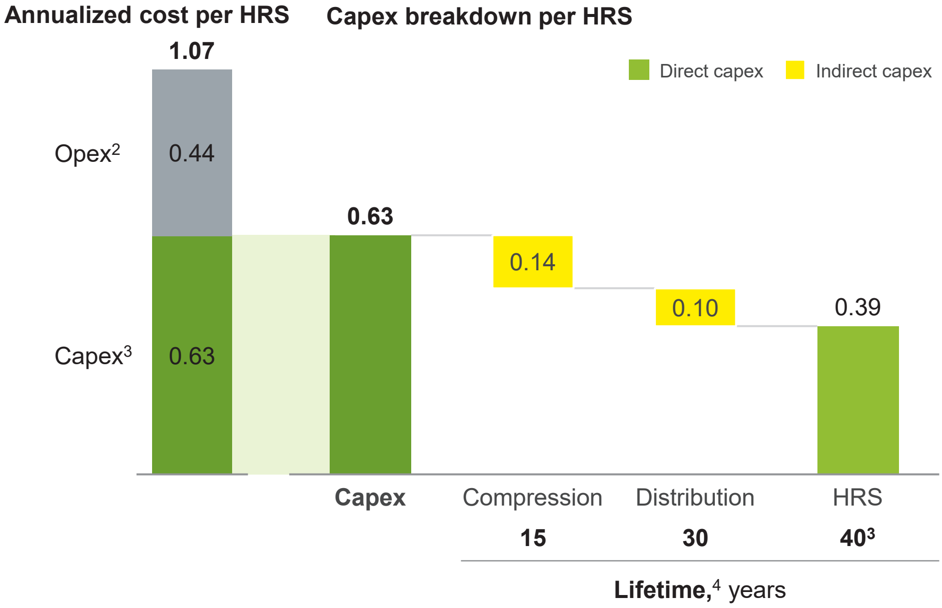
Exhibit 16

2030 FCEV infrastructure investment

2030, European average, €/kg[1]

Example of gaseous hydrogen delivered at 350 bar:

- **Compression** from 30 to 300 bar
- **Distribution** in a 950 kg truck over 300 km
- **HRS** with maximum 1,000 kg/day on average yearly utilization of 80%



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[1] Converted from dollars (exchange rate €1.18/$1.00).
[2] Incl. maintenance and software, excl. distribution (e.g., trucking labor).
[3] Annualization of a cost of capital of 7%.
[4] Years for the onsite compressor.

Source: McKinsey Hydrogen Cost Model: Supply and Distribution

2.B.2

Location and minimum network requirements

Next, we define the location parameters and minimum network requirements that drive (and constrain) our infrastructure projections.

We segment charging and refueling locations as follows:

- **Private or destinations.** Privately owned locations such as individual homes, apartment buildings, hotels, and places of work (not included for the HRS network).
- **Fleet hubs.** Semiprivate locations that serve captive fleets of PCs (like taxis) or commercial vehicles (like delivery vehicles and long-haul trucks).
- **Streets.** Public locations open to multiple users and vehicle types, mostly in urban, suburban, or rural areas.
- **Highways.** Public locations open to multiple users and vehicle types engaged in longer-distance (domestic and cross-border) and higher-speed transit.

For minimum network requirements, the minimum viable network to support and incentivize the uptake of BEVs or FCEVs is considered. For BEVs, early deployment by private-sector players and support from policymakers has already led to a viable minimum network and a virtuous cycle of growth.

On the other hand, hydrogen refueling infrastructure has seen little private investment and is still in the early stages of deployment, with a minimum network yet to be reached. To ensure user satisfaction and support FCEV uptake, we have defined minimum network parameters as follows:[36]

- **TEN-T highways.** One HRS per 150 km; minimum three HRS per member state by 2030.
- **Non-TEN-T highways.** One HRS per 200 km; minimum three HRS per member state by 2030.
- **Urban areas.** One HRS per 30 km, minimum five HRS per member state by 2030; one HRS per 20 km by 2050.

Minimum network requirements vary by member state depending on the total kilometers of roadway, urban density, and location. Certain countries (such as the Netherlands) may not have sufficient urban areas or roadways to yield a minimum above the lower bound and thus default to three HRS along highways and five in urban areas.

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[36] Informed by European Commission AFIR proposal. For further details, see section 3.A.1.

2.B.3

Refueling behaviors and utilization

This report defines xEV refueling behavior according to where and how vehicles refuel or recharge. We consider three main factors: (1) infrastructure location (residential, streets, fleet hubs, and highways), (2) infrastructure capacity (including charger technology and daily station capacity), and (3) minimum network required (the number of chargers and stations per kilometer of road). Our modeling aligns different vehicle segments (for example, LCVs) and use cases (like delivery vehicles) with specific refueling behavior profiles. This is provided based on observations of current refueling behaviors and expectations around how these behaviors could evolve in the new transportation ecosystem.

For example, with BEV charging in 2025, it is assumed that PCs for private use will charge at home or at the workplace roughly 40 percent of the time, on streets about 45 percent of the time, and on highways and at fleet hubs about 15 percent of the time. On the other hand, for heavy-duty BEV trucks used for long-haul transportation, it is assumed that about 85 percent of charging will occur at fleet hubs with the remainder occurring on highways and streets. Each location is also associated with a type of charging technology (for example, AC slow chargers at private locations or homes; DC fast chargers on highways).

Finally, projecting required charger deployment throughout the EU necessitates assumptions around average utilization per charging point. These assumptions vary by year, location, and charger type and are specified for slow and fast AC and DC chargers.

In our model, we assume that FCEV PCs will refuel hydrogen at a pressure of 700 bar and FCEV commercial vehicles (LCVs, trucks, and buses) will refuel with a lower-pressure 350 bar system. For FCEV PCs, it is assumed that roughly 65 percent of refueling would happen at street stations with the remainder occurring on highways and at fleet hubs. FCEV trucks on the other hand would satisfy the majority of their refueling needs (around 70 percent) on highways with another 25 percent at fleet hubs and the small remainder (about 5 percent) at street stations.

Utilization of HRS throughout Europe is also dynamic, beginning somewhat lower as hydrogen demand from FCEVs has yet to surpass minimum network requirements and increase to around 80 percent average daily utilization over time.

For a more detailed view of how refueling behaviors and technology splits by location are factored into our infrastructure deployment strategy, please consult the Methodology Box in Chapter 3.

2.C

Modeling approach for BEV infrastructure requirements

We use McKinsey's EVCI model to project BEV infrastructure requirements for a particular adoption scenario throughout the EU. Inputs to the model include a single or a set of vehicle adoption projections (in our case, the "net-zero" adoption scenario, including power train mix ranges post-2030), energy demand per vehicle (based on the mileage and energy efficiency of each power train), use-case assumptions by vehicle segment or subsegment, and technology assumptions by vehicle segment and use case. The model also assumes a utilization level per charger that evolves with the overall ecosystem (Exhibit 17).

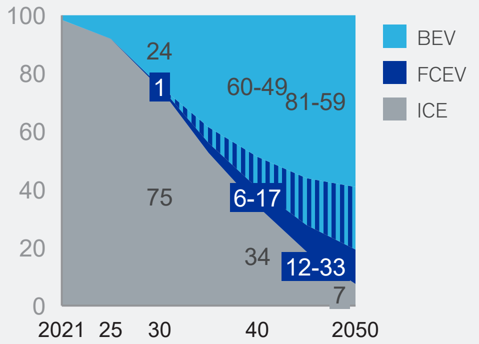
As the output, the model indicates the total number of chargers by type (DC or AC) and location (private, street, or highway). Initial capital expenditures per charger, replacement costs, and charger lifetime are used to calculate the annual and cumulative costs of deploying charging infrastructure.

Exhibit 17

The EVCI model starts from the EV park, modeling energy demand and charging behavior in order to derive infrastructure needs

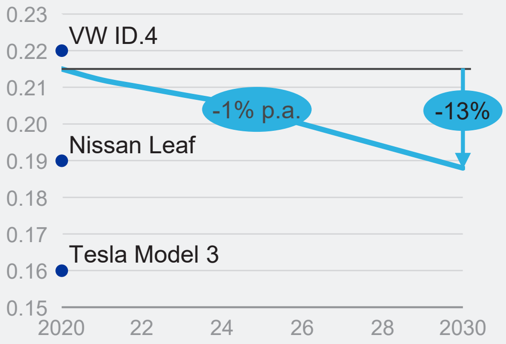
1 EV park

Car park split, % by power train



2 Energy demand

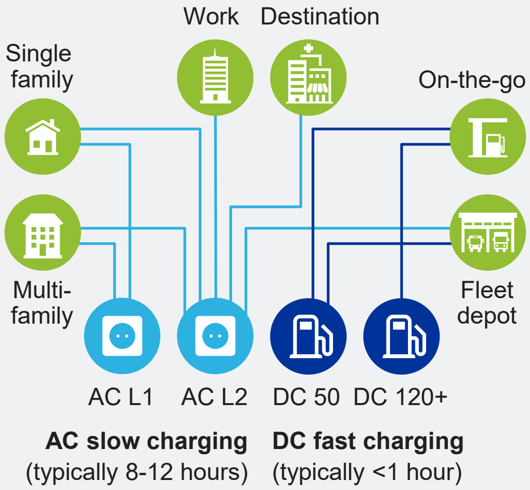
Vehicle efficiency, an average EV, kWh/km



Detailed calculation of energy demand for each available data split through multiplication with real-world annual driving distances and vehicle efficiency

3 Charging behavior

Use cases and techno-logies



Assumption-based derivation of charging patterns regarding use case and technologies

4 Infrastructure need

Charger utilization, %

Example: DC 150 kW charger	**2020**	**2030**	
Work	1%	10%	▲
Fleet depot	30%	30%	▶
Destination	3%	15%	▲
On-the-go	3%	15%	▲

Calculation of required charging infrastructure based on actual charging capacity and expected utilization

Source: McKinsey Center for Future Mobility (Feb 2022)

2.D

Modeling approach FCEV infrastructure requirements

The Hydrogen Refueling Infrastructure Model functions similarly for FCEVs, using the vehicle adoption case as input. Hydrogen demand is projected based on each vehicle segment's mileage and energy efficiency assumptions. From there, the model considers refueling behaviors by vehicle segment and use case. In contrast to the EVCI model, the Hydrogen Refueling Infrastructure Model runs a size mix optimization that determines the optimal size of HRS to build (for example, large 1,000 kg per day or extra-large 4,000 kg per day) based on station economics and projected utilization. The model then applies minimum network logic (see Section 2.B.2) to project the annual development of new HRS (Exhibit 18).

Exhibit 18

The Hydrogen Refueling Infrastructure model estimates the number of HRS and deployment costs for a given FCEV adoption scenario

FCEV adoption scenario

For 4 segments split into subsegments and vehicle use cases

PCs LCVs Trucks Buses

For the EU-27+2 countries (Norway and the United Kingdom)

From 2025 to 2050

Hydrogen demand

Per country per vehicle subsegment and use case

Based on expected hydrogen consumption per subsegment and mileage per vehicle use case

Split over 3 refueling behavior use cases

Fleet hub Highway Street station

For 2 technologies

Gaseous hydrogen delivered at 350 and 700 bar[1]

HRS infra-structure

Optimized total infrastructure (incl. station size mix) required to meet hydrogen demand

Compression Trucking HRS

Minimum network requirements to meet initial demand

Trucking: Decrease of trucking distance over time,[2] and increase of on-site production

HRS: Small (200 kg/day), medium (480 kg/day), large (1,000 kg/day), extra-large (4,000 kg/day)

Infrastructure costs

Annual capex (€/year) for each step along the supply chain

Based on the HRS infrastructure required and the actual hydrogen demand (kg/year) per HRS

[1] Liquid hydrogen assumptions under development.

[2] Assuming increasing density of pipeline infrastructure.

Source: McKinsey Hydrogen Insights Hydrogen Refueling Infrastructure model

Chapter 3

Deploying BEV and FCEV infrastructure in the EU

To demonstrate the magnitude and speed with which new infrastructure must be deployed to support the decarbonization of European road transportation, this chapter lays out a pathway for the development of supporting infrastructure based on the vehicle-adoption scenarios in Chapter 2.

The projections, particularly beyond 2030, are not meant to be forecasts or predictions but rather demonstrate the size and scope of action needed to support a fully decarbonized road transportation system. The objective is not to present a future world in which battery-electric and fuel-cell technologies compete but rather a world where both can evolve as part of a complementary and synergistic ecosystem.

As a result, in the near term (through 2030), we present a detailed view of infrastructure requirements based on current trends in BEV and FCEV uptake across segments. Beyond 2030, we present our results as a range, demonstrating the uncertainty around: (1) how different power train technologies and their costs will evolve, (2) the future price of electricity and hydrogen, (3) supply-side production capacities, and (4) future regulation.

Key takeaways

Between 2022 and 2030, we estimate an investment of €220 billion is required to develop xEV infrastructure in our ranged "net-zero" scenario, with ~5% of that investment going toward FCEVs.

Between 2030 and 2050, an investment of €806 billion to €1 trillion in xEV infrastructure would be required under our ranged "net-zero" scenario, with ~6% to ~15% of that investment going toward FCEVs.

The optimal blend of xEV infrastructure combines both FCEV refueling and BEV charging as this lowers the overall capex cost of investment compared to a 100% BEV scenario.

The ramp-up of FCEV power trains across Europe may be accelerated by synergies such as an increase in demand for clean hydrogen from industry. This could lower midstream infrastructure investment costs.

Factors like shortages of skilled labor and raw materials may act as bottlenecks and limitations for xEV infrastructure development in Europe as a whole.

3.A

Defining the optimal blend of infrastructure to support zero-emission mobility

For this study, we consider four guiding principles to determine the blend of infrastructure for zero-emission mobility, with particular emphasis on infrastructure cost:

- **Infrastructure cost.** The capital expenditures required to deploy supporting infrastructure for BEVs and FCEVs as part of the future vehicle fleet.
- **Timing and speed of deployment.** The rate at which infrastructure can be rolled out to support and drive xEV adoption. This factor is also linked to sustainability impact.
- **Feasibility.** The availability of critical resources (such as labor and sustainably sourced raw materials) and adequate funding to deploy the infrastructure.
- **Sustainability impact.** All else being equal, the impact of BEVs and FCEVs is assumed to be equivalent from an emission-reduction perspective. While our assumption here looks only at tailpipe emissions, the overall sustainability impact would be driven by emissions from the full value chain, including hydrogen and electricity production, transportation emissions, and sun-to-wheels efficiency, which are beyond the scope of this study.

We can further view the blend of infrastructure as (1) the mix of the infrastructure deployed for each power train for an existing or projected vehicle park and (2) the ratio of BEV charging versus FCEV refueling infrastructure if deployment choices could be made independent of the existing or projected vehicle park. In this chapter, we will look at both.

- For (1), we will look at how to deploy infrastructure against our “ranged” adoption scenario in a way that seeks to minimize costs while meeting the remaining optimization criteria.
- For (2), we will consider several sensitivities to our “ranged” scenario to illustrate how overall system costs might be impacted given changes in overall vehicle uptake or the mix between BEVs and FCEVs on the road.

Methodology

3.A.1

Assessing and minimizing costs

Defining costs within the scope

Cost projections for both BEV and FCEV infrastructure focus on capital expenditures within the midstream (distribution[37]) and downstream (charging and refueling station) segments of the respective value chains. This facilitates the comparison from a pure infrastructure investment perspective. The responsibility for funding this infrastructure and bearing the ongoing costs are discussed in Chapter 5.

Our analysis considers the capital expenditures needed to deploy charging points and HRS (namely planning and engineering, installation and preparation, and hardware) and those required for electricity and hydrogen distribution to the charging points and HRS (Exhibit 19).

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[37] Excluding costs associated with developing and installing a hydrogen pipeline network required to reduce the distribution distance.

Exhibit 19

An estimate of the total infrastructure costs

🟦 Included in the overall infrastructure cost estimates

	FCEV	BEV
Downstream	HRS capex: **HRS infrastructure hardware** (e.g., pumps, on-site compressors)	Chargers capex: **home charger hardware and public charger infrastructure and hardware**
Midstream	Trucking capex: **trucks and lorries to carry hydrogen** Compression capex: **infrastructure and hardware for the compression** of hydrogen prior to its transportation	Grid capex: **grid upgrade costs** implied by the road transportation industry
Upstream	All hydrogen **production costs**	All electricity **production costs**
Other	All **opex** (e.g., HRS operators, truck drivers, and electricity needed by the stations)	All **opex** (e.g., maintenance, software, and electricity distribution charges)

Source: McKinsey analysis

The estimates in the “distribution” category are limited to the additional capital expenditures required to serve new xEVs on the road. For BEVs, additional costs (such as grid costs) implied by the BEV car park increase have been considered. For FCEVs, capital expenditures for transportation compression and hydrogen trucking to stations have been considered. The proportion of compression and distribution capital expenditures shared with other hydrogen use cases (like industrial uses) have been excluded, as have pipeline infrastructure capital expenditures, assuming that a hydrogen pipeline would be developed for other end uses.

The analysis also excludes all operational expenses (such as electricity and hydrogen costs, station and trucking labor, permits, safety and maintenance, and SG&A) and all upstream costs (like electricity and hydrogen production).

Defining a combined deployment strategy

When looking at xEV infrastructure deployment, we identified specific levers that could affect costs and improve network development timing and feasibility while meeting refueling and charging demand. We identified three key elements for our analysis: refueling behavior and the location of refueling and recharging facilities, capacity needs for refueling and recharging, and minimum network requirements.

Focusing on use cases of the evolving xEV fleet

First, we looked at refueling behavior by location to determine where best to deploy infrastructure given users’ evolving needs. For BEVs, we considered private (like homes or places of work), semiprivate (such as fleet hubs), and public charging networks (on streets and highways). PC charging would be concentrated in private locations and streets, while a smaller portion of charging would occur on highways and at fleet hubs (like taxi fleets). The opposite would be true for commercial vehicles that would charge primarily at fleet hubs or highways, requiring focused deployment of DC fast chargers. Given the early adoption of BEVs across multiple vehicle segments, we assume the near-term focus would be on deploying private and semiprivate chargers for these vehicles followed by an acceleration in public charger deployment.

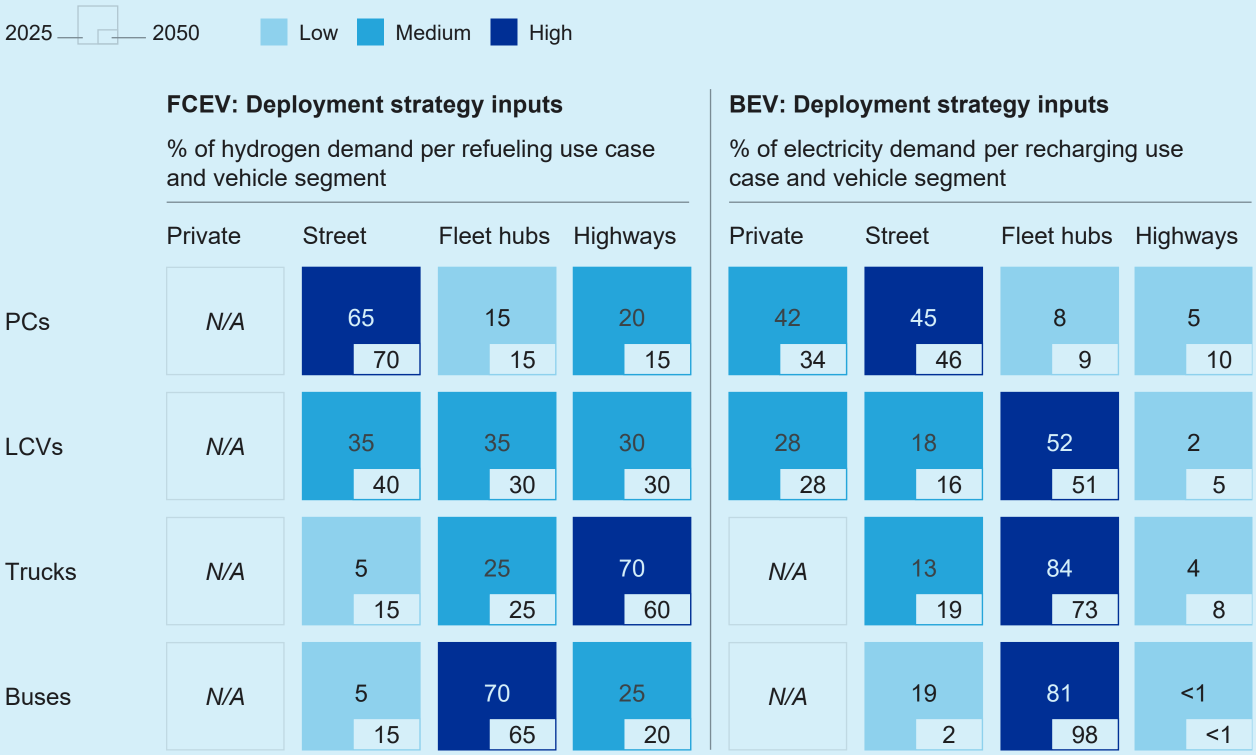
There is an opportunity to focus infrastructure rollout on FCEVs to serve early adopters (for example, heavy-duty trucks and taxi fleets). Therefore, early HRS deployment could focus on streets to serve taxis and allow for expansion into other PC segments and on highways to serve a future FCEV truck fleet. In the longer term, street station deployment may grow, along with fleet hubs to serve commercial segments and buses.

In summary, we assume infrastructure deployment for BEVs to be concentrated in private locations for PCs, in fleet hubs for commercial vehicles, and on highways for FCEVs (Exhibit 20).

Methodology

Exhibit 20

FCEVs and BEVs have different deployment strategy inputs for each use case



	FCEV: Deployment strategy inputs % of hydrogen demand per refueling use case and vehicle segment				BEV: Deployment strategy inputs % of electricity demand per recharging use case and vehicle segment			
	Private	Street	Fleet hubs	Highways	Private	Street	Fleet hubs	Highways
PCs	N/A	65 70	15 15	20 15	42 34	45 46	8 9	5 10
LCVs	N/A	35 40	35 30	30 30	28 28	18 16	52 51	2 5
Trucks	N/A	5 15	25 25	70 60	N/A	13 19	84 73	4 8
Buses	N/A	5 15	70 65	25 20	N/A	19 2	81 98	<1 <1

Source: McKinsey Center for Future Mobility; McKinsey Hydrogen Insights Hydrogen Demand model

Focusing on the right capacity at a minimum cost

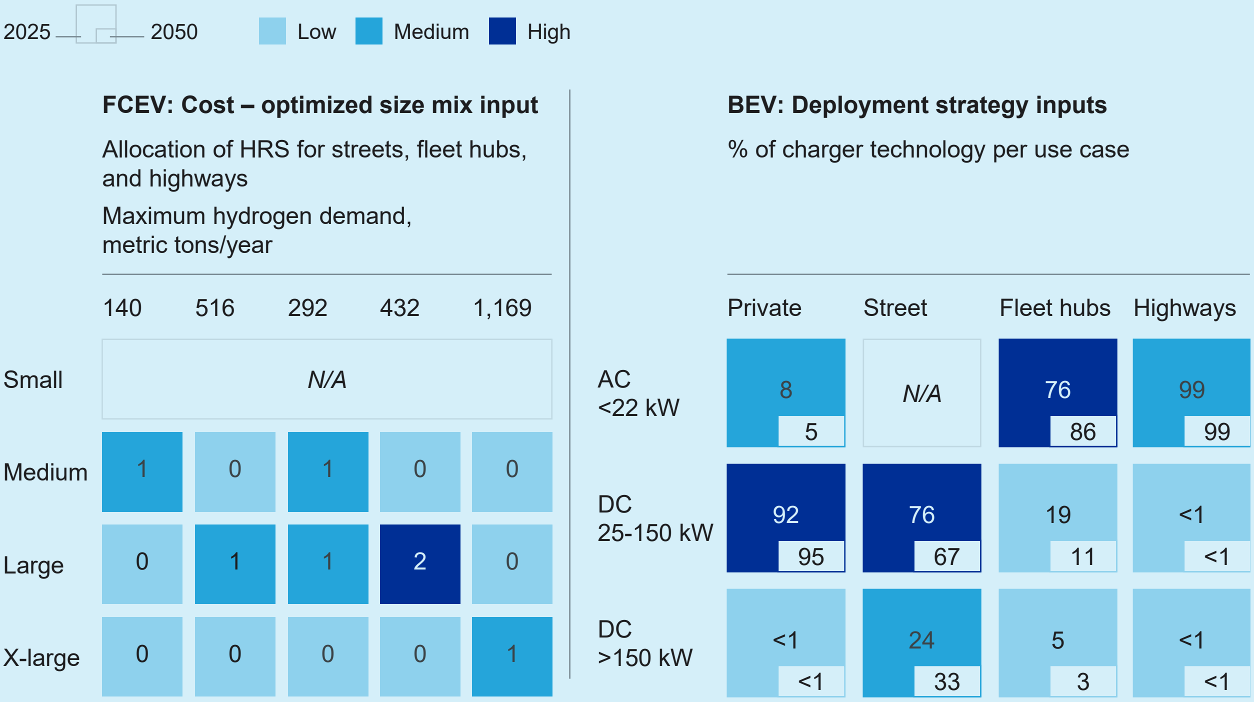
Second, our deployment approach focuses on the right capacity of infrastructure based on anticipated user requirements and utilization. Our model assumes that a mix of charger types will be deployed across various locations to serve the different vehicles and users at those locations. For example, DC fast chargers will be concentrated at fleet hubs and on highways to enable on-the-go charging, while slower AC chargers will be deployed on streets and in private locations and in overnight fleet hubs that allow for longer charge times (Exhibit 21).

For FCEVs, the model's optimization logic pushes for larger station capacities as they are more economically efficient if minimum utilization levels are achieved. Extra-large HRS are the most cost-efficient, given sufficient utilization. The higher initial capital cost is compensated for by more hydrogen being distributed and more vehicles being served, thus delivering a favorable return on investment. Furthermore, an initial build-up of higher capacity stations eliminates the need to upgrade costs later as hydrogen refueling demand rises.

Methodology

Exhibit 21

FCEVs cost-optimize the size-mix based on the HRS demand per year; BEVs use a combination of charger technologies per use case



FCEV: Cost – optimized size mix input

Allocation of HRS for streets, fleet hubs, and highways

Maximum hydrogen demand, metric tons/year

	140	516	292	432	1,169
Small	*N/A*				
Medium	1	0	1	0	0
Large	0	1	1	2	0
X-large	0	0	0	0	1

BEV: Deployment strategy inputs

% of charger technology per use case

	Private	Street	Fleet hubs	Highways
AC <22 kW	8 5	*N/A*	76 86	99 99
DC 25-150 kW	92 95	76 67	19 11	<1 <1
DC >150 kW	<1 <1	24 33	5 3	<1 <1

Source: McKinsey Center for Future Mobility; McKinsey Hydrogen Insights Hydrogen Demand model

Pushing the boundaries of minimum network deployment

Given the current state of deployment of BEV infrastructure and the acceleration of BEV adoption, minimum network requirements are close to being met. A minimum number of HRS would need to be deployed for FCEVs to satisfy refueling requirements across various user segments and enable early adoption. In the latest EU proposal for the AFIR, a minimum of one HRS per 150 km of TEN-T network is necessary to support sustained FCEV adoption. However, in addition to the AFIR proposals, our model considers a minimum network of HRS on highways (both TEN-T and non-TEN-T) and urban areas and mandates at least one station within a 30 km radius in 2030, increasing to five stations per member state in 2030. This shifts to a minimum of one station within a 20 km radius by 2050. In the longer term, network density will grow depending on technology adoption, and infrastructure expansion will follow accordingly.

3.B

Combined infrastructure deployment and costs in the EU

Starting from our “ranged” adoption scenario, we project aggregated infrastructure requirements for the EU-27 plus the United Kingdom and Norway. We first project infrastructure requirements and costs to portray the level of near-term mobilization and coordination needed across Europe. Looking toward 2050, the evolving road transportation ecosystem is less certain, particularly with regard to the roles BEVs and FCEVs will play. Here, we depict a range of possible futures, sensitivities, and relative penetrations of BEVs and FCEVs across segments to highlight the cost impact of these changes on the overall xEV ramp-up.

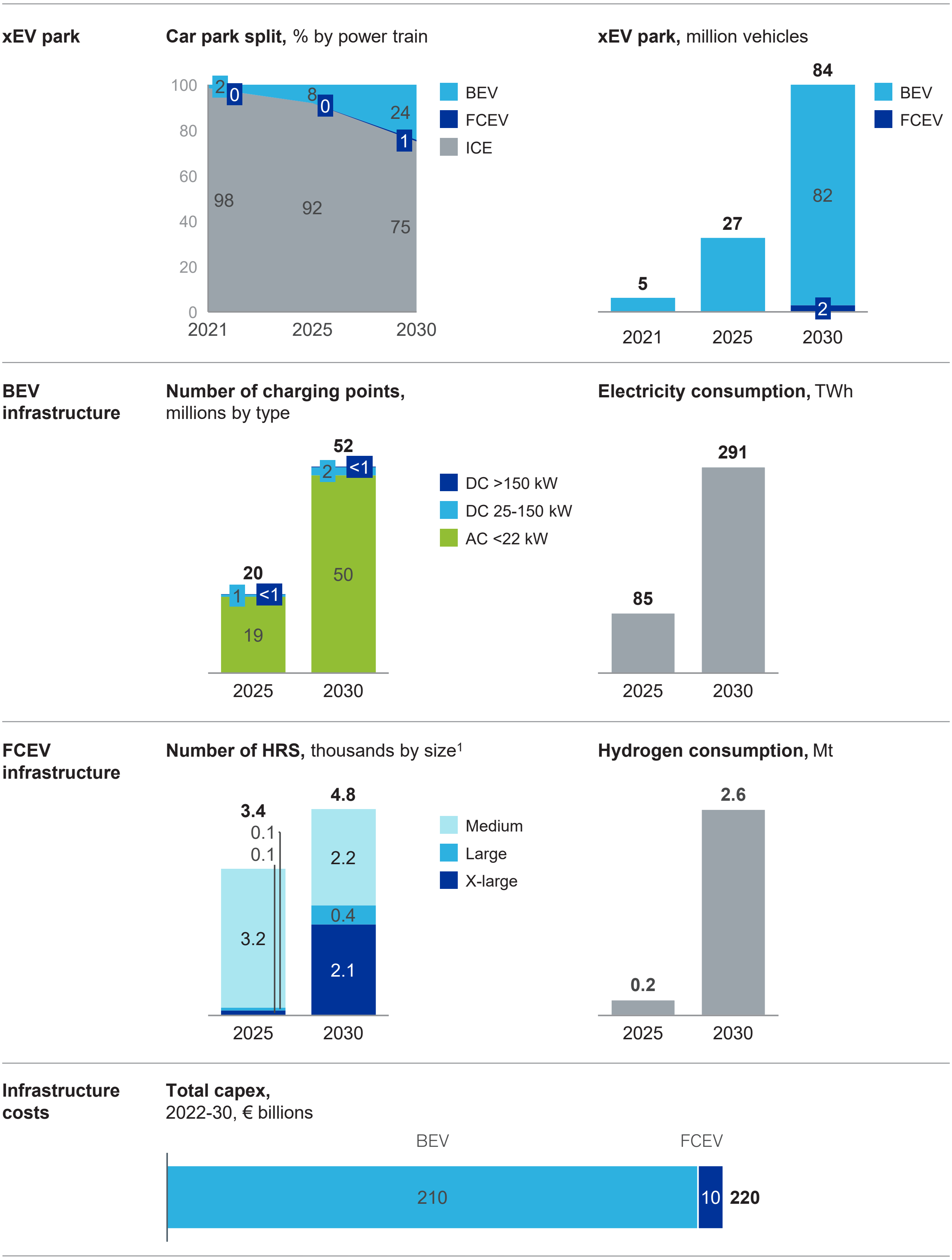
3.B.1

Infrastructure deployment through 2030

An increasing share of xEVs on the road would require BEV and FCEV infrastructure to be rolled out quickly. Through 2030, our “ranged” scenario would require some 52 million charging points to be installed across Europe and nearly 5,000 HRS. This compares with around 270,000 chargers and around 200 HRS today (Exhibit 22).

Exhibit 22

The EU car park is expected to be made up of ~25% xEVs by the end of 2030—mostly BEVs—resulting in an investment need of €220 billion



[1] Medium station = 480 kg/day capacity; large station = 1,000 kg/day capacity; x-large = 4,000 kg/day capacity.

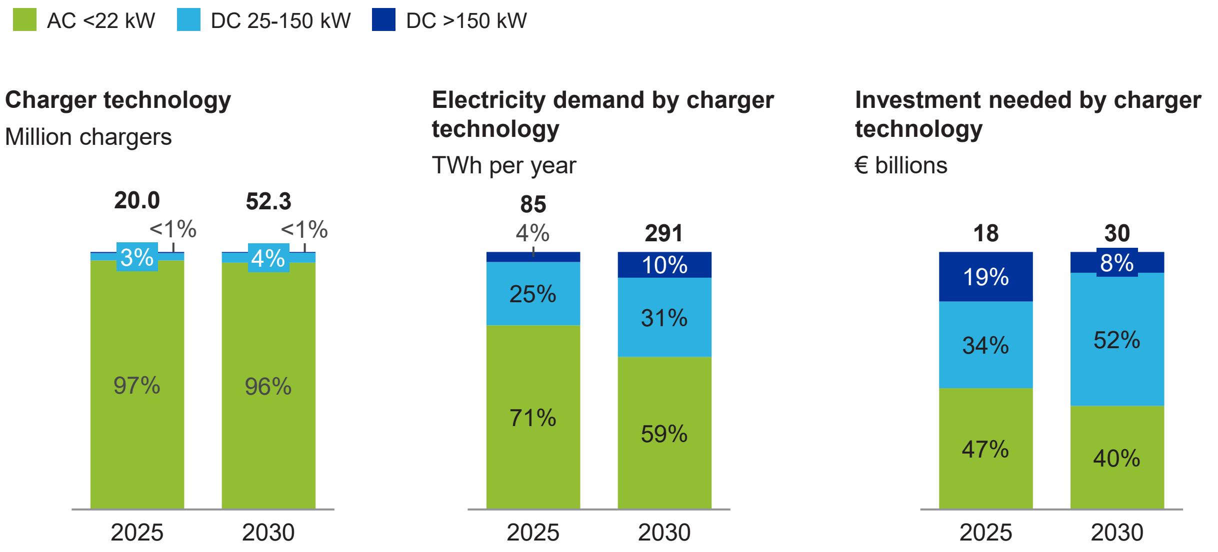
Source: McKinsey Center for Future Mobility

When looking specifically at charger deployment through 2030, most would be up to 22 kW AC chargers, deployed at private locations and allowing users to charge at home. However, despite the large absolute number of chargers deployed in this way (roughly 50 million by 2030), a large portion of the electricity delivered (31 percent by 2030) and investment needed (52 percent by 2030) is attributed to 25 to 150 kW DC or more than 150 kW DC charging in semiprivate or public domains (Exhibit 23, Exhibit 24).

Exhibit 23

While slow AC chargers are the most deployed by volume (96% in 2030), fast chargers drive most BEV investments (60% in 2030)

EU-27+2

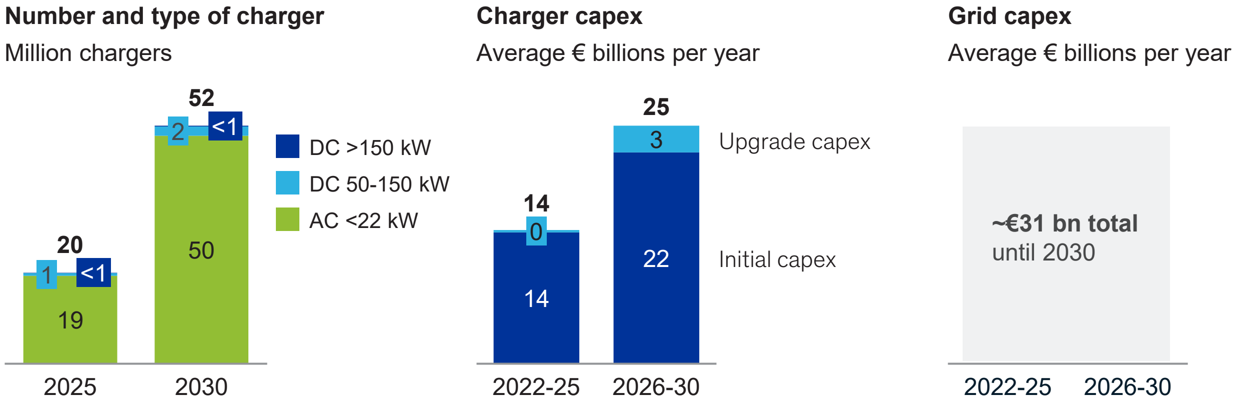


Source: McKinsey Center for Future Mobility; McKinsey Hydrogen Insights FCEV infrastructure model; McKinsey Hydrogen Insights hydrogen demand model

Exhibit 24

Most chargers deployed will be AC <22 kW, with charger capex accounting for ~85% of BEV investment needs until 2030

EU-27+2

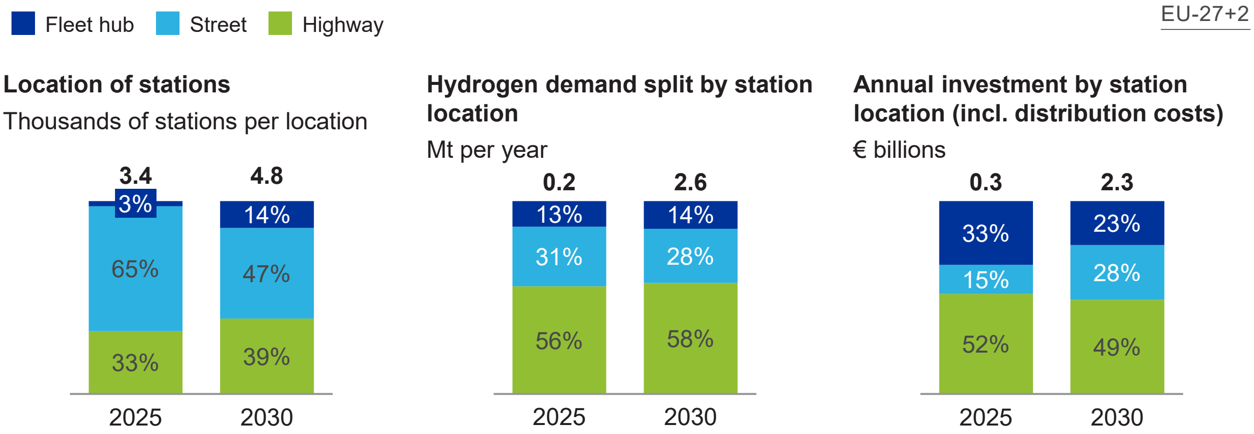


Source: Eurelectric; McKinsey Center for Future Mobility; McKinsey Hydrogen Insights FCEV infrastructure model; McKinsey Hydrogen Insights hydrogen demand model

For FCEVs, the first stations would be split in terms of location across highways, streets, and semiprivate fleet hubs. By 2030, approximately 47 percent of HRS would be on streets, 39 percent on highways, and the final 14 percent at fleet hubs. However, from an energy perspective, highway stations would serve the bulk of hydrogen demand (around 58 percent) through 2030. Roughly half of the early investment would go toward these highway stations, which would primarily serve early adopters in the long-haul, heavy-duty trucking segment but could also support vehicles in other segments traveling long distances (Exhibit 25, Exhibit 26).

Exhibit 25

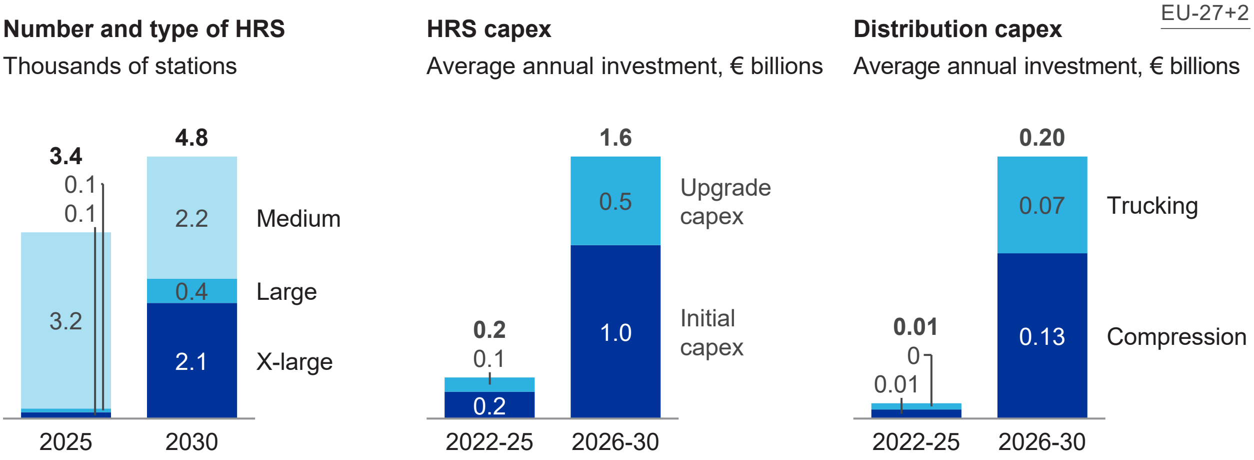
Through 2030, ~85% of HRS would be along highways or on streets



Source: McKinsey Center for Future Mobility; McKinsey Hydrogen Insights FCEV infrastructure model; McKinsey Hydrogen Insights hydrogen demand model

Exhibit 26

FCEV investment consists of HRS capex (90%) and distribution capex (10%)



Note: The cost of hydrogen dispensed by HRS varies depending on the country it is built in, the pressure it operates at, and the efficiency of station technology. Small HRS in the EU are estimated to dispense hydrogen at a cost of between €3 to €5 in 2030 and €3 to €4 per kilogram in 2050, medium HRS at a cost of between €3 to €5 in 2030 and €2 to €3 in 2050, large HRS at a cost of between €3 to €5 in 2030 and €2 to €3 in 2050, and extra-large HRS at a cost of between €3 to €4 in 2030 and €2 t0 €3 in 2050. Converted from dollars (exchange rate €1.18/$1.00).

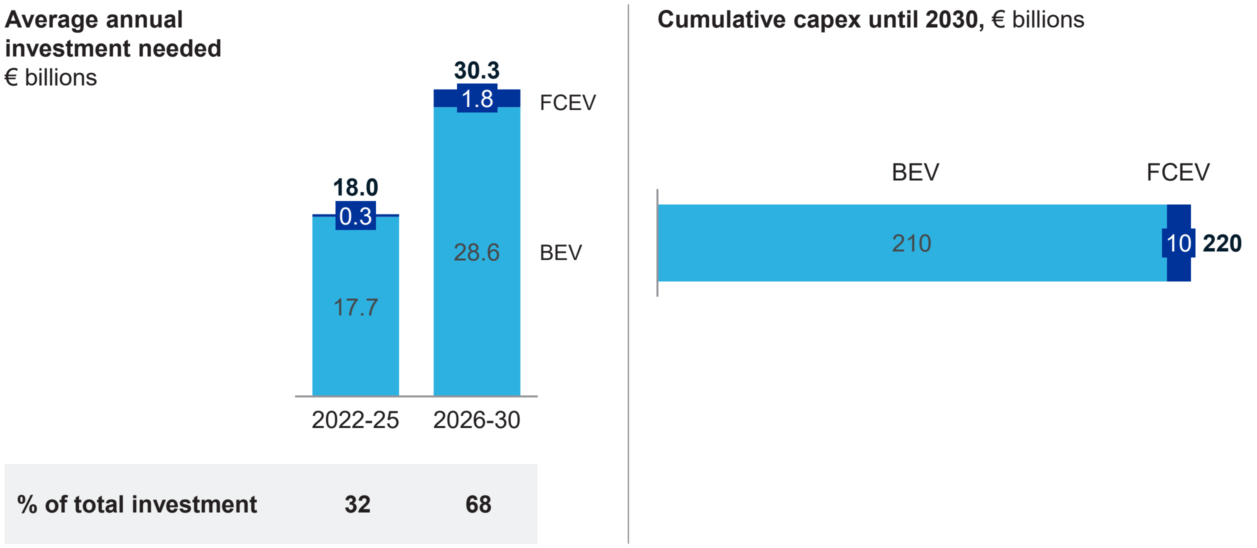
Source: McKinsey Center for Future Mobility; McKinsey Hydrogen Insights FCEV infrastructure model; McKinsey Hydrogen Insights hydrogen demand model

Cumulative investment in Europe's combined recharging and refueling infrastructure would reach €220 billion by 2030. This is in context of the more than €3 trillion that would need to be spent in transportation by 2030 to transition the sector on a path to net-zero by 2050.[38] The average annual investment on xEV infrastructure would increase to nearly €30 billion per year between 2026 and 2030 compared to the 2022 to 2025 average of about €18 billion. Roughly 68 percent of the total investment in xEV infrastructure would come after 2025 (Exhibit 27). While the bulk of the investment (around 95 percent) is needed to meet BEV charging infrastructure demand, the amount spent on HRS will help fuel-cell technologies scale-up in relevant segments.

Exhibit 27

The cumulative BEV and FCEV investment up to 2030 is €220 billion, with ~70% being incurred after 2025

EU-27+2



Source: McKinsey Center for Future Mobility; McKinsey Hydrogen Insights FCEV infrastructure model; McKinsey Hydrogen Insights hydrogen demand model

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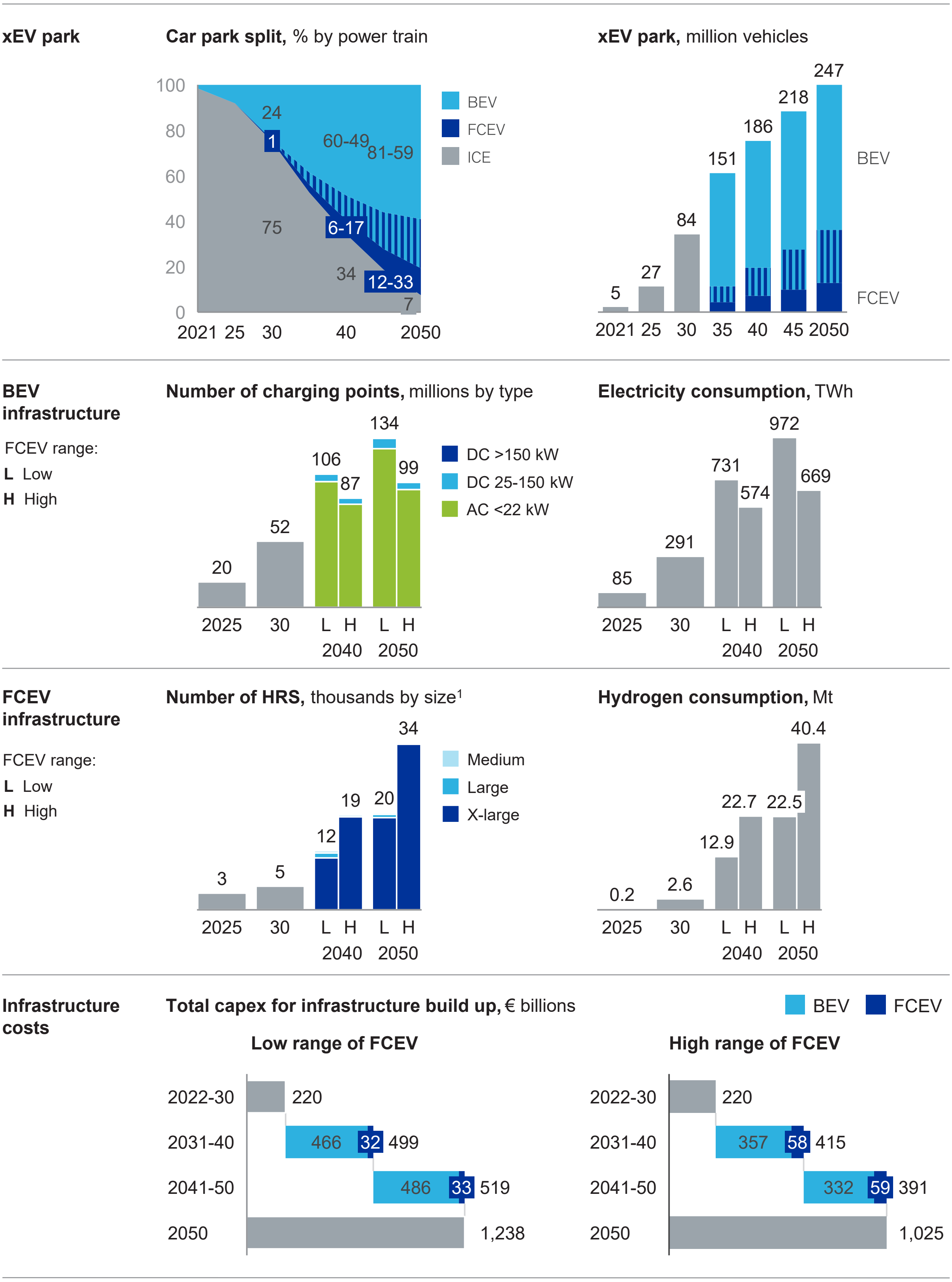
[38] *Net-zero Europe: Decarbonization pathways and socioeconomic implications*, McKinsey, November 11, 2020.

Exhibit 28

The EU car park is expected to increase from ~25% to 93% xEVs between 2030 and 2050, triggering a significant infrastructure investment

EU-27+2



[1] Medium station = 480 kg/day capacity; large station = 1,000 kg/day capacity; x-large = 4,000 kg/day capacity.

Source: McKinsey Center for Future Mobility

3.B.2

Infrastructure deployment beyond 2030 and sensitivity analysis

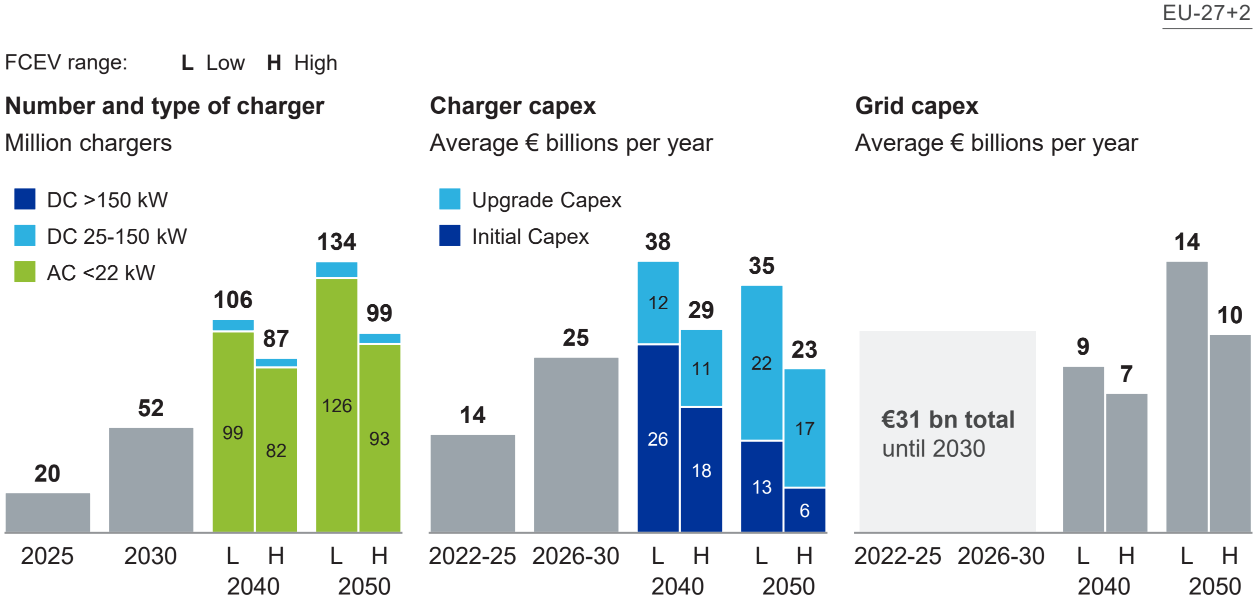
The EU-27 (plus the United Kingdom and Norway, which are included in this analysis) will need to deploy between 99 and 134 million chargers to support BEVs and 20,000 to 34,000 HRS to support FCEVs. Roughly 70 percent of the total investment would be driven by charger deployment (€689 billion to €952 billion of the total spend on charging infrastructure from 2030 to 2050), including grid upgrades (about €7 billion to €14 billion annually from 2030 to 2050) related to electric mobility. The remainder of the post-2030 investment (about €65 billion to €117 billion through 2050) would go toward the rollout of HRS and the distribution network (Exhibit 28).

Digging deeper into the longer-term deployment of BEV infrastructure, we see an acceleration of charger deployment beyond 2030. Average annual spending would peak during the 2030s (at between €29 billion and €38 billion) as charger technologies and costs improve, new charger deployment decelerates, and a larger portion of the capital expenditures beyond 2040 is made up of replacements rather than new installations.

However, grid costs to support zero-emission mobility are expected to increase through 2050, reaching an average annual cost of €10 billion to €14 billion in the EU between 2040 and 2050 (Exhibit 29; for further details, see Box 1 Estimating grid upgrade costs).

Exhibit 29

BEV investment consists of a mix of charger and distribution capex, with the former accounting for ~75% of the total between 2030 and 2050



Source: Eurelectric; McKinsey Center for Future Mobility; McKinsey Hydrogen Insights FCEV infrastructure model; McKinsey Hydrogen Insights hydrogen demand model

Box 1

Estimating grid-upgrade costs related to zero-emission mobility

In a second-level effect of transportation electrification, the grid will be impacted by the adoption of xEVs and the deployment of charging infrastructure. As a result, grid costs have been included in the total BEV infrastructure costs.

A review of prior studies shows that these costs can vary by country and analytical approach, suggesting uncertainty around the actual figures. There are also uncertainties around the key drivers of the impact of BEVs on grid costs.

Low-impact scenario. BEVs can have a very low impact on the grid if mostly charged at home or work, with smart charging capable of shifting demand freely to avoid peak consumption hours. There may also be V2G functionality in a share of the BEV car park to further alleviate short, localized peaks and provide additional capacity in periods of high demand. In addition, by 2050, the majority of the electricity grid distribution hardware will be due for its regular upgrade (such hardware has a 30- to 50-year lifecycle) and can be replaced. These upgrades will primarily be driven by the need to accommodate an increasing share of renewable energy sources and by electrification in other sectors (for example with heat pumps in buildings) where demand cannot be shifted as easily.

High-impact scenario. If BEV charging behavior mimics ICE fueling behavior—predominantly using powerful public fast-chargers and providing little to no flexibility in demand—then BEVs will have a higher impact on the grid. This scenario assumes there will be no widespread usage of bidirectional charging (V2G) and that BEV adoption precedes the large-scale electrification of other sectors such as buildings or heavy industry. xEV adoption would then be the key trigger to upgrade the grid rather than heat pumps. Additionally, labor shortages may limit the ability to upgrade the grid cost-efficiently and in a timely manner.

While some studies for individual member states project their analysis until 2050, xEV adoption is considered in combination with other effects (such as the electrification of buildings through heat pumps and renewable energy). So far, no study provides a comprehensive view of what grid upgrade costs would amount to on a European level until 2050.

Bearing in mind uncertainties about the extent to which BEV charging can impact the electricity grid, we use two factors to estimate likely grid upgrade costs to sustain BEV infrastructure. The first is a top-down estimation of distribution fees: as distribution fees cover infrastructure costs, we can calculate capital expenditures from the expected added power demand through xEV adoption. The second is a bottom-up calculation based on prior research: isolating xEV adoption effects and addressing characteristic differences between member states with an impact on grid costs, using:

- The available headroom in the system (underutilization of the current grid)
- The total length of distribution lines (size of the grid)
- The share of underground distribution lines (effort level required for upgrades)

This methodology shows that grid upgrade costs implied by BEV deployment will amount to between €200 billion and €260 billion between 2022 and 2050. Over this period, most of the investments (85 to 90 percent) will be made after 2030. Smart charging may reduce this cost by smoothing electricity demand and lowering upgrade costs to between €190 billion and €270 billion between 2022 and 2050.

Exhibit 30

BEVs are only one of many factors impacting distribution systems in the near to long term

Total required grid upgrades

Other effects (buildings, renewables)

BEV effect

The **combination of multiple drivers** defines the extent and total cost of grid upgrades

- Increased share of renewables
- Electrification of buildings (e.g., heat pumps)
- Electrification of industry

BEVs

- Modernization of grid infrastructure
- Increased grid resilience
- Digitization of the grid

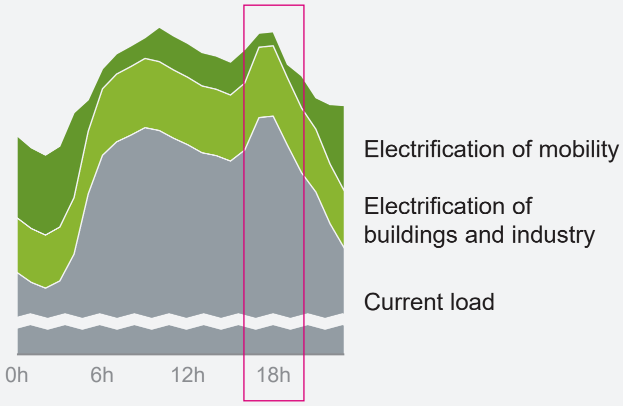
State of the art: Prior studies **approximate total costs** of required grid upgrades

- For Europe up to 2030 (Eurelectric)
- For Germany up to 2050 (Agora)

We quantify the BEV effect by

- **Comparing scenarios** from prior studies with low or high BEV penetration while keeping other factors constant (see Agora)
- Determining the **relative effect of BEVs on peak load**, compared with other electricity demand

Illustrative hourly load profile, MW

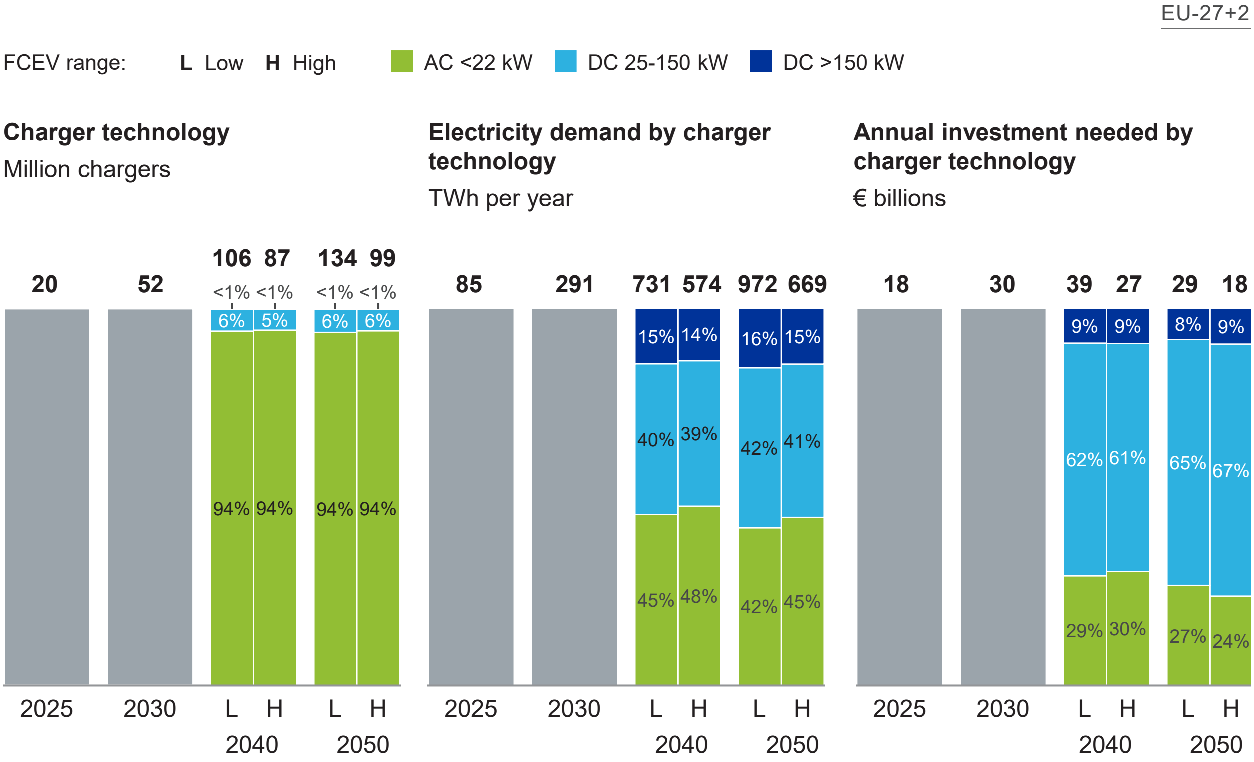


Source: McKinsey Global Energy Perspective

Looking at the charger landscape toward 2050, up to 22 kW AC chargers continue to dominate but are expected to deliver a lower proportion of overall energy over time (roughly 42 to 45 percent by 2050) as higher-capacity DC chargers become more widespread. Similarly, the spend on AC chargers is expected to fall (to around 24 to 27 percent of the total) as more DC chargers are deployed. Through 2050, 25 to 150 kW DC chargers would comprise the bulk of investment on the BEV side, accounting for €12 billion to €19 billion of the €18 billion to €29 billion charger spend per year (Exhibit 31).

Exhibit 31

While slower AC chargers will be the most deployed by volume, fast chargers, especially 25 to 150 kW DC chargers, will drive the majority of BEV investment



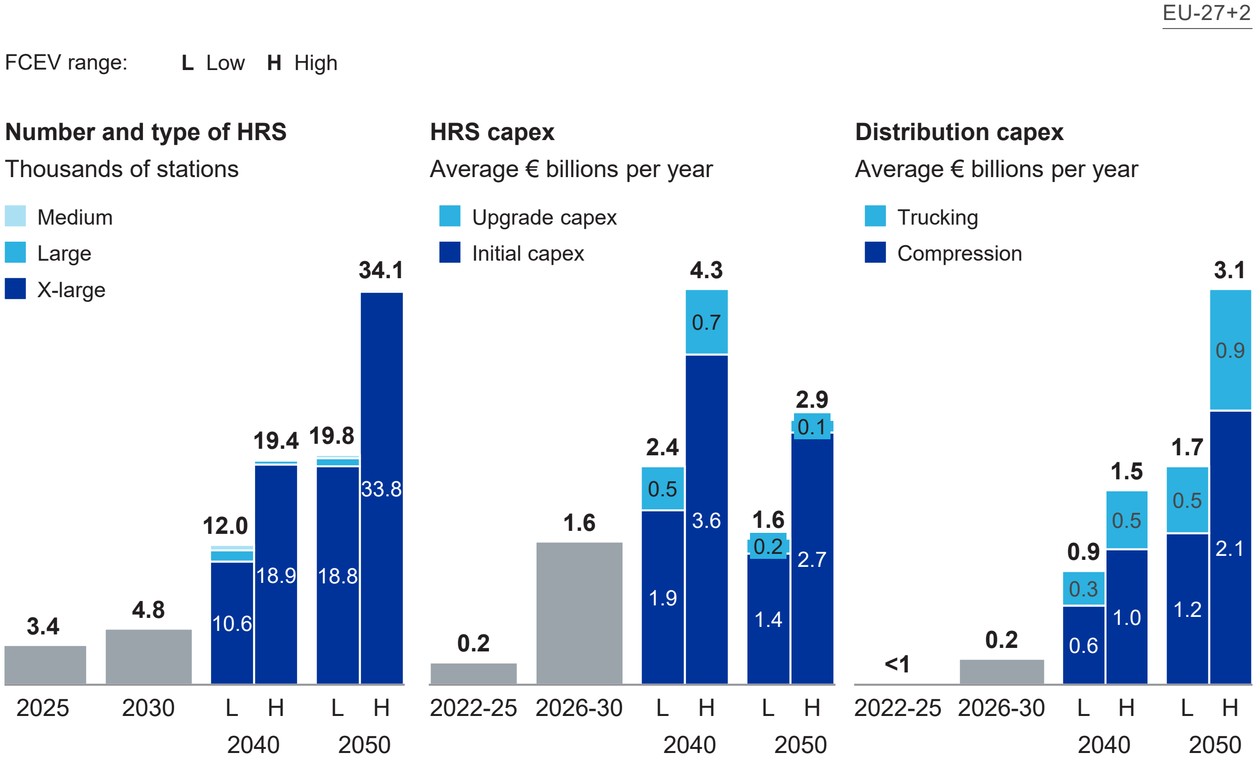
Source: McKinsey Center for Future Mobility; McKinsey Hydrogen Insights FCEV infrastructure model; McKinsey Hydrogen Insights hydrogen demand model

Looking at FCEV infrastructure investments, our "ranged" scenario would require roughly 19,800 to 34,100 HRS to be deployed by 2050, the majority of which would be extra-large stations with a capacity of at least 4,000 kg per day. As with BEV infrastructure spending, annual investments are expected to peak in the 2030s as this period sees the highest vehicle adoption, which then decelerates again after 2040, due to technology and cost improvements.

Like grid costs for BEVs, distribution capital expenditures for FCEVs continue to increase annually through 2050, reaching between €1.7 billion to €3.1 billion per year during the 2040s. A key assumption underpinning trucking estimates in this period is that the trucking distance between pretransportation compression sites and HRS will decrease due to the development of local production sites and hydrogen pipeline networks (excluded from capital expenditures calculations) (Exhibit 32).

Exhibit 32

Despite an increasing number of HRS, HRS capex will decline compared to distribution capex after 2040

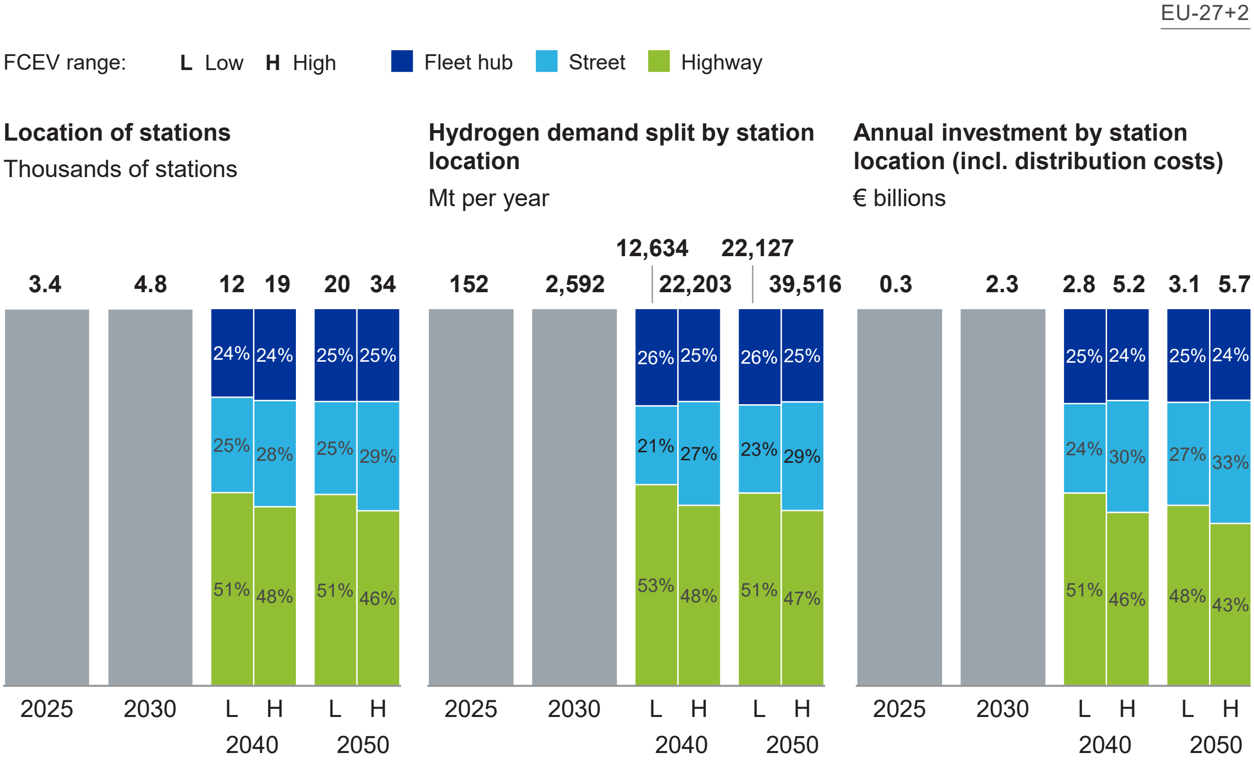


Source: McKinsey Center for Future Mobility; McKinsey Hydrogen Insights FCEV infrastructure model; McKinsey Hydrogen Insights hydrogen demand model

Over time, the mix of HRS would shift with more highway stations being deployed from 2030 onward. By 2050, highway stations would comprise roughly 46 to 51 percent of all HRS, while fleet-hub stations would comprise 25 percent, and street stations 25 to 29 percent (versus a 47 percent share in 2030). As with BEVs, the bulk of energy would be delivered via higher-capacity infrastructure, primarily on highways. Here, highway stations would satisfy 47 to 51 percent of total hydrogen demand and account for 43 to 48 percent of the total investment required to deploy HRS in Europe or about €75 billion to €127 billion in total through 2050 (Exhibit 33).

Exhibit 33

Beyond 2030, roughly half of the HRS network would be located on highways with the remaining stations on streets and at fleet hubs



Source: McKinsey Center for Future Mobility; McKinsey Hydrogen Insights FCEV infrastructure model; McKinsey Hydrogen Insights hydrogen demand model

In the “ranged ” scenario, the total costs for the BEV and FCEV infrastructure ecosystem would reach between €1.0 trillion and €1.2 trillion. This is a sizeable fraction of the estimated €28 trillion needed for the EU to fully complete its net-zero transition, in all sectors, in the same time frame and the roughly €12 trillion that will be spent on transportation to transition the sector to net-zero by 2050.[39] Importantly, while the bulk of investment (79 to 82 percent) would be made post-2030, the mobilization of €220 billion in the near term is not trivial, nor is doing so in a coordinated way across member states and their regions. We explore some key challenges for infrastructure deployment in the EU later in Chapter 3 and infrastructure deployment in member states in Chapter 4 (Exhibit 34).

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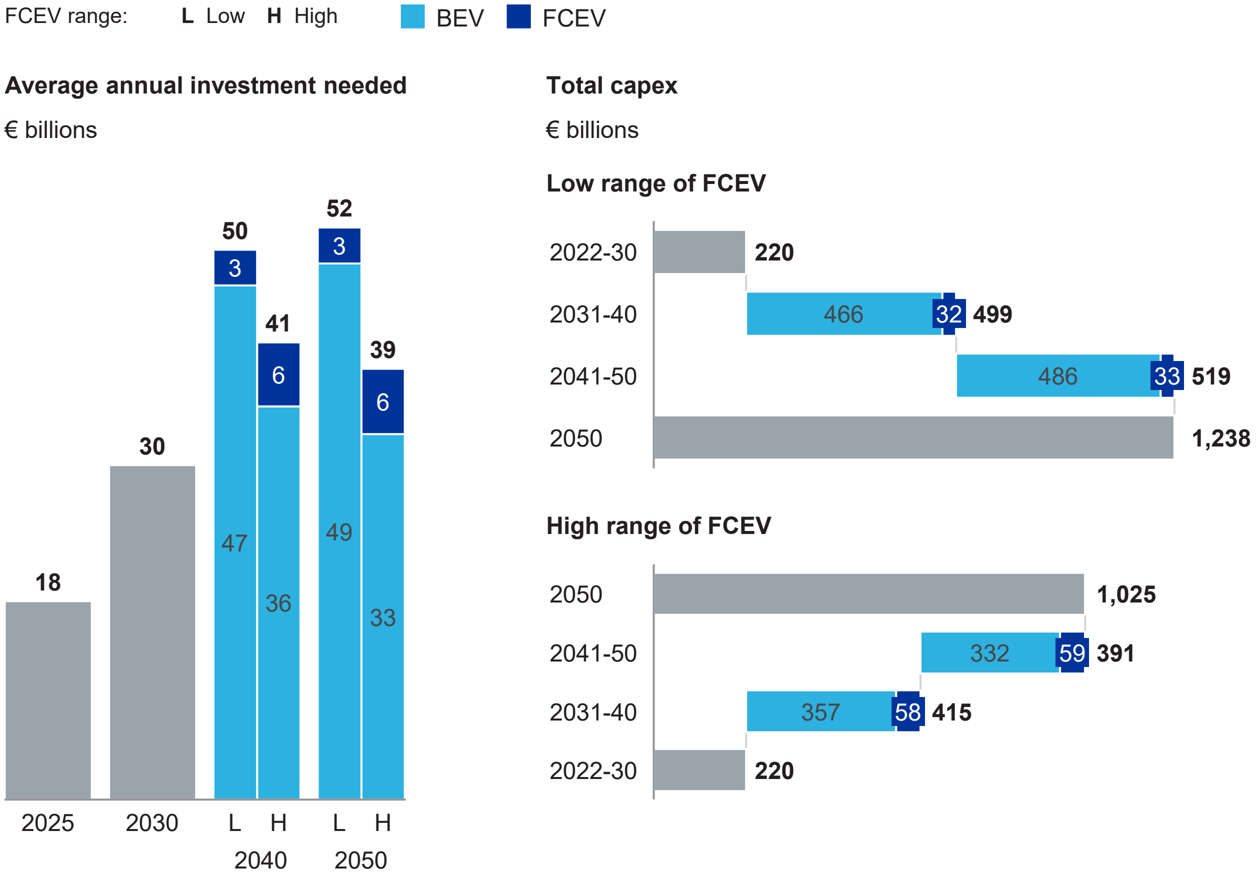
[39] *Net-zero Europe: Decarbonization pathways and socioeconomic implications*, McKinsey, November 11, 2020.

Exhibit 34

Through 2050, a total investment of between €1.0 trillion and €1.2 trillion would be needed, the bulk of which is required beyond 2030



Source: McKinsey Center for Future Mobility; McKinsey Hydrogen Insights FCEV infrastructure model; McKinsey Hydrogen Insights hydrogen demand model

Extreme scenarios and sensitivities

With several long-term possible futures envisaged, we modeled two extreme sensitivities to our “ranged” scenario to demonstrate the impact on infrastructure costs should the power train mix shift in one direction or the other. These sensitivities are not meant to be forecasts or predictions but provide a theoretical degree of change to infrastructure system requirements should various inputs shift (such as the power train mix).

Exhibit 35 shows infrastructure capital expenditure requirements for both the theoretical 100 percent BEV and FCEV model cases compared with the “ranged” scenario for the whole of Europe.

1. **The 100 percent BEV versus a “ranged” combined scenario.** The theoretical scenario in which no FCEV infrastructure is developed and there is no adoption of FCEVs results in higher overall infrastructure costs than our “ranged” scenario. Comparing the two scenarios until 2050, infrastructure costs would increase to cumulative capital expenditures of €1.5 trillion from between €1.0 trillion and €1.2 trillion for the “ranged” scenario, representing a 26 to 52 percent increase. Until 2030, the increase in cumulative capital expenditures is approximately 12 percent or €247 billion, up from €220 billion for the “net-zero” scenario. Looking at the evolution of average annual capital expenditures in line with the cumulative capital expenditures, the difference in cost increases over time from around 16 percent in the 2026 to 2030 period, to 24 to 49 percent in the 2031 to 2040 period, and 35 to 79 percent in the 2041 to 2050 period.

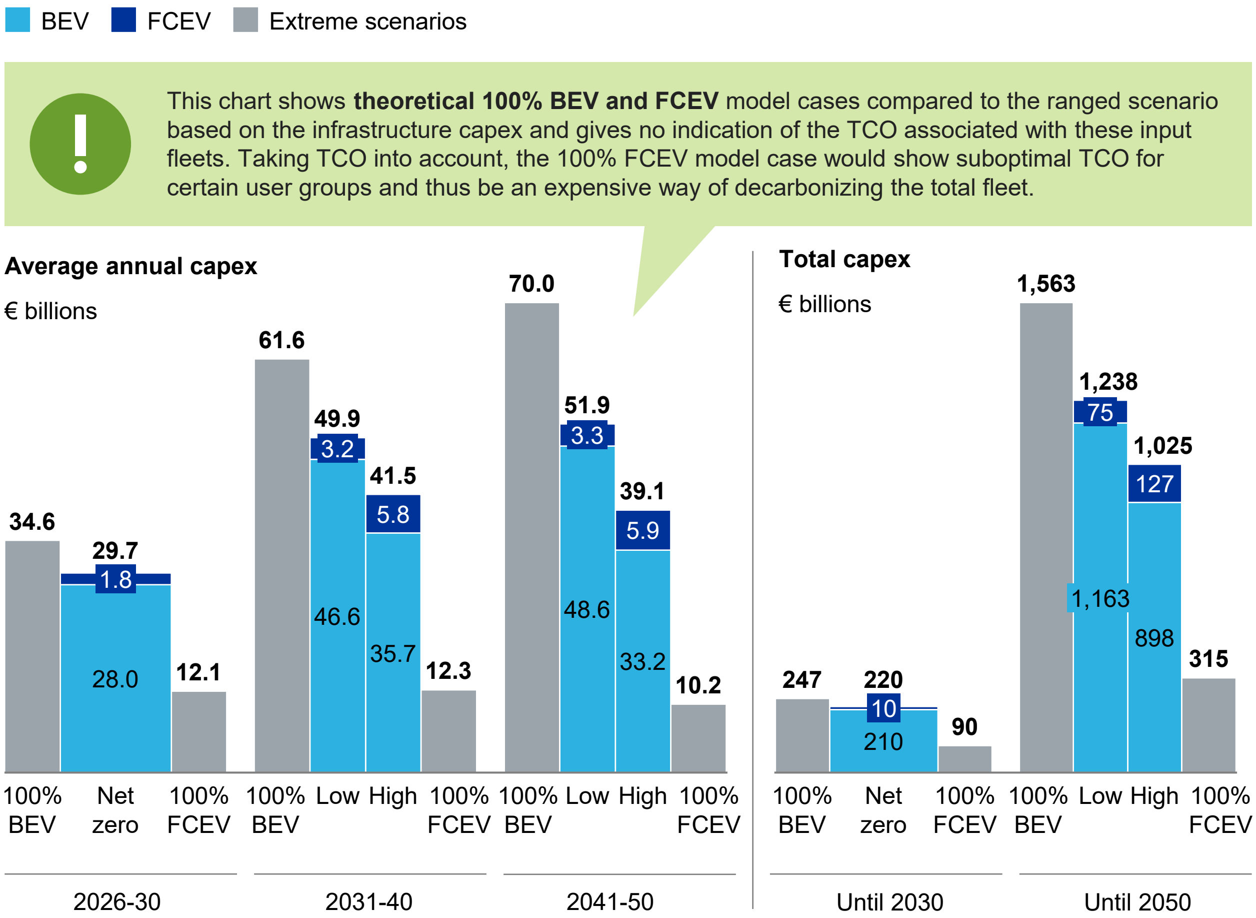
2. **The 100 percent FCEV versus a “ranged” combined scenario.** The theoretical scenario in which no (additional) BEV infrastructure is developed and there is no (additional) adoption of BEVs results in lower overall infrastructure costs versus our “ranged” scenario. Comparing the two scenarios until 2050, we see that total infrastructure costs would decrease to €0.3 trillion from between €1.0 trillion and €1.2 trillion for the “ranged” scenario, representing a 69 to 75 percent decrease. Until 2030, the decrease in cumulative capital expenditures is approximately 59 percent to €90 billion, down from €220 billion for the “net-zero” scenario. Looking at the evolution of average annual capital expenditures in line with cumulative capital expenditures, the difference in cost increases over time from 59 percent in the 2026 to 2030 period, to 70 to 75 percent in the 2031 to 2040 period, and 75 to 80 percent in the 2041 to 2050 period.

Note: these figures contain infrastructure capital expenditures only and do not incorporate other cost perspectives, such as TCO. Taking TCO into account, the 100 percent FCEV case would show suboptimal TCO and thus be an expensive way of decarbonizing the fleet. Furthermore, individuals would not be able to make choices based on their personal use cases or economics.

(For further discussion on TCO, please see the “Incorporating complementary viewpoints on costs” section later in this chapter).

Exhibit 35

An infrastructure capex comparison of extreme power train split cases



This chart shows **theoretical 100% BEV and FCEV** model cases compared to the ranged scenario based on the infrastructure capex and gives no indication of the TCO associated with these input fleets. Taking TCO into account, the 100% FCEV model case would show suboptimal TCO for certain user groups and thus be an expensive way of decarbonizing the total fleet.

Source: McKinsey Center for Future Mobility; McKinsey Hydrogen Insights FCEV infrastructure model; McKinsey Hydrogen Insights Hydrogen Demand model; McKinsey Global Energy Perspective

Sensitivity to accelerated FCEV adoption

With several futures envisaged, we modeled an “accelerated” scenario to our “net-zero” scenario to demonstrate the impact on infrastructure costs should the adoption of FCEV power trains increase faster to 2030. These sensitivities are not forecasts or predictions but provide a theoretical degree of change to infrastructure system requirements should input shift (such as the mix of BEVs and FCEVs in this case).

Impact of increasing the FCEV share in the vehicle mix. Starting from our “net-zero” scenario in which FCEVs account for around 13 percent of the 2030 vehicle park, a 10 percent increase in FCEVs (or increasing the FCEV share from 13 percent to just over 14 percent of total vehicle park) yields a 14 percent decrease in total infrastructure system costs (Exhibit 36).

Exhibit 36

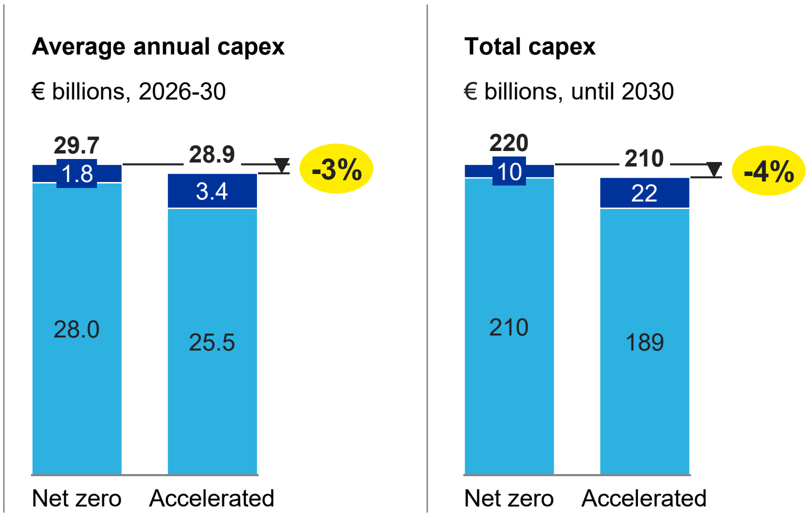
Accelerated FCEV uptake through 2030 could reduce total infrastructure capex requirements

🟦 BEV ■ FCEV

Sensitivity

Comparison of input xEV car parks until 2030:

The "net-zero" scenario compared to an "accelerated" FCEV share in this period with increase of 10% points in FCEVs vs. total xEVs, offset by 10% point decrease in BEVs



Source: McKinsey Center for Future Mobility; McKinsey Hydrogen Insights FCEV infrastructure model; McKinsey Hydrogen Insights Hydrogen Demand model; McKinsey Global Energy Perspective

Increasing the share of FCEVs in the xEV power train mix would reduce the overall system investments required but dramatically increase investments needed for FCEV rollout—particularly in the short term (around 380 percent higher in 2022 to 2025 than in the lower "net-zero" scenario and 93 percent higher in the 2025 to 2030 period). The capital-expenditure-intensive nature of large and extra-large stations is the key driver behind the increase in investment requirements to deploy FCEV infrastructure. In the short term (until 2030), there would be proportionally more large and extra-large stations to deploy to feed the uptake in hydrogen demand from the increase in the share of FCEVs in the xEV mix than in the "net-zero" scenario.

However, this larger FCEV fleet could still rely on the minimum network envisaged and the number of HRS will not be a driver of increased FCEV infrastructure investment needs. Instead, the capacity overbuilds planned in the "net-zero" scenario will be sufficient to supply the demand implied by an increase in the share of FCEVs in the xEV mix, though station utilization rates will be higher. Even with this increase in FCEVs, the minimum network will become insufficient in both scenarios from around 2025 onward, and additional stations will need to be deployed.

Box 2

Exploring FCEV adoption: Acceleration of FCEV PC adoption thanks to uptake by captive fleets

FCEVs are in the early stages of deployment, currently representing less than 1 percent of vehicles on the road across segments. Opportunities to increase and accelerate FCEV penetration are welcomed by the industry. Thanks to technological advantages displayed by fuel-cell power trains in HDVs (trucks and buses), there is hope that commercial vehicles (LCVs, trucks, and buses) will experience the largest acceleration in FCEV penetration in the near future. There may also be an opportunity for more rapid FCEV expansion in other segments, particularly through captive fleet vehicles, such as taxis. Increased penetration in this segment could further catalyze the development of FCEV infrastructure.

FCEVs display some key advantages when deployed as part of a captive fleet (like urban taxis) and can help scale-up the overall xEV ecosystem and supporting infrastructure.

Increased BEV infrastructure access and capacity. BEV taxi drivers can potentially block chargers to maintain maximum charge while waiting for customers, making access difficult for noncommercial drivers of PCs. Deploying FCEVs for taxi fleets can help free up existing public BEV chargers and reduce the need to install more.

Solution to insufficient at-home charging. BEV taxi drivers—especially those living in cities with distributed taxi fleets (like Paris)—may have limited access to secured home or overnight charging; however, operating FCEVs with access to HRS would solve this issue.

TCO is not the core decision driver for vehicle selection. TCO is a primary driver of vehicle selection for many. Thus, the lower TCO for BEV PCs in the short term makes them preferential for certain users. However, this difference is potentially less important for independent taxi drivers who accept to join a fleet based on a "packaged" costs offered to them by taxi operators. Higher customer acquisition and revenue potential can trump vehicle costs in the vehicle selection process for these users.

Station location is less critical for taxis. In cities with distributed taxi activity, such as Paris, taxi drivers do not rely on the same refueling hubs and are willing to drive to refueling stations that are farther away (like at airports). Moreover, while in service, taxi drivers do not keep vehicles at a centralized hub.

Increased customer adoption with reduced off-take risk for OEMs. Automotive OEMs want assurance that vehicles will be sold before they increase production. FCEV deployed as part of taxi fleets could provide a starting point for technology development and spur early customer adoption by corporates and individuals (for example, by giving more zero-emissions alternatives to companies choosing only "green" taxis). Higher-volume orders (like those from captive fleets) could potentially help reduce off-take risk in the earliest stages of deployment.

3.B.3

Cross-border connectivity and deployment along TEN-T corridors

As cross-border connectivity is critical to Europe's economy, we also explore implications for infrastructure deployment along key transportation corridors in the EU. To do so, we investigated the results of our infrastructure models and implications in the context of Europe's TEN-T corridors.[40] We acknowledge the AFIR (discussed in Section 1. B.2 Regulatory support for zero-emission mobility in member states) and will use this as the point of comparison in our discussion.[41]

For public chargers in 2050, the results are presented per vehicle segment:

1. **LDVs.** Depending on the upper or lower end of the "ranged" scenario, between 27,000 and 32,000 public fast chargers would be located along the TEN-T corridors. This results in between 93 and 111 public fast chargers per 100 km of roadway. There is a variability of between 56 and 202 public fast chargers per 100 km of roadway between the corridors.

2. **HDVs.** Depending on the upper or lower end of the "ranged" scenario, between 5,500 and 8,200 public fast chargers would be located along the TEN-T corridors. This results in between 19 and 29 public fast chargers per 100 km of roadway.

The difference in the number of chargers required for LDVs and HDVs is due to the difference in the number of vehicles on the road. While there are a multitude of BEV PCs on the road, in the scenarios discussed above there are fewer HDVs compared to FCEVs, and the majority engages in off-highway charging (Exhibit 37).

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[40] "The Trans-European Transport Network (TEN-T) policy addresses the implementation and development of a Europe-wide network of railway lines, roads, inland waterways, maritime shipping routes, ports, airports and railroad terminals. The ultimate objective is to close gaps, remove bottlenecks and technical barriers, as well as to strengthen social, economic and territorial cohesion in the EU." https://transport.ec.europa.eu/transport-themes/infrastructure-and-investment/trans-european-transport-network-ten-t_nl.

[41] The AFIR text is currently under discussion and subject to change. Our analysis is based on the text in April 2022.

Methodology

For both public chargers and HRS in 2050, the same methodology was applied to assess xEV infrastructure deployment needs along TEN-T corridors. The Electric Vehicle Charging Infrastructure (EVCI) model calculates the total number of chargers needed on European highways and then models what share of this total is required in the TEN-T. The breakdown considers various factors which are different for each country and TEN-T network. The key factors for the calculation are: (1) the proportion of kilometres on TEN-T corridors compared to the total highway kilometres for each country, (2) the annual average daily traffic per TENT-T corridor, and (3) the proportion of HDVs versus LDVs per TEN-T corridor. Furthermore, an annual average daily traffic weighting factor was applied to estimate the total number of public chargers and HRS on the TEN-T and their average distribution per 100 km of road for each segment. The public fast charger analysis was done for each vehicle segment, while HRS was estimated for both segments combined.

Exhibit 37

In 2050, ~100 chargers are required per 100 km on TEN-T for LDVs compared to 20 to 30 for HDVs

Main corridors of EU TEN-T road network, 2050, highway stations

▇ Lower bound ▇ Higher bound

Public fast chargers on highways, 2050

TEN-T corridor	Length Thousand km	LDVs Thousand		LDVs Per 100 road km		HDVs Thousand		HDVs Per 100 road km	
Mediterranean	6.4	3.9	4.9	61	77	0.9	1.2	13	19
Scandinavia–Mediterranean	4.9	4.9	5.7	100	117	0.7	1.0	14	21
Atlantic	4.6	2.6	3.1	56	66	0.4	0.6	9	13
North Sea–Baltic	3.1	4.3	4.9	139	159	1.0	1.5	34	50
Orient–East Mediterranean	2.9	2.0	2.7	67	92	0.5	0.9	17	31
Baltic–Adriatic	2.7	1.8	2.5	68	93	0.7	1.2	27	43
North Sea–Mediterranean	1.7	3.1	3.4	178	197	0.4	0.6	26	35
Rhine–Danube	1.4	2.2	2.7	157	193	0.5	0.8	36	56
Rhine–Alpine	1.1	2.0	2.2	183	202	0.3	0.4	27	38
Total	**28.9**[1]	**27-32**		**93-111**[2]		**5.5-8.2**		**19-29**[2]	

[1] Referred to current completed road kilometers.
[2] Weighted average.

Source: McKinsey; Trans-European Transport Network (TEN-T)

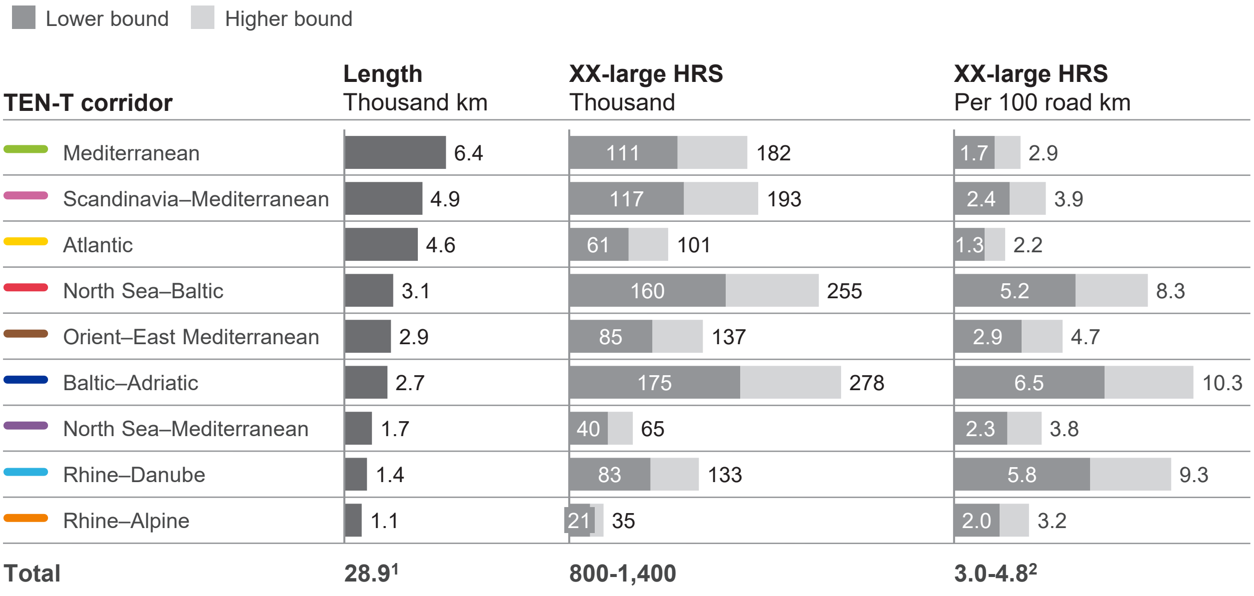
In 2050, depending on the upper or lower end of the "ranged" scenario, between 800 and 1,400 extra-extra-large HRS can be found on each TEN-T corridor. This results in an average of between 3.0 and 4.8 HRS per 100 km of roadway. There is a variability of between 1.3 and 10.3 HRS per 100 km of roadway between the corridors.

An HRS on the TEN-T is considered extra-extra-large if it has eight to 16 nozzles and a maximum daily capacity of 16,000 kg, or is four times the size of an extra-large station (that is 4,000 kg maximum daily capacity and two to four nozzles) (Exhibit 38).

The higher number is in line with the 2019 average of 4.8 petrol stations located every 100 km on the TEN-T.

Exhibit 38

In 2050, on average between 3 and 4.8 XX-large HRS are expected per 100 km on TEN-T highways



TEN-T corridor	Length Thousand km	XX-large HRS Thousand	XX-large HRS Per 100 road km
Mediterranean	6.4	111 182	1.7 2.9
Scandinavia–Mediterranean	4.9	117 193	2.4 3.9
Atlantic	4.6	61 101	1.3 2.2
North Sea–Baltic	3.1	160 255	5.2 8.3
Orient–East Mediterranean	2.9	85 137	2.9 4.7
Baltic–Adriatic	2.7	175 278	6.5 10.3
North Sea–Mediterranean	1.7	40 65	2.3 3.8
Rhine–Danube	1.4	83 133	5.8 9.3
Rhine–Alpine	1.1	21 35	2.0 3.2
Total	**28.9**[1]	**800-1,400**	**3.0-4.8**[2]

[1] Referred to current completed road kilometers.
[2] Weighted average.

Source: McKinsey; Trans-European Transport Network (TEN-T)

3.C

Incorporating complementary viewpoints on costs

The comparison between BEV and FCEV costs has different outcomes when incorporating different views. This section investigates views on the TCO and cost of energy delivered.

— **TCO.** Prior to 2030, most segments display lower TCO for BEVs than FCEVs; after 2030, FCEV TCO becomes cheaper in some segments, notably those that display high yearly mileage (like heavy-duty trucking and long-distance buses).

— **Cost of energy delivered.** If the electricity to power BEVs and make green hydrogen to fuel FCEVs comes from the same source, BEVs display lower energy costs than FCEVs. This is due to FCEVs having a less energy-efficient value chain than BEVs, notably due to the additional steps incurred (like electrolysis and compression).

3.C.1

TCO

In a TCO view, the BEV versus FCEV comparison has a different outcome than when solely comparing infrastructure costs. When including operating expenditures and depreciation costs, BEVs are cheaper in all segments prior to 2030. After 2030, FCEVs slowly become cheaper in certain segments but BEVs remain most attractive for LCVs and HDVs traveling shorter distances in the long term (Exhibit 39).

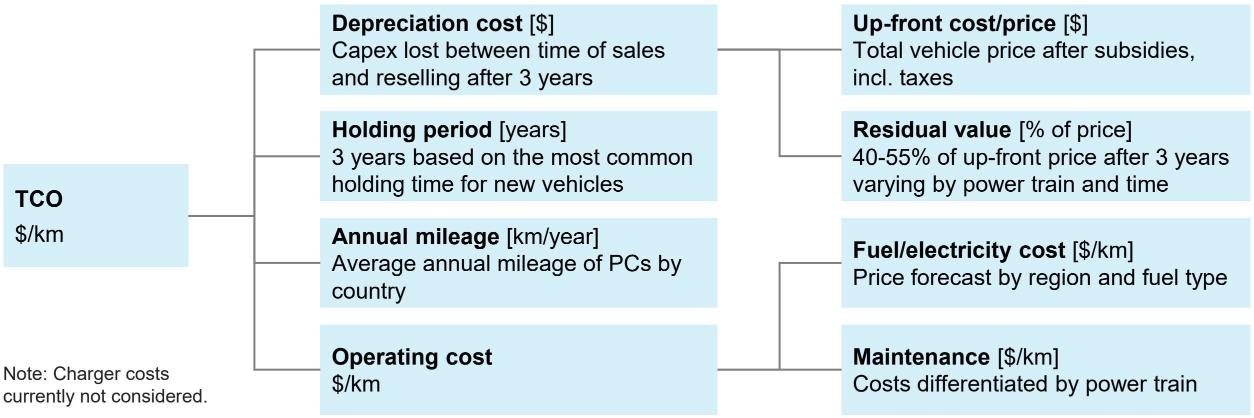
For PCs, the TCO of the two technologies is expected to converge. The TCO for FCEVs is expected to reach parity with BEVs around 2030 for private-use PCs and in 2029 for high annual mileage cars (like taxis). Post-2030, TCOs are expected to continue decreasing, with FCEVs displaying lower TCOs than BEVs in this segment. Uncertainties around some key TCO drivers remain (including battery costs, fuel cell costs, and hydrogen refueling costs), which could either push out or pull forward this timeline.

For commercial vehicles, FCEV and BEV TCOs are also converging. However, discrepancies will remain between the different types of commercial vehicles. HDVs and long-distance buses (coaches), are expected to display lower TCOs for FCEVs than BEVs. Fuel cell and battery HDVs and long-distance buses are expected to reach TCO parity around 2028 and 2027, respectively. In other commercial vehicle segments (like LCVs, MDVs, and short- and medium-distances buses), BEV TCO is expected to remain lower than FCEV TCO for the foreseeable future. Additional uncertainties around some key TCO drivers (including battery costs, fuel cell costs, and hydrogen refueling costs) remain, which could either push out or pull forward this timeline.

Given converging power train costs, countries with different operating costs will reach TCO parity at different points in time. For example, Germany may have a large advantage in hydrogen prices due to a large volume of expected local hydrogen production and high electricity prices and should reach TCO parity between FCEV and BEV PCs in 2030. Other countries with cheap electricity and lower potential for local hydrogen production may take more time to reach TCO parity between BEVs and FCEVs.

Exhibit 39

The TCO power train is derived from annual depreciation (capex) and operational costs (opex)



TCO
$/km

Depreciation cost [$]
Capex lost between time of sales and reselling after 3 years

Holding period [years]
3 years based on the most common holding time for new vehicles

Annual mileage [km/year]
Average annual mileage of PCs by country

Operating cost
$/km

Up-front cost/price [$]
Total vehicle price after subsidies, incl. taxes

Residual value [% of price]
40-55% of up-front price after 3 years varying by power train and time

Fuel/electricity cost [$/km]
Price forecast by region and fuel type

Maintenance [$/km]
Costs differentiated by power train

Note: Charger costs currently not considered.

Source: McKinsey Center for Future Mobility – Electrification

3.C.2

Cost of energy delivered

From a cost of energy delivered perspective, the BEV and FCEV comparison also has a different outcome than from an infrastructure cost point of view. Well-to-wheels efficiency is significantly higher for BEVs than FCEVs at around 80 to 90 percent for BEVs (losses occur during transmission, charging, and tank-to-wheel) versus around 25 to 35 percent for FCEVs (losses occur in the electrolysis process, during distribution, and tank-to-wheel). Therefore, if a BEV and an FCEV use the same source of renewable energy, the energy cost to drive 100 km in a BEV would be significantly lower than for an FCEV. This is due to higher efficiency rates for BEVs as a result of less fractured well-to-wheels value chains (the FCEV well-to-tank value chain includes additional steps like electrolysis, compression, liquefaction, and hydrogen transportation, that induce high energy losses).[42]

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[42] Hydrogen Council "Roadmap towards zero emissions" Report.

3.D

Synergies to consider for BEV and FCEV infrastructure deployment in the EU

In this section, we discuss the synergies that can present additional opportunities across technologies, industries, and sectors.

Methodology

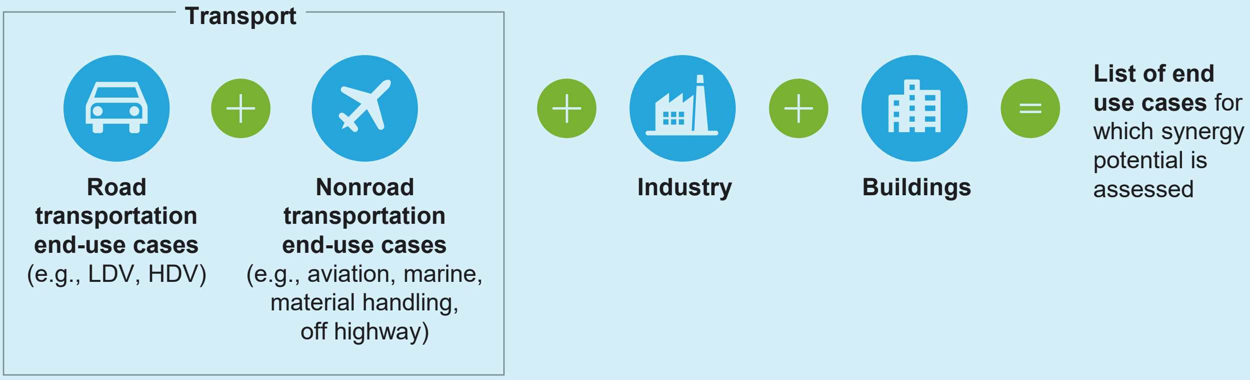
Multiple synergies may arise from the deployment of BEV and FCEV infrastructure. We have explored these synergies across the infrastructure value chain. They include upstream synergies through economies of scale, thanks to increasing demand from different use cases, and midstream synergies around the interoperability of the distribution network.

To assess these synergies, we broadened the horizon from the road transportation use cases that are the focus of this report to other energy consumers in nonroad transportation (like aviation, marine, and railway), industry, and buildings. We looked at individual synergies between these use cases and FCEVs or BEVs (Exhibit 40).

Exhibit 40

Methodology: Synergy potential has been assessed for transport, nonroad transport, industry and building end-use cases

Energy consumers



Source: McKinsey Hydrogen Insights

For FCEVs, the competition around hydrogen supply (see limitations) could be reframed as an opportunity for synergies. As the upstream infrastructure is identical for most use cases, capacities need not be built exclusively for one use case but shared among all. This implies that a critical demand level supporting the build out of green hydrogen supply is reached early on and that cumulative demand across all use cases will rapidly drive down costs through economies of scale. We expect these economies of scale to account for half of the total expected cost reduction of around 70 percent for electrolyzers by 2030, through a combination of more efficient production techniques at higher volumes (for example, roll-to-roll processing for membrane or diaphragm coating), better write-off or fixed-cost coverage for specialized production equipment, and a higher level of competition in larger markets (Exhibit 41).

Exhibit 41

Upstream and midstream sections of the road transportation fuel-cell value chain have synergies with nonroad transportation use cases

Synergies between FCEV downstream, mid- and upstream value chains

Upstream	**Hydrogen supply**	Nonroad transportation shares the **same upstream infrastructure** (e.g., electrolyzers, plant equipment) as road transportation end use cases—unveiling a potential for **economies of scale** Road transportation will benefit from the development of **production capacity at strategic sites** (e.g., ports and industrial sites)
Midstream	**Compression**	**Interoperability of compression infrastructure** will allow road and nonroad transportation (e.g., building and industry) to mutually benefit from the development of such infrastructure
	Distribution	**Interoperability of distribution networks** (e.g., pipeline transmission network, local buffer storage) will allow road and nonroad transportation (e.g., off-road transportation, building, industry) to mutually benefit from the development of such infrastructure
Downstream	**Refueling**	**Limited opportunities** for nonroad transportation to refuel at FCEV HRS

Source: McKinsey Hydrogen Insights; expert inputs

A similar argument can be made for midstream synergies. While the infrastructure for compression and distribution is only partially shared between road transportation and non-road transportation or industries, there could still be interoperability between the use cases leading to shared benefits (such as, increased fixed-cost coverage and economies of scale) for certain applications (Exhibit 42, Exhibit 43).

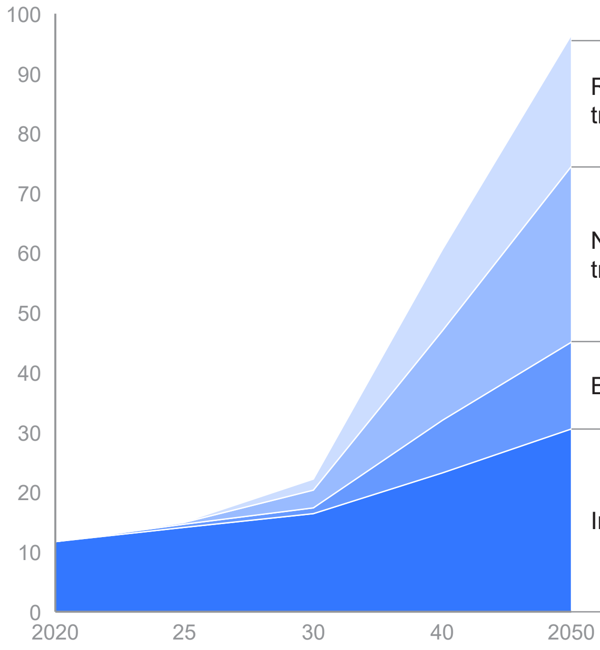
Exhibit 42

Nonroad transportation, building, and industry will account for ~100 million metric tons of total hydrogen demand by 2050 and share a significant part of their value chain with road transportation end-use cases

✓ Shared ⋰ Partly shared[1] ✕ Not shared

Hydrogen demand per end use for EU-27+2,

M metric tons of hydrogen



	Upstream	**Midstream**	**Downstream**
Road transportation	✓	✓	✓
Nonroad transportation	✓	⋰	✕
Buildings	✓	✓	✕
Industry	✓	⋰	✕

---

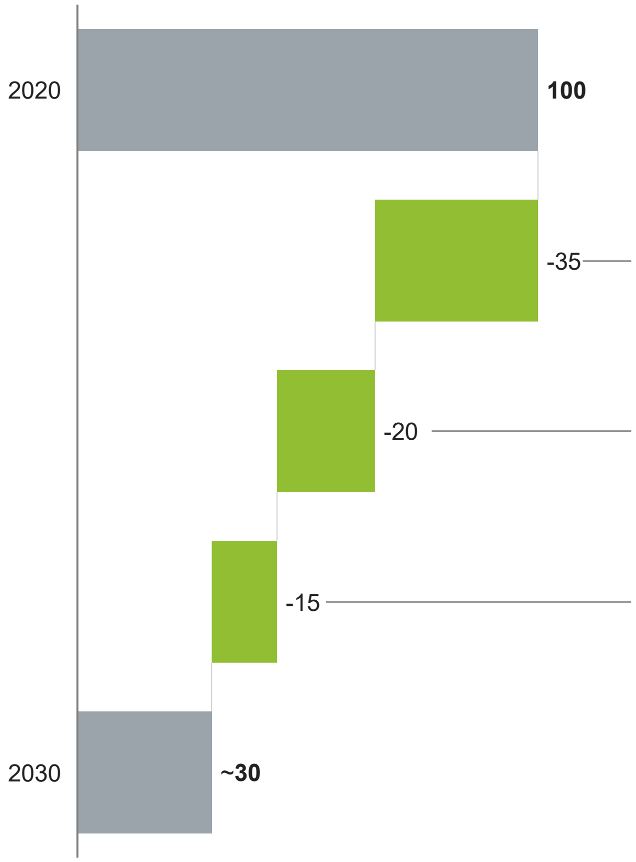
[1] Maritime (35% of nonroad transportation demand in 2050) does not share midstream infrastructure.

Source: McKinsey Hydrogen Insights

Exhibit 43

Production scale will account for ~35% of electrolyzer cost decreases, unveiling potential of economies of scale

Expected electrolyzer cost decrease, percent



Drivers of cost decrease

Increased production scale. Higher manufacturing volumes and shift to, e.g., roll-to-roll processing for membrane or diaphragm coating, better write-offs of specialized production equipment (e.g., x-ray scanners to determine leakage or brittleness of hydrogen conducting pipes and seals), and broader supply base with higher level of competition

Improved system design. Optimization of plant layout, pipework, interconnection, finding the optimal size, and leveraging modular design for multiple use cases; technology transfer from renewables in power electronics and transformers

Improved stack design. Reduction of precious metal content in catalysts (e.g., 80-90% reduction in platinum (Pt) and iridium (Ir) loadings for PEM); increased power density for both PEM and alkaline

Source: Expert interviews; McKinsey Hydrogen Insights

For BEVs, the synergies are also centered around upstream opportunities. The prevalence of BEVs will require an increase in renewable power generation, which—with increased demand for renewables in other sectors—could reduce costs through economies of scale. The overall power capacity will need to satisfy demand even in peak hours. With the ability to smart charge at off-peak hours, BEVs will play a significant role in making the best use of this power capacity by flattening the demand profile throughout the day. With V2G functionality, BEVs could further increase the system's stability and alleviate the need to design the system to cope with extreme demand or supply (due to volatile renewable power generation) spikes (Exhibit 44, Exhibit 45).

Exhibit 44

Upstream and midstream sections of the road transportation battery value chain presents synergies with nonroad transportation

Synergies between BEV downstream, mid- and upstream value chains

Upstream	**Electricity supply**	Road and nonroad transportation will **mutually benefit** from **increased green electricity production capacity,** notably through economies of scale The development of road transportation uses, notably thanks to **smart charging,** can **make energy available** to other uses (e.g., through V2G technology)
Midstream	**Electricity grid**	The development of road transportation and other use cases using **batteries** (e.g., building, distributed energy resource systems), thanks to smart charging, can **enhance peak demand management** and thus benefit all other uses **Grid extensions** required for the electrification of buildings (e.g., heat pumps) and industry **will happen simultaneously** with grid extensions required for road transportation uses
Downstream	**Charging**	**Limited opportunities** for nonroad transportation end-use case to use BEV chargers

Source: McKinsey Center for Future Mobility

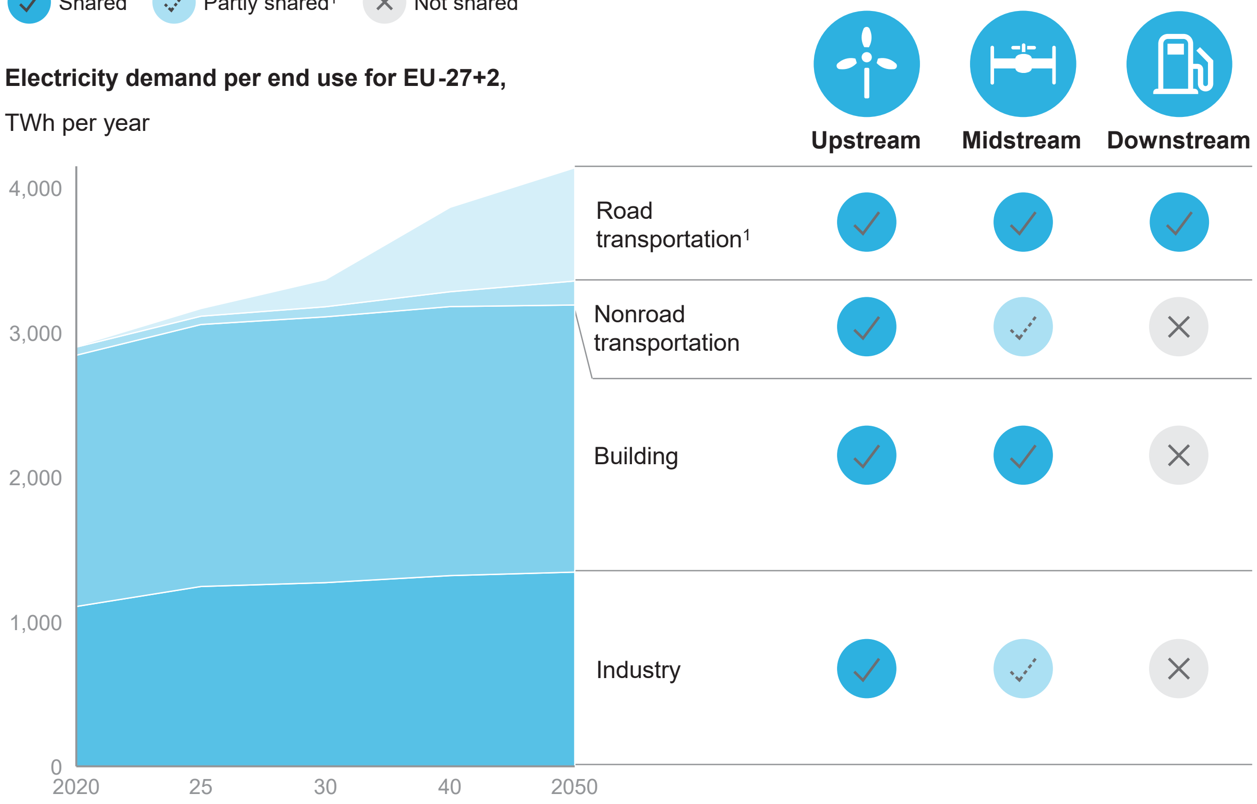
Exhibit 45

Nonroad transportation, building, and industry will account for >80% of total electricity demand by 2050 and share a significant part of their value chain with road transportation end-use cases

✓ Shared ⋰ Partly shared[1] ✕ Not shared

Electricity demand per end use for EU-27+2,

TWh per year



	Upstream	Midstream	Downstream
Road transportation[1]	✓	✓	✓
Nonroad transportation	✓	⋰	✕
Building	✓	✓	✕
Industry	✓	⋰	✕

---

[1] Excluding electrolysis for FCEV.

Source: McKinsey Hydrogen Insights

BEVs have already kicked off a significant ramp-up in battery innovation. With BEV adoption increasing further, battery prices are expected to continue to decline. In addition to the V2G functionality, this price decline will make battery buffers increasingly viable, further stabilizing power generation, for example, by reducing current volatility through renewables.

Synergies between BEVs and other renewable electricity use cases will not be limited to upstream electricity supply but carry over to opportunities around transmission and distribution grids. The ability to smart charge helps reduce power-generation requirements, the peak load on (local) electricity distribution grids, and, consequently, the need to upgrade. As it is, a certain level of grid upgrades will be required to support the electrification of buildings, industry, and road transportation and BEVs will share this burden (Exhibit 46).

Exhibit 46

Smart charging allows BEVs and other use cases using batteries to lower grid pressure and thus benefit to all other use cases

Applicability ✓ Yes (✓) Partial (i.e., can decrease response) ✗ No

		Smart charging			
Energy service	**Standard charging** Unidirectional power flow from grid to vehicle at a certain point in time	**V1G** Unidirectional power flow from grid to vehicle at variable points in time	**V2G** Bidirectional power flow between the grid and vehicle at variable points in time	**Stationary storage** Bidirectional power flow between the grid and stationary battery at variable points in time	**Grid investments** Grid reinforcement to increase resilience to load variability
Peak shaving/ load leveling	✗	✓	✓	✓	✓
Frequency regulation	✗	(✓)	✓	✓	✗
Voltage control	✗	(✓)	✓	✓	✓

Source: McKinsey Center for Future Mobility

3.E

Limitations and bottlenecks for infrastructure deployment in the EU

We start with a set of key concerns around the deployment of BEV and FCEV infrastructure and develop a fact base tailored to each concern to arrive at a data-driven assessment of potential limitations. In total, we answer ten typical questions raised by experts associated with the development of BEV and FCEV infrastructure. The questions are centered around the topics of energy supply, distribution capacities, raw material availability, labor, regulatory support, the attractiveness for private investments, and concerns around efficiency and capacity in distribution, regulation, and vehicles (Exhibit 47).

The availability of green hydrogen (Question 1) is particularly relevant as hydrogen demand for FCEVs is in direct competition with hydrogen demand from other sectors, be it industry, buildings or other (nonroad) transportation sectors. This risk may be mitigated by initiatives like the REPowerEU Plan, which aims to increase hydrogen supply by setting a target of ten million metric tons of domestic renewable hydrogen production and ten million metric tons of renewable hydrogen imports by 2030. Green hydrogen supply may be further stimulated by increased requirements for sustainable fuel use laid out in the Fit for 55 plan by the European Commission.[43]

Using a comprehensive database of announced hydrogen production projects, we assessed the cost trajectory and overall production potential for different types of hydrogen (green, blue, and grey). One risk is that grey hydrogen will continue to form a large part of the hydrogen produced, or the technology to capture CO_2 from blue hydrogen will not materialize, preventing the decarbonization of road transportation. A second risk is that green hydrogen produced in a continuous process will compete for the limited renewable energy resources, requiring further grid upgrades. We consider it likely that the overall hydrogen supply will be able to cover demand from most uses, with the aim of green hydrogen playing an increasing role in hydrogen supply. However, to meet demand, we will likely continue to rely on a large share of blue hydrogen, with more than 50 percent of hydrogen supply relying on carbon capture and storage to achieve CO_2 neutrality (Exhibit 48).

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[43] EU REPowerEU Plan.

Exhibit 47

We’ve aspired to answer ten top-of-mind questions on the challenges facing the deployment of xEV infrastructure

✔ Yes ✓ Under certain circumstances ✗ No

Energy supply	**1. Will there be enough green hydrogen supply to meet FCEV demand?**	✓	Green hydrogen supply will exceed road transportation demand
	2. Will there be enough green electricity supply to meet BEV demand?	✔	Green electricity supply will exceed road transportation demand, but the total energy mix will still include other sources (e.g., natural gas)
Raw materials	**3. Will there be sufficient raw materials available to support the transition to clean mobility?**	✓	For example, a material like nickel could be in short supply, especially if recycling is not intensified. There is significant ongoing research into using alternative metals
Labor	**4. Will there be enough skilled labor to support the transition to clean mobility?**	✓	There is a need to upskill labor to specific needs to meet demand (e.g., electricity and gas jobs)
Investments	**5. Can the FCEV and BEV industries attract sufficient (early) investors without additional incentives?**	✗	Without supporting incentives, high up-front investments (esp. for FCEV infrastructure) can deter early investors
Distribution	**6. Is trucking the most efficient way of distributing hydrogen?**	✓	Yes, for small quantities and a nascent network, but for large quantities a pipeline is more efficient
	7. Is the grid strong enough to support the energy transition and BEV penetration?	✗	The grid will require additional investments to support the energy transition
Infrastructure and vehicles	**8. Are there local regulatory requirements that impede FCEV development?**	✔	There are some local environmental regulations that require HRS developers to apply for specific permits if capacity surpasses a threshold
	9. Is the FCEV value chain energy efficient compared to BEVs?	✗	FCEVs are less efficient than BEVs due to losses when producing, transporting, and converting hydrogen back to electricity[1]
	10. Are enough FCEV models available to the customers?	✗	Current model announcements place the short-term model availability of FCEVs far below that of BEVs and ICE vehicles. However, FCEV vehicle technology is rapidly developing

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[1] However, green hydrogen may represent renewable energy otherwise not captured entering the energy value chain.

Source: McKinsey Center for Future Mobility; McKinsey Hydrogen Insights FCEV infrastructure model; McKinsey Hydrogen Insights Hydrogen Demand model; McKinsey Global Energy Perspective

The ten top-of-mind questions surrounding limitations and bottlenecks for xEV infrastructure were developed through engagement with subject matter experts. We present deep dives on questions 1, 2, and 6 over the following pages.

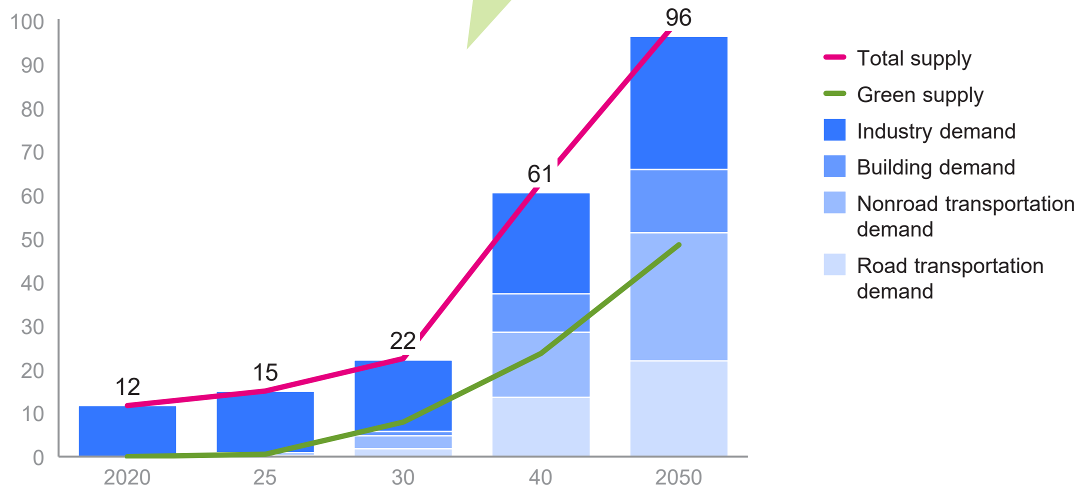
Exhibit 48

1. Will there be enough green hydrogen supply to meet FCEV demand?

Hydrogen supply will cover demand from the different end-use cases and will increasingly become green

Note on supply: The supply figures on this graph should increase due to the REPowerEU plan announced by the European Commission, which sets a target of 10 million metric tons of domestic renewable hydrogen production and 10 million metric tons of renewable hydrogen imports by 2030, alongside proposals to substantially increase the renewable hydrogen fuel production in the Renewable Energy Directive.

Hydrogen supply and demand,[1]
M metric tons



[1] Hydrogen supply and demand for EU-27+2 as of Q4 2021.

Source: McKinsey Hydrogen Insights

Another major concern is the availability of skilled labor (Question 4) required to support the envisioned mobility transition. We highlighted the current shortages based on vacancy rates in three key sectors required for the mobility transition (construction, utilities supply, and transportation and storage) in selected member states. While there is already an ongoing shortage in some of these trades in some member states (for example, construction workers in Germany)—an issue that is expected to become more widespread with changes in demographics and increased demand for these skills—the impact of labor shortages is not limited to the mobility industry and opportunities for large-scale up- or reskilling of the current workforce might exist to meet the demand (Exhibit 49).

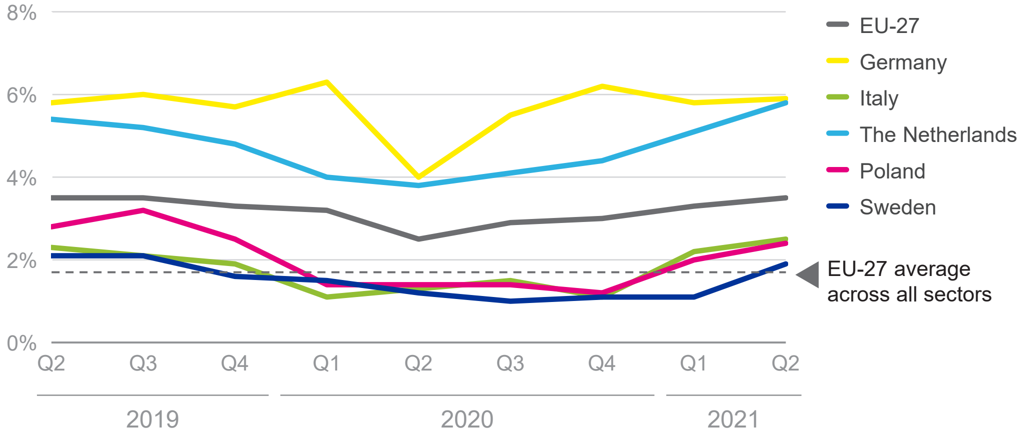
Exhibit 49

2. Will there be enough skilled labor available to support the transition to clean mobility?

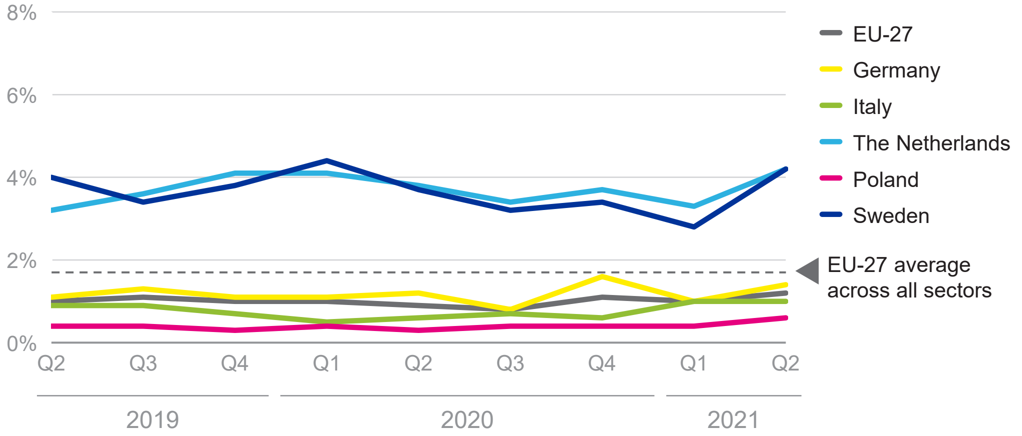
EU labor shortage could impact the construction and operation of HRS and chargers as well as the development of the hydrogen trucking network

Job vacancy rate, %

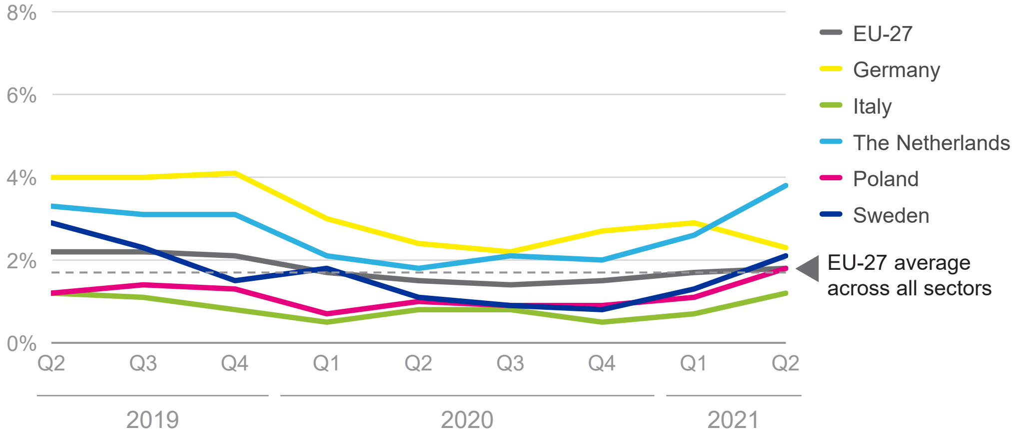
Construction



Electricity, gas, and steam supply



Transportation and storage



Source: Eurostat

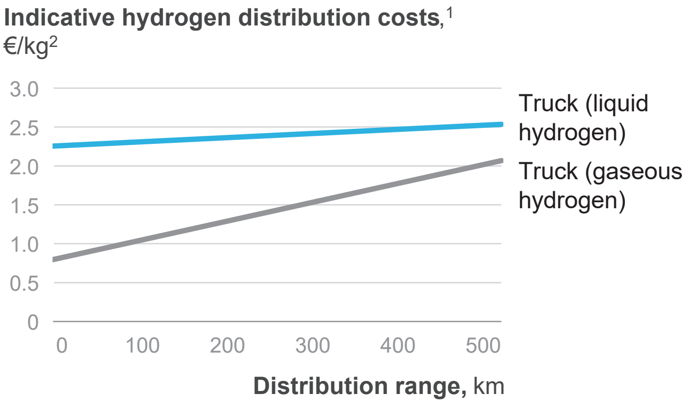
Within our analysis, we assumed a hydrogen distribution network based on the trucking of hydrogen in its gaseous form, rather than the usage of pipelines or trucking of liquid hydrogen (Question 6). However, as we reach larger hydrogen quantities with increasing FCEV adoption (and other use cases, see Synergies) a pipeline network for hydrogen distribution becomes viable. The infrastructure costs for hydrogen distribution we derive in Chapter 3 thus represents a conservative estimate; however, there are potential operational savings in a more refined and diversified distribution network, leveraging and combining the advantages of each mode of transportation (Exhibit 50).

Exhibit 50

6. Is trucking the most efficient way of distributing hydrogen?

In the short term, trucking gaseous hydrogen is the most appropriate delivery method

Trucking gaseous hydrogen is the most cost-effective solution in the short to medium-term



Each type of transportation has advantages and disadvantages

Level of advantage: ░ Low ▒ Medium █ High

	Truck (gaseous hydrogen)	Truck (liquid hydrogen)	Hydrogen pipeline
Capacity	░	▒	█
Distance	░	█	█
Variable costs	░	▒	█
Fixed costs	█	▒	░

[1] Including estimate of cost of compression and liquefaction, 2030.
[2] Converted from dollars (exchange rate €1.18/$1.00).

Source: IEA Hydrogen 2019; McKinsey Center for Future Mobility

Chapter 4

Deploying BEV and FCEV infrastructure in member states

Europe is diverse. In thinking about the continent's alternative power train infrastructure, there are as many on-the-ground realities as there are countries. At a member-state level, infrastructure requirements will differ in terms of overall investments required, timing of deployment, and investment split between technologies. Somewhere between a futile attempt at a one-size-fits-all infrastructure approach and 29 separate models, is the development of archetypes into which multiple countries can be clustered. We use these member-state archetypes to compare and contrast xEV infrastructure deployment with the hopes of better understanding the opportunities and challenges that may be faced at the country level.

Key takeaways

In order to facilitate an assessment of how xEV investment and resource requirements vary across the EU, 27+2 Member States are allocated to archetypes based on their existing degree of xEV development, renewable energy potential, national income, population density, and thoroughfare traffic (among other factors).

Each archetype would have different infrastructure investment requirements to reach the "net-zero" scenario of this report.

Member States with dense transportation networks and large territories tend to have higher xEV infrastructure development costs, particularly after 2030.

The development of FCEV infrastructure across Member State archetypes may be accelerated by the increasing deployment of hydrogen production facilities at nearby ports and industrial sites.

The development of FCEV infrastructure may be slowed down across Member States depending on variations in the availability of skilled labor to construct and operate HRS infrastructure, regulatory challenges, shortages of key raw materials, and the availability of green hydrogen.

4.A

Methodology and rationale for selection of five member states

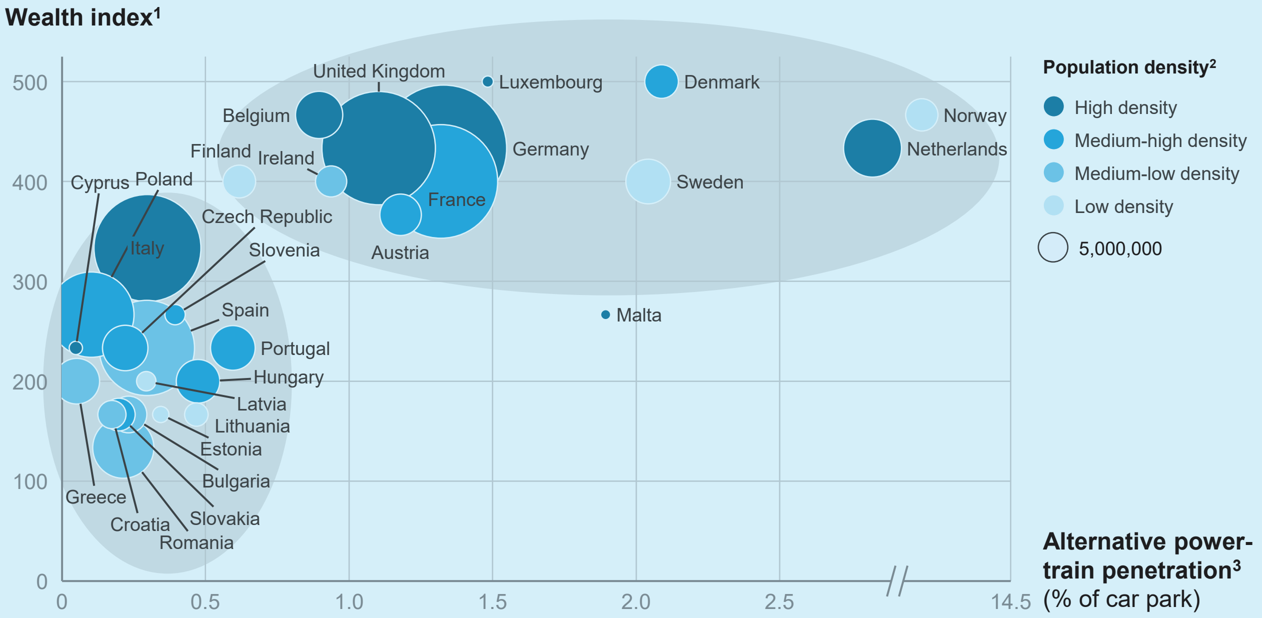
In distilling archetypes, we considered more than a dozen criteria across five quantitative categories:

- **Economics.** The set of data that includes income, urbanization, and average vehicle lifetime
- **Infrastructure readiness.** Alternative power train, road, and rail infrastructure
- **Renewable energy availability.** The level of development and penetration of renewable energy sources

Exhibit 51

Two clusters were identified based on high BEV and FCEV penetration combined with high wealth, and vice-versa

Analysis of economic situation vs. current EV adoption



[1] Measures a country's household income, vehicle age, % urban population.
[2] High density ≥ 200/km²; medium-high density = between 100/km² and 200/km²; medium-low density = between 50/km² and 100/km²; low density >50km².
[3] Includes share of BEVs and FCEVs in the total car park (only PCs).

Source: McKinsey Proprietary Data; Eurostat; World Bank; ACEA Vehicles in Use Europe, January 2021

Methodology

- **xEVs adoption.** The current level of BEV or FCEV adoption
- **Hydrogen availability.** The announced production cost and capacity

Along with these quantitative metrics, we also considered the following qualitative category:

- **Regulation.** Exploring the range of government subsidies, investment, and policies as they relate to EV strategy and policy

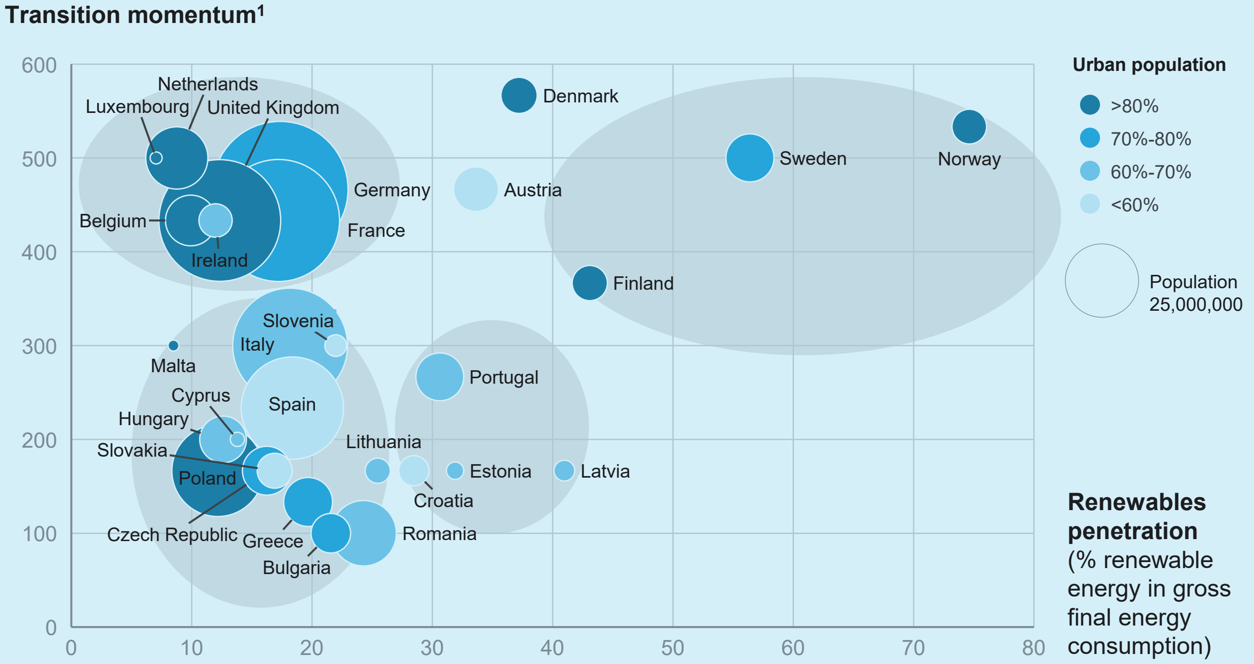
All countries were evaluated during three successive compounding analyses derived from the criteria above:

- **Analysis 1:** Wealth momentum + alternative power train penetration → two clusters (Exhibit 51)
- **Analysis 2:** Transition potential + renewable energy penetration → two additional clusters (Exhibit 52)

Exhibit 52

Four clusters were identified based on each quadrant of the economic and EV criteria versus renewable energy penetration

Analysis of current EV adoption vs. renewable energy availability



[1] Measures a country's organic potential, by taking into account household income, alternative power train penetration, vehicle age.

Source: McKinsey Proprietary Data; Eurostat; World Bank; ACEA Vehicles in Use Europe, January 2021

Methodology

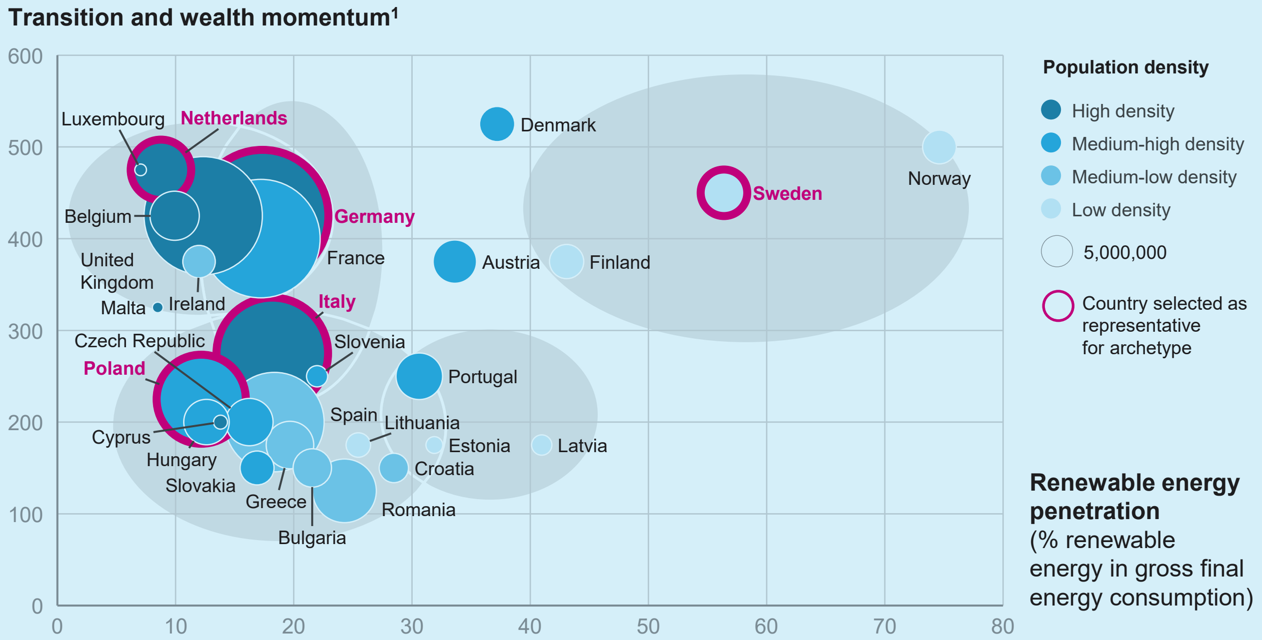
— **Analysis 3:** Transition and wealth momentum + renewable energy penetration → one additional cluster for a total of five clear archetypes (Exhibit 53):

- **Progressive leaders** are highly progressive, wealthier countries that exhibit the strongest levels of both xEV adoption and renewable energy development.
- **Large hydrogen and EV leaders** also lead in the area of electrification but lag behind progressive leaders in renewable energy development. They tend to be large and densely populated nations.
- **Small EV and infrastructure leaders** perform above average in terms of EV penetration but lag behind in renewable energy development. They are smaller in size but densely populated.
- **First followers** are high-density and moderate-income countries that have exhibited slower rates of EV adoption and renewable energy penetration than their counterparts but are following closely behind.
- **Other followers** have the lowest EV adoption rates and below-average renewable energy penetration.

Exhibit 53

Five clusters were identified based on all economic and EV criteria versus renewable energy penetration

Analysis of the economic situation and EV adoption vs. renewable energy availability



[1] Measures a country's organic potential, by taking into account household income, EV penetration, vehicle age, % urban population.
[2] High density ≥ 200/km²; medium-high density = between 100/km² and 200/km²; medium-low density = between 50/km² and 100/km²; low density >50km².

Source: McKinsey Proprietary Data; Eurostat; World Bank; ACEA Vehicles in Use Europe, January 2021

Methodology

With all EU member states plus Norway and the United Kingdom distributed across the five archetypes, we sought to highlight a single member state from each archetype. We wanted each selected member state to clearly represent their respective archetype. We also wanted the group of five to be diverse, but at the same time we did not want to select a member state that was an outlier within its archetype. Thus, we looked for the most extreme current situations and starting points, sought to ensure our selection included an array of differences in time scenarios, cross-border traffic, length of EU membership, and participation in TEN-T across the group of five selected member states.

With these considerations in mind, the following EU member states were selected:

- **Sweden.** Among progressive leaders, Sweden exhibits the highest EV penetration, the most developed EV infrastructure, and the highest level of renewable energy development and penetration.

- **Germany.** Among large EV leaders, Germany's size and the complexity of its road infrastructure system and city networks along with its high TEN-T corridor exposure sets it apart within the archetype.

- **The Netherlands.** Among small EV and infrastructure leaders, the Netherlands are an extreme example of being small in surface area and dense in population.

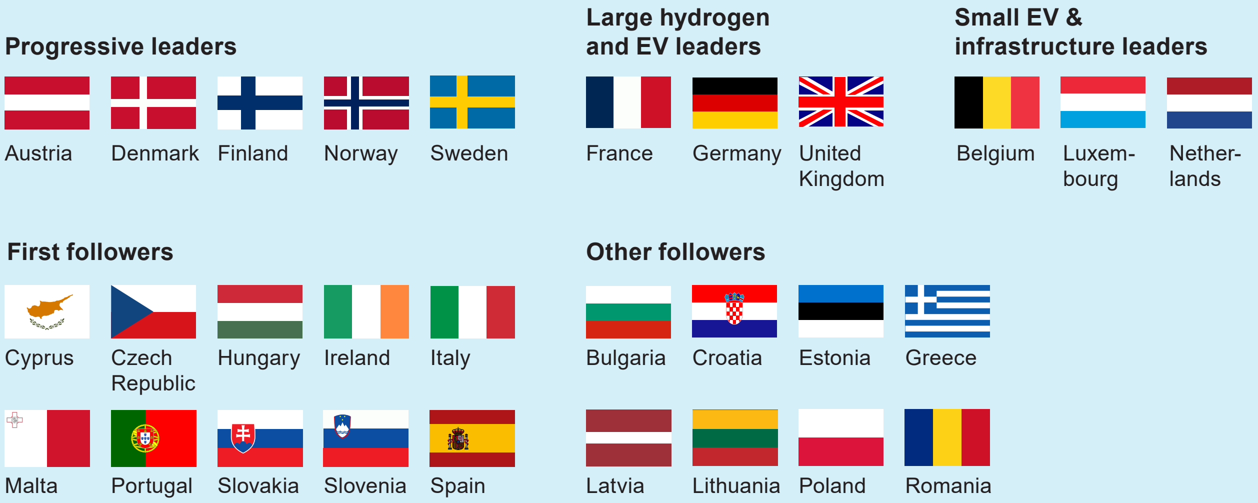
- **Italy.** Among first followers, Italy is remarkable in both its potential to successfully develop renewables and its public announcements regarding plans for hydrogen development.

- **Poland.** Among other followers, Poland has a very high level of cross-border traffic.

The following sections present deeper dives into xEV infrastructure deployment within these member states.

Exhibit 54

Archetypes for EU 27+2 States



4.B

Comparing infrastructure deployment across member states

xEV infrastructure deployment across member states will differ in terms of overall investment required, timing of deployment, and investment split between technologies. Understanding these differences can help decision makers capture opportunities and overcome key challenges that might arise during the mobility transition.

Overall investment requirements and timing of investments in infrastructure will vary by member state

When looking specifically at capital expenditures, we see large differences in overall investment required for infrastructure across the five member-state archetypes. In absolute terms, large, densely populated countries like Germany would spend five to ten times more than smaller countries like the Netherlands or Sweden (Exhibit 55). The higher absolute investment for Germany is primarily driven by a larger vehicle park (along with population) and more kilometers of road on which a viable network would need to be built. Countries like Sweden would spend the least in absolute terms, largely due to their smaller vehicle fleet, sparser road network, and higher existing levels of charger deployment.

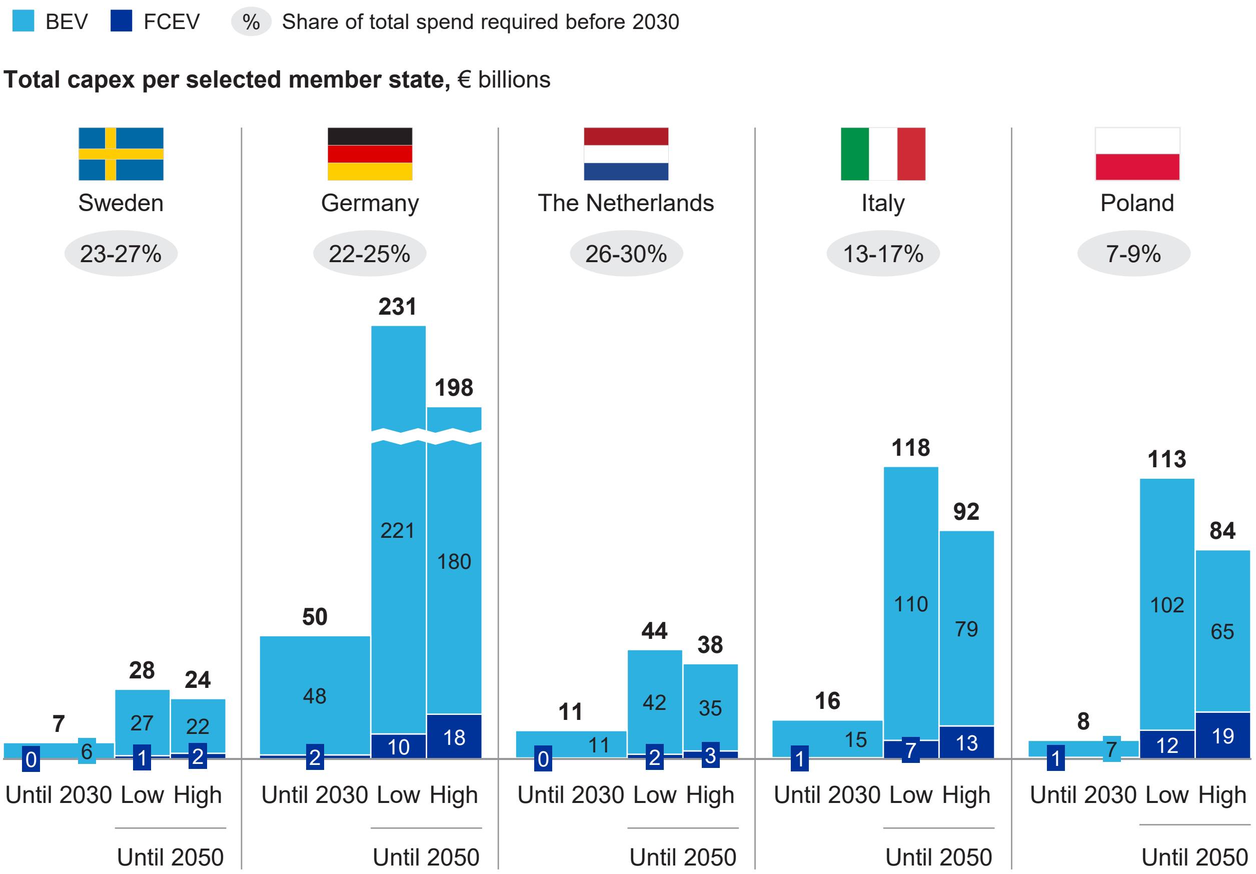
Overall investment required for infrastructure would also not be split evenly over time across the different member states. Progressive leaders such as Sweden, and hydrogen and xEV leaders such as Germany and the Netherlands would need to invest 25 to 30 percent of their total required investment until 2050 before 2030 to support the projected xEV car park. In contrast, member states such as Italy and Poland would need to invest just 8 to 15 percent before 2030 to support the projected xEV car park, with the bulk of investment in those countries needed post-2030. This is mainly driven by the projected xEV uptake.

By GDP, investment in infrastructure will be higher for some member states (for example, Poland) than for others (for example, the Netherlands) (Exhibit 56). While there is a correlation between GDP and the overall investment required, member states lagging in xEV penetration versus the EU average will need to spend more to catch up. In addition, the mix of vehicle types is a key determining factor: Poland, for example, has a significantly higher share of HDVs than other countries; the comparatively higher investment required to serve these vehicle segments drives up the total investment required in these countries.

In Sweden, Germany, and the Netherlands, this is lower in all periods versus the average; Italy is in line with the European average, and Poland is well above the average.

Exhibit 55

The timing of overall infrastructure investments varies according to member-state specificities

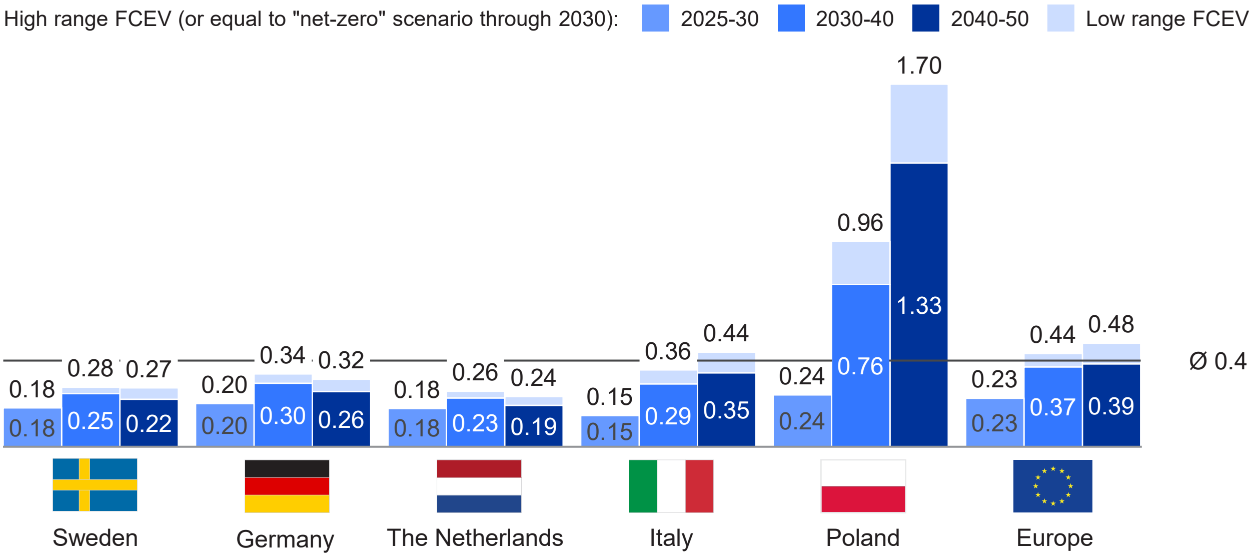


Source: McKinsey Center for Future Mobility; McKinsey Hydrogen Insights FCEV infrastructure model; McKinsey Hydrogen Insights Hydrogen Demand model; McKinsey Global Energy Perspective

Exhibit 56

The share of infrastructure investments differs per country based on the GDP

Share of average annual capex to the 2020 GDP



Source: McKinsey Center for Future Mobility; McKinsey Hydrogen Insights FCEV infrastructure model; McKinsey Hydrogen Insights Hydrogen Demand model; McKinsey Global Energy Perspective; IMF: World Economic Outlook (WEO) Database – October 2021

The overall investment split between BEV and FCEV varies across member states

While the car park split between BEVs and FCEVs across member states is mostly similar in Sweden, Germany, the Netherlands, and Italy, the split in Poland contains more FCEVs compared to other countries. This difference is mostly driven by the car park split per vehicle segment: in Poland it is due to the higher proportion of HDVs and the expectation that hydrogen will play a larger role in decarbonizing the heavy-duty transportation segment.

This difference results in a variation in the split of overall investment required for BEV and FCEV infrastructure across member states. At the low end of the “ranged” scenario (where FCEVs represent a lower share of the overall car park) most member states’, investments in BEV represent approximately 95 percent of total investment required until 2050, whereas in member states such as Poland, it will represent approximately 90 percent of total investment needed until 2050. At the high end of the “ranged” scenario, a similar dynamic can be observed. In most member states the BEV investment represents approximately 90 percent, whereas in Poland this is around 77 percent (Exhibit 57)

Difference between member states’ infrastructure capacity and location drive the variability in overall investment split

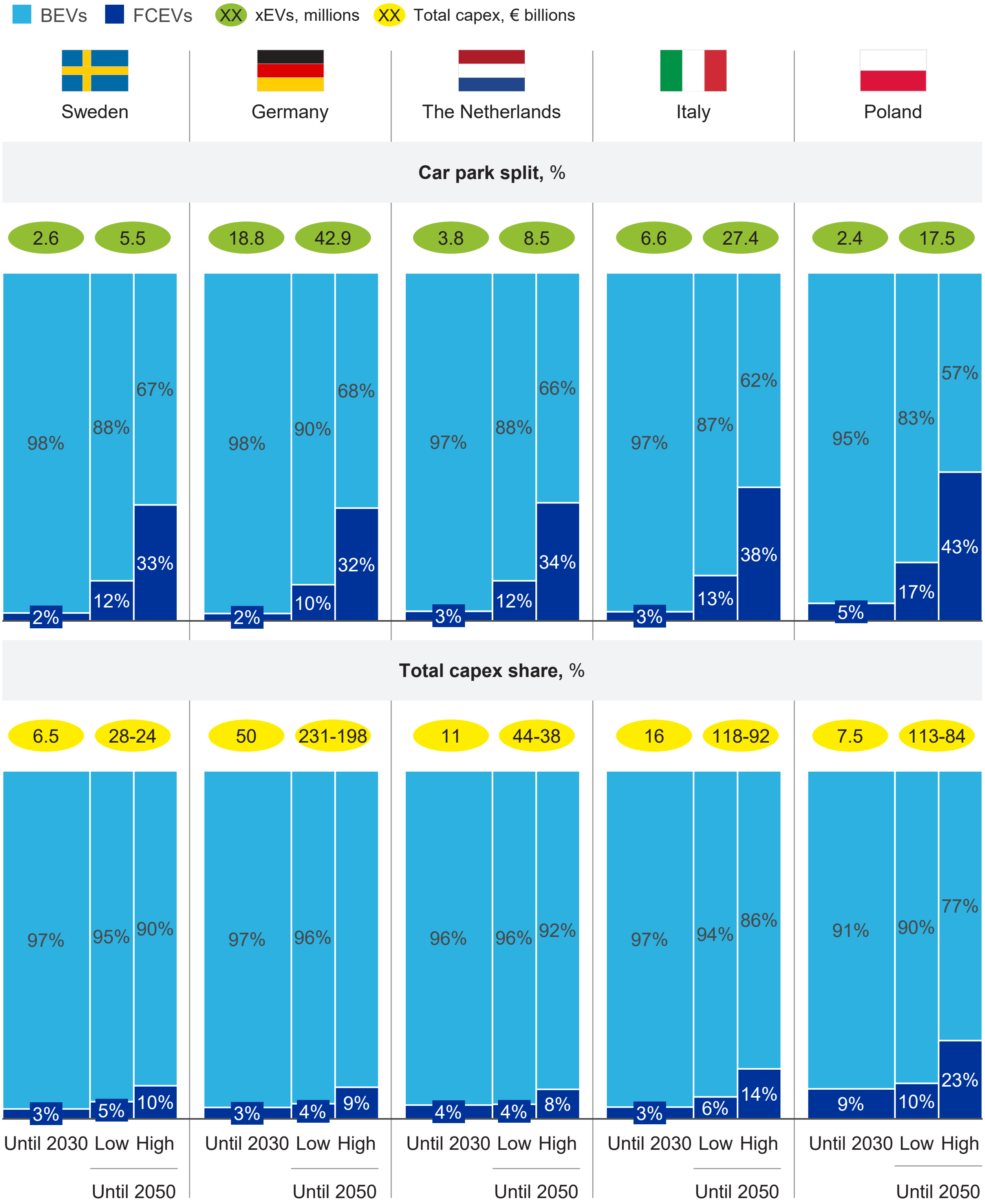
Zooming in on a comparison of infrastructure capacity and location for HRS and chargers, differences in both the FCEV and BEV deployment can be observed between Sweden and Poland.

For BEVs, the differences in the overall investment split arise from differences in the respective member state’s existing infrastructure networks. Member states such as Sweden are expected to see a more pervasive deployment of home chargers than member states like Poland (by 2050, around 82 percent of chargers deployed in Sweden will be home chargers versus 72 percent of chargers deployed in Poland).

For FCEVs, member states such as Poland will tend to have more extra-large stations than member states like Sweden (by 2050 at the low end of the “ranged” scenario, approximately 70 percent of HRS deployed in Sweden will be extra-large stations versus around 99 percent in Poland). In 2050, at the high end of the “ranged” scenario, HRS capacity is similar, driven by the fact that more capacity is needed due to more FCEVs on the road in Sweden for the same network density. In terms of the location of HRS, by 2050, in Sweden, between 39 and 41 percent will be located on highways compared to 53 to 56 percent in Poland. This is driven by the difference in the vehicle segment split between the two countries and the expected difference in their refueling behavior (Exhibit 58).

Exhibit 57

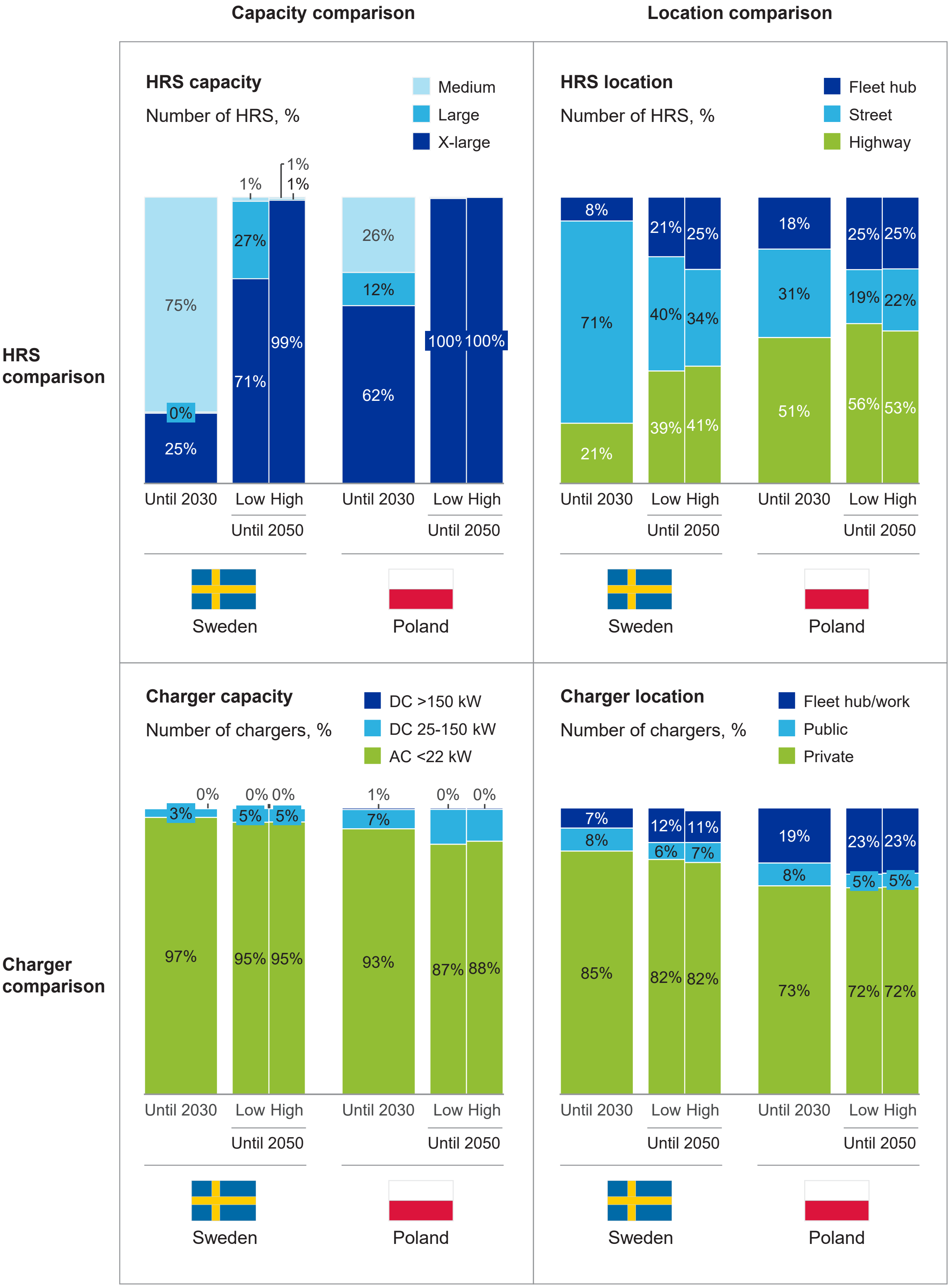
The split in overall investment required for infrastructure varies across member states



Source: McKinsey Center for Future Mobility; McKinsey Hydrogen Insights FCEV infrastructure model; McKinsey Hydrogen Insights Hydrogen Demand model; McKinsey Global Energy Perspective

Exhibit 58

Differences between member states' infrastructure network drive the variability in overall investment split



Source: McKinsey Center for Future Mobility; McKinsey Hydrogen Insights FCEV infrastructure model; McKinsey Hydrogen Insights Hydrogen Demand model; McKinsey Global Energy Perspective

4.C

Synergies and limitations for xEV infrastructure deployment in member states

4.C.1

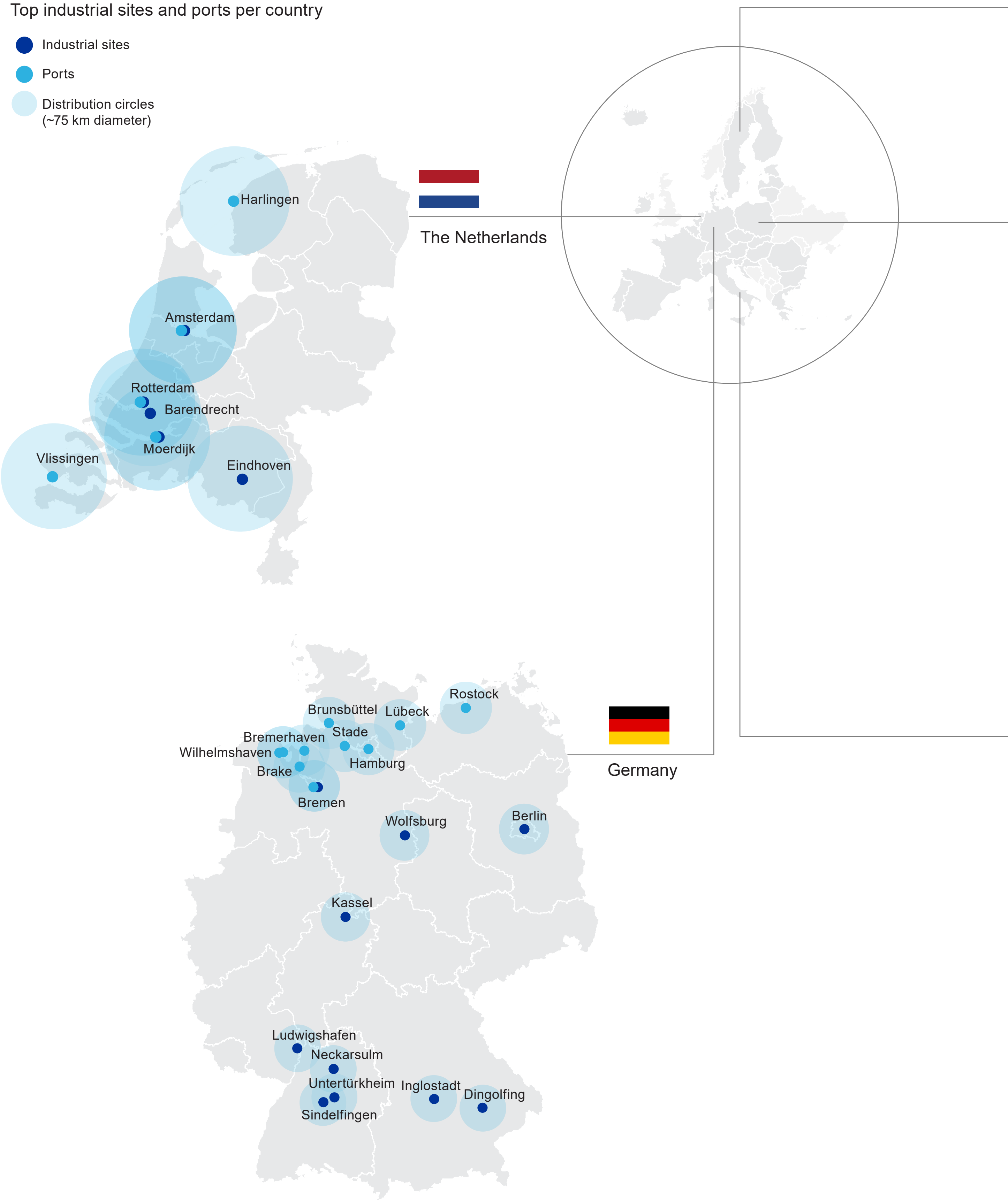
Synergies via deployment of hydrogen production facilities at ports and industrial sites

The development of local hydrogen production facilities in key ports and industrial sites could create synergies with other hydrogen users by enabling the development of an integrated hydrogen network that can serve multiple industries and in turn reduce distribution range and costs (Exhibit 59).

Exhibit 59

The deployment of hydrogen production facilities at ports and industrial sites could reduce average distribution distances and lower system costs

Top industrial sites and ports per country



Source: McKinsey Hydrogen Insights


Sweden
Luleå
Gävle
Gimo
Södertälje
Stockholm
Norrköping
Oxelösund
Torslanda
Gothenburg
Ringhals
Falkenberg
Oskarshamn
Helsingborg
Landskrona
Malmö
Karlshamn
Trelleborg
Poland
Gdynia
Gdansk
Police
Szczecin
Poznan
Blonie
Stryków
Pruszków
Wroclaw
Dabrowa
Teresin
Chorzów
Myslowice
Italy
Belluno
Bergamo
Treviso
Trieste
Venice
Venezia
Turin
Genoa
La Spezia
Carrara
Ravenna
Forlì-Cesena
Leghorn
Ancona
Foggia
Naples
Salerno
Matera
Taranto
Gioia Tauro

4.C.2

Potential limitations within member states

Looking at potential limitations within member states, we follow a similar approach to that taken with the EU-wide perspective. We look at key limitations and bottlenecks across six key categories (energy supply, raw materials, labor, investments, distribution, and infrastructure and vehicles) and provide an indication of each archetypal member state's exposure to said limitations. In doing so, we see that while progressive leaders tend to be the least exposed to common barriers for xEV infrastructure deployment, all member states are expected to see significant barriers with respect to labor, raw materials, infrastructure, and vehicles. Those under follower archetypes, such as Italy and Poland, are expected to see additional and significant barriers in energy supply, given lower renewable energy and hydrogen production capacities and fewer existing financial mechanisms (such as subsidies) to overcome high up-front investment costs. These countries may, however, have an advantage in terms of access to affordable labor to support accelerating installations of both charging and refueling infrastructures (Exhibit 60).

Exhibit 60

The different member-state archetypes display different sensibilities to typical limitations; with progressive leaders being the least exposed to them

L Low barriers M Certain barriers may apply H High barriers

	Sweden	Germany	The Netherlands	Italy	Poland
	Progressive leaders in both xEV and renewable energy development	**Large hydrogen & EV leaders**; lagging behind in renewable energy development	**Small EV and infrastructure leaders**; lagging behind in renewable energy development	**First followers**	**Other followers**
Energy supply	L Already strong renewable energy potential capacities	M Low renewable energy potential capacities but green or blue hydrogen production capacities		H Low renewable energy potential capacities	
Raw materials	H Iridium and nickel could be in supply shortage if recycling is not intensified				
Labor	H There is a risk of a shortage of human resources to construct, operate, and run the HRS and charger infrastructure			M Lower risk of a shortage of human resources to construct, operate, and run the HRS and charger infrastructure—though still existent	
Investments	M High up-front investment needed (especially for FCEV infrastructure) can deter investors but subsidies are already in place in most member states			H High up-front investment needed (especially for FCEV infrastructure) can deter investors and low/no subsidies are already in place in most member states	
Distribution	L FCEV infra-structure often located next to production site; limited grid upgrade costs	M Need to develop a detailed distribution net-work; potential high grid upgrade costs	L FCEV infra-structure often located next to production site; limited grid upgrade costs	M Need to develop a detailed distribution network; potential high grid upgrade costs	
Infrastructure and vehicles	H Most countries have regulatory requirements that can impede the deployment of HRS; FCEVs are less efficient than BEVs; current model announcements place the short-term model availability of FCEVs far below that of BEVs and ICE vehicles				

Source: Eurostat; HYLaw.eu database; IEA Hydrogen 2019; McKinsey Hydrogen Insights; McKinsey Center for Future Mobility

Chapter 5

Conclusion and recommendations

Transitioning to a decarbonized mobility system is a critical lever to achieving the EU's net-zero ambition. The shift to xEVs in road transportation will be key to achieving that goal. However, as the European road fleet shifts away from ICE vehicles, so must its vehicle infrastructure. Through our investigation of xEV infrastructure requirements, we arrived at two key insights:

1. **Two infrastructures are better than one.** A future optimal mix of infrastructure would include both BEV and FCEV infrastructures. Decarbonizing the EU road fleet through the deployment of two technologies can reduce risk and is expected to cost less from an infrastructure perspective than if only BEV infrastructure were deployed. Our analysis found that a 100% BEV ecosystem could cost €3 trillion to €5 trillion more through 2050 from an infrastructure perspective than a combined ecosystem. The development of multiple technologies can also reduce the risk of resource exhaustion and alleviate other deployment bottlenecks that might arise should only one technology be pursued. Last, the availability of both technologies could accelerate xEV adoption as users gain the ability to choose between power trains based on their needs.

   Investing in both technologies delivers infrastructure and TCO advantages over investing in only one. Yet, this transition comes at a cost: while some of the xEV demand is driven by an increasingly attractive TCO, mass adoption will only be ensured when every xEV owner has access to a reliable and strategically deployed charging and refueling network. To deploy the 99 million to 134 million chargers and 20,000 to 34,000 HRS needed to support the future European road fleet, a total infrastructure investment of around €1.0 trillion to €1.2 trillion will be required by 2050—of which most will be invested post-2030 (only €220 billion will be invested by 2030).

2. **Uncertainties around FCEV adoption represent a limited investment risk in the near term.** Uncertainties around FCEV penetration will have a limited impact on the number of refueling stations deployed and the overall investment costs through 2030 as the development of a minimum network is required—no matter the FCEV penetration rate—to support the development of the technology. The overall investment required to fund FCEV infrastructure development in the near term is also quite low in relative terms. Until 2030, the investment in FCEV infrastructure would be roughly €10 billion (or just about 5 percent of the total investment through 2030).

From our observations on the optimal deployment of BEV and FCEV infrastructure, we derived a number of recommendations to help guide decision makers:

Implement policies to support the development of both BEV and FCEV technologies. A supportive regulatory environment is needed to ensure the uptake in both technologies and the required infrastructure build-out. "Technologically neutral" policies (or those that do not specifically favor one technology over the other) will be needed to support organic development in the geographies and use cases most attractive for user adoption.

Provide financial support to achieve at-scale infrastructure deployment. Satisfying minimum network requirements and providing support for cross-border traffic will be critical in the early stages of xEV adoption. While the roll-out of a minimum network for charging is well underway, the deployment of a commensurate HRS minimum network is still quite nascent. As initial utilization for such a network to support FCEVs is low, an intervention by policymakers would be required. It should be targeted at stations with the strongest network effect, triggering additional private FCEV infrastructure investments. Over time, HRS deployment would need to accelerate, particularly along international roadways. We estimate that by 2050, between 800 and 1,400 extra-extra-large HRS would be needed along each TEN-T corridor to support cross-border traffic. This results in an average of between 3.0 and 4.8 HRS per 100 km of roadway.

For BEVs, charging infrastructure needs to be deployed even in locations where the business case is not convincing in the short term. In such locations—such as rural areas, where upgrades may be expensive or relatively uncommon—support could be beneficial for the rollout of charging infrastructure and the required grid upgrades.

Plan infrastructure to accommodate for accelerating xEV adoption. Infrastructure should be upwards-compatible, with standardized technologies and interoperability. Planning for networks, including the power grid, should consider the at-scale scenario, and technology needs to be upgradeable to higher charging and refueling outputs (and potentially different charging technologies such as inductive charging). Fast-charging infrastructure and HRS also need to be developed with the ability to expand over time.

Balance EU-level coordination with tailored member-state support. Collaboration between EU member states is key to achieving highly effective infrastructure for both technologies. Well-coordinated efforts in renewable electricity generation, hydrogen production, and infrastructure development are required to utilize local advantages (such as wind or solar capacities) while ensuring reliable transportation infrastructure throughout Europe.

Member states would also need to enact different policies to support an "optimal" mix of infrastructure for themselves. The current state of infrastructure development, existing xEV penetration, and recharging and refueling habits vary between member states which will impact the infrastructure framework outlook, the timing of deployment, and overall investment needs. While the majority of investments may come from the private sector, targeted support might be needed to ensure sufficient deployment.

Address specific barriers to accelerate xEV uptake and infrastructure development. In addition to the need for targeted support to ensure xEV infrastructure deployment, other key barriers need to be addressed, including upgrades to the EU's complex electricity grid to support electrified road transportation. Our analysis suggests between €200 billion and €260 billion would need to be invested through 2050 specifically in grid upgrades to support BEV charging. Additional FCEV models would also need to be launched to satisfy users' needs. Other common barriers, such as raw-material availability, labor supply, hydrogen transportation, and FCEV's energy efficiency, will need to be addressed but are considered noncritical.

Capture ecosystem synergies through the deployment of xEV infrastructure. The development of both BEV and FCEV technologies presents synergies with other end uses. Potential synergies exist especially on the upstream and midstream sections of both technologies' respective value chains (notably through the interoperability of infrastructure and the additional capacity developed). Significantly, the development of a hydrogen production and distribution ecosystem can support decarbonization in other sectors whereas improvements to the electrical grid needed to support BEVs would also support increased electrification throughout the EU economy.

Abbreviations

AFID
European Commission Alternative Fuels Infrastructure Directive

AFIR
European Commission Alternative Fuels Infrastructure Regulation

BEV
Battery electric vehicles

CNG
Compressed natural gas

EU
European Union

EU-27
All 27 European Union member states

EU-27+2
All 27 European Union member states, plus Norway and the United Kingdom

EVCI
Electric vehicle charging infrastructure

FCEV
Fuel cell electric vehicles

GDP
Gross domestic product

GHG
Greenhouse gas

HDCV
Heavy-duty commercial vehicle, such as a truck

HDV
Heavy-duty vehicle, such as a bus

HRS
Hydrogen refueling station

ICE
Internal combustion engine

LCV
Light commercial vehicle, such as a van

LDV
Light-duty vehicle, such as a car

LNG
Liquefied natural gas

MSRP
Manufacturer’s suggested retail price

NPF
National policy framework

OEM
Original equipment manufacturer

PC
Passenger car

R&D
Research and development

RED II
European Commission Renewable Energy Directive from 2018

RFNBOs
Renewable fuels of nonbiological origin

TCO
Total cost of ownership

TEN-T
European Commission Trans-European Transport Network policy

V1G
Unidirectional power flow from grid to vehicle at variable points in time

V2G
Bidirectional power flow between the grid and vehicle at variable points in time

xEV
Electric power train vehicle, including BEVs and FCEVs

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