## Title

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# 2030 Hydrogen Goals in the Road Transportation Sector:

## A comparative analysis between the European Union and California

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# Abstract

This paper reviews and analyzes the hydrogen-related targets and policies set for 2030 in California and the European Union, particularly related to the transportation sector. Both regions have strongly committed to decarbonizing transportation and transitioning toward clean energy sources, including hydrogen fuel cell vehicle technology. We examine the projected hydrogen demand for light and heavy-duty vehicles, plans for hydrogen production and use, and infrastructure needed, such as refueling stations. We also review announced policy frameworks and strategies driving the transition to clean hydrogen energy in California and the EU. We also consider the impact of US-level policies on California and its hydrogen/fuel cell vehicle efforts. This paper reflects the situation in these jurisdictions as of December 2024. Potential changes in policy given the change in US administration in January of 2025 are not considered.

Our investigation finds that concerning vehicles, both jurisdictions have adopted an ambitious yet largely technology-neutral approach, allowing for the coexistence of battery-electric and fuel-cell electric vehicles. However, each has some policies and targets specific to promoting fuel cell vehicles; support for developing hydrogen systems is also typically fuel-specific in both jurisdictions and includes regulations and incentives. The policies address challenges such as sourcing low-carbon hydrogen, achieving cost competitiveness, and meeting the growing demand for clean electricity. Additionally, based on the targets set by California and the EU for 2030 regarding light and heavy-duty vehicles, buses, and hydrogen refueling stations (HRS), on a per-capita basis, California demonstrates somewhat greater ambition in both vehicles and HRS than the EU, by 2030.

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# 1 Introduction

As the global community strives to meet the ambitious targets outlined in various climate agreements (e.g. Paris Agreement, the Kyoto Protocol, and the United Nations Framework Convention on Climate Change (UNFCCC) [1]), the focus on sustainable and zero-emission mobility has intensified [2] Hydrogen ($H_2$) is emerging as a key energy pathway for decarbonization and mitigating air pollutant emissions in the transportation sector, owing to its potential to offer zero emissions operation for both GHGs and pollutants from vehicles and, if produced with renewables, throughout the production pathway. [3]

The European Union (EU) and California (CA) lead environmental policy and target-setting entities. They are strongly committed to significantly reducing carbon emissions and facilitating a transition towards a clean energy future powered by renewable and sustainable sources. This commitment is encapsulated in their ambitious goals for achieving net-zero greenhouse gas emissions, with the EU targeting the year 2050 and California setting its sights on 2045. [4] [5]

This paper reviews the transportation sector hydrogen-related goals and targets set for 2030 in California and the European Union. By reviewing and analyzing these targets, a detailed picture emerges of how hydrogen implementation is expected to unfold in the coming years. The paper offers insights into the relative targets, strategies, and challenges in integrating hydrogen as a key component of the transportation sector's transition to cleaner energy sources in these regions.

To conduct this study, we looked at the hydrogen plans of the European Commission and selected Member States, as well as those of California within the broader U.S. context, and how national policies affect California. We also compared targets and projected hydrogen demand for light and heavy-duty vehicles (trucks and buses) and hydrogen refueling stations. Finally, our investigation covered announced policy frameworks and the strategies propelling the transition to clean $H_2$ energy in these regions. Overall, we attempt to provide a foundational understanding of these hydrogen landscapes, underscoring the importance of collaborative efforts to drive the adoption of $H_2$ technology for a sustainable future in transportation.

The paper proceeds with an overview of hydrogen energy policies in each jurisdiction, a presentation of targets and quantitative pathways, and a review of specific policies and how these are intended to help reach targets.

# 2 Transportation and Hydrogen Energy Policy Overview: California and European Union

Both CA and the EU have developed low-carbon policy frameworks as instrumental tools to accelerate transport decarbonization and have included $H_2$ as a potentially important contributor. Implementation of these policies is meant to accelerate the clean energy transition towards achieving their goals and targets. This section covers the basic set of policies, both general types that affect transportation and $CO_2$ emissions and more specific ones that relate to $H_2$ implementation strategies at state, nation, and continental levels.

## 2.1 California Overview

California is arguably the leading state in the US in terms of setting low-carbon transportation targets and policies. It has a number of ambitious programs that require and promote the adoption of zero-emission vehicles (ZEVs), including several types of ZEV (e.g., electric, plug-in hybrid, or hydrogen). For example, in both the Advanced Clean Cars II (ACCII) program and the Advanced Clean Trucks (ACT) program, both of which require manufacturers to sell an increasing percentage of ZEVs over time, manufacturers can meet the sales requirements with various combinations of these ZEV types, including 100% BEV and no FCEVs, if they choose. [6] [7] One specific policy (California Energy Commission (CEC) funding for station building) [8] does allocate a percentage to hydrogen stations, and one California Air Resources Board (CARB) program (Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project (HVIP)) [9] does provide a specific incentive amount for fuel cell trucks. These initiatives aim to promote the development and adoption of zero and near-zero-emission vehicles to significantly lower greenhouse gas emissions, improve air quality, and enhance energy security and economic growth. This multi-dimensional strategy demonstrates California's dedicated approach to accelerating the transition towards a cleaner, more sustainable energy future, aligning with national objectives. [10]

At the national (US) level, funding for developing hydrogen systems has increased dramatically in the past 2 years. In October 2023, the U.S. Office of Clean Energy Demonstrations (OCED) selected and awarded seven hydrogen hubs across the United States, including one in California (named ARCHES), as part of a concerted effort to accelerate the nation’s transition to cleaner energy sources. This initiative, backed by a USD 7 billion federal investment into constructing key systems (of which $1.2 billion is targeted for CA), aims to catalyze the development of regional hydrogen eco-systems that integrate clean production, consumption, and infrastructure. The initiative seeks to enhance all aspects of the hydrogen value chain—from production and storage to distribution and utilization. This approach is designed to significantly contribute to the United States’ broader objectives of reducing carbon emissions and advancing toward a sustainable energy future, underscoring the government’s commitment to innovative and environmentally responsible energy solutions. [11]

The state reports that ARCHES’ plans for hydrogen uptake in California, including targets of 5000 heavy-duty fuel-cell trucks and 1000 fuel-cell buses in use by 2030 along with other end-use investments, ultimately are expected to reduce carbon emissions by up to 2 million metric tons annually, equivalent to the pollution generated by 445,000 gasoline-powered cars each year. Moreover, it is expected to create an estimated 220,000 new jobs, including 130,000 in construction and 90,000 in permanent positions, while generating an estimated $2.95 billion annually in economic value from improved health and health cost savings. Notably, 40% of the benefits from these projects will be directed towards disadvantaged communities, ensuring equitable distribution of the initiative's benefits. [12]

Coupled with the ZEV sales requirements (outlined above), vehicle incentive programs such as the Clean Vehicle Assistance Program offer grants and affordable financing options tailored to assist income-qualified Californians in acquiring new or used plug-in hybrid, fuel cell, or electric vehicles. The program aims to ensure clean vehicles are within reach and financially feasible for all eligible individuals. [13]

The Low-Carbon Fuel Standard (LCFS) is another important California policy affecting hydrogen uptake in the transportation sector. This policy [14] creates a target carbon intensity for all transportation fuels sold in the state. It scores dozens of specific fuel pathways (life-cycle basis) to determine whether they are above or below the target, thereby either paying for credits or selling credits. Depending on credit values, this can have a potentially significant impact on end-user prices. The policy also has a mechanism to grant credit values (and effectively subsidies) to stations that sell hydrogen based on their capacity rather than sales. This has helped support stations during early periods of low utilization.

## 2.2 European Union Overview

In 2020, the European Commission adopted a comprehensive strategy on hydrogen aimed at catalyzing policy action across five key domains: investment support, production and demand facilitation, market and infrastructure development, research collaboration, and international engagement. The strategy underscores the EU's commitment to the role of hydrogen in the transition towards a sustainable and low-carbon future. It focuses on producing renewable and consuming hydrogen in hard-to-abate sectors, including industry, heavy-duty road transport, aviation, and shipping. [15]

The REPower EU Communication of 2022 outlined renewable hydrogen's potential to significantly reduce the EU’s dependency on fossil fuel imports, notably from Russia. It introduced the ambition of producing 10 million tons of renewable hydrogen domestically and 10 million tons of imported hydrogen to the EU. [16]

This is embedded in the European Green Deal, introduced by the Commission in December 2019 [17]. The European Green Deal represents an ambitious set of policies aiming to achieve climate neutrality by 2050. In tandem, the Net-Zero Industry Act is a crucial pillar of the Green Deal Industrial Plan, designed to create a conducive regulatory environment that incentivizes investments in key products essential for achieving climate neutrality. The Net Zero Industry Act identifies 19 net zero strategic technologies, including hydrogen technologies, such as electrolyzers and fuel cells. For those, EU manufacturing should reach a benchmark of at least 40 % of the EU's annual deployment needs to achieve the EU's 2030 climate and energy targets and 15 % of world production by 2040. [18]

Subsequently, as part of the European Green Deal, in 2021, the European Commission adopted a package of legislative proposals known as Fit-for-55, which aims to strengthen the EU's position as a global climate leader [19]. This initiative includes a comprehensive regulatory framework for the production, consumption, infrastructure development, and market rules for a future hydrogen market. It also establishes binding quotas for renewable hydrogen consumption in industry and transport. Notably, the Renewable Energy Directive obliges fuel suppliers to achieve a minimum renewable share of the energy content in the fuels they supply for the transport sector. This integrated approach underscores the EU's commitment to advancing sustainable energy practices and reducing carbon emissions across various sectors. The rules include a binding sub-target for renewable hydrogen (renewable fuel of non-biological origin- RFNBO) [20]. Implementing the directive, the EU also defined under which conditions hydrogen, hydrogen-based fuels, or other energy carriers can be considered renewable fuels of non-biological origin (RFNBOs), and a draft definition of low-carbon hydrogen is in preparation [21] [22]. The alternative fuels infrastructure directive requires EU Member States to roll out a minimum of refueling infrastructure, including for hydrogen, according to typical technical specifications. [23]

In the road transport sector, the hydrogen-specific EU legislation is complemented by regulations on the $CO_2$ emissions standards for vehicles. The EU regulation requires progressive reductions in average $CO_2$ kg/km for passenger cars and vans to reach zero $CO_2$ emissions by 2035. This will require 100% sales of zero-emission vehicles (ZEVs - either battery-electric or fuel cell-electric vehicles) [24]. This, therefore, also incentivizes a strong growth in ZEV sales over the period 2025-2035. The rules for heavy-duty vehicles foresee step-wise emissions reductions reaching -90% by 2040 compared to 2019 (fleet average per manufacturer) [25]. However, these rules do not incentivize $H_2$ FCEVs per se since EVs could provide all of the market growth in ZEVs needed to hit the targets.

In addition, the recent revision of the European emissions trading system (ETS) introduced a separate ETS 2 for the road transport sector [26]. This cap-and-trade system incentivizes fuel suppliers to reduce the emissions of their fuel sales and promotes sales of low-carbon electricity and hydrogen.

## 2.3 California Zero Emission Vehicles (ZEV) Regulation

California currently has two main regulatory programs related to advancing the uptake of ZEVs by requiring manufacturers to sell increasing numbers over time: Advanced Clean Cars (ACC II) for light-duty vehicles and Advanced Clean Trucks (ACT) for medium and heavy-duty vehicles. The ACC II regulations build upon the state's burgeoning zero-emission vehicle market and robust motor vehicle emission control regulations to enhance them, requiring a complete transition to 100% zero-emission vehicle sales by 2035, with the expectation of achieving a 100% ZEV fleet (stock) of vehicles by 2045. The targets through 2035 are somewhat lower for trucks, though a recent provision in a related rule now sets these to 100% ZEV sales by 2036. One additional policy in this set is the Advanced Clean Fleets (ACF) rule, requiring certain (typically larger) fleets to purchase increasing numbers of ZEVs over time. This is meant to create a demand vector that aligns with the sales requirements in the ACT [27] . These rules are ZEV "technology neutral," allowing any zero-emission vehicle technology, such as battery-electric, hydrogen fuel cell electric, and plug-in hybrid electric vehicles [6].

The requirements under ACC II are for automakers to deliver to the California market an increasing number of zero-emission light-duty vehicles each year, beginning in model year 2026. The ramp-up from 2026 to 2035 is shown in **Table 1.** Under the Advanced Clean Cars II framework, the zero-emission vehicle requirements are structured to ensure that by the 2035 model year, all new vehicles sold in California will be 100% zero-emission or clean plug-in hybrid-electric vehicles.

As of mid-2024, California is already selling around 25% ZEVs (nearly all BEVs and PHEVs), so the 35% target for 2026 seems within range. Given the ZEV sales share requirements, the substantial ramp-up after that may also be achievable.

**Table1. Requirements in increasing the number of ZEV LDV. Data from: [28]**

| Model year | LDV ZEV and PHEV percentages of new vehicle sales |
|---|---|
| 2026 | 35% |
| 2027 | 43% |
| 2028 | 51% |
| 2029 | 59% |
| 2030 | 68% |
| 2031 | 76% |
| 2032 | 82% |
| 2033 | 88% |
| 2034 | 94% |
| 2035 | 100% |

For trucks, the ACT and ACF regulations form part of a comprehensive approach to expedite the large-scale transition of zero-emission medium- and heavy-duty vehicles from Class 2b to Class 8 [7]. The regulation consists of two key components. Manufacturers certifying Class 2b (large pickup trucks) through Class 8 (tractor-trailer trucks) are required to sell zero-emission trucks as the minimum percentage of their total annual California sales, increasing from 2024 to 2035. The ACT Manufacturer Zero-Emission Sales Percentage Requirement is outlined in **Table 2.** The 2036 100% target was added as part of the ACF rulemaking, though it applies to OEM sales rather than fleets.

**Table 2. ACT Manufacturer Zero-Emission Sales Percentage Requirement. (Table taken from [29] and 2026 values from [30])**

| Model Year | Class 2b-3 | Class 4-8 | Class 7-8 |
|---|---|---|---|
| 2024 | 5% | 9% | 5% |
| 2025 | 7% | 11% | 7% |
| 2026 | 10% | 13% | 10% |
| 2027 | 15% | 20% | 15% |
| 2028 | 20% | 30% | 20% |
| 2029 | 25% | 40% | 25% |
| 2030 | 30% | 50% | 30% |
| 2031 | 35% | 55% | 35% |
| 2032 | 40% | 60% | 40% |
| 2033 | 45% | 65% | 40% |
| 2034 | 50% | 70% | 40% |
| 2035 | 55% | 75% | 40% |
| 2036 | 100% | 100% | 100% |

Moreover, the ACF regulation applies to “high priority” federal fleets and fleets engaged in drayage operations and those owned by state and local agencies. High-priority fleets are entities that own, operate, or direct at least one vehicle in California and have either annual revenue of $50 million or more or own, operate, or have common control of a total of 50 or more vehicles. Federal government agencies that own, operate, or direct the operation of at least one vehicle in California are also subject to this regulation. The regulation affects medium- and heavy-duty on-road vehicles with a gross vehicle weight rating exceeding 8,500 pounds, off-road yard tractors, and light-duty mail and package delivery vehicles [31] [32].

Drayage trucks are Class 7 and 8 vehicles that transport goods to and from seaports and intermodal railyards. Starting December 31, 2023, these trucks must be registered in California's Truck Regulation Upload, Compliance, and Reporting System (TRUCRS). Non-zero-emissions "legacy" trucks can register until the end of 2023 and continue operating through their minimum useful life. From January 1, 2024, only zero-emissions drayage trucks can register, requiring all drayage trucks entering seaports and intermodal railyards to be zero-emissions by 2035 [31]. California State and local government fleets must ensure that 50% of vehicle purchases are zero-emissions (ZEV) starting in 2024, increasing to 100% by 2027. A compliance report is required by April 1, 2024. Small government fleets and those in designated counties will begin ZEV purchases in 2027 [31].

Under the ACF, fleets categorized as High Priority and Federal Fleets or State and Local Government Fleets can use the ZEV Milestones Option, detailed in **Table 3**, to meet their ZEV targets.

**Table 3. ZEV Fleet Milestones by Milestone Group and Year. Table from [33]**

| Percentage of vehicles that must be ZEV | 10% | 25% | 50% | 75% | 100% |
|---|---|---|---|---|---|
| Milestone Group 1: Box trucks, vans, buses with two axles, yard tractors, light-duty package delivery vehicles | 2025 | 2028 | 2031 | 2033 | 2035 and beyond |
| Milestone Group 2: Work trucks, day cab tractors, buses with three axles | 2027 | 2030 | 2033 | 2036 | 2039 and beyond |
| Milestone Group 3: Sleeper cab tractors and specialty vehicles | 2030 | 2033 | 2036 | 2039 | 2042 and beyond |

The relationship between the Advanced Clean Fleet (ACF) and Advanced Clean Trucks (ACT) regulations is meant to be one of mutual reinforcement. ACF is a complementary measure to ACT, requiring fleets to incorporate an increasing percentage of zero-emissions vehicles such as battery electric, long-range plug-in electric hybrids, and hydrogen fuel cell medium- and heady-duty trucks (MDHD) trucks. Together, ACF and ACT contribute to the overarching goal of reducing emissions and promoting sustainable mobility in California. The ACF also contains a provision requiring the sales of only ZEV trucks (thus applying to ACT) by 2036, sooner than fleet provisions in ACF require this. It should also be noted that the entire ACF rule is currently voluntary until the US EPA grants necessary approvals through the Federal Clean Air Act California waiver process. [34]

## 2.4 European Union Vehicle $CO_2$ Standards

In March 2023, the EU adopted a groundbreaking amendment to the $CO_2$ emissions performance standards for light-duty vehicles and vans. This amended regulation aims to contribute to a net reduction of greenhouse gas emissions by at least 55% by 2030 compared to 1990 levels and to work towards achieving climate neutrality by 2050, in alignment with the European Climate Law. It also seeks to offer benefits to EU citizens and vehicle users through the expanded adoption of clean and affordable zero-emission vehicles and to spur innovation in zero-emission technologies, thereby reinforcing the EU's leadership in automotive technology and fostering employment within the EU [35]. The targets set for 2025 and beyond are based on the Worldwide Harmonized Light Vehicles Test Procedure (WLTP). These targets are depicted in **Table 4.**

**Table 4. Fleet $CO_2$ targets (g/km) for new passenger cars and vans. Data from [36]**

| Year target | Cars | Vans |
|---|---|---|
| 2021 – 2024 | 118 | 205 |
| 2025 – 2029 | 93 | 153 |
| 2030 – 2034 | 49 | 90 |
| 2035 | 0 | 0 |

Building on these efforts, in early 2024, the EU agreed on an amended Regulation on $CO_2$ emission standards for heavy-duty vehicles. It will set stricter $CO_2$ emission standards for heavy-duty vehicles beginning in 2030 and broaden the regulation to include smaller trucks, city buses, long-distance buses, and trailers. To accelerate the rollout of zero-emission buses in urban areas, starting in 2030, all new city buses must be zero-emission [37]. **Table 5** displays the existing and newly agreed targets of the regulation on $CO_2$ emissions standards for HDVs.

**Table 5. Existing and the newly agreed targets of the regulation on $CO_2$ emissions standards for HDV. Data from [37]**

| Year | Previous Targets | New Targets – Compared to 2019 levels |
|---|---|---|
| 2025 | -15% | - |
| 2030 | -30% | -45% |
| 2035 | - | -65% |
| 2045 | - | -90% |

# 3 2030 Hydrogen goals and projections with a focus on the transportation sector

The European Union and California have outlined ambitious objectives targeting net-zero emissions or carbon neutrality by 2050 and 2045, respectively.

## 3.1 European Union

The Hydrogen Strategy and the REPower EU Communication outline the EU's overarching hydrogen ambition, published in 2020 and 2022, respectively [38]. The scenarios used for the impact assessment [39] underpinning the European Commission communication on Europe's 2040 climate target [40] assume an increase of (renewable) hydrogen consumption in the EU's transport sector from almost zero in 2015 to 14-16 Mtoe (million tons of oil equivalent) in 2040 and 35-40 Mtoe in 2050. In 2040, nearly all hydrogen used in the transport sector (more than 90%) would be consumed by road transport alone. The share of hydrogen in the total energy consumption of the transport sector increases from almost zero in 2015 to 6-7% in 2040 and 18-21% in 2050. The share of fuel-cell cars could increase to 5% in 2040 and 14% in 2050 (see **Figure 1** below). The share of fuel-cell vans could rise to 5% in 2040 and 15-16% in 2050. The share of hydrogen heavy-goods vehicles (HGVs) could increase to 12-14% in 2040 and 26-31% in 2050 (see **Figure 2** below). For buses and coaches, the share of hydrogen vehicles could reach 15-16% in 2040 and 32-37% in 2050.

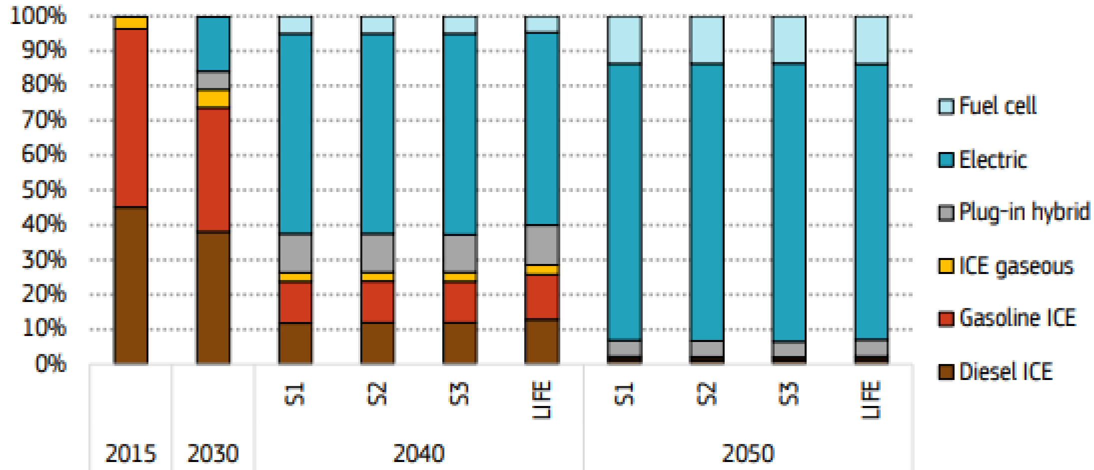
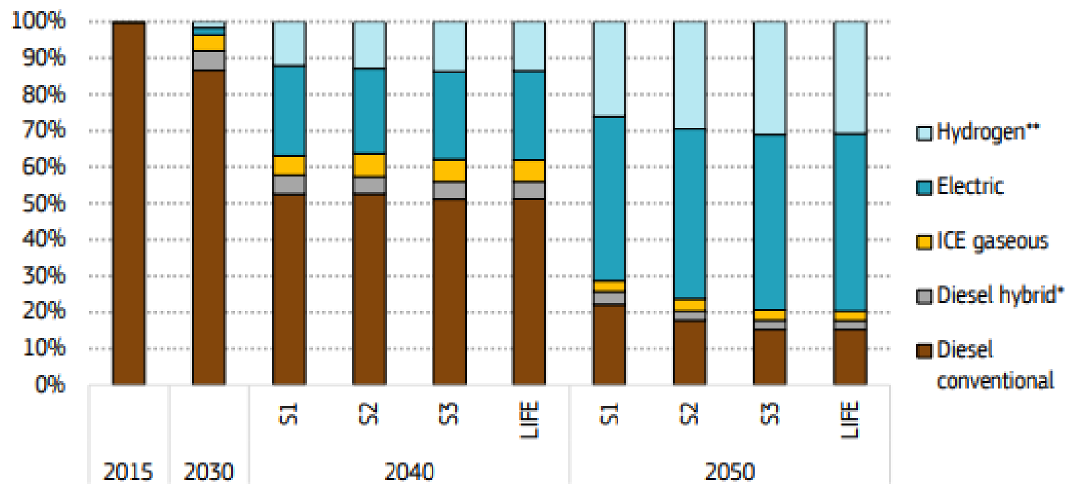



**Figure 1. Distribution of the EU passenger car stock by type of drivetrain. Taken from [41]**




*Note: *Diesel hybrid vehicles include plug-in hybrids. **Hydrogen vehicles include fuel-cell vehicles and hydrogen ICE vehicles.*

**Figure 2. Distribution of the EU heavy-goods vehicle stock by type of drivetrain. Taken from [42]**

Additionally, **Table 6** examines how the EU's transportation sector projections align the number of stations with the fleet of Light-Duty Vehicles (LDV) and Heavy-Duty Vehicles (HDV) as well as Hydrogen Refueling Stations (HRS). The Alternative Fuels Infrastructure Regulation (AFIR) guidelines project a maximum of 658 stations by 2030, including 424 for nodes and 234 for distances between them [43]. Given the expected number of LDV and HDV vehicles in the EU by 2030 and assuming average HRS capacities of 2,400 kg $H_2$/day (since the specific number of stations for LDV and HDV is not detailed in the EU's projections), we calculate the anticipated utilization rates for these stations. Additionally, we present alternative scenarios (Alternative View 1 and 2 in **Table 6**) that contain the authors' calculations of the resulting average station utilization given the numbers of vehicles and stations shown above (View 1) and the number of vehicles that would be required to achieve an 80% station utilization rate (View 2), which would support better station profitability.

**Table 6. EU's transportation and hydrogen goals and potential targets**

| | LDV | HDV | Notes |
|---|---|---|---|
| Number of HRS in 2030 | 658 | | Maximum, based on the AFIR mandate, assuming a refueling point every 200 km on the TEN-T network and on in each urban node |
| Average Daily capacity of stations | 2,400 | | Assumption, based on recent data |
| Number of FCEV vehicles by 2030 | 275,000 | 40,000 | Lower figures than in AFIR impact assessment [43] to account for reduced ambition (by 1/3) in adopted legislation compared to proposal |
| Fuel consumption $kgH_2$/day per vehicle | 0.9 | Buses: 20<br>HDV: 30 | Based on FCEV efficiency and driving distance data |
| Total fuel demand by vehicles (million $kgH_2$/year) | 90.3 | 419.7 | Number of vehicles X yearly $H_2$ use |
| $H_2$ available at HRS (million $kgH_2$/year) | 461 | | Max refueling capacity @ 80% |
| Alternative view 1: Station utilization rate (with given capacity and vehicles) | 20% | | Result of hydrogen demand vs station capacity |
| Alternative view 2: Number of HRS needed for 80% utilization with given number of vehicles | 129 | | Number of stations needed to have sufficient capacity to refuel vehicles; compared to actual number which may be needed for geographic coverage |

The evaluation of the EU's transportation sector projections reveals that, to support the assumption of 658 hydrogen refueling stations (HRS) for LDVs and HDVs by 2030, these stations would need to maintain a 20% utilization rate to meet the anticipated vehicle demand based on the projected volumes and consumption patterns.

Alternatively, the EU projections suggest that to reach an 80% utilization rate, the number of HRS for LDVs and HDVs would need to be reduced to 129. Additionally, it should be noted that this study's station count does not include privately accessible stations that fleets, such as bus depots, might establish for their refueling requirements.

## 3.2 California

While California has clear targets for ZEV sales, it has not set mandatory targets for specific technologies such as BEVs or FCEVs. However, the ARCHES program has set some clear targets for vehicles and hydrogen fuel production, and some other government reports have indicated relevant targets that together can be pieced to provide a coherent picture of a possible hydrogen and FCEV future in the state.

Again, only some, if any, of California's targets shown in **Table 6** stem from legislation, though the Governor has endorsed specific targets. Most are derived from California Air Resources Board (CARB) and California Energy Commission reports identifying potential targets or funding allocations. The hydrogen hub “ARCHES” has also announced specific targets for 2031 (not differentiated from 2030 goals in the table). Finally, the authors have linked various targets in this table to provide a more complete picture across multiple indicators [44][45]. The table provides the sourcing and logic of each of the variables shown.

Additionally, **Table 7** evaluates how well California's transportation sector goals align the number of stations with the number of vehicles for both Light and Heavy-Duty Vehicles and Hydrogen Refueling Stations (HRS). Here, we show the projected numbers of LDV and HDV stations and targets for FC vehicles. Assuming average station capacities of 1,000 kg $H_2$/day for LDV stations and 4,000 kg $H_2$/day for HRS, we also calculate the resulting station utilization rates (as we do for the EU above). This is shown in Alternative View 1, with low utilization rates resulting. Alternatively, in Alternative View 2, we show the number of vehicles needed if an 80% utilization rate is to be achieved (to help ensure station profitability).

**Table 7. California's transportation and hydrogen goals and potential targets**

| | LDV | HDV | Notes |
|---|---|---|---|
| Number of HRS in 2030 | 175[1] | 60 | Based on funding and announced targets at various times by CEC and (for HDV stations), ARCHES |
| Average Daily capacity of stations | 1000 | 4000 | Assumption, based on recent data |
| Number of FCEV vehicles by 2030 | 120,000 | 6,000 | LDVs: UC Davis scenario<br>HDVs: ARCHES target |
| Fuel consumption $kgH_2$/day per vehicle | 0.9 | Buses: 20<br>HDV: 30 | Based on FCEV efficiency and driving distance data |
| Total fuel demand by vehicles (million $kgH_2$/year) | 39.42 | 62.1 | Number of vehicles X yearly $H_2$ use |
| $H_2$ available at HRS (million $kgH_2$/year) | 51.1 | 70.1 | Max refueling capacity @ 80% |
| Alternative view 1: Station utilization rate (with given capacity and vehicles) | 77% | 89% | Result of hydrogen demand vs station capacity |
| Alternative view 2: Number of HRS needed for 80% utilization with given number of vehicles | 135 | 53 | Number of stations needed to have sufficient capacity to refuel vehicles; compared to actual number which may be needed for geographic coverage |

After analyzing California's transportation sector goals, the results suggest that to maintain the target of 175 hydrogen refueling stations (HRS) for light-duty vehicles (LDV), the capacity utilization of these stations would be 77% to meet the vehicle demand based on projected goals and consumption. On the other hand, based on vehicle consumption and $H_2$ available at stations for heavy-duty vehicles (HDV), 80% capacity will not be enough to satisfy the vehicle's demand.

Alternatively, to achieve an 80% utilization rate for these stations, California would need to adjust the number of stations to 135 for LDVs and 53 for HDVs. It is also important to note that the station

[1] CARB's Joint Agency Staff Report on Assembly Bill 8: 2022 Annual Assessment of Time and Cost Needed to Attain 100 Hydrogen Refueling Stations in California indicates known plans and funding for only 175 stations by 2027. 168 being funded by the Clean Transportation Program and an additional 7 by the private sector.

count reported in this study does not include additional private-access stations that fleets, including bus depots, may plan for refueling purposes.

## 3.3 Comparing CA and EU targets and projections

Following the analysis presented in Tables 6 and 7, **Table 8** provides a summary of the goals and projections for Light-Duty Vehicles (LDV), Heavy-Duty Vehicles (HDV), buses, and Hydrogen Refueling Stations (HRS) for both California (CA) and the EU. **Figure 3** illustrates the projected annual hydrogen demand, expressed in million kg $H_2$/year. Currently, the EU operates 187 hydrogen refueling stations [46] .

**Table 8. $H_2$ goals/projections in the transportation sector by 2030 for EU and CA. CA and EU data is based on [47]and [48]**

| | Light Duty Vehicles (LDV), Number of FCEV vehicles expected on road by 2030 | Heavy Duty Vehicles (HDV), Number of FCEV vehicles expected on road by 2030 | Buses, Number of FCEV vehicles expected on road by 2030 | Hydrogen Refueling Stations (HRS) by 2030 |
|---|---|---|---|---|
| CA | 120,000 | 5,000 | 1,000 | 235 |
| EU | 275,000 | 40,000 | | 658 |

Given the number of vehicles targeted for 2030, **Figure 3** provides the EU and CA projected demand of $H_2$ per year proportion based on their goals and projections. The demand was calculated assuming an LDV consumption of 0.9 kg$H_2$/day, an HDV consumption of 30 kg$H_2$/day, and 20 kg$H_2$/day for buses.

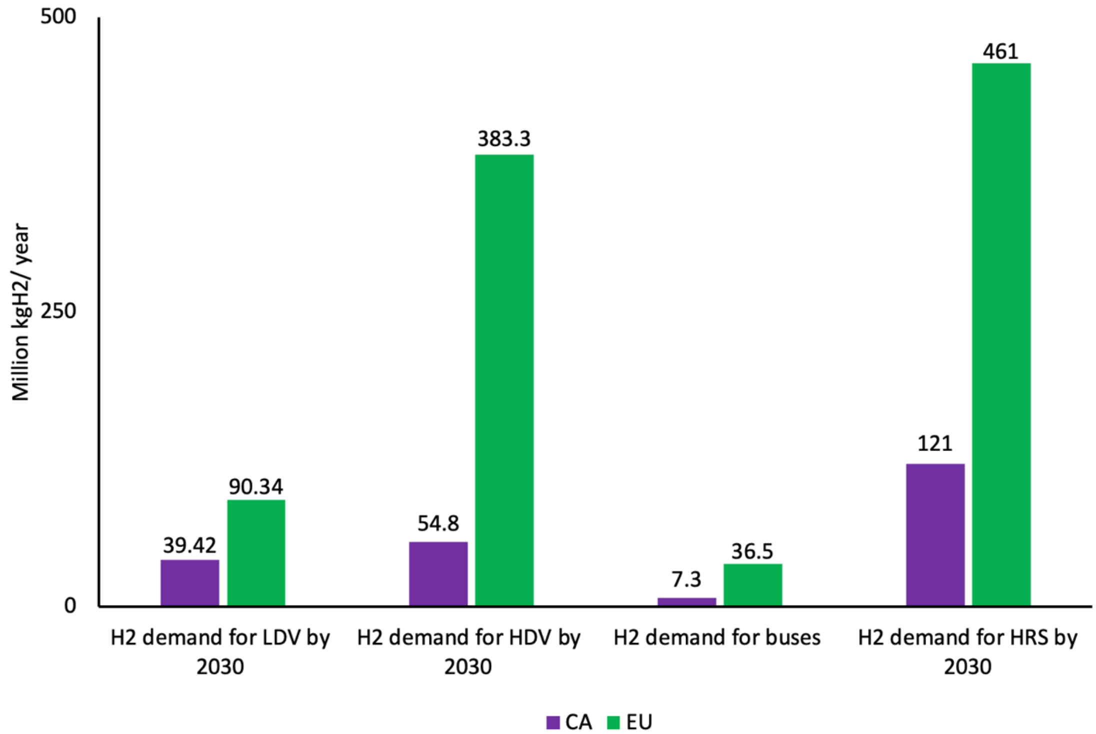



**Figure 3. $H_2$ demand expected based on $H_2$ goals for various vehicle types by 2030 for the EU and CA**

The European Commission Impact Assessment for the alternative fuels infrastructure regulation [48] lacks specifications regarding the distribution of heavy-duty vehicles (HDVs) and buses among the projected number of vehicles anticipated on the road by 2030. The number in the impact assessment (~60.000 HDVs and buses) was linked with the level of ambition of the original Commission proposal. The adopted legislation is more compatible with around 40.000 HDVs and buses by 2030. For the sake of simplicity, we assume 35,000 trucks and 5,000 buses to calculate the required $H_2$ demand. This approach facilitates comparing the overall goal and individual country targets in Europe. Similarly, the level of ambition of the light-duty sector was assumed to be 416.000 hydrogen fuel-cell vehicles by 2030. Considering the finally adopted legislation, it would also have to be reduced to ~275.000 vehicles [49].

It is also helpful to compare expected $H_2$ demand between the EU and CA on a per-capita basis, considering the significant difference in population sizes—448.4 million in the European Union [50], approximately 11.5 times greater than CA's population of 38.97 million [51]. This is shown in **Figure 4.**

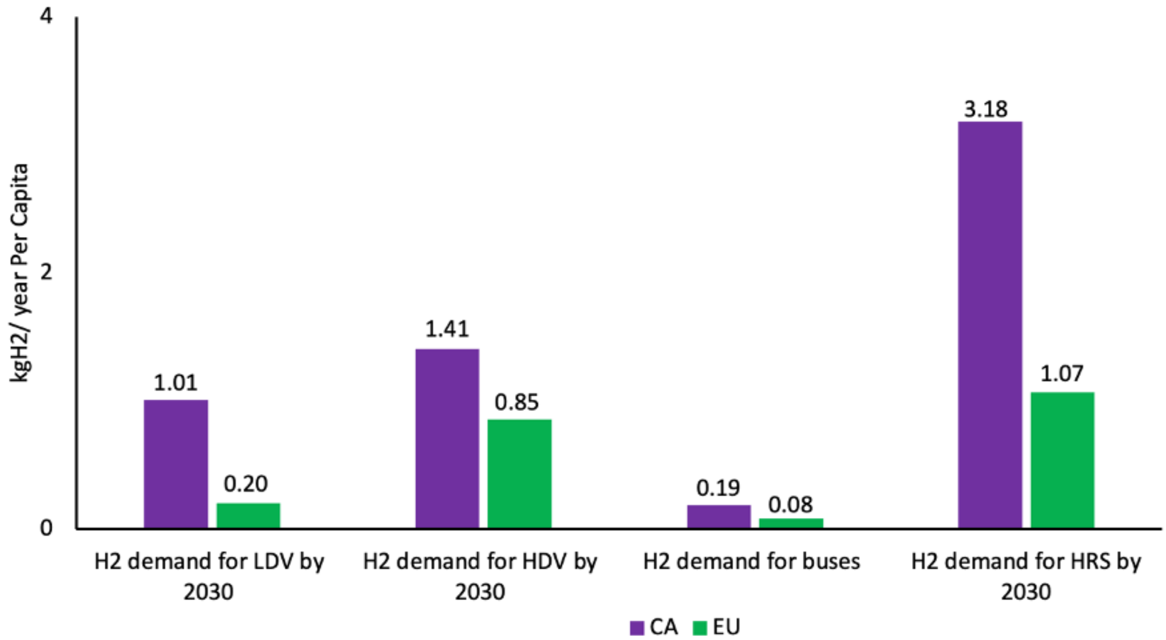



**Figure 4. $H_2$ expected demand per capita, based on 2030 targets for EU and CA**

The per capita estimates for 2030 shown in **Figure 4,** by vehicle type and for refueling stations, illustrate that while the EU has much higher overall projections per capita, California has greater ambition. This, in turn, reflects the rapid increase in demand California strives for in its ZEV sales targets, which are part of its general aim for climate neutrality by 2045. The specific ZEV sales targets for LDVs, trucks, and buses by 2030, at the assumed contribution from FCEVs, lead to 1 $kgH_2$, 1.41 $kgH_2$, and 0.19 $kgH_2$/capita, respectively. In contrast, the EU has more moderate projections and less aggressive policies, leading to comparatively lower hydrogen demand in the transportation sector.

## 3.4 European Member Country $H_2$ goals

In addition to the EU as a whole, some Member States also have relevant hydrogen goals and targets. We identify seven European member countries that have established significant goals or targets and published roadmaps or other relevant documents. These typically outline objectives for the transportation sector and the extent of progress made by $H_2$ implementation. **Table 9** shows the specific transportation sector goals for each country by 2030**.**

**Table 9. Selected EU Member States and their transportation sector goals by 2030. Data sources [52] [53][54][55] [56] [57] [58] [59] [60] [61] [62] [63] [64]**

| Country | LDV expected on road by 2030 | HDV vehicles expected on road by 2030 | Buses vehicles expected on road by 2030 | HRS expected by 2030 |
|---|---|---|---|---|
| France | 300,000 to 450,000 | 5,000 to 10,000 | - | 1,700 |
| Netherlands | 300,000 | - | - | - |
| Germany | - | 25,000 | 5,000 | 1,000 |
| Spain | 5,000 to 7,500 | | 150 to 200 | 100 to 150 |
| Belgium | - | - | - | 20 |
| Sweden | - | - | - | 130 to 140 |
| Italy | - | 4,000 | - | - |
| **Total** | 605,000 to 757,500 | 39,000 to 46,500 | 5,150 to 5,200 | 2,950 to 3,010 |

While these countries have set overarching hydrogen goals for 2030, a detailed review of **Table 9** reveals a lack of specificity for the numbers or kinds of vehicles and stations in most of these countries. Notably, Belgium and Sweden have yet to indicate vehicle numbers, only stations, at least in the sources reviewed for this paper. Among the countries evaluated, only Spain and Germany have disclosed projections for the expected number of buses on the roads by 2030.

**Figures 5** to **8** compare the goals set by the countries included in this study with the overall European Union goals for each category, including light-duty vehicles, heavy-duty vehicles, buses, and hydrogen refueling stations. These visual representations offer insights into the alignment or disparity between individual country objectives and the broader EU-level ambition.

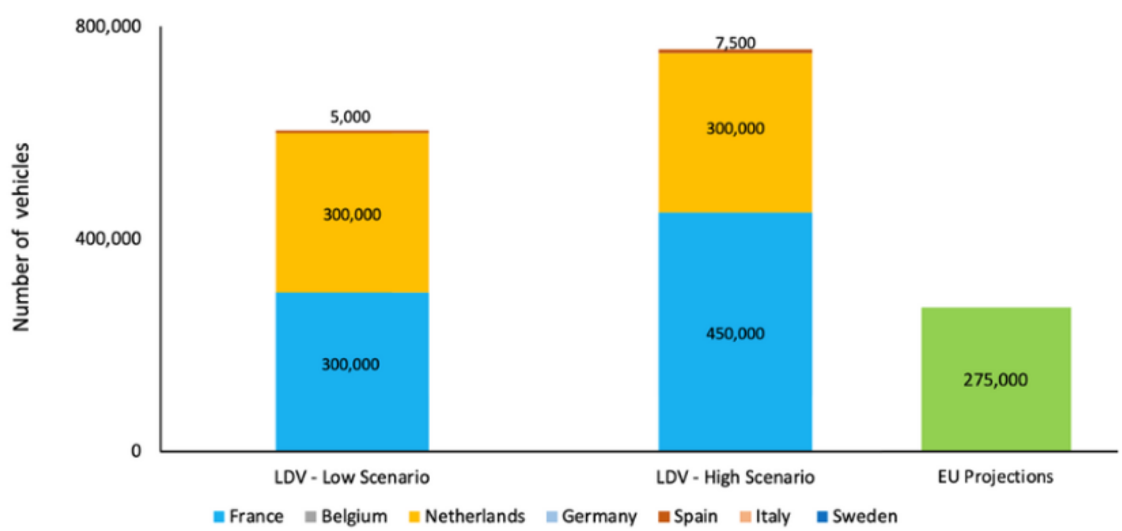



**Figure 5. Comparison of LDV Goals Between Individual Countries and EU Overall Projections.**

In both the low and high scenarios, the cumulative LDV goals from individual countries exceed the projected number of LDVs expected on roads by 2030, compared to the overall EU projections. **Figure 5** highlights variations in ambition and targets among EU nations, underscoring the complexity of aligning national objectives with overarching EU ambition. The difference between the individual countries' goals and the EU targets can be attributed to the EU's need to estimate an overall goal that can later be adjusted as countries set their targets. This flexibility allows the EU to accommodate national differences and integrate diverse strategies, reflecting each member state's unique circumstances and ambitions. Additionally, individual countries may set more ambitious targets to address specific national priorities or to lead by example in the transition to sustainable transportation. The EU can ensure a more adaptive and inclusive framework for achieving climate and energy objectives by setting a flexible overarching goal.

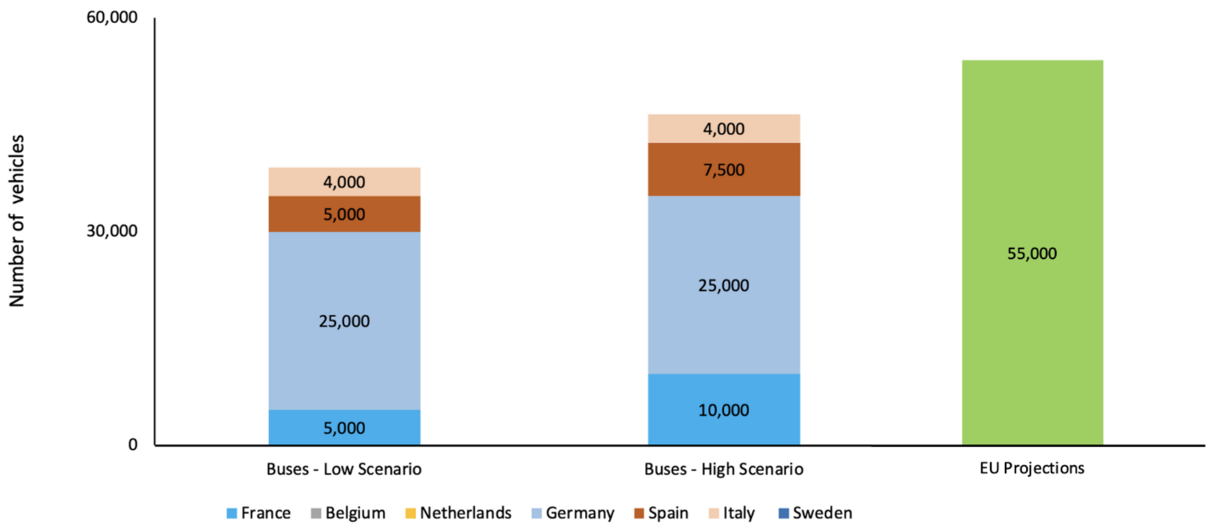



**Figure 6. Comparison of HDV Goals Between Individual Countries and EU Overall Projections.**

On the other hand, noteworthy figures emerge when comparing individual countries' cumulative HDV goals to the EU's overall objectives. In the low scenario, these goals represent ~71% of the EU's projections; in the high scenario, they reach ~84.5%. This suggests that the four countries analyzed in this study have made significant strides towards achieving the EU's overarching projections.

It is worth highlighting that these percentages are significantly influenced by Germany's reported goal of having 30,000 commercial vehicles on the road by 2030. Due to the lack of specification, this study will assume that 25,000 Heavy Duty Vehicles and 5,000 buses will be expected on the roads by 2030 in Germany. This figure stems from the Hydrogen Action Plan Germany 2021-2025, derived from the discussions and analyses outlined in the National Hydrogen Strategy (NWS) published by the German government in 2020. It is crucial to recognize that these goals are part of a series of recommendations and have not yet been officially endorsed by the German government [57]. Therefore, while they provide valuable insights, it's essential to await formal confirmation before fully incorporating them into analyses.

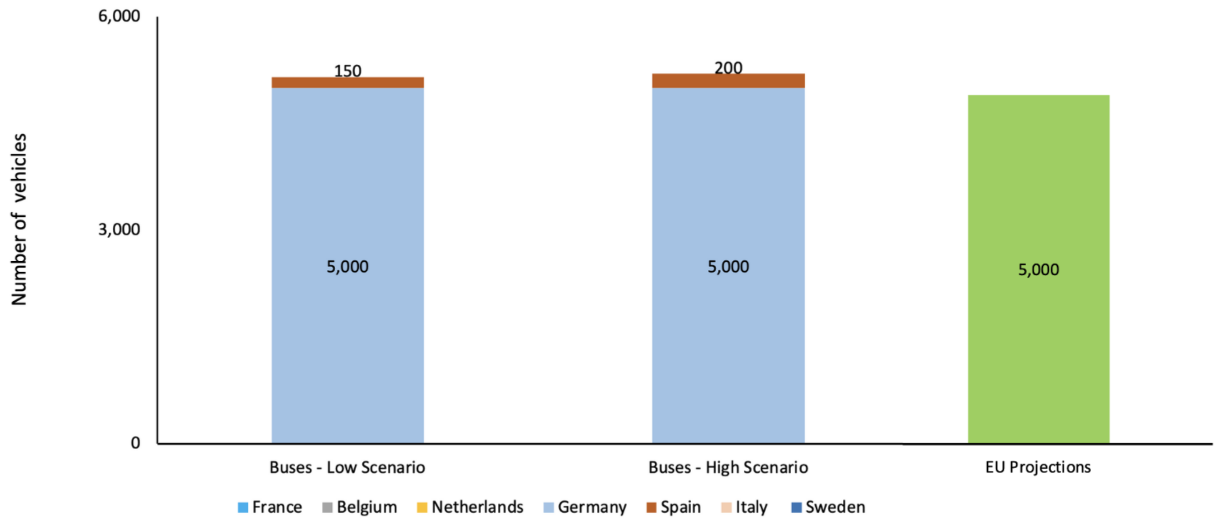



**Figure 7. Comparison of Bus Goals Between Individual Countries and EU Overall Projections.**

Considering the cumulative bus objectives of individual countries compared to the overarching goals of the European Union, as depicted in **Figure 7**, Germany achieves 100% of the EU's collective projections in both the low and high scenarios. However, it is important to clarify that the goals for buses in Germany and EU-wide projections are based on assumptions made in this study, based on broad policy approaches, due to a lack of detailed information at publication. Among the countries analyzed, only Spain has officially published its targets regarding the number of buses expected to be operational by 2030.

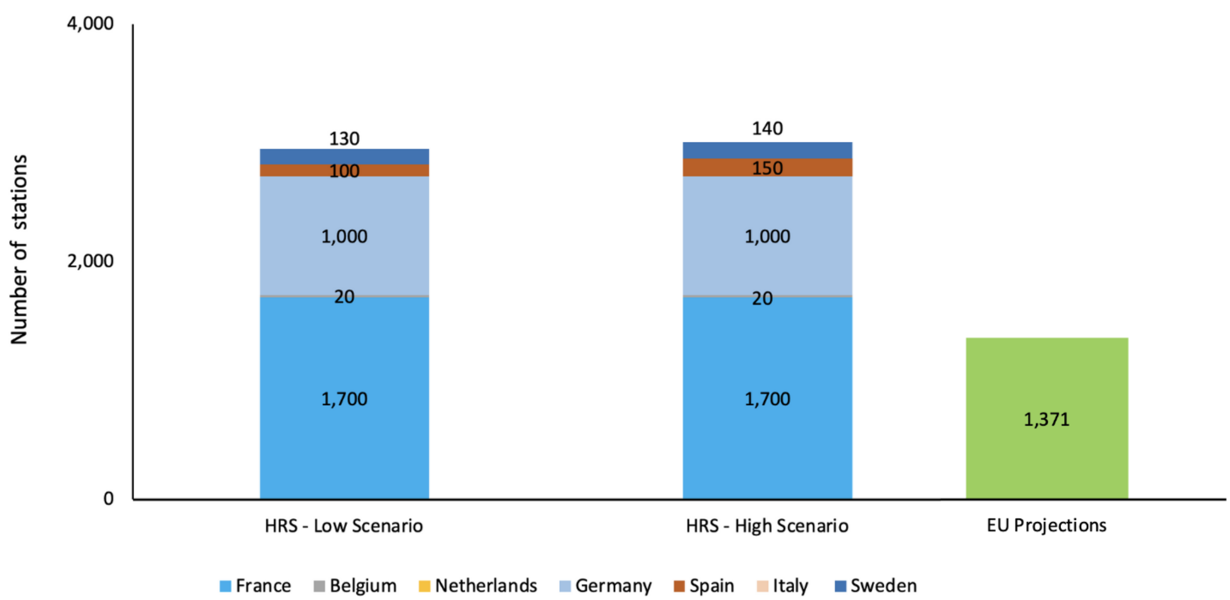



**Figure 8. Comparison of HRS Goals Between Individual Countries and EU Overall Projections.**

The higher cumulative hydrogen refueling station (HRS) goals set by five European countries compared to the EU's overall projections illustrate member states' diverse ambitions and priorities. As additional countries announce their HRS targets, we expect installations to increase further by 2030. As discussed in **Figure 5** results, the differences between individual countries' targets and the EU's overall projections are based on the EU's need to establish broad, flexible assumptions that might diverge from what individual countries set as their own specific goals.

# 4 Consumer Costs and Market Strategies

## 4.1 California Hydrogen Price at Hydrogen Refueling Stations (HRS)

As of April 2024, hydrogen prices at California stations range from about $30.00 to $36.00 per kg $H_2$ [65] [66]. According to an analysis by S&P Global, some key challenges affecting hydrogen supply and prices are fuel reliability, starting with challenges associated with the rising cost of feedstocks due to Russia's invasion of Ukraine; station deficiencies; unforeseen costs of operating and maintaining fueling stations; and the decline in Low-Carbon Fuel Standard (LCFS) credit values [67].

The Energy Earthshots Initiative by the U.S. Department of Energy (DOE) aims to expedite the development of abundant, cost-effective, and dependable clean energy solutions over the next decade to reduce the cost of hydrogen at stations. By achieving the Energy Earthshots objectives, America can overcome the most challenging remaining obstacles in combating the climate crisis. This effort will also accelerate the Biden–Harris Administration's ambition of achieving net-zero carbon emissions by 2050, all while generating well-paying union jobs and fostering economic growth. The inaugural Energy Earthshot, known as the Hydrogen Shot and launched on June 7, 2021, is focused on reducing the cost of clean hydrogen production by 80%, bringing it down to $1 per 1 kilogram within a decade. The DOE goals for $H_2$ production state ~$5kg$H_2$ by 2020, $2kg$H_2$ by 2030, and $1kg$H_2$ by 2030 [68]. The production cost for low-carbon hydrogen through water electrolysis using a Proton Exchange Membrane (PEM) in North California is about $3.99 per kg$H_2$ [69]. To accomplish the DOE goals, the cost must be reduced by $1.99 per kg$H_2$ in the next 6 years.

Moreover, to address the current high cost of hydrogen, California, through its AB 8 program, co-funds the deployment of at least 100 hydrogen fueling stations to enable the launch of a consumer FCEV market. To fulfill the state's climate and air quality objectives, substantial expansion in adopting zero-emission vehicles in the upcoming years is imperative. Establishing adequate fueling infrastructure for the anticipated ZEV fleet is a crucial initial phase, as underscored by the enactment of Assembly Bill 8 in 2013. CARB personnel collaborate with various entities, including the California Energy Commission, the Governor's Office of Business and Economic Development, the California Fuel Cell Partnership, and other relevant stakeholder groups. This concerted effort aims to guarantee that hydrogen fueling infrastructure is poised to facilitate the introduction and widespread implementation of Fuel Cell Electric Vehicles (FCEVs) [70].

In addition, the actual and projected prices of gasoline and diesel in California are important to consider when evaluating the competitiveness of hydrogen. As of 2024, California's average cost of gasoline and diesel is around $4.6 and $5 US dollars per gallon, respectively [71] [72]. Future projections in California suggest that these prices will continue to rise due to various factors, including decarbonization efforts, increasing environmental regulations, and market dynamics [71]

[72][73]. As gasoline and diesel become more expensive, hydrogen presents a more attractive alternative fuel option. This shift could enhance the adoption of hydrogen-powered vehicles, supporting California's goals for a cleaner and more sustainable energy future.

## 4.2 California FCEV Cost

In 2024, the price of Fuel Cell Electric Vehicles (FCEVs) remains relatively high compared to conventional gasoline vehicles and even some battery electric vehicles (BEVs). The cost of an LD-FCEV can range from $50,000 to $70,000, depending on the model and manufacturer [74] [75]. High production costs, limited production volumes, and the expense of hydrogen fuel infrastructure contribute to these prices. However, California is actively working to make FCEVs more affordable for consumers through various policies and strategies.

California offers financial incentives to reduce the initial cost of purchasing FCEVs. The San Joaquin Valley Air Pollution Control District Rebate Program and Redding Electric Utility (REU) provide rebates of up to $3,000 for eligible FCEV buyers [76]. Programs like the Bay Area Air Quality Management District's (BAAQMD) Clean Cars for All and South Coast Air Quality Management District program offer up to $9,500 for replacing an older vehicle with an FCEV, subject to income qualifications [77] [76]. These rebates help lower the effective purchase price, making FCEVs more accessible to a broader range of consumers.

The Zero-Emission Vehicle (ZEV) mandate is another key strategy. This mandate requires automakers to produce a certain percentage of zero-emission vehicles, including FCEVs, to be sold in the state [78]. By encouraging manufacturers to invest in FCEV technology and scale production, the ZEV mandate helps drive down costs through economies of scale.

California collaborates with various stakeholders, including the California Energy Commission (CEC), the Governor's Office of Business and Economic Development (GO-Biz), and the California Fuel Cell Partnership (CaFCP). These partnerships focus on advancing hydrogen technology, promoting FCEV adoption, and developing a robust hydrogen infrastructure [79]. This collaborative approach ensures that all aspects of FCEV deployment are addressed, from production and infrastructure to consumer incentives.

Looking to the future, California plans to expand its incentive programs and increase investment in hydrogen infrastructure. The state aims to establish a network of over 200 hydrogen refueling stations by 2025, ensuring that infrastructure keeps pace with the growing number of FCEVs on the road [80]. Additionally, through the awarded $H_2$ Hub, California is exploring ways to integrate renewable energy sources into hydrogen production, which could further reduce costs and enhance the sustainability of FCEVs [12].

Through these combined efforts, California is making significant strides toward making FCEVs more affordable and accessible to consumers. These initiatives are crucial for achieving the state's long-term climate goals and fostering a cleaner, more sustainable transportation system.

## 4.3 European Union: Hydrogen Price at HRS

The current average price of hydrogen dispensed at public $H_2$ refueling stations in the EU varies widely, between around €10 and €20 in Western Europe, equivalent to between $11 and 22 USD per kg $H_2$ [81]. The European hydrogen market faces several challenges that influence supply and pricing dynamics. These include high production costs, limited infrastructure, scaling up hydrogen production, market development complexities, and evolving regulatory frameworks to promote hydrogen adoption and sustainability [82] [83].

In response to these challenges, the EU has implemented strategic initiatives to scale up hydrogen production and expand infrastructure. The European Commission's Hydrogen Strategy aims to accelerate hydrogen production, distribution, and integration across member states [84]. To support the development of the hydrogen market, the EU is implementing various policies and funding mechanisms. For instance, the European Hydrogen Bank will provide around 3 billion EUR from the EU's Innovation Fund to support hydrogen purchases and help cover the cost gap between renewable and fossil-based hydrogen [85]. These initiatives are aligned with Europe's ambitious climate goals and seek to enhance energy security and foster economic growth through sustainable energy solutions.

Additionally, the current average price of conventional fuels like gasoline and diesel in the EU are $2.3 and $1.7 US dollars/ liter, which is equivalent to $8.7 and $6.4 US dollars per gallon, respectively [86] [87]. These prices are projected to increase due to stringent environmental policies, market forces, tax schemes, and the EU's tightening carbon market. This development could help hydrogen emerge as a competitive alternative [88] [89]. Its lower environmental impact and potential cost-effectiveness position hydrogen as a critical component in Europe's transition towards a carbon-neutral economy, supporting the adoption of Fuel Cell Electric Vehicles (FCEVs) and other clean transportation technologies.

Strategic investments in hydrogen infrastructure, collaborative partnerships between EU institutions, member states, and industry stakeholders, as well as ongoing advancements in hydrogen technology, underscore the EU's commitment to building a robust and resilient hydrogen economy [90] [91] [92]. These efforts aim to reduce greenhouse gas emissions, drive innovation, and create new economic opportunities while bolstering energy independence throughout the European Union.

## 4.4 European Union FCEV Cost:

In 2024, the adoption of Fuel Cell Electric Vehicles (FCEVs) in the EU faced cost barriers compared to conventional vehicles and some battery electric vehicles (BEVs). Prices for LD-FCEVs typically range from €60,000 to €78,000, equivalent to $64,000 and $83,305 US dollars, respectively. These prices reflect high production costs and the current manufacturing scale [93]. Overcoming these challenges requires innovative strategies and policies to enhance affordability and stimulate market growth.

To address the affordability, the European Commission has approved Important Projects of Common European Interest (IPCEI) to support hydrogen projects, including IPCEI Hy2Tech and IPCEI Hy2Use [94] [95], which provide public funding for FCEV-related projects. Countries like the Netherlands and Germany have implemented tax and purchase incentives to make FCEVs more economically viable for consumers [96] [97]. These measures aim to reduce the upfront costs of purchasing FCEVs and promote their uptake across diverse socioeconomic groups.

The EU's regulatory framework also plays a crucial role in driving down costs and expanding the market for FCEVs. The $CO_2$ emission standards require automakers to produce vehicles with lower $CO_2$ emissions yearly. The goal is for their fleets sold in EU member states to reach 0 g $CO_2$ per km in 2035. This mandate encourages automakers to invest in FCEV technology and increase production volumes, potentially leading to economies of scale that could lower prices over time [35].

Looking forward, the EU plans to intensify investments in hydrogen infrastructure and expand incentive programs to enhance FCEVs' competitiveness further. Initiatives such as the EU's Horizon Europe framework and public-private partnerships aim to accelerate technological innovation in hydrogen production and distribution, potentially driving down costs associated with hydrogen fueling [97] [91].

The EU is paving the way for a more affordable and sustainable future for Fuel Cell Electric Vehicles by fostering a supportive policy environment, investing in infrastructure development, and promoting technological innovation. These efforts align with the EU's broader climate objectives and aim to reduce greenhouse gas emissions from the transportation sector while supporting economic growth and job creation across Europe.

# 5 Conclusions

The transportation sector's transition towards a zero-emission future is a multifaceted challenge that requires a range of technology and energy solutions and a concerted effort from policymakers, industry leaders, and stakeholders to achieve this future across regions and nations. The European Union and California have strongly committed to this transition by setting ambitious goals and targets for adopting hydrogen fuel cell technology in various transportation segments.

One notable aspect is the technology-neutral approach adopted by both regions, which allows for the coexistence and deployment of battery and fuel-cell electric vehicles. This flexibility enables leveraging the strengths of each technology, catering to diverse mobility needs, and facilitating a more comprehensive decarbonization strategy. However, it also means few direct requirements or incentives for hydrogen or (especially) fuel-cell vehicles, which creates uncertainty about the future growth in the market and its ultimate size.

Several other challenges persist, necessitating collaborative efforts and innovative solutions. First, sourcing low-carbon and renewable hydrogen remains a bottleneck. Limited supply (and unclear prospects for supply growth) hinder widespread adoption. Addressing this challenge will require substantial investments in scalable production methods, infrastructure development, and integrating renewable energy sources into the hydrogen supply chain.

Second, hydrogen's cost competitiveness as a transportation fuel compared to conventional fossil fuels is a critical factor influencing its widespread adoption. While the EU and California have implemented ambitious policies for reducing hydrogen production costs, achieving cost parity per km will require sustained deployment and scaling efforts, ongoing research and development efforts, and supportive policy frameworks, notably carbon pricing.

In particular, the competition for scarce electricity generation, transmission, and distribution capacity in the EU and CA poses a challenge, as the transportation sector's electrification, including from both EVs and FCEVs, will increase the demand for clean electricity. Hydrogen may require about twice the number of electrons per km delivered than EVs, and there may be significant concerns about allocating significant capacity to $H_2$ instead of the more efficient EV pathway. Addressing this challenge will necessitate strategic planning across sectors, grid modernization, and the expansion of renewable energy capacity to meet the growing energy needs of the transportation sector.

Ultimately, the successful integration of hydrogen fuel and vehicle technology in the transportation sector will contribute to mitigating greenhouse gas emissions and air pollution, fostering innovation, creating new economic opportunities, and enhancing energy security. Achieving a zero-emission target by 2035 requires rapid investments, scale-up, and cost reductions for hydrogen to become competitive and economically sustainable.

The future development will play out in the triangle between the forces of comparative technological progress in fuel cell and battery electric vehicles (‘technology’), the level of public support measures (‘policy’), and consumer preferences (‘psychology’).

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