The European hydrogen market landscape

November 2024

Disclaimer

The aim of this report is to reflect the situation in the European hydrogen market landscape as of the end of 2023, unless stated otherwise. The authors believe that this information comes from reliable sources, but do not guarantee the accuracy or completeness of this information.

The data of the European Hydrogen Observatory will continuously be updated. These updates will take place annually for most datasets, while for some it can also be done on a case by case basis. As a result, the information used as of writing of this report might differ from the updated data that is presented on the European Hydrogen Observatory.

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Executive summary

This report aims to summarise the status of the European hydrogen market landscape in 2023. It is based on the information available at the European Hydrogen Observatory (EHO) platform, the leading source of data and information on hydrogen in Europe (EU27, EFTA and the UK), providing a full overview of the hydrogen market and the deployment of clean hydrogen technologies.

Hydrogen production by process

As of the end of 2023, a total of 512 operational hydrogen production facilities across Europe were identified, reflecting an increase of 36 facilities compared to 2022. The cumulative hydrogen production capacity was approximately 11.23 Mt, remaining almost constant from 2022 (-1%). However, hydrogen output in Europe decreased by 3.5% from 2022, totalling approximately 7.94 Mt, which resulted in an average capacity utilization rate of 71%.

Among these facilities, 368 (representing 99.1% of total capacity) are conventional installations, capable of producing 11.13 Mt of hydrogen through methods encompassing reforming, by-product production from ethylene and styrene, and by-product electrolysis. The remaining 144 facilities, with a cumulative capacity of 0.10 Mt, utilize “clean” technologies, including reforming with the simultaneous capture of associated emissions (commonly known as carbon capture), facilities and hydrogen production through water electrolysis. In 2023, no new hydrogen production facilities with carbon capture technology were commissioned, maintaining the total of such installations at three. Additionally, a notable presence of water electrolysis-based hydrogen production projects in Europe was identified. A total of 141 water electrolysis projects were identified, with 88 of them having a minimum capacity of 0.5 MW. These projects collectively contributed to a production capacity of 258.39 MW (or 0.05 Mt), marking an increase of 48.2% compared to 2022. Furthermore, 66 such projects were found to be under construction and are anticipated to contribute an additional 1,857 MW (or 0.35 Mt) of water electrolysis capacity upon becoming operational, with the estimated timeframe ranging from 2024 to 2026.

Hydrogen production by market type

In 2023, the distribution of the total production capacity by market type stayed nearly unchanged. A significant 88% (9.85 Mt) of the total hydrogen production capacity in Europe is dedicated to on-site captive consumption, indicating that it is primarily produced and used within the facility. The remaining 12% of capacity is specifically allocated for external distribution and sale, characterizing what's known as merchant consumption.

Hydrogen trade

Despite the prevailing dominance of captive hydrogen production within Europe, it's noteworthy that a total of 29,767 tonnes of hydrogen was traded and distributed across Europe in 2023, reflecting a 12.9% decline compared to the volume traded in 2022. These transfers often occur through dedicated hydrogen pipelines or transportation via trucks. In 2023, an example of this growing trend was the hydrogen export from Belgium to the Netherlands, which remained the single most significant hydrogen flow between European countries, making up 65% of all hydrogen traded in Europe. Although it continued to be the dominant route, its share of the total hydrogen traded decreased by 10% compared to 2022. Belgium earned distinction remaining Europe's leading hydrogen exporter, with 71% of the hydrogen that flowed between European countries originating from its facilities. Conversely, the Netherlands played a pivotal role remaining Europe's primary hydrogen importer, accounting for 66% of the hydrogen imported into the continent. The expected rise of the clean hydrogen market in Europe, coupled with the European Union's ambition to import 10 Mt of renewable hydrogen from non-EU sources by 2030, is expected to drive an increase in hydrogen flows, both exports and imports, among European countries.

Hydrogen demand

In 2023, the total demand for hydrogen in Europe was estimated to be 7.93 Mt, reflecting a 3.2% decrease compared to 2022. The biggest share of hydrogen demand comes from refineries, which were responsible for 57% of total hydrogen use (4.55 Mt), followed by the ammonia industry with 25% (2.00 Mt). Together these two sectors consumed 82% of the total hydrogen consumption in Europe. Clean hydrogen demand, while currently making up less than 0.4% of the overall hydrogen demand, is notably driven by the industrial heat and mobility sector. Forecasts project an impressive growth trajectory in total hydrogen demand for Europe over the coming decades. Projections show a remarkable 127% surge from 2030 to 2040, followed by a substantial 63% increase from 2040 to 2050. Considering the current hydrogen demand, there is a projected 56% increase until 2030. Throughout the three decades under examination, the industrial sector is anticipated to maintain its predominant position, consistently demonstrating the highest demand for hydrogen. However, this conclusion refers to average values and variations may exist.

Hydrogen Fuel Cell Electric Vehicles (FCEV)

The total number of Hydrogen Fuel Cell Electric Vehicles (FCEV) registrations in Europe in 2023 was estimated at 1,026 units. In comparison to the previous year, the number of registrations decreased by 34%. Despite the decline in FCEV registrations from 2022 to 2023, the total FCEV fleet in Europe still increased from 5,567 units to 5,939 (+7%) during the same period. Notably, passenger cars dominated the landscape, constituting 83% of the total FCEV fleet.

Hydrogen pipelines and storage

Hydrogen infrastructure, including pipelines and storage facilities, plays a critical role in supporting the expansion and distribution of hydrogen. In 2023, the hydrogen pipeline network across Europe consisted of 17 pipelines, spanning a total length of 1,581 km. Within Europe, the largest networks are situated in Belgium and Germany, at approx. 600 km and 400 km, respectively. Of particular importance is the cross-border network of France, Belgium, and the Netherlands spanning a total of 964 km. In 2023, four hydrogen storage projects employing different technologies (salt and hard rock cavern, depleted gas field) were in operation, most in a demonstration phase.

Hydrogen refuelling stations (HRS)

To keep pace with the rising number of Fuel Cell Electric Vehicles (FCEVs) on European roads and promote their wider integration, it is key to ensure sufficient accessibility to refuelling infrastructure. Consequently, many countries are endorsing the establishment of hydrogen refuelling stations (HRS) so that they are publicly accessible on a nationwide scale. More recharging and refuelling stations for alternative fuels will be deployed in the coming years across Europe enabling the transport sector to significantly reduce its carbon footprint following the adoption of the alternative fuel infrastructure regulation (AFIR). Part of the regulation's main target is that hydrogen refuelling stations serving both cars and lorries must be deployed from 2030 onwards in all urban nodes and every 200 km along the TEN-T core network. Since 2015, the total number of operational and publicly accessible HRS in Europe has grown at an accelerated pace from 38 to 187 by May 2024. Germany takes the lead having the largest share at approximately 46% of the total number of HRS, with 86 stations currently operational. The majority of HRS (91%) in Europe are equipped with 700 bar car dispensers.

Hydrogen production cost

In 2023, the levelized production costs of hydrogen generated through steam methane reforming (SMR) in Europe averaged approximately 3.76 €/kg H_2. When incorporating a carbon capture system, the average cost of hydrogen production via SMR in Europe increased to 4.41 €/kg H_2. Additionally, the production costs of hydrogen in Europe for 2023 by water electrolysis, utilizing grid electricity, averaged 7.94 €/kg H_2. Hydrogen production costs through electrolysis with a direct connection to a renewable energy source had an average estimated cost of 6.61 €/kg. Compared to 2022, the cost gap between SMR and grid-connected electrolysis increased by 0.56€/kg.

Break-even price of renewable hydrogen

Based on the 2023 prices, it was calculated that the switch to clean hydrogen in oil refining production activities becomes economically competitive with natural gas-based hydrogen (SMR) as soon as clean hydrogen is available for the off-taker at a price between 2.7 and 5.6 €/kg, depending on the EU country. Correspondingly, the break-even prices for clean hydrogen adoption in other sectors are as follows: primary steel making at 4.7 €/kg, maritime applications at 1.5 – 2.7 €/kg and heavy-duty trucks (at the pump) at 2.4 – 5.8 €/kg. Compared to 2022, break-even prices for oil refining decreased, while it increased for steel making and maritime applications.

Electrolyser manufacturing capacity

By the end of 2024, it is expected that the total water electrolyser manufacturing capacity in Europe will grow to 8.8 GW/year. As of May 2024, 5.4 GW per year is already operational, an increase of 2.29 GW per year compared to May 2023, with an additional 3.4 GW planned to become operational. Alkaline technologies make up 46% of the total capacity. Looking ahead to 2026, ongoing projects are expected to raise the total capacity to 10.5 GW/year.

Electrolyser sales

Approximately 65 MW of water electrolysers were sold by European water electrolyser manufacturers in 2023, a slight increase compared to 2022 (+5%). Alkaline and Proton Exchange Membrane (PEM) technologies accounted for 43% and 36% of total sales respectively.

Electrolyser cost

The cost assessment of electrolyser technologies reveals distinct financial profiles. The alkaline electrolyser is reported to have a Capital Expenditure (CAPEX) of 1666 €/kW and an Operational Expenditure (OPEX) of 43 €/kW/year. In contrast, the Proton Exchange Membrane (PEM) electrolyser demonstrates a comparatively higher cost structure, with an estimated CAPEX of 1970 €/kW and OPEX of 64 €/kW/year.

Fuel cell market

Fuel cell deployment in Europe has showed an increasing trend over the past decade. The total number of shipped fuel cells were around 13,200 units in 2022 and a total capacity of 228.1 MW. The most significant increase in capacity occurred between 2018 and 2022 (+186.9MW).

Key insights

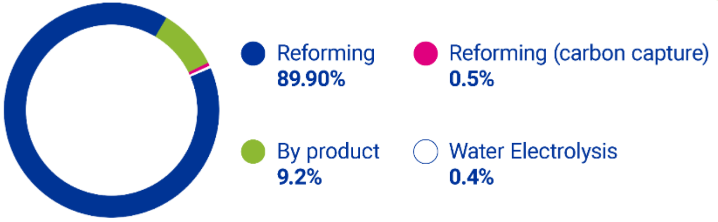
Production

512 Operational hydrogen production plants in Europe in 2023 (+7.6% from 2022)

11.23 Mt of total annual production capacity in 2023 (-0.9% from 2022)

7.94 Mt produced in 2023 (-3.5% from 2022)

Hydrogen production capacity by production process in 2023



258.39 MW
of water electrolysis capacity in operation in 2023 coming from 141 projects (+48.2% from 2022)

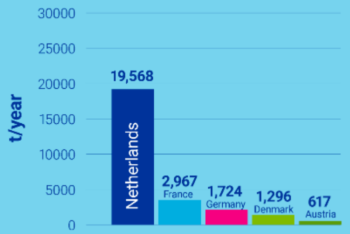
Another 66 projects were under construction in 2023, totalling a capacity of 1,857 MW

5.40 GW/year
of electrolyser manufacturing capacity in May 2024 (+10.4% from Dec. 2023)

Alkaline 52% **PEM 48%**
SO <1% AEM <1%

64.97 MW
of electrolysers sold in 2023 by European manufacturers (+5.0% from 2022)

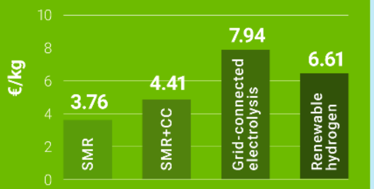
Trade



A total of 29,767 tonnes of hydrogen was exchanged between European countries in 2023 (-12.9% from 2022)

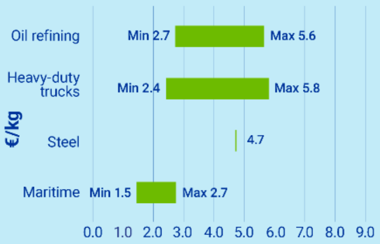
Costs

Average levelised hydrogen production costs by technology in 2023.



Compared to 2022, the cost gap between SMR and grid-connected electrolysis increased by 0.56€/kg

Estimated break-even price for renewable hydrogen by end-use in 2023.



Compared to 2022, break-even prices for oil refining decreased, while it increased for steel making and maritime applications

Electrolysers cost in 2023

Alkaline	PEM
CAPEX 1,666€/kW	**CAPEX** 1,970€/kW
OPEX 43€/kW/year	**CAPEX** 64€/kW

Distribution & Storage

1,581 km of hydrogen distribution network

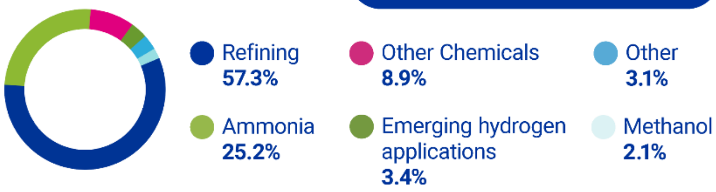
187 publicly accessible and operational hydrogen refuelling

by May 2023

End Use

7.93 Mt of total hydrogen demand in 2023 (-3.2% from 2022)

A total fleet of 5,939 (+6.6% from 2022) Hydrogen fuel cell electric vehicles in 2023, of which 4,938 were passengers cars



Overview

The use of hydrogen as a clean energy source and feedstock is a topic of increasing interest in Europe and around the world due to its potential for reducing greenhouse gas emissions and supporting the transition to a more sustainable energy system.

This report aims to summarise the status of the European hydrogen market landscape. It is based on the information available at the European Hydrogen Observatory (EHO) initiative, the leading source of data on hydrogen in Europe, exploring the basic concepts, latest trends, and role of hydrogen in the energy transition. The data presented in this report is based on research conducted until the end of September 2024. This report contains information on current hydrogen production and trade, distribution, and storage, end-use, cost and technology manufacturing as of the end of 2023, except if stated otherwise, in Europe. A substantial portion of the data gathering was carried out within the framework of Hydrogen Europe's efforts for the European Hydrogen Observatory. Downloadable spreadsheets of the data can be accessed on the website: https://observatory.clean-hydrogen.europa.eu/.

The production and trade section provides insights into hydrogen production capacity and production output by technology in Europe and into international hydrogen trade (export and import) to and between European countries.

The section referring to distribution and storage presents the location and main attributes of operational dedicated hydrogen pipelines and storage facilities, as well as publicly accessible and operational hydrogen refuelling stations in Europe.

The end-use section provides information on annual hydrogen consumption per end-use in Europe, the deployment of hydrogen fuel cell electric vehicles in Europe, the current and future hydrogen Valleys in Europe, and the leading scenarios for future hydrogen demand in Europe in 2030, 2040 and 2050 by sector.

The cost chapter offers a comprehensive examination of the levelised cost of hydrogen production by technology and country. This chapter also gives estimations of renewable hydrogen break-even prices for different end-use applications, in addition to electrolyser cost components by technology.

Finally, a chapter on technologies manufacturing explores data on the European electrolyser manufacturing capacity and sales, and the fuel cell market.

01

Production and trade

Introduction

This chapter provides an overview of the current hydrogen production and trade statistics of Europe. The analysis undertaken for this chapter was completed using data reflecting the end of 2023, unless otherwise specified.

The section on hydrogen production assesses data on hydrogen production capacity, production outputs and number of production plants per country by production process and consumption profile, expressed in million tonnes (Mt) per year. Data was estimated by Hydrogen Europe based on a set of assumptions updated annually and subsequent verifications with industry stakeholders.

International hydrogen trade data was collected by Hydrogen Europe based on Eurostat's existing international hydrogen trade data statistics and subsequent verification with industry stakeholders.

Interactive data dashboards and downloadable spreadsheets on hydrogen production & hydrogen trade can be accessed on the European Hydrogen Observatory website.

1.1.

Hydrogen production overview

By the end of 2023, there were 512 operational hydrogen production facilities in Europe capable of producing 11.23 Mt of hydrogen annually, remaining almost constant compared to 2022 (-1%). In 2023, 7.94 Mt of hydrogen was produced. Considering the estimated hydrogen consumption, hydrogen production facilities, on average, operated at a utilization capacity of 71%. Hydrogen production capacity by country is given in Figure 1.

In 2023, Germany, the Netherlands, Poland, France, and Italy remained the top five countries in hydrogen production capacity, collectively representing 57% of Europe's total. This unchanged ranking from 2022 highlights the continued dominance of these nations in the European hydrogen sector. Hydrogen production capacity varies significantly among countries, primarily influenced by their industrial foundations, since it is mainly linked to the reforming capacity required within the refining and ammonia sectors. The eight countries with the highest production capacity collectively represent 74% of the total hydrogen production capacity within Europe. The remaining 19 countries possessing hydrogen production capabilities account for just 26% of the overall installed capacity within Europe.

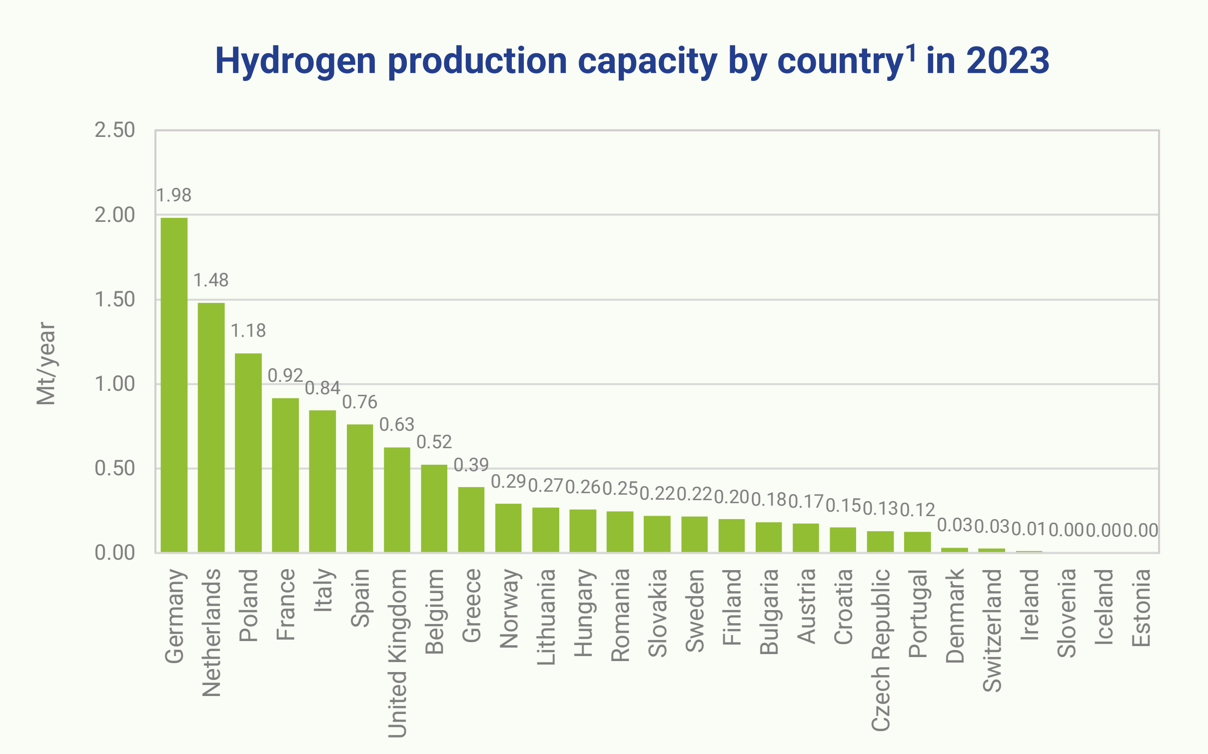


Figure 1. Production capacity (Mt/year) by country[1] in 2023.

A breakdown of average production capacity utilization by country or region reveals significant variations (Figure 2).

Portugal and Finland led the way with the highest average production capacity utilization, achieving 92% of their production capacity. Greece followed closely behind with an average production capacity utilization of 89%. In contrast, Croatia and Romania reported the lowest average production capacity utilization levels, both falling below 50%.

Notably, while Germany, the Netherlands, Poland, France, and Italy together represent 57% of total hydrogen production capacity, their average utilization remains comparatively low at 67%.

Figure 3 shows the annual hydrogen production output, measured in Mt, for various countries. Four countries, Germany, the Netherlands, Poland, and Spain collectively account for almost 50% of the total hydrogen output of Europe.

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[1] Production capacities for Slovenia, Iceland and Estonia are less than 3,000 t/y so they appear as 0.00 Mt.

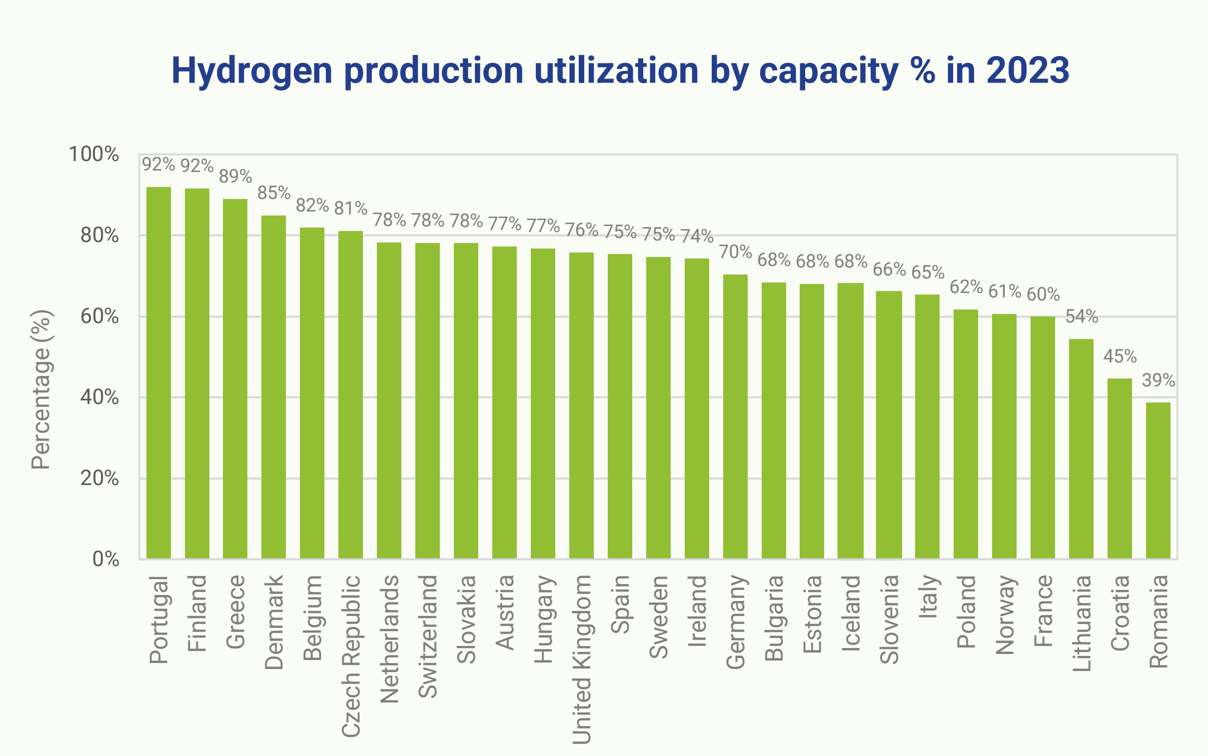

Figure 2. Hydrogen production utilization (%) in 2023, calculated as the output divided by production capacity.

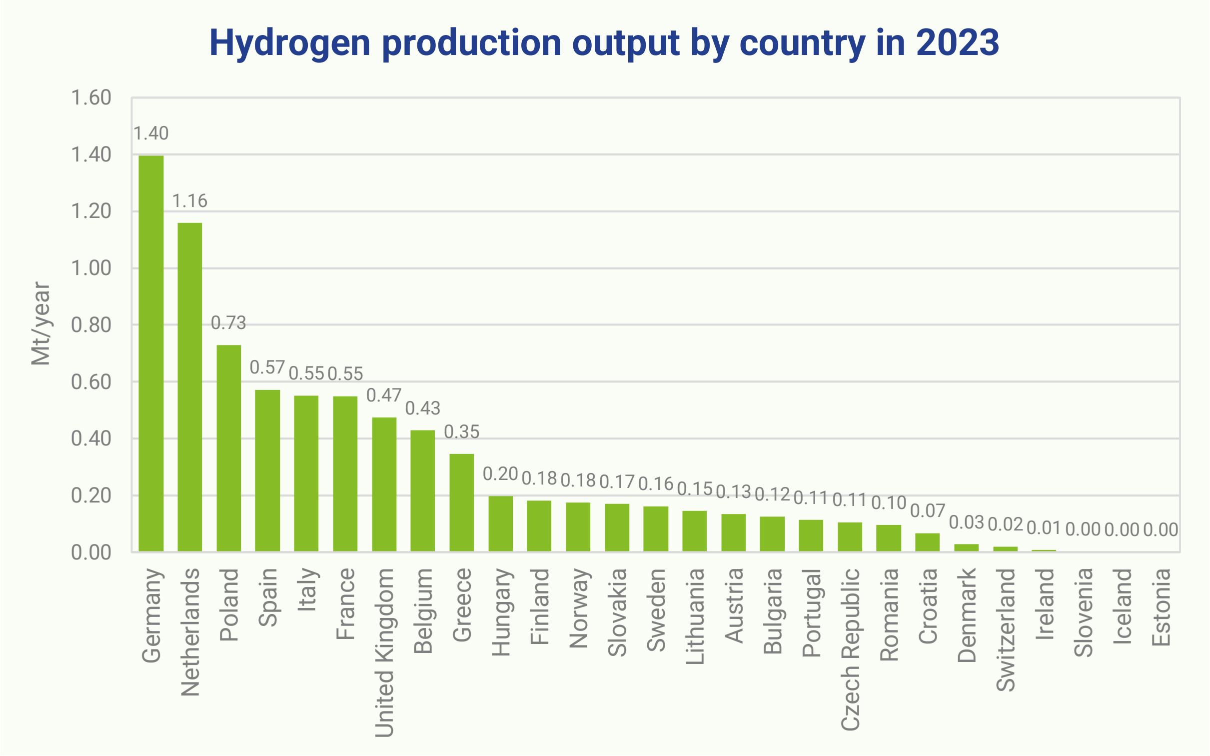

Figure 3. Hydrogen production output (Mt/year) by country in 2023.

1.2.

Hydrogen production per production process

Explanatory descriptions of the various hydrogen production processes referenced in this chapter are given in Table 1.

Table 1. Outline of the terminology employed in this chapter to describe various methods of hydrogen production.

Reforming	Generation of hydrogen through processes like steam reforming, partial oxidation, gasification, and autothermal reforming of fossil fuels. These methods represent the most substantial capacity for hydrogen production. Additionally, this category encompasses hydrogen produced as a by-product within refineries, such as during catalytic reforming.
By-product (ethylene, styrene)	Hydrogen production capacity that arises as a by-product during the manufacturing of ethylene and styrene.
By-product (electrolysis)	Hydrogen production capacity that arises as a by-product during the manufacturing of chlorine and sodium chlorate.
Reforming (with carbon capture)	Generation of hydrogen through processes that make use of fossil fuels while simultaneously capturing the associated CO_2 emissions such as steam reforming, gasification, partial oxidation and autothermal reforming.
Water electrolysis	Hydrogen production capacity based on the use of installed electrolysis equipment for splitting water into hydrogen and oxygen gases by using electricity.

A comprehensive representation of the distribution of hydrogen production capacity across various production processes in 2023 is given in Figure 4. Reforming stands out as the predominant method for hydrogen production, commanding a substantial 89.9% share of the total hydrogen production capacity. In contrast, hydrogen production capacity stemming from by-products generated during the manufacturing of ethylene, styrene, chlorine, and sodium chlorate comprises a relatively smaller fraction, accounting for approximately 9.2% of the overall production capacity. At last, “clean” processes that combine reforming with the simultaneous capture of associated emissions (commonly known as carbon capture) and hydrogen production through water electrolysis represent a notably minor segment, contributing to less than 1% of the total hydrogen production capacity.

Germany, Netherlands, Poland, Italy, France, Spain, UK, and Belgium constitute Europe’s top 8 hydrogen producers (Figure 5), accounting for 73% of the hydrogen produced via reforming, 83% of the hydrogen produced as a by-product, 59% of the hydrogen produced through water electrolysis, and almost 100% of the hydrogen produced via reforming coupled with carbon capture.

In these countries, hydrogen production primarily relies on reforming processes, constituting approximately 89% of their total hydrogen production. Hydrogen produced as a by-product follows, contributing to around 10% of their total hydrogen output. In contrast, water electrolysis and reforming with carbon capture collectively represent less than 1% of the total hydrogen production in these eight countries.

Hydrogen production via reforming is the dominant method among the remaining 19 hydrogen-producing countries as well (Figure 6), constituting approximately 93% of the total hydrogen production in these countries. Hydrogen produced as a by-product follows closely, accounting for nearly 6% of their total hydrogen production. Additionally, hydrogen generated through water electrolysis comprises less than 1%. It is worth noting that these countries do not engage in hydrogen production via reforming coupled with carbon capture.

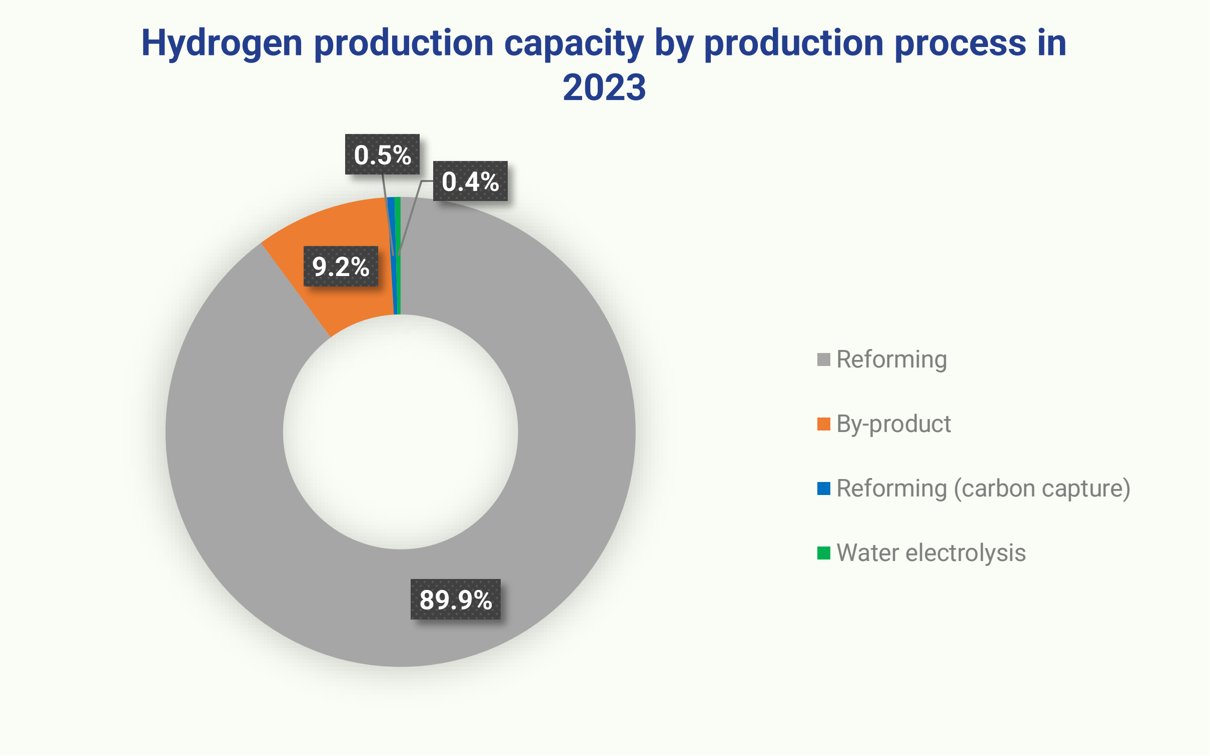

Figure 4. Hydrogen production capacity by production process in 2023.

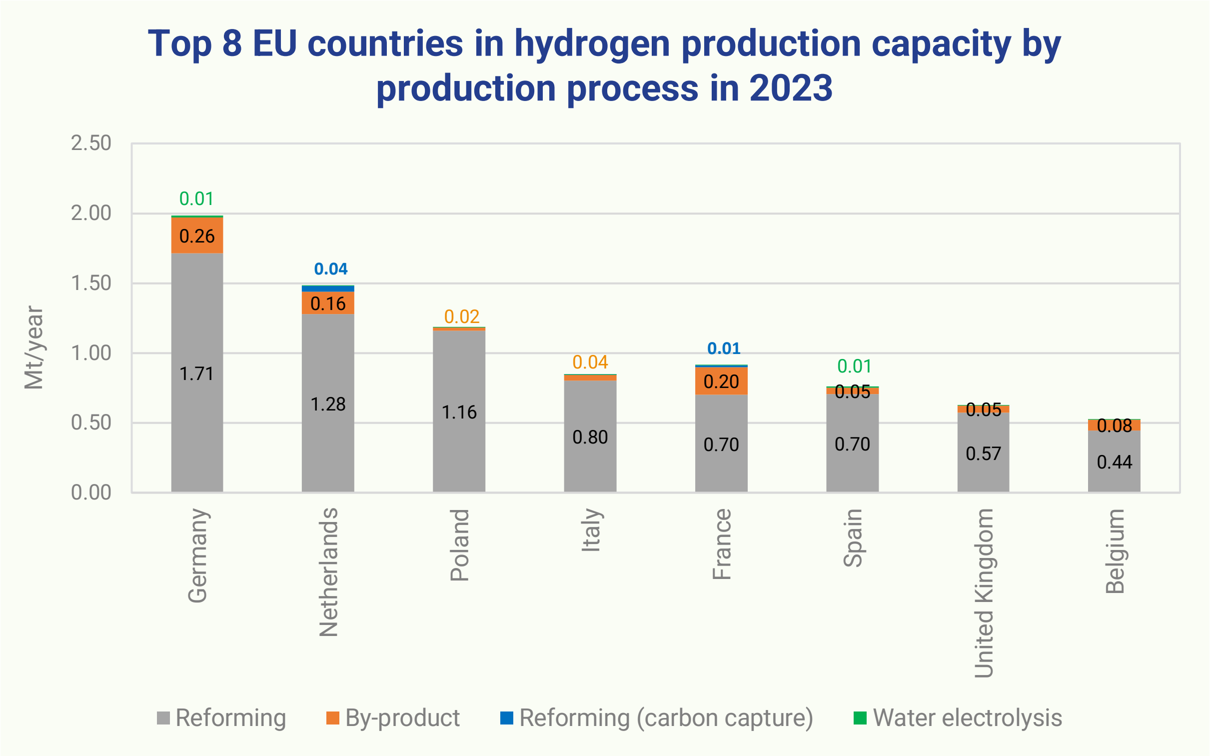

Figure 5. Top 8 EU countries in terms of hydrogen production capacity by production process.

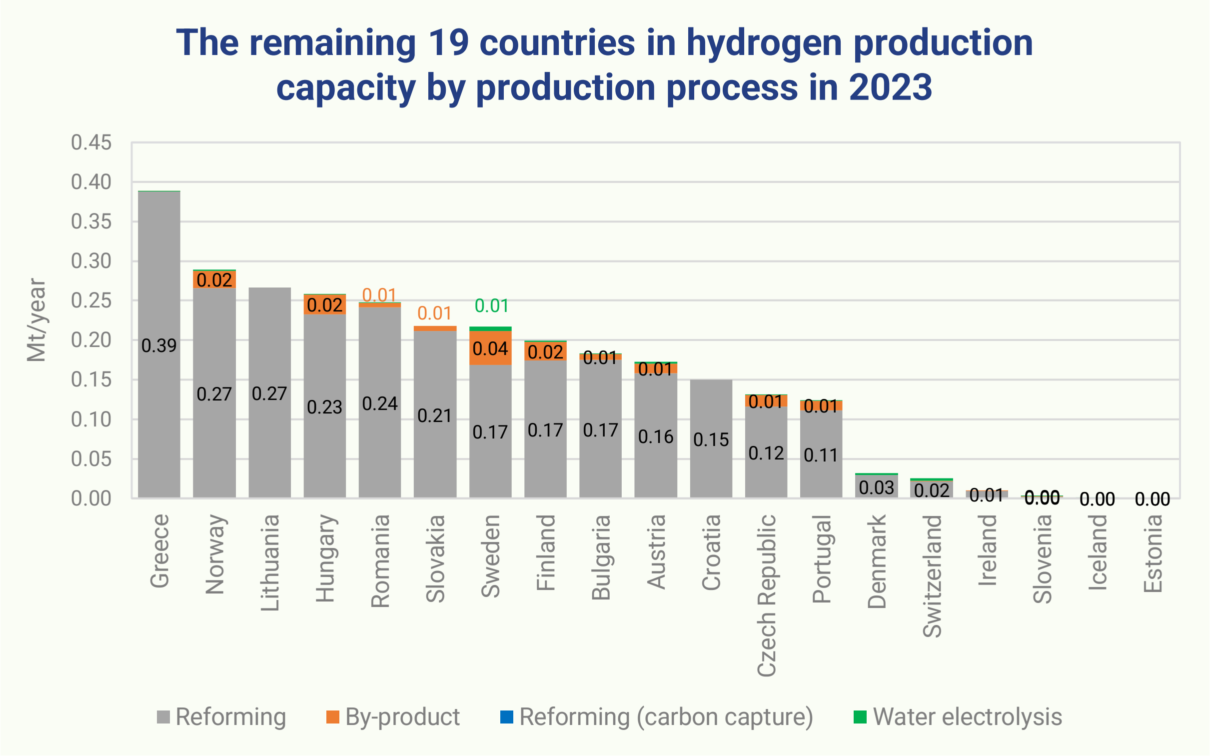

Figure 6. The remaining 19 countries in terms of hydrogen production capacity by production process[2].

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[2] Slovenia Iceland and Estonia have production capacities of less than 2,800 t/y, which are reflected as 0.00 Mt

In this section, the hydrogen production capacity is subdivided into three categories: conventional hydrogen production, reforming with carbon capture, and power-to-hydrogen technologies. These categories are examined in greater detail below.

1.2.1.

Conventional production capacity

The conventional hydrogen production methods refer to reforming, by-product production from ethylene and styrene, and by-product electrolysis (i.e., capacity from chlorine and sodium chlorate production).

The most prevalent method for hydrogen production is steam reforming of natural gas (SMR). Less commonly utilized methods include partial oxidation (POX), gasification, and autothermal reforming (ATR). These methods find extensive applications in various industries, including refining, ammonia production, methanol production and other large-scale hydrogen production processes.

While natural gas serves as the predominant feedstock, hydrogen is also produced from liquid hydrocarbons such as liquefied petroleum gas (LPG) and naphtha.

The conventional production methods of reforming, by-product production from ethylene and styrene and by-product electrolysis amounts to 11.13 Mt of hydrogen per year, distributed across 368 production facilities, representing 99.1% of total production capacity in 2023. Considering the estimated hydrogen consumption, these facilities, on average, operated at a utilization production capacity of 71%, with a total output of 7.86 Mt.

Hydrogen generated via reforming is manufactured at 237 plants. The total production capacity for hydrogen via reforming is estimated to be 10.09 Mt per year, which constitutes approximately 91% of the total capacity of conventional hydrogen production and an output of 7.86 Mt (71% utilization rate).

Hydrogen, generated as a by-product of other industrial processes is manufactured at 131 plants. The collective production capacity for by-product hydrogen is estimated to be approximately 1.03 Mt per year, which constitutes approximately 9.3% of the total capacity of conventional hydrogen production and an output of 0.63 Mt in 2023. This figure encompasses:

- 0.42 Mt/year of by-product hydrogen capacity and 0.30 Mt output (72% utilization) originating from ethylene production.
- 0.34 Mt/year of by-product hydrogen capacity and 0.21 Mt output (62% utilization) derived from the chlor-alkali process.

- 0.22 Mt/year of by-product hydrogen capacity and 0.07 Mt output (34% utilization) stemming from styrene production.
- 0.06 Mt/year of by-product hydrogen capacity and 0.04 Mt output (75% utilization) resulting from sodium chlorate production.

Comparatively, the largest amount of conventional hydrogen production capacity is found in the chemical industry (e.g. hydrogen peroxide, cyclohexane, aniline, caprolactam, oxo alcohols, toluene diisocyanate, hexamethylenediamine, adipic acid, hydrochloric acid, tetrahydrofuran and others) and refineries, producing about 43% and 53% respectively.

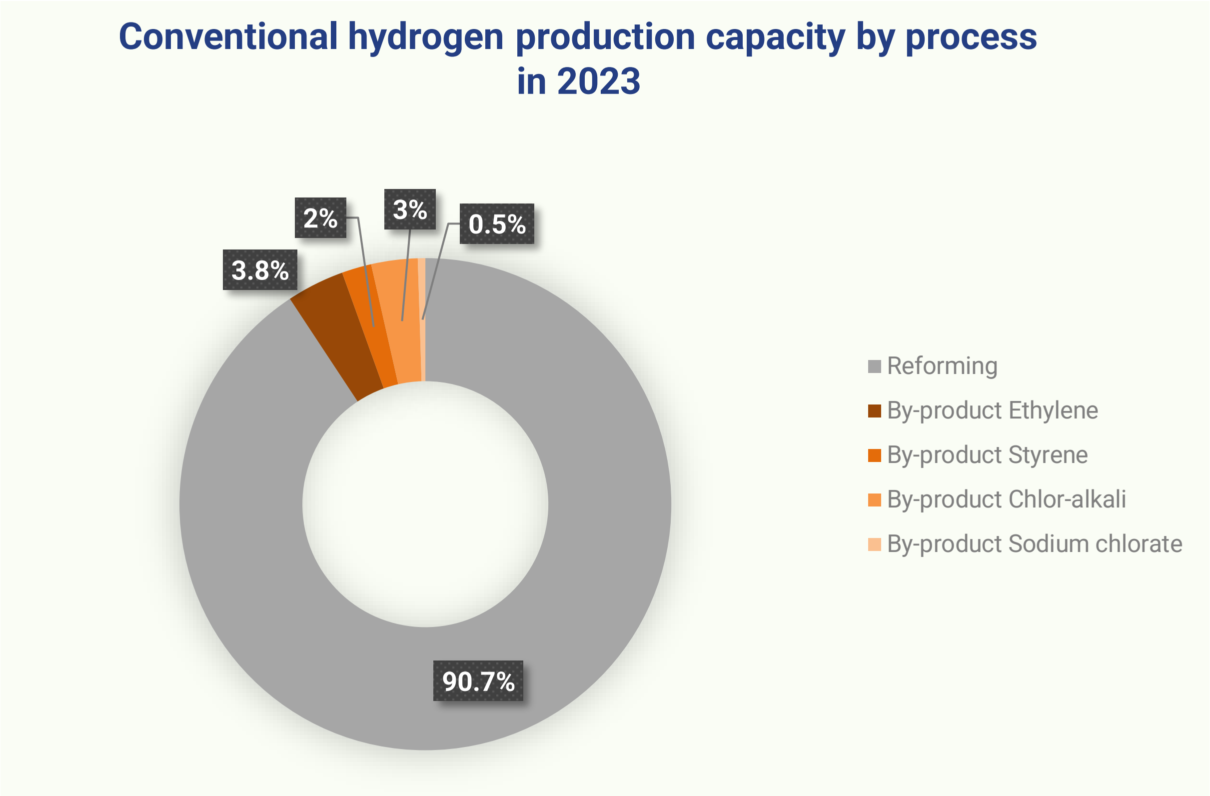

Figure 7. Conventional hydrogen production capacity by process in 2023.

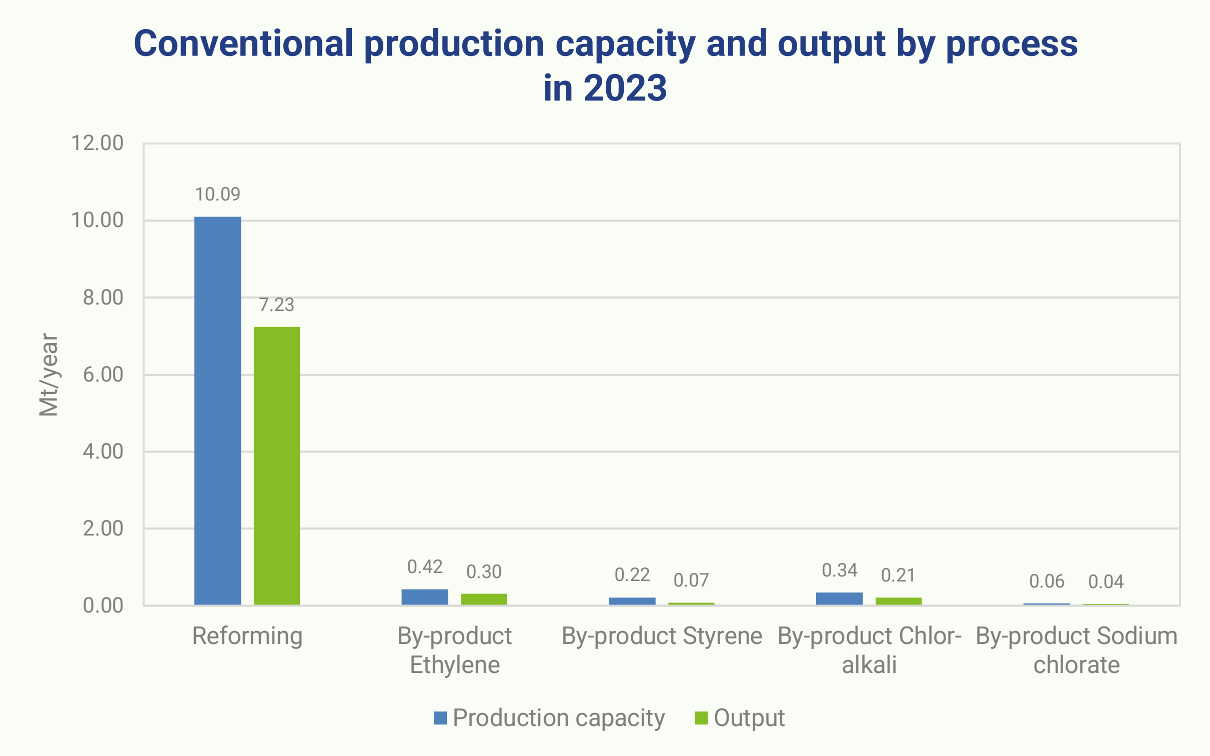

Figure 8. Conventional production capacity and output by process in 2023.

1.2.2.

Reforming with carbon capture

In total, reforming with carbon capture, commonly referred to as "blue" hydrogen, accounts for 56,148 tonnes of production capacity per annum, representing 0.5% of the overall total hydrogen production capacity.

During 2023, there were no newly commissioned hydrogen production facilities incorporating carbon capture technology.

Among the 245 existing hydrogen production plants utilizing the reforming method, **only three** of them benefit from **carbon capture technologies:**

- Gruppo Sapio hydrogen production unit in Mantova, Italy with a capacity of around 1,182 t/year that started operating in 2016.
- Air Liquide Cryocap installation in Port Jerome, France, capturing CO_2 from hydrogen supplied to an Exxon refinery, with a capacity of around 13,394 t/year that started operating in 2015.
- Shell refinery in Rotterdam, Netherlands where CO_2 from hydrogen production is captured and sold for agricultural use as part of the OCAP project since 2004, with a capacity of 41,571 t/year.

1.2.3.

Water electrolysis hydrogen production capacity

Hydrogen can also be produced with electricity by splitting water via water electrolysis. Water electrolysis installations have been proliferating in the last several years with an increasing number of not only demonstration but also commercial projects being deployed.

207 clean hydrogen production and consumption projects, of which **141 in operation** (88 with a capacity of >0.5 MW capacity) and **66 under construction (>0.5 MW)** in 2023

As of end of 2023, 44 extra water electrolysis hydrogen production and consumption projects became operational compared to 2022, bringing the total to 141 projects in Europe (88 with a minimum capacity of 0.5 MW). These additions increased the total production capacity by 88.11 MW, reaching 258.39 MW (or 0.05 Mt) in 2023. A further 66 projects were under construction (i.e., construction work has begun) and are expected to deliver an additional 1,857 MW (or 0.35 Mt) of water electrolysis capacity once operational (by 2026).

Figure 9 illustrates the average production capacity (in MW) for operational plants and those under construction with a capacity exceeding 0.5 MW. Notably, the projects currently under construction are projected to significantly outperform existing operational plants, with an anticipated average capacity of 31.15 MW—around 10 times higher than the current operational plant's average capacity.

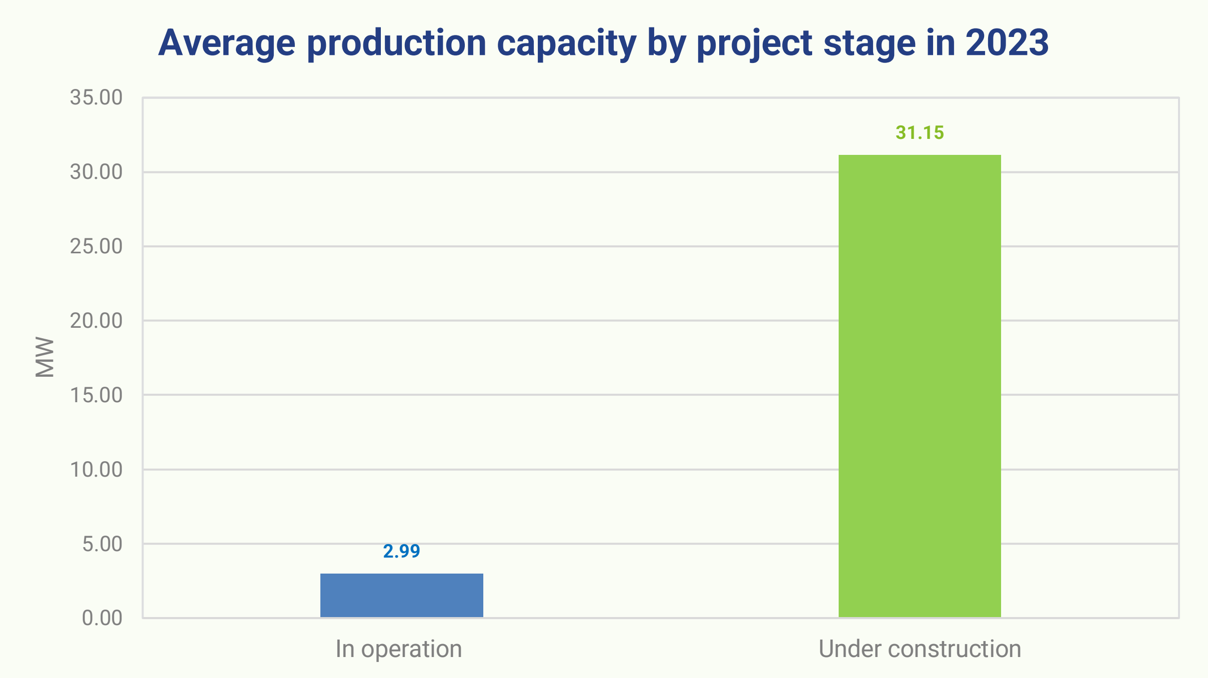

Figure 9. Average production capacity (in MW) for plants in operation and under construction of a capacity of above 0.5 MW.

Figure 10 provides an overview of the electrolyser size, in terms of capacity (MW), alongside the number of operational plants (capacity >= 0.5 MW) by December 2023.

Across Europe the water electrolysis landscape is categorized by various project capacities. Notably, there are 3 projects featuring capacities equal to or exceeding 10 MW, which collectively constitute 21% of the total water electrolysis capacity, amounting to 50 MW.

Furthermore, there are 12 projects with capacities in the range of 5 MW to less than 10 MW, collectively contributing 33% of the total water electrolysis capacity within this geographical region, resulting in a cumulative capacity of 77.8 MW.

Additionally, 51 projects fall within the capacity range of 1 MW to less than 5 MW, contributing significantly to the total installed water electrolysis capacity, accounting for 40% (95.19 MW).

In contrast, projects with capacities less than 1 MW collectively represent 6% of the total water electrolysis capacity, with a total capacity of 14.08 MW, distributed among 22 projects.

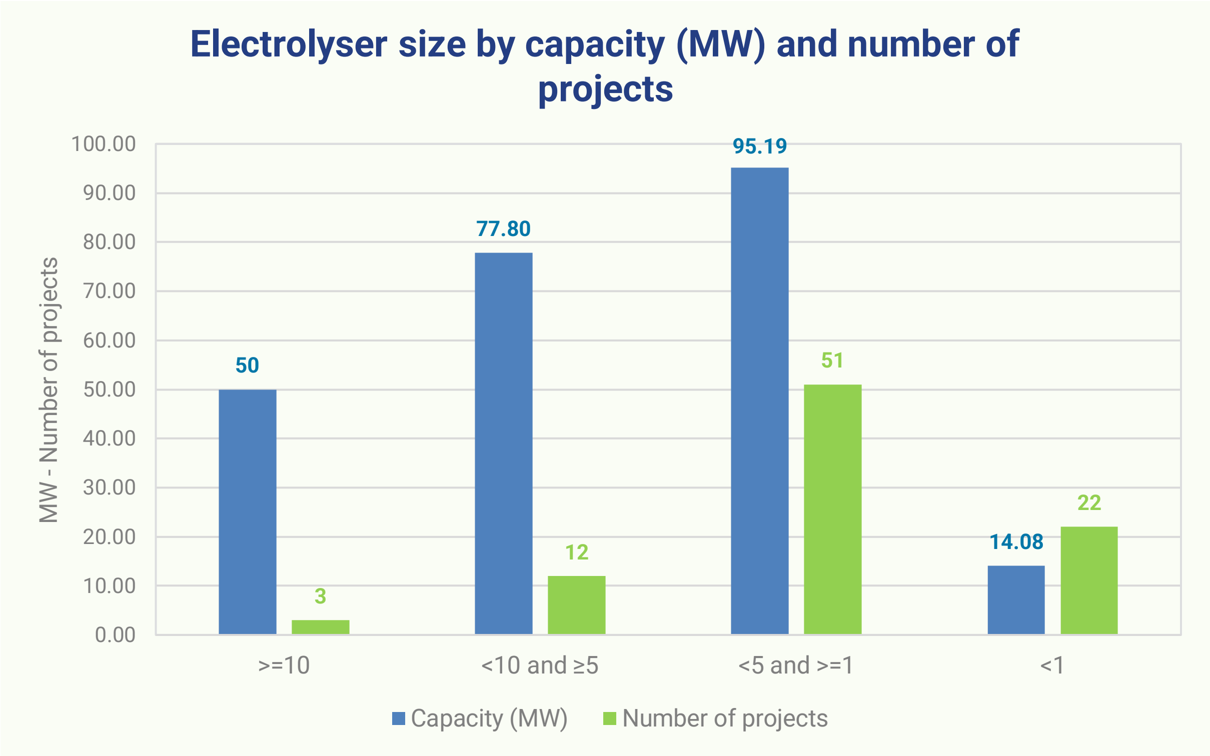

Figure 10. Electrolyser size in terms of capacity (MW) and number of projects.

Figure 11 provides an overview of the total water electrolysis capacity in megawatts (MW) for existing plants and the additional capacity (capacity >= 0.5 MW) anticipated from plants currently under construction across Europe.

When considering the production capacity of existing plants, Germany stands out as the dominant player, contributing 31% of the total water electrolysis installed capacity, equivalent to 73.31 MW (or 12,116.90 t/year), within Europe. Spain and Sweden follow accounting for 15% and 12% of the total installed water electrolysis capacity, respectively, corresponding to 35.92 MW and 29.50 MW.

However, the landscape is set to change with the plants currently under construction, which are poised to place Sweden, Germany and France, at the forefront. These new developments are expected to contribute a substantial increase in their water electrolysis production capacity, with Sweden adding 833.00 MW (or 137,680.75 t/year), Germany adding 246.30 MW (or 40,709.21t/year) and France contributing 226.50 MW (or 40,238.15 t/year), to their respective total production capacities by 2026.

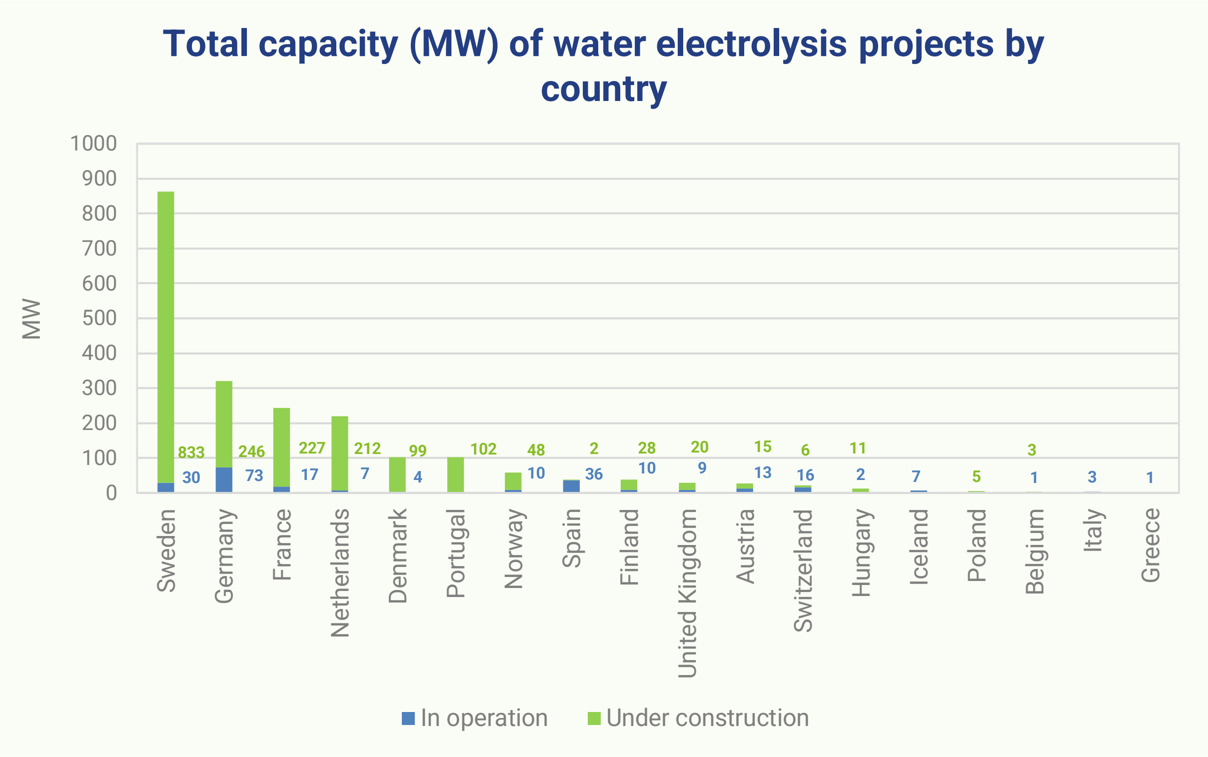

Figure 11. Total power-to-hydrogen capacity (MW) by country.

Figure 12 provides an overview of the total number of water electrolysis projects (capacity >= 0.5 MW) currently being in operation or under construction across Europe.

Germany, France, and the UK are the top three European countries by number of projects, with respectively 47, 21 and 12 water electrolysis production projects either in operation or under construction. No non-electrolytic clean hydrogen production projects with a minimum production capacity of 9,000 t/year have been identified as being in operation or under construction.

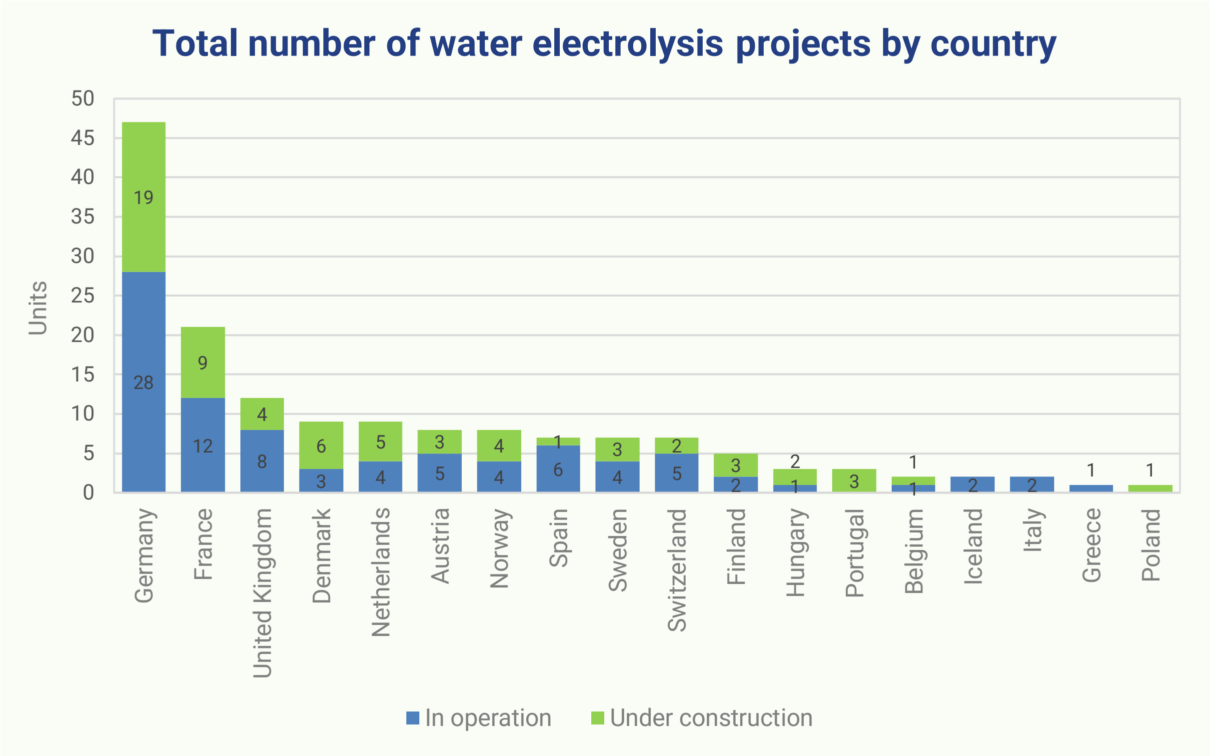

Figure 12. Total number of power-to-hydrogen projects by country.

1.3.

Hydrogen production by market type

The market type of the hydrogen production plants has been divided into two main categories; captive hydrogen, when hydrogen is consumed by an on-site facility, and merchant hydrogen, when production is intended for external distribution and sale.

Figure 13 presents the distribution of the overall production capacity designated for both captive and merchant market.

In terms of hydrogen production capacity allocation, facilities earmarked for on-site captive consumption continued to dominate with the highest share, constituting 88% (+1% vs. 2022) of the total production capacity, equivalent to 9.85 Mt. In contrast, hydrogen production plants intended for external distribution and sale, representing merchant market, comprise just 12% (-1% vs. 2022) of the total production capacity, amounting to 1.38 Mt.

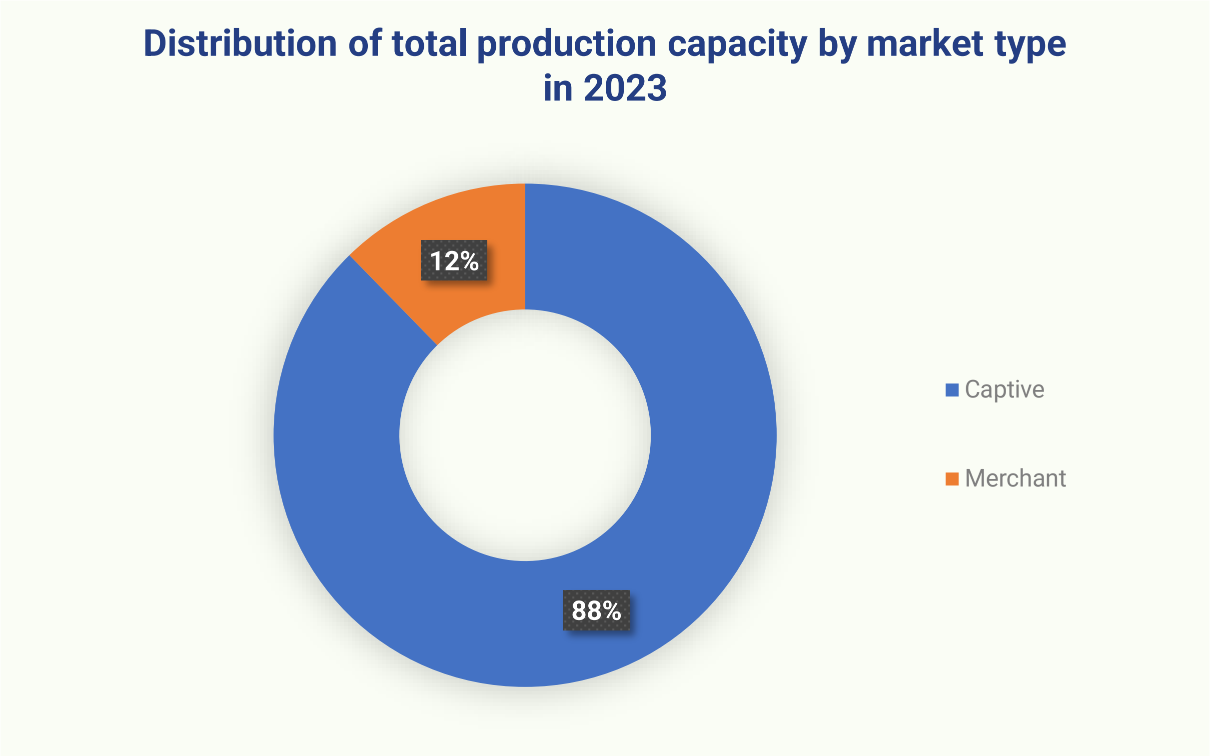

Figure 13. Distribution of total production capacity by consumption profile in 2023.

1.3.1.

Captive

On-site captive hydrogen production is by far the most common method of hydrogen supply for large hydrogen consumers. These include refineries as well as ammonia, methanol, and hydrogen peroxide production plants. The predominant technology for this type of installation is hydrocarbon reforming mostly steam methane reforming (SMR). The capacity numbers in this section also include by-product hydrogen production capacity at refineries. Hydrogen is produced at refineries as a by-product of different refining processes. Since it is mostly used on-site, it methodologically belongs to captive production.

In 2023, hydrogen production facilities via reforming allocated for on-site captive consumption dominated with 151 units. Following closely, facilities utilizing water electrolysis methods were responsible for 139 units of hydrogen production. Captive by-product hydrogen production facilities were a noteworthy category, totalling 120 units. These units were further categorized as follows:

- 38 units were associated with ethylene production.
- 12 units were integrated into styrene manufacturing processes.

- 58 units were integral to chlor-alkali production operations.
- 11 units were associated with sodium chlorate production processes.

A limited presence of facilities utilizing reforming with carbon capture was identified, with only one facility dedicated to on-site captive consumption.

These statistics illustrate the diverse landscape of hydrogen production methodologies in 2023, with a strong emphasis on reforming and a growing interest in water electrolysis, alongside the utilization of by-product hydrogen production in various industrial sectors. Additionally, the adoption of reforming with carbon capture remained relatively minimal, with only one facility identified for on-site captive consumption.

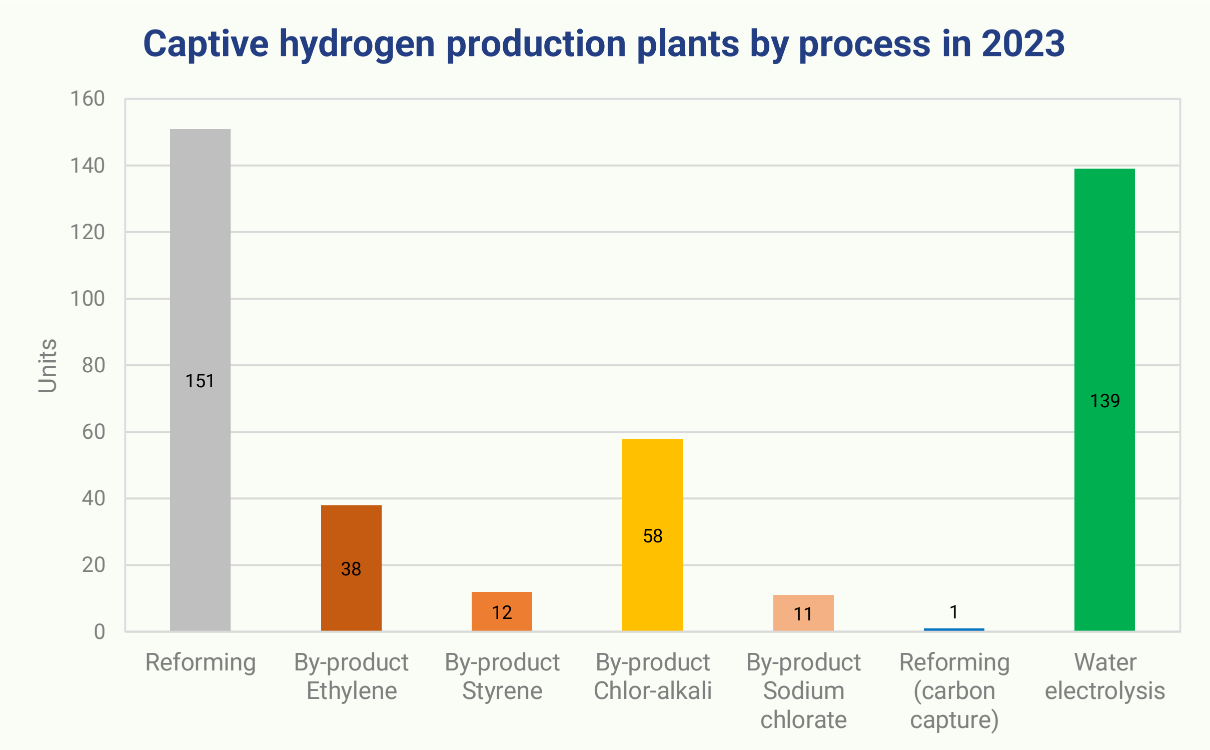

Figure 14. Total units of captive hydrogen production plants by process in 2023.

During 2023, 88% of the total hydrogen production capacity, equivalent to 9.85 Mt, across 411 production facilities, was designated for on-site captive consumption. Of this capacity, 90%, or 8.85 Mt, was generated through reforming processes. Approximately 9% or 0.91 Mt of the hydrogen allocated for on-site captive consumption originated from by-product hydrogen production, with 0.41 Mt associated with ethylene production, 0.22 Mt associated with styrene production, 0.22 Mt associated with chlor-alkali production and 0.06 Mt with sodium chlorate production. Reforming with carbon capture and water electrolysis collectively accounted for less than 1% of the total hydrogen production capacity allocated for on-site captive consumption.

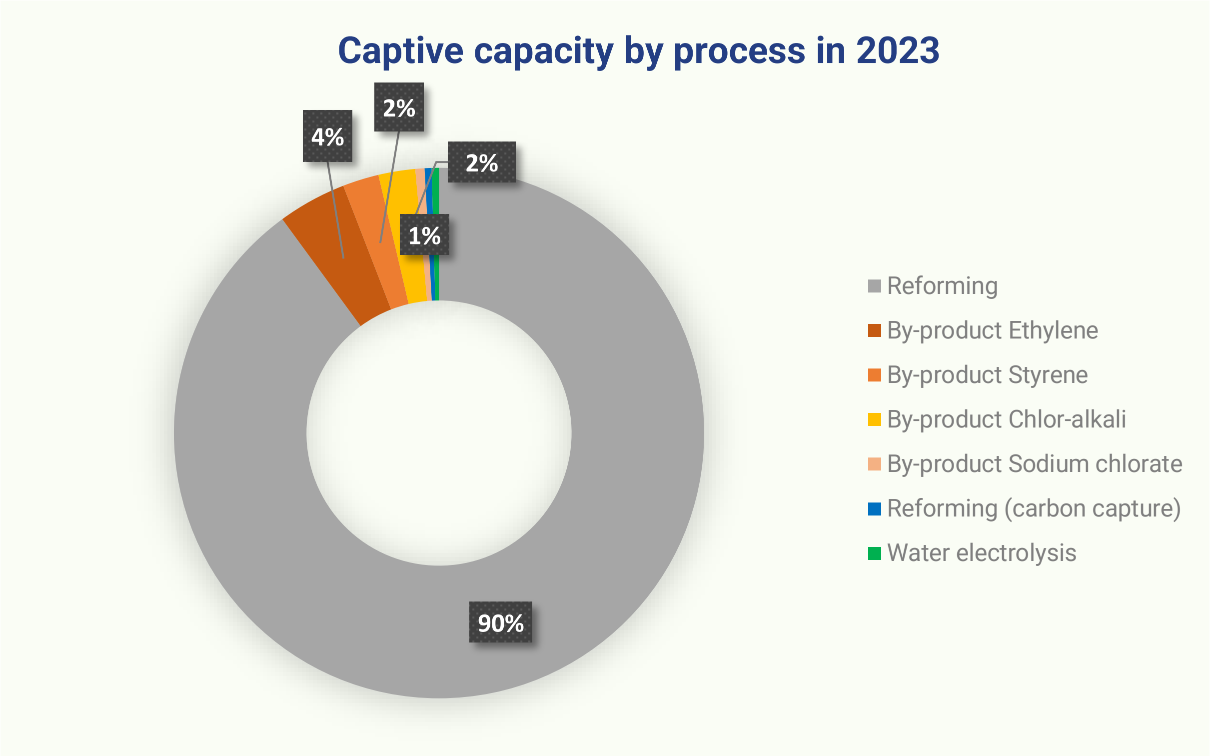

Figure 15. Captive capacity by process in 2023.

It is crucial to highlight that our categorization of captive reforming encompasses hydrogen generated within refineries as a by-product of refining operations, such as during catalytic reforming. These capacities are classified as captive because, even though they result from by-product generation, the hydrogen volumes are exclusively utilized on-site, akin to other forms of purely captive production.

1.3.2.

Merchant

Another substantial category within conventional hydrogen production comprises merchant plants, primarily engaged in the production of hydrogen for external distribution and sale. Merchant reforming represents 12.4% of total conventional hydrogen production capacity (1.38 Mt per year).

Merchant hydrogen plants utilizing fossil fuels can be categorized into two primary sub-divisions: 1) facilities operated by merchant industrial gas producers, primarily serving a single major consumer, with any surplus capacity aimed at the retail hydrogen market, and 2) small and medium-scale hydrogen production sites designed for the direct supply of retail customers. In terms of scale, it's worth noting that merchant plants dedicated to a single significant consumer are similar in size to captive hydrogen production facilities, whereas those solely serving retail customers tend to be notably smaller.

In the year 2023, reforming facilities intended for external distribution and sale, denoted as "merchant market" clearly dominated the field, totalling 86 units. This category accounted for approximately 85% of the total number of merchant plants.

Subsequently, there were by-product hydrogen production facilities, with a total of 11 units. These facilities were directly associated with the chlor-alkali production process. Additionally, there was a single unit associated with ethylene production. In contrast, reforming with carbon capture and water electrolysis methods was relatively less common, with each of them comprising only 2 units. This indicates a relatively limited presence of these technologies within the landscape of merchant hydrogen production facilities in 2023. This data highlights the prominence of reforming facilities and the lesser prevalence of by-product hydrogen production, reforming with carbon capture, and water electrolysis methods within the overall distribution of merchant hydrogen production facilities in 2023.

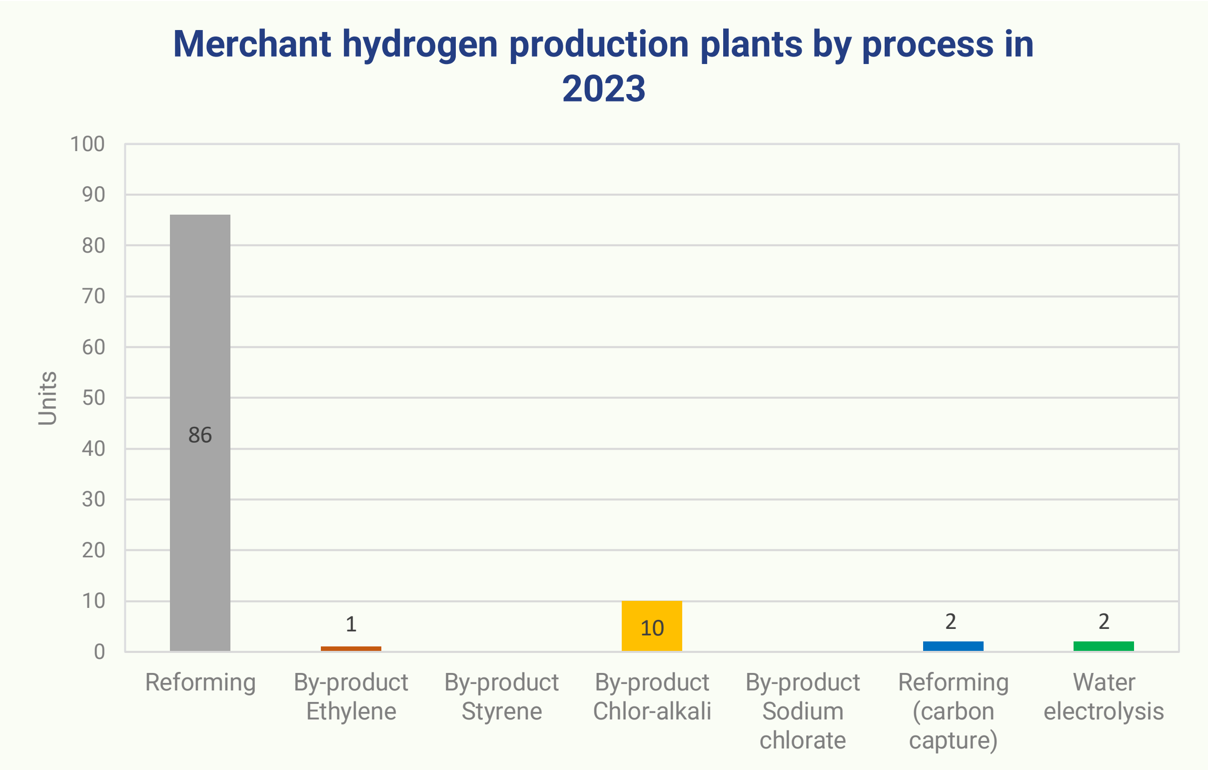

Figure 16. Total units of merchant hydrogen production plants by process.

During 2023, 12% of the total hydrogen production capacity, equivalent to 1.38 Mt, across 101 production facilities, was allocated on merchant plants, primarily engaged in the production of hydrogen for external distribution and sale. Of this capacity, 90%, or 1.24 Mt, was generated through reforming processes. The remaining 9% of hydrogen allocated on merchant plants, originated from by-product hydrogen production, with 0.01 Mt associated with ethylene production, and 0.12 Mt associated with chlor-alkali production.

Reforming with carbon capture accounted for 1% of the total hydrogen production capacity allocated for merchant consumption, while water electrolysis represented less than 1% of the capacity.

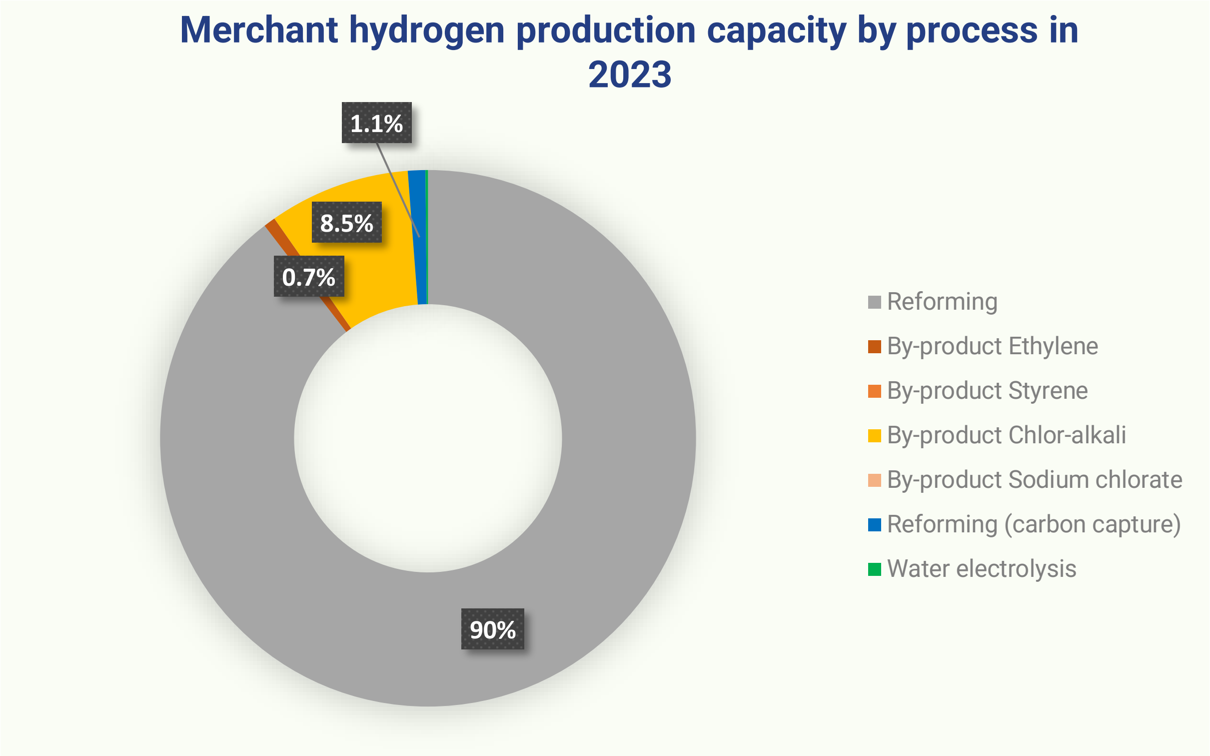

Figure 17. Merchant capacity by process.

1.4.

Hydrogen trade

As specified in section 1.3, even though the European hydrogen market is currently predominantly captive, thousands of tonnes of hydrogen are already traded and distributed around Europe, often via dedicated hydrogen pipelines or trucks. With the emergence of the clean hydrogen market in Europe and the EU's ambition to import 10 million tonnes of renewable hydrogen from outside the EU by 2030, hydrogen flows (exports and imports) to and between European countries are expected to gradually increase.

Note: Hydrogen-based commodities flows (e.g., ammonia, methanol, other e-fuels) are not currently captured in the scope of the data. As the international hydrogen market is expected to take off, the European Hydrogen Observatory foresees a review of the scope of the analysis to ultimately extend it to other commodities relevant to the hydrogen market.

In 2023, a total of 29,767 tonnes of hydrogen was traded in Europe, marking a 13% decrease from 2022. Hydrogen export from Belgium to the Netherlands, with 19,272 tonnes traded (65% of all hydrogen traded in Europe) remained the single biggest flow to and between European countries even though, its share of total hydrogen traded in Europe decreased by 10% compared to the previous year. Alongside the Belgium-Netherland flow, the flows Netherlands-France (4.7%), Belgium-France (4.3%), France-Germany (4.1%) and Sweden-Denmark (3.9%) accounted for 82% of all European hydrogen trades in 2023.

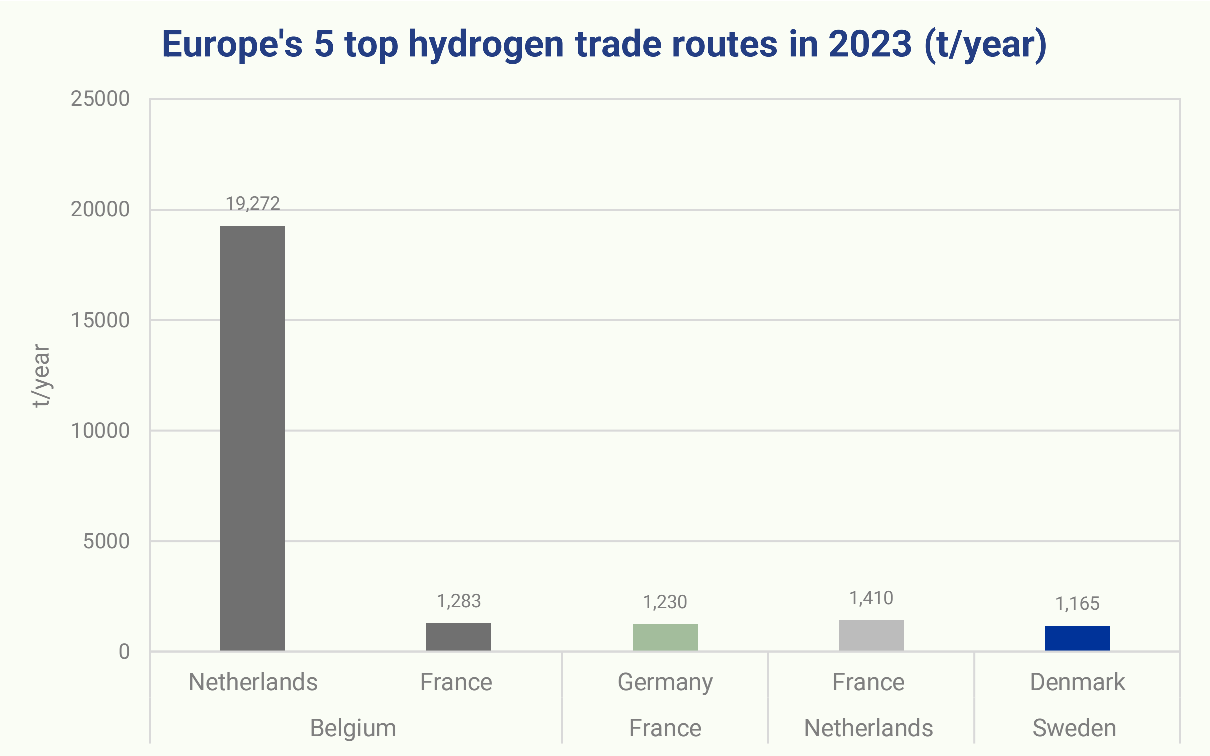

Figure 18. Europe's top 5 hydrogen trade routes (t/year).

1.4.1.

Exports

Belgium exported 71% (21,159 tonnes) of the 29,767 tonnes of hydrogen that flowed to and between European countries, remaining Europe's single largest exporter of hydrogen. Alongside Belgium, the Netherlands (10.6%), France (4.8%), Sweden (4.2%) and Germany (3.9%) accounted for almost 95% of European hydrogen exports in 2023. In 2022, Belgium accounted for an even larger share, exporting 78% of the total 34,173 tonnes. This represents a 7% decline in Belgium's export share and a significant decrease in total export volume. Despite this shift, Belgium continued to lead European hydrogen exports in 2023, though the overall export landscape became more distributed among other countries.

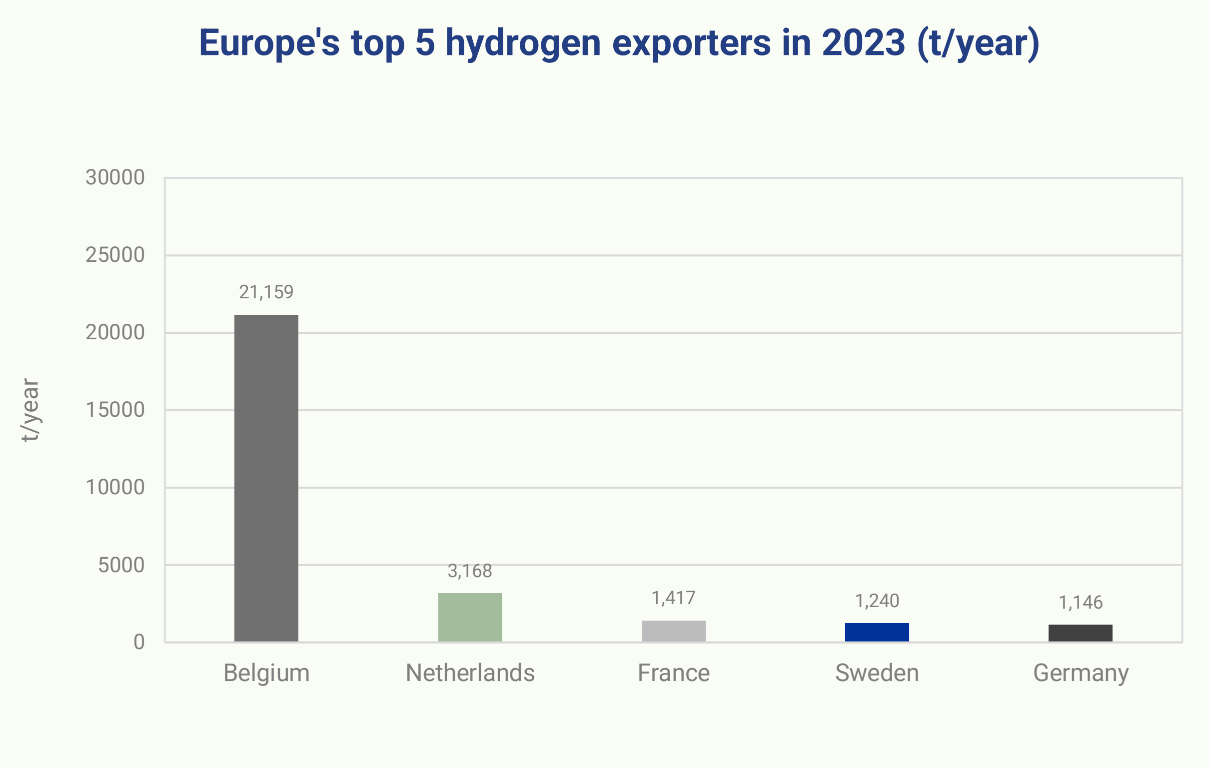

Figure 19. Europe's top 5 hydrogen exporters in 2022 (t/year).

1.4.2.

Imports

In 2023, the Netherlands imported 66% (19,568 tonnes) of the 26,767 tonnes of hydrogen that flowed to and between European countries, remaining Europe's single largest importer of hydrogen. Alongside the Netherlands, France (10.0%), Germany (5.8%), Denmark (4.4) and Austria (2.1%) accounted for almost 88% of European hydrogen imports in 2023.

In 2022, Netherlands accounted for an even larger share, importing 76% of the total 34,173 tonnes. This represents a 10% decline in Netherland's import share and a significant decrease in total import volume. Despite this shift, Netherlands continued to lead European hydrogen imports in 2023, though the overall import landscape became more distributed among other countries.

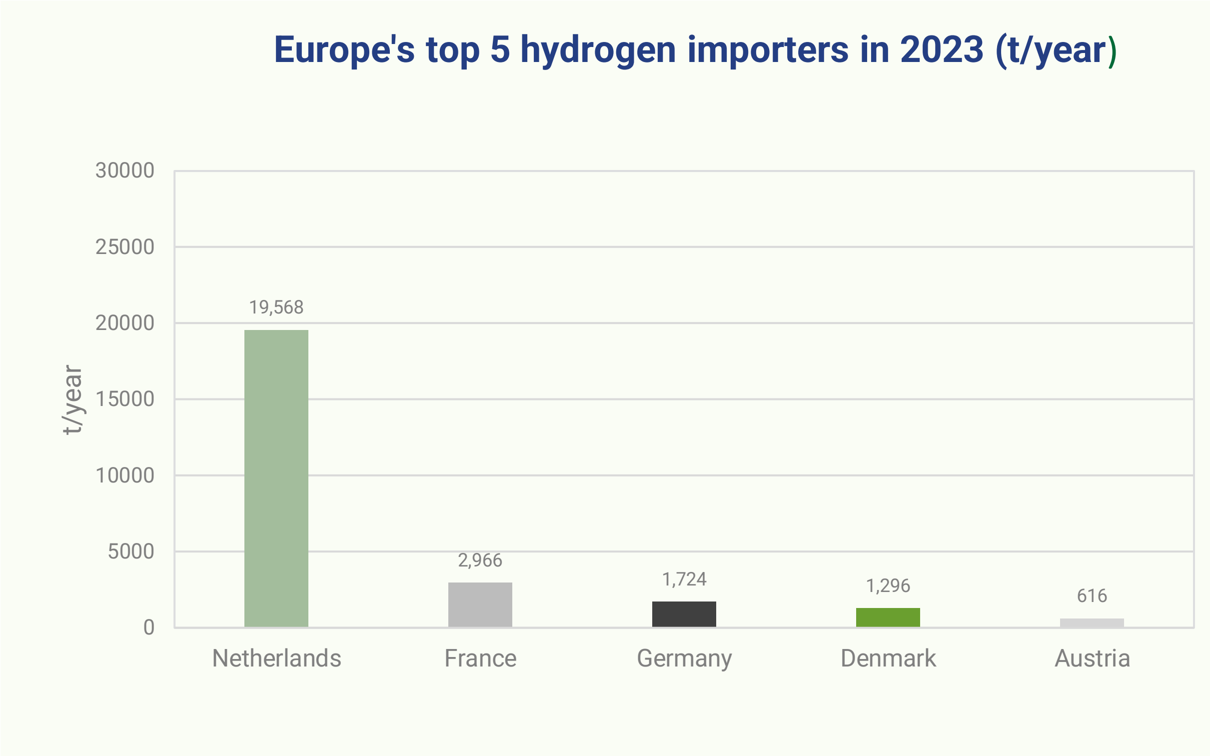

Figure 20. Europe's top 5 hydrogen importers in 2023 (t/year).

02

Distribution and storage

Introduction

This chapter provides an overview of the latest advancements in hydrogen distribution and storage infrastructure across Europe, mainly exploring data on operational hydrogen pipelines and storage facilities, their location and main attributes, and publicly accessible and operational hydrogen refuelling stations (HRS), presented by location and dispenser type (700 bar for cars, 350 bar for cars or/and 350 bar for heavy duty) across Europe.

Data on hydrogen pipelines and storage projects is based on desk research conducted by Deloitte and reflects the situation as of May 2024. The HRS data is sourced from the HRS Availability Map in May 2024. Only operational and public HRS are considered in the dataset. The HRS Availability Map is an initiative of the Clean Hydrogen Partnership, where the availability status of all HRS is actively monitored real-time. The historical data is compiled using a combination of historic data of the HRS Availability Map, expertise of the Clean Hydrogen Partnership and desk research.

Interactive data dashboards and downloadable spreadsheets on hydrogen pipelines and storage & hydrogen refuelling stations can be accessed on the European Hydrogen Observatory website.

2.1.

Hydrogen pipelines and storage

Hydrogen infrastructure, including pipelines and storage facilities, plays a critical role in supporting the expansion and distribution of hydrogen. In 2023, the hydrogen pipeline network across Europe consisted of 17 pipelines, spanning a total length of 1,581 km.

Within Europe, the largest networks are situated in Belgium and Germany, at approx. 600 km and 400 km, respectively. Of particular importance is the cross-border network of France, Belgium, and the Netherlands spanning a total of 964 km.

Today, existing pipelines serve industrial clusters with strong chemicals (e.g., ammonia) and petrochemicals (e.g., refineries) activities. The current hydrogen pipeline network is mostly situated in Belgium, the Netherlands, Germany, and France. Overall, access to data is limited by the fact that these pipelines are private.

In 2023, four hydrogen storage projects employing different technologies were operational. Specifically, two projects utilizing salt cavern technology in France and Germany, one project using hard rock cavern technology in

Sweden, and one project utilizing depleted gas field technology in Austria. Table 2 provides a brief overview of these storage technologies.

Table 2. Outline of the terminology employed in this chapter to describe various technologies of hydrogen storage.

Salt cavern	Salt caverns are artificial cavities created within geological salt deposits, typically located 500 to 1,500 meters underground. Formed by drilling into the salt and dissolving it with injected water, these caverns allow for the extraction of brine, leaving a secure, airtight space. Due to their size and depth, salt caverns are ideal for storing hydrogen under pressure[3].
Hard rock cavern	Hard rock caverns are advanced underground storage structures created in metamorphic or igneous rock, lined with concrete and either steel or plastic. These caverns are designed for high-pressure operations and frequent injection and withdrawal cycles, making them suitable for peaking purposes. While they require less cushion gas and are ideal for hydrogen storage, their high development costs and potential for steel embrittlement due to hydrogen exposure are notable considerations[4].
Depleted gas field	A depleted gas field is an underground geological formation that has been emptied of its natural gas reserves and is repurposed for hydrogen storage. These fields are ideal for storage due to their existing geological integrity, including an impermeable cap rock that helps to securely contain hydrogen under pressure[5].

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[3] ENGIE. (n.d.). Hydrogen underground storage: Salt caverns. Innovation ENGIE. Retrieved September 18, 2024, from https://innovation.engie.com/en/articles/detail/hydrogen-underground-storage-salt-caverns/25906/general

[4] Hydrogen Portal. (n.d.). Hydrogen underground storage: Status of technology and perspectives. Retrieved September 18, 2024, from https://hydrogen-portal.com/hydrogen-underground-storage-status-of-technology-and-perspectives/

[5] U.S. Department of Energy. (2020). Hydrogen storage: Technologies and market potential. Retrieved September 18, 2024, from https://www.energy.gov/eere/fuelcells/hydrogen-storage

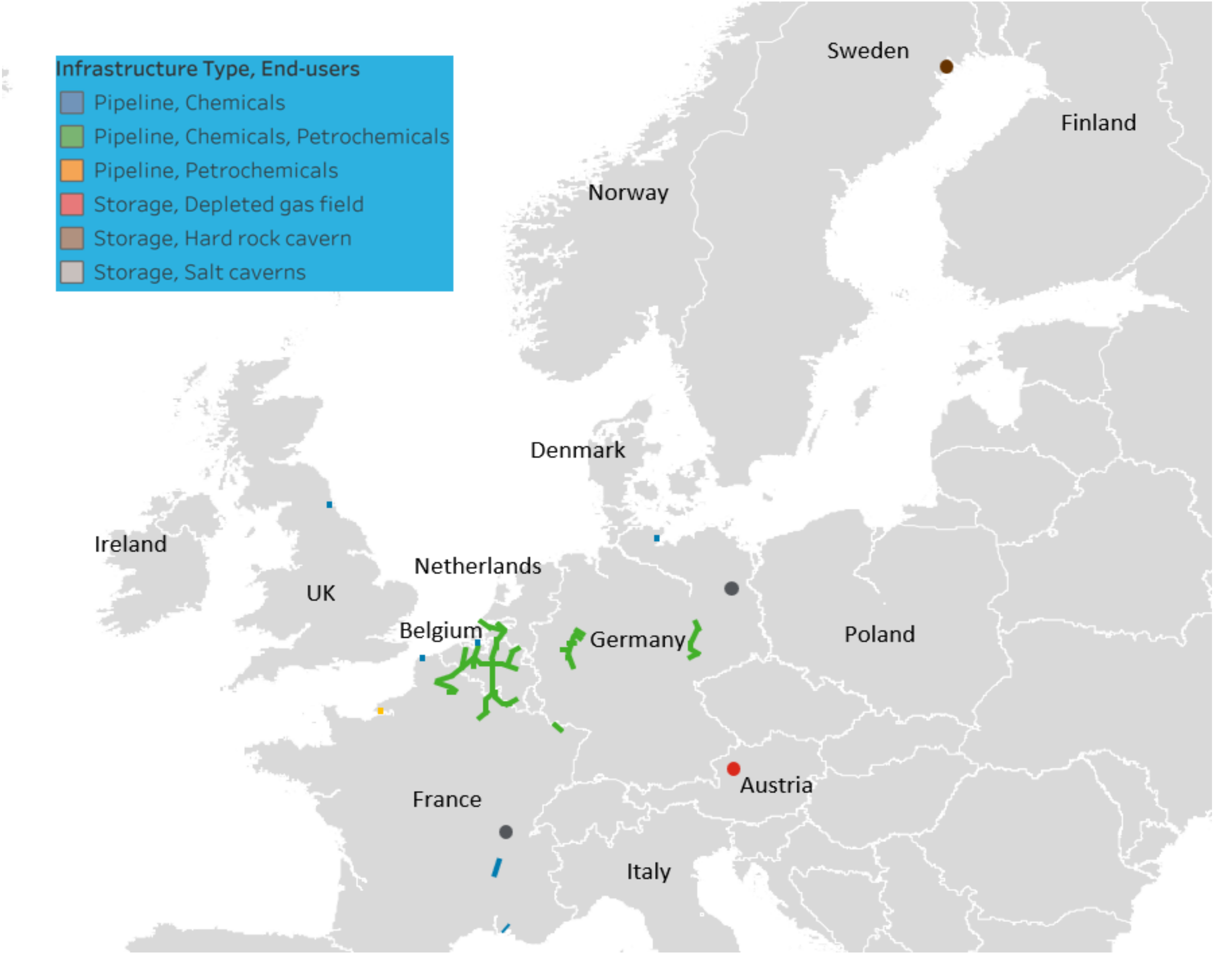

Figure 21. Map of hydrogen pipelines by end user and storage facilities by technology.

European hydrogen infrastructure projects

The REPowerEU Plan introduced actions to rapidly reduce dependence on Russian fossil fuels and speed up the green transition. It was acknowledged that accelerated efforts are needed to deploy hydrogen infrastructure for producing, storing, importing, and transporting 20 million tonnes of hydrogen by 2030 – a significant contribution to decarbonising our economy while guaranteeing the security of supply.

ENTSOG, GIE, CEDEC, Eurogas, GEODE, and GD4S in cooperation with the European Hydrogen Backbone initiative started a bottom-up process to gather all relevant hydrogen infrastructure projects to present the data in an interactive, user-friendly, and publicly accessible map that could be used by stakeholders and policymakers. The interactive Hydrogen Infrastructure map brings together the hydrogen perspective and projects of Transmission System Operators (TSOs) of gas, Distribution System Operators (DSOs), Storage System Operators (SSOs) and LNG System Operators (LSOs), as well as third-party promoters developing projects in consortia along the whole value chain.

For the latest information on hydrogen infrastructure projects (transmission pipelines, distribution pipelines, terminals and ports, storages, as well as demand and production projects), please visit [the Hydrogen Infrastructure Map.]()

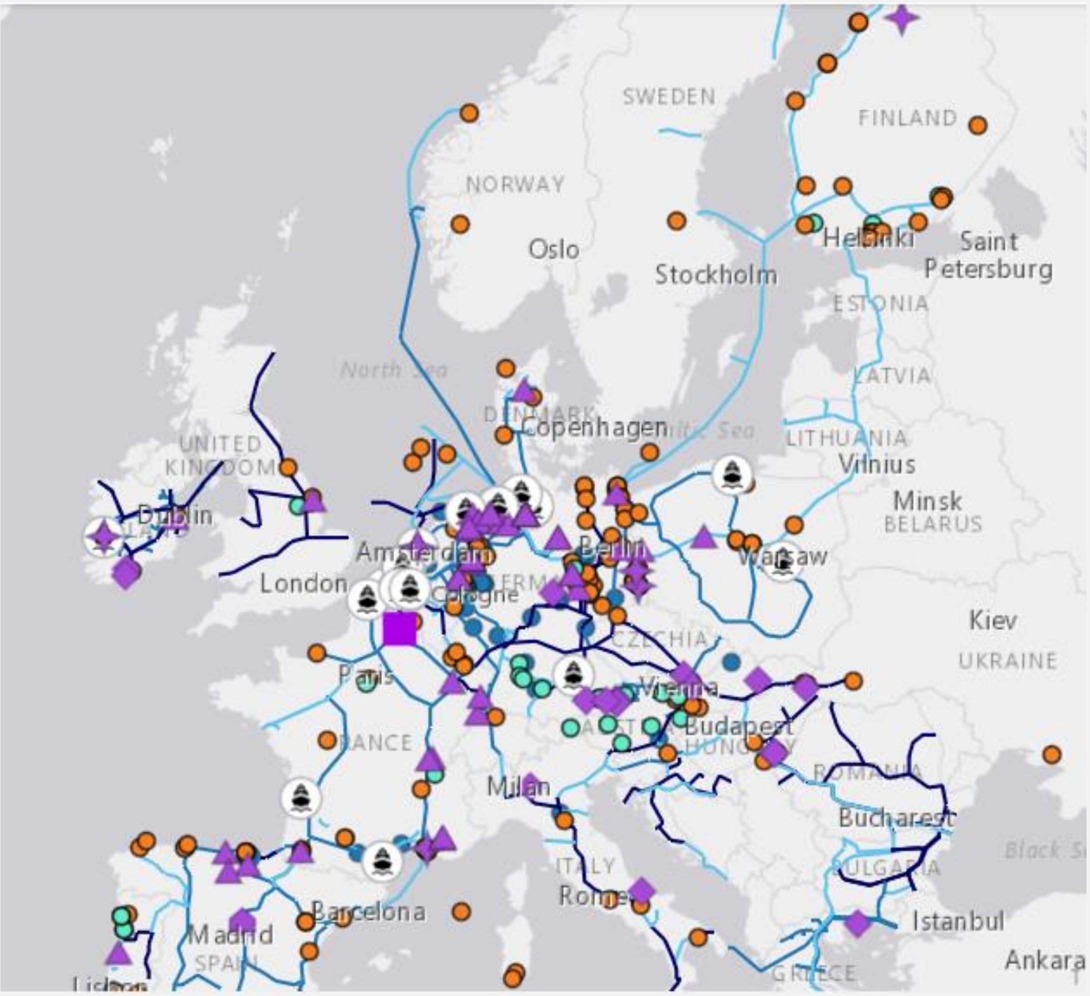

Figure 22. Hydrogen infrastructure projects interactive map.

Key numbers:

>130: Hydrogen transmission projects

>60: Hydrogen distribution projects

>70: Hydrogen storage projects

>20: Hydrogen terminals & ports projects

>20: Hydrogen demand projects

>170: Hydrogen production projects

2.2.

Hydrogen refuelling stations

In order to keep pace with the rising number of fuel cell electric vehicles (FCEVs) on European roads and promote their wider integration, it is key to ensure sufficient accessibility to refuelling infrastructure. Consequently, many countries are endorsing the establishment of hydrogen refuelling stations (HRS) so that they are publicly accessible on a nationwide scale.

More recharging and refuelling stations for alternative fuels will be deployed in the coming years across Europe enabling the transport sector to significantly reduce its carbon footprint following the adoption of the alternative fuel infrastructure regulation (AFIR). As part of the regulation's main targets hydrogen refuelling stations serving both cars and lorries must be deployed from 2030 onwards in all urban nodes and every 200 km along the TEN-T core network.

The historical data on publicly accessible and operational HRS in Europe are presented in Figure 23. Since 2015, the total number of HRS in Europe has grown at an accelerated pace to 187 operational and publicly accessible HRS by the summer of 2024, which is almost a tenfold increase over ten years.

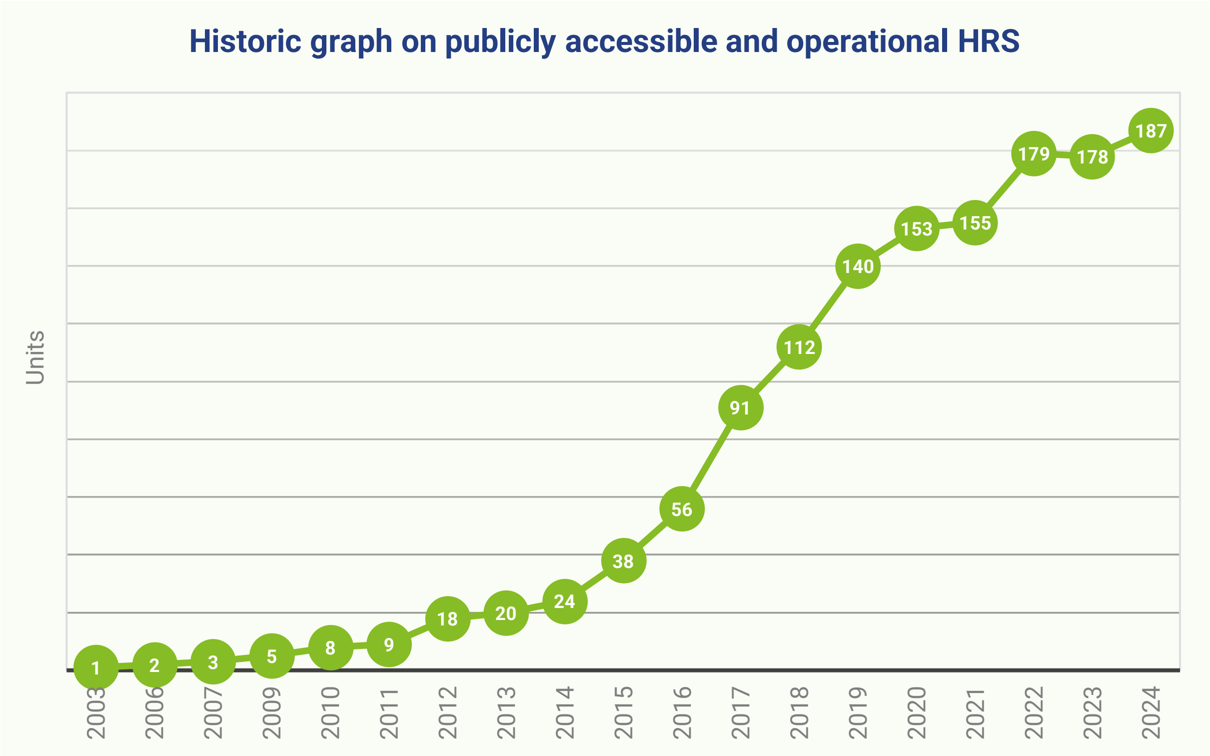

Figure 23.Historic graph on publicly accessible and operational HRS in Europe from 2003 to 2024.

187 publicly accessible and operational hydrogen refuelling stations in Europe by May 2024, reflecting a 5% increase compared to May 2023

Figure 24 demonstrates the number of publicly accessible and operational HRS by country by May 2024. Germany takes the lead, with the highest number of HRS, accounting for approximately 46% of the total, with 86 stations currently operational. France and the Netherlands follow, holding the second and third largest shares, with 14% (27 stations) and 13% (24 stations), respectively.

Until now, the description has focused on HRS which may include one or multiple dispensers. Figure 25 provides a breakdown of the dispensers by type.

The majority of dispensers are 700 bar car dispensers, comprising 57% of the total dispenser count, which amounts to 175 units. In second place are 350 bar heavy duty (HD)[6] dispensers, making up 24% of the total, with 74 units in operation. Additionally, 350 bar car dispensers account for 19% of the total, totalling 60 units. In 2023, the share of heavy-duty dispensers increased by 9% compared to 2022.

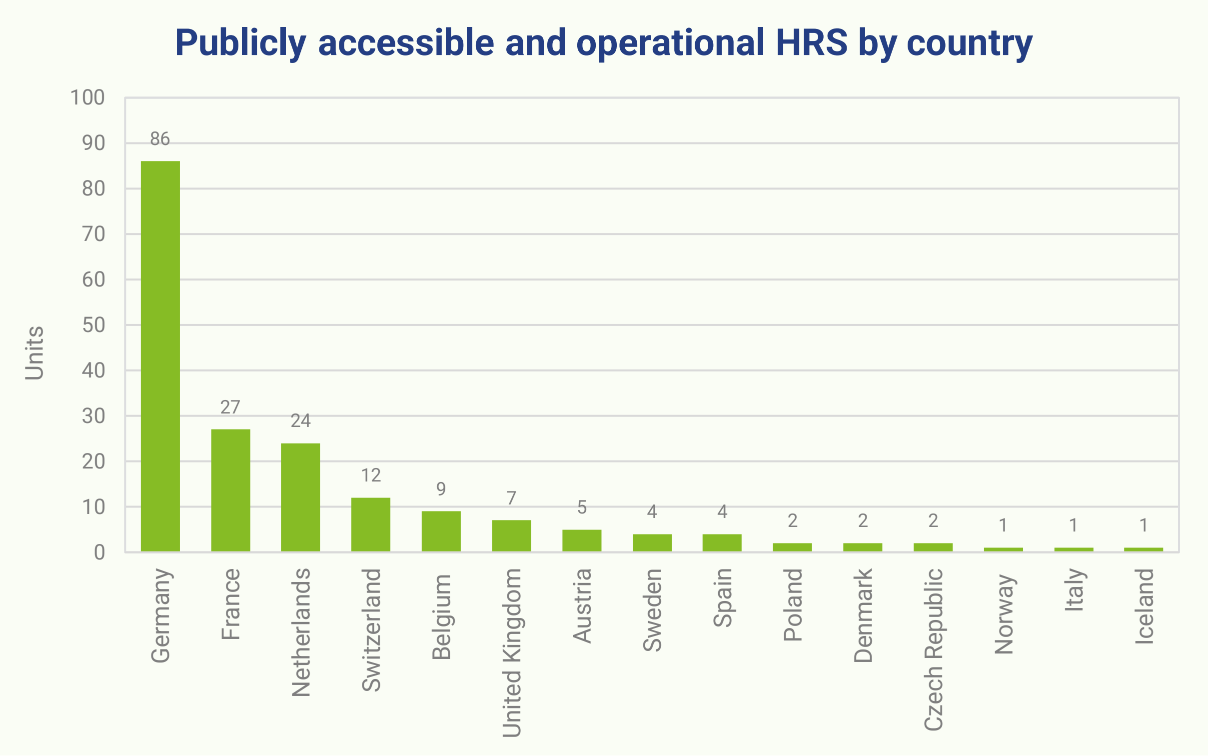

Figure 24. Publicly accessible and operational HRS by country by May 2024.

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[6] Heavy duty dispensers can be used both for buses and trucks

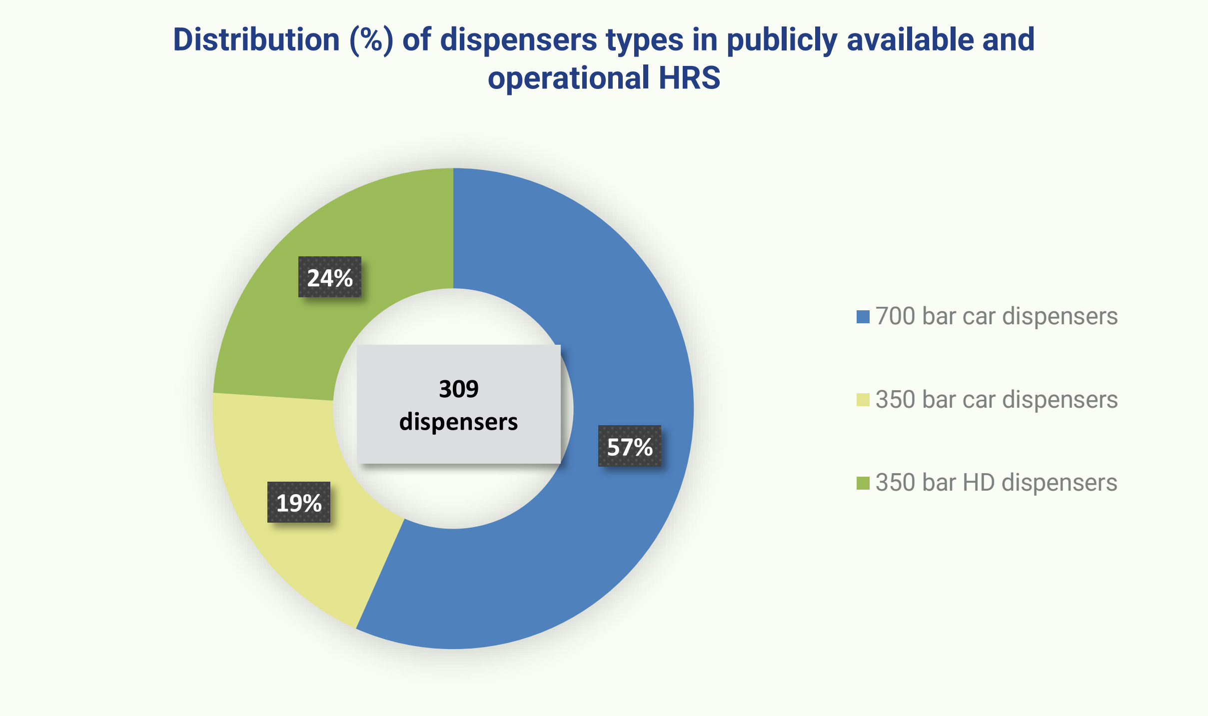

Figure 25. Distribution of the different types of dispensers in HRS in Europe.

Figure 26 shows the total number of dispensers by country and type in Europe. Germany takes the lead, representing approximately 37% of the total number of dispensers in Europe, with a total of 113 dispensers. Within Germany, 700 bar car dispensers constitute the prevailing type, with 85 units, followed by 350 bar HD dispensers, amounting to 17 units, and 350 bar car dispensers, totalling 11 units.

Following Germany are France, the Netherlands, Switzerland, and the United Kingdom, contributing 62, 49, 21, and 16 dispenser units, respectively. The remaining countries, including Belgium, Sweden, Poland, Austria, Spain, Czech Republic, Denmark, Italy, Norway, and Iceland, collectively account for less than 16% of the total number of dispensers, with a combined total of 48 units.

Overall, the 700 bar car dispensers are the predominant dispenser type in most countries, except France (mainly), and Spain, where 350 bar car dispensers dominate and Italy where 350 bar HD are taking the lead. Compared to Germany, a lot of 350 bar car dispensers are operational in France.

The analysis delves deeper, investigating the availability of the various dispenser types in HRS (Figure 27) by May 2024. The majority of HRS are equipped with only 700 bar car dispensers, comprising 47% of the total HRS. 19% of HRS offer dispensers that accommodate refuelling for either heavy duty at 350 bars or cars at 700 bars. A smaller fraction, constituting 15% of the HRS, are equipped with all available dispenser types, this share has increased by 6% compared to May 2023. This rise highlights a positive trend in the enhancement of refuelling infrastructure, which is crucial for supporting the growth of hydrogen mobility and ensuring greater refuelling flexibility across Europe.

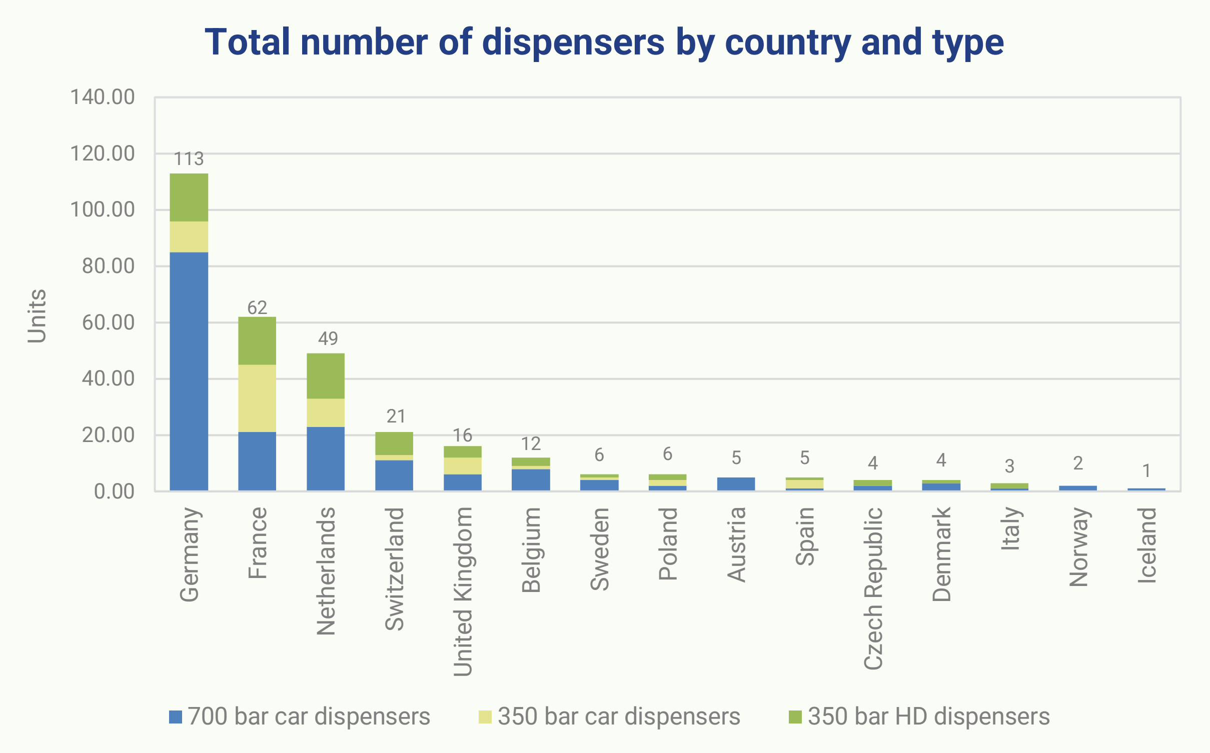

Figure 26. Total number of dispensers by country and type.

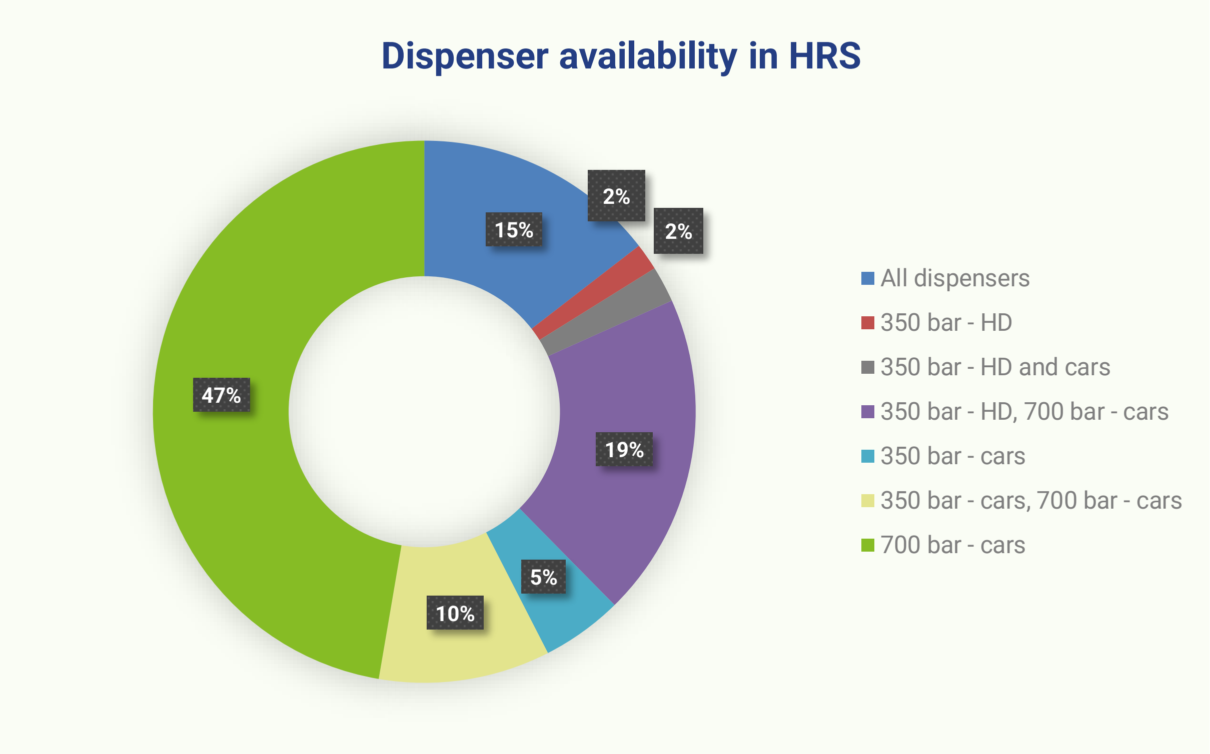

Figure 27. Dispenser availability in HRS.

Figure 28 illustrates the distribution of dispenser availability for the HRS on a national level.

Among the 15 countries analysed, over 40% of the total HRS infrastructure is equipped solely with 700 bar car dispensers in 7 countries. In Austria, Iceland, and Norway, all HRS are exclusively equipped with 700 bar car dispensers. Germany stands out with 72% of its stations (62 out of 86) offering only 700 bar dispensers. Similarly, in Belgium, Sweden, and Denmark, more than half of the HRS network is equipped exclusively with 700 bar car dispensers.

In Czech Republic and Italy, all the HRS are equipped with both 350 bar (heavy duty) and 700 bar (cars) dispensers, in Switzerland and Denmark, this combination is seen in 50% of the HRS (6 units and 1 unit respectively). In the UK, 43% of HRS are equipped with 350 bar car and 700 bar car dispensers. On the other hand, in Spain, most HRS (over 50%) feature only 350 bar car dispensers.

Poland stands out as all its HRS are equipped with all dispenser types. In France, half of the HRS offer this configuration. Meanwhile, in the UK and the Netherlands, over 20% of HRS are equipped with dispensers covering all types, reflecting a notable share of comprehensive fuelling options.

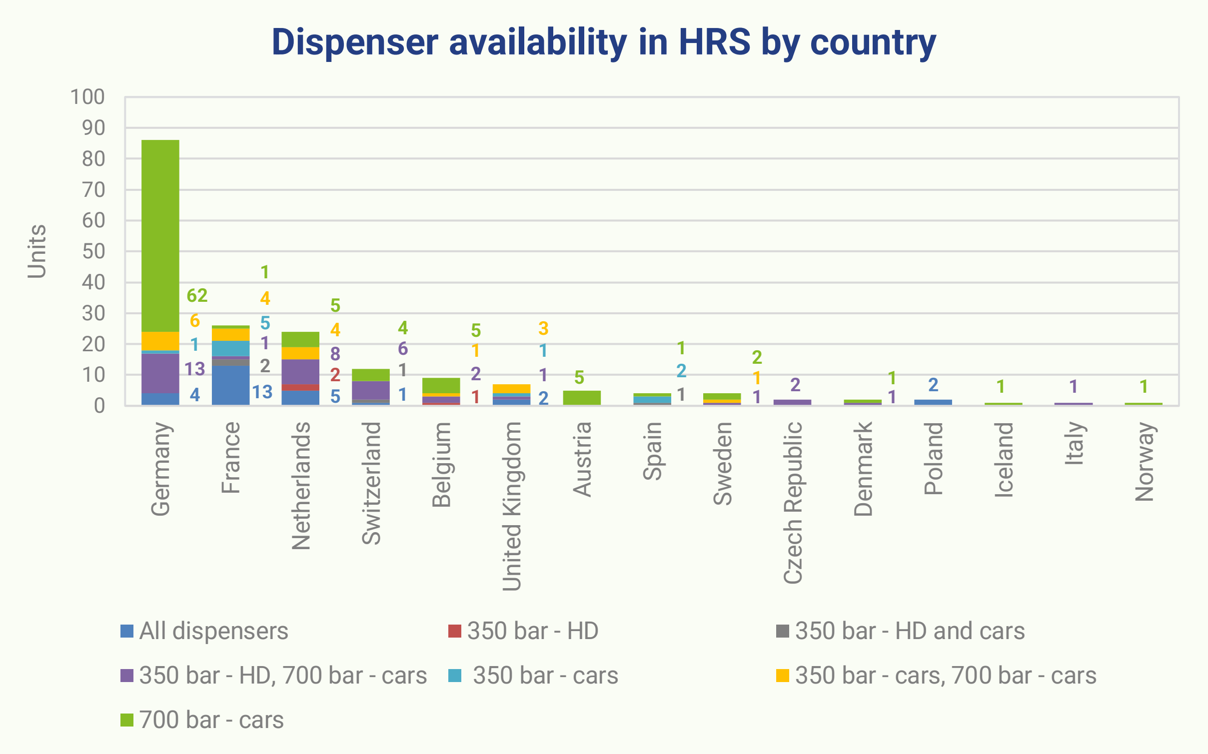

Figure 28. Dispenser availability in HRS on a national level.

03

End-use

Introduction

This chapter provides an overview of the hydrogen demand within Europe, and additionally goes into more detail about the deployment of hydrogen fuel cell electric vehicles (FCEVs), hydrogen valleys and hydrogen demand forecasts.

For hydrogen demand, this report assesses data on annually consumed hydrogen, expressed in volume per country and by sector. The data reflect the situation of 2023 and were collected by Hydrogen Europe and verified with industry stakeholders.

The hydrogen demand forecast takes into account the primary hydrogen demand scenarios in Europe for the years 2030, 2040, and 2050 across various sectors (industry, transport, buildings and electricity). These scenarios originate from modelling studies that were conducted by many organizations for which the model outputs can differ based on the underlying narratives, parameters, and assumptions. A list, sectorial scope and key assumptions & narratives of these studies is available in Appendix A.3. The hydrogen demand forecast section is designed to facilitate comparison between the results of scenarios and to provide a snapshot of the distribution of the projected demand (upper bound, median, lower bound).

This chapter also refers to the current and future hydrogen Valleys that are developing hydrogen-based technologies, that are well-reported by the Mission Innovation Hydrogen Valleys Platform.

Finally, the deployment of FCEVs in Europe is assessed, covering the FCEV market evolution in both fleet and registration numbers until 2023. The historical data of FCEV is sourced from the European Alternative Fuels Observatory (EAFO). EAFO collects the FCEV data mainly from public authorities – i.e., ministries or national statistical offices, which are reviewed together with Eurostat on an annual basis.

Interactive data dashboards and downloadable spreadsheets on hydrogen demand, hydrogen fuel cell electric vehicles & hydrogen demand forecasts can be accessed on the European Hydrogen Observatory website.

3.1.

Hydrogen demand overview

The total demand for hydrogen in Europe in 2023 has been estimated at 7.93 Mt, a slight decrease compared to 2022 (-3%). Note that this total demand is slightly deviating from the total production (7.94 Mt). The demand in Europe may differ from what is produced due to hydrogen that is being imported, exported, or vented into the atmosphere.

Figure 29 presents a breakdown of hydrogen demand across the different applications. The biggest share of hydrogen demand comes from refineries, which were responsible for 57% of total hydrogen use (≈4.55 Mt). In refineries, hydrogen plays a pivotal role in hydrotreating and hydrocracking operations. Hydrotreatment constitutes a vital component of diesel refining, encompassing various processes such as hydrogenation, hydrodesulfurization, hydrodenitrification, and hydrodemetallization. Meanwhile, hydrocracking involves the conversion of lengthy and unsaturated substances into products with a reduced molecular weight compared to the initial feedstock.

Following is the ammonia industry with 25% (≈2.00 Mt), where hydrogen is typically used in combination with nitrogen in the Haber-Bosch process. Another 11% is consumed for methanol production and other uses in the chemical industry (e.g., hydrogen peroxide, cyclohexane, aniline, caprolactam, oxo alcohols, toluene diisocyanate, hexamethylenediamine, adipic acid, hydrochloric acid, tetrahydrofuran, and others). The category “Other” of 3% includes hydrogen production or import that was not allocated to a specific end-use.

The “Emerging hydrogen applications” category includes blending in natural gas pipelines, production of e-fuels, industrial heat, residential heat, power generation, mobility, and steel. The emerging application with the highest demand in 2023 was industrial heat consuming 0.26 Mt of hydrogen (or 3.3% of the total demand). This represents hydrogen burned for its energy content, mostly produced as a by-product from ethylene, styrene, chlorine, or sodium chlorate production. The other emerging hydrogen applications represented only a small portion of the market (0.10%).

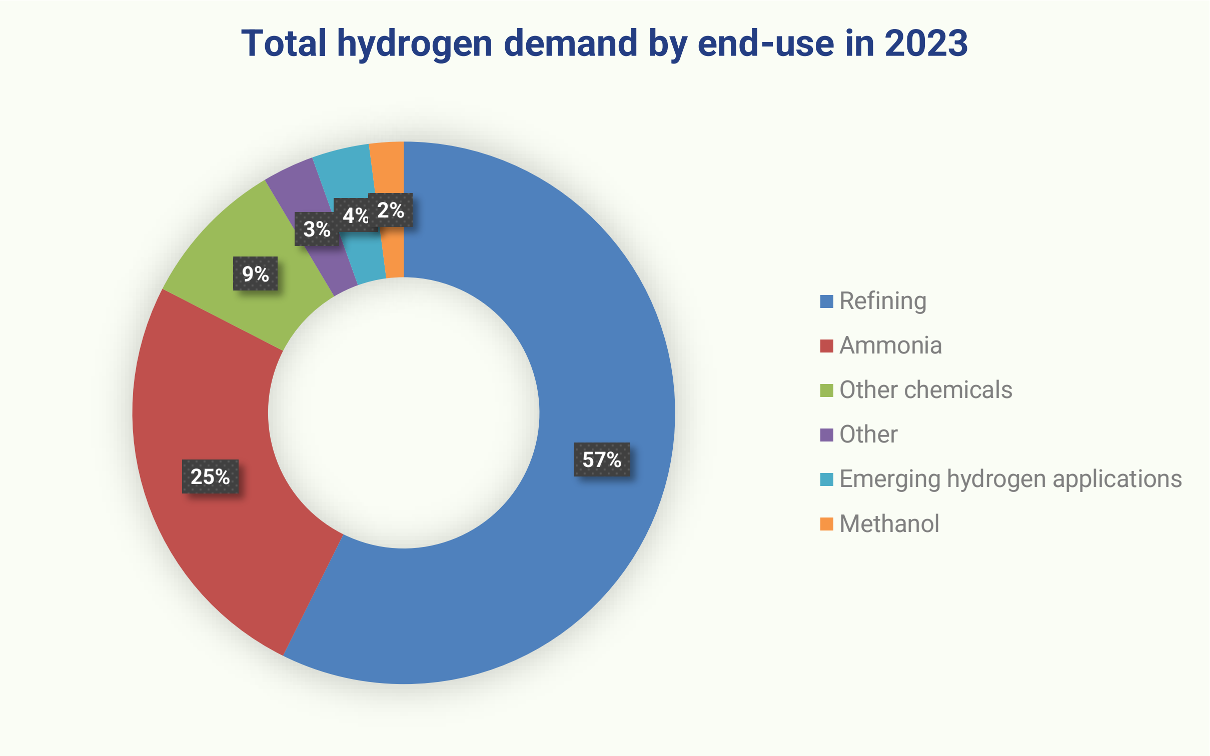

Figure 29. Total hydrogen demand by end-use in 2023.

As illustrated in Figure 30, just four countries, namely Germany (17%), the Netherlands (15%), Poland (9%), and Spain (7%), account for around 50% of the combined hydrogen demand in Europe (3.86 MT/year).

Figure 30 also depicts the amount of clean hydrogen that is being consumed compared to the amount of conventional hydrogen. In 2023, in total 26.86 kt of clean hydrogen was consumed in Europe, which refers to hydrogen being produced from water electrolysis, compared to 7.91 Mt of conventional hydrogen.

Germany emerges as the predominant consumer, exhibiting the highest conventional hydrogen consumption among European countries, constituting 17% of the total European demand, equivalent (1379.36 kt/year). Netherlands and Poland follow closely, representing 15% and 9% of the overall conventional hydrogen demand, with an annual consumption of 1172.83 kt and 728.54 kt respectively.

In contrast, Latvia, and Iceland, each exhibit modest conventional hydrogen consumption, with annual usages of less than 150 tonnes, positioning them as the countries with the lowest levels of conventional hydrogen consumption in Europe. Notably, Estonia reports no consumption of conventional hydrogen.

In most European countries, clean hydrogen accounts for less than 10% of their total hydrogen consumption. However, in Iceland and Estonia, nearly all hydrogen consumed is produced from renewable sources.

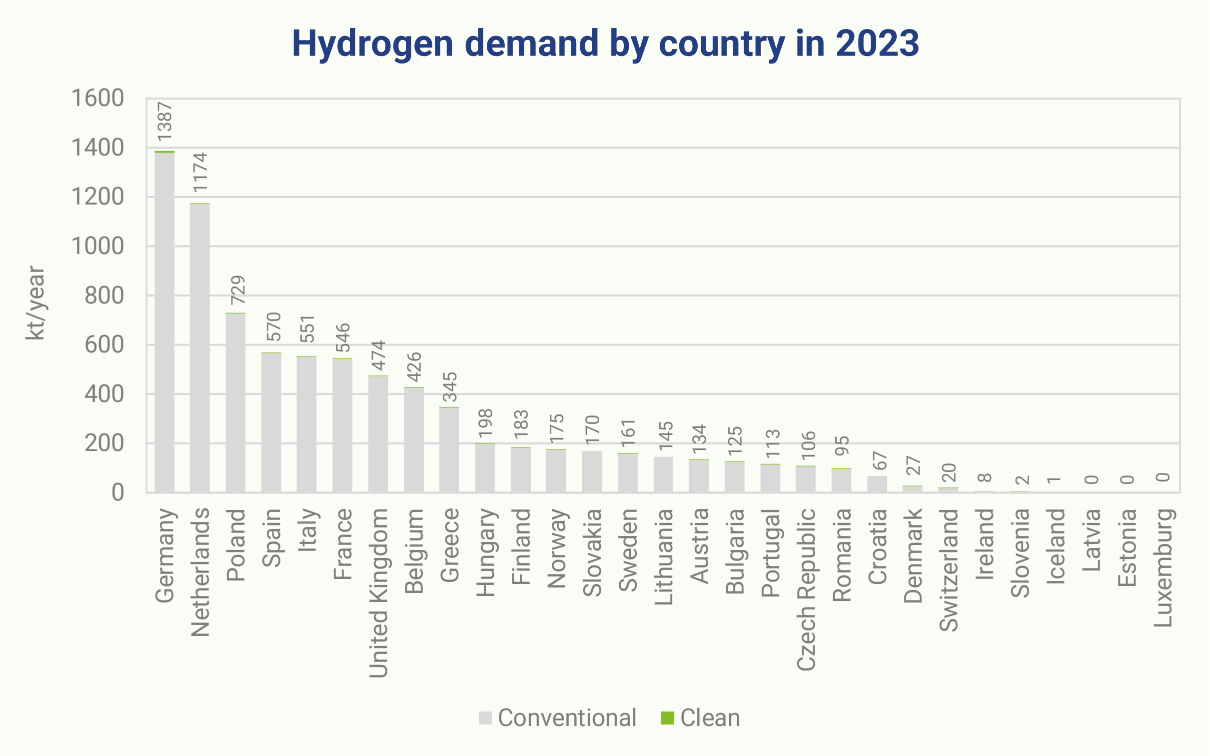

Figure 30. Hydrogen demand by country[7] in 2023.

3.2.

Demand for conventional and clean hydrogen

3.2.1.

Conventional hydrogen demand

Figure 31 provides the consumption of conventional hydrogen (i.e., produced via reforming and by-products) of various end-use sectors across Europe as of end of 2023. Conventional hydrogen demand in 2023 was estimated at 7.91 Mt, a slight decrease of 0.26 Mt from 2022, accounting for 99.7% of the total hydrogen demand.

The refining sector stands out as the primary driver of conventional hydrogen consumption in most countries accounting for 58% of the total demand. Germany, Italy, the Netherlands, Spain and Poland are the top 5 countries with the

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[7] Conventional hydrogen consumption for Slovenia and Iceland are less than 150 t/y and 0 t/y for Estonia so they appear as 0 kt/y.

largest consumption in the refining sector contributing to 8.3%, 6.4%, 6.2%, 5.9% and 4.8% of the total demand, respectively. In many countries such as Italy, Spain, Greece, Finland, Portugal, Denmark and Ireland, the refining industry accounts for most of the domestic conventional hydrogen consumption (>80%).

The ammonia industry accounts for 25% of the total conventional hydrogen demand. The largest consumers within the ammonia industry are the Netherlands, Germany and Poland, contributing to 5.0%, 4.2% and 4.1% of the total demand. In some countries, such as Lithuania, Austria, Bulgaria, Slovakia and Poland, the ammonia industry plays a predominant role in driving their conventional hydrogen consumption, accounting for over 40% of their total demand.

For the production of other chemicals, 9% of the conventional hydrogen demand is used, with the largest consumers being the Netherlands, UK and Germany contributing to 2.9%, 1.4% and 1.2% of the total demand, respectively. The production of other chemicals was most hydrogen demanding in Slovenia, Switzerland and Hungary, amounting to 85%, 33% and 32% of their total hydrogen demand, respectively.

The methanol industry accounts for 2% of the total conventional hydrogen demand. Germany, Norway and Romania consumed the most, 0.99%, 0.73 and 0.24% of the total demand, respectively. The production of methanol was most hydrogen demanding in Norway, and Romania contributing to 33% and 20% of their total demand, respectively.

Finally, next to the other category, the emerging hydrogen applications account for 3% of the total conventional hydrogen demand. Industrial heat was responsible for almost this entire demand (±99.6%). The largest consumers are Germany, France and Belgium, contributing to 0.84%, 0.43% and 0.42% of the total demand. The emerging hydrogen applications were most hydrogen demanding in Latvia, amounting to 94% of its total hydrogen demand. Notably, in Luxembourg, despite negligible demand for conventional hydrogen, all hydrogen usage is directed towards emerging applications, specifically in the mobility sector.

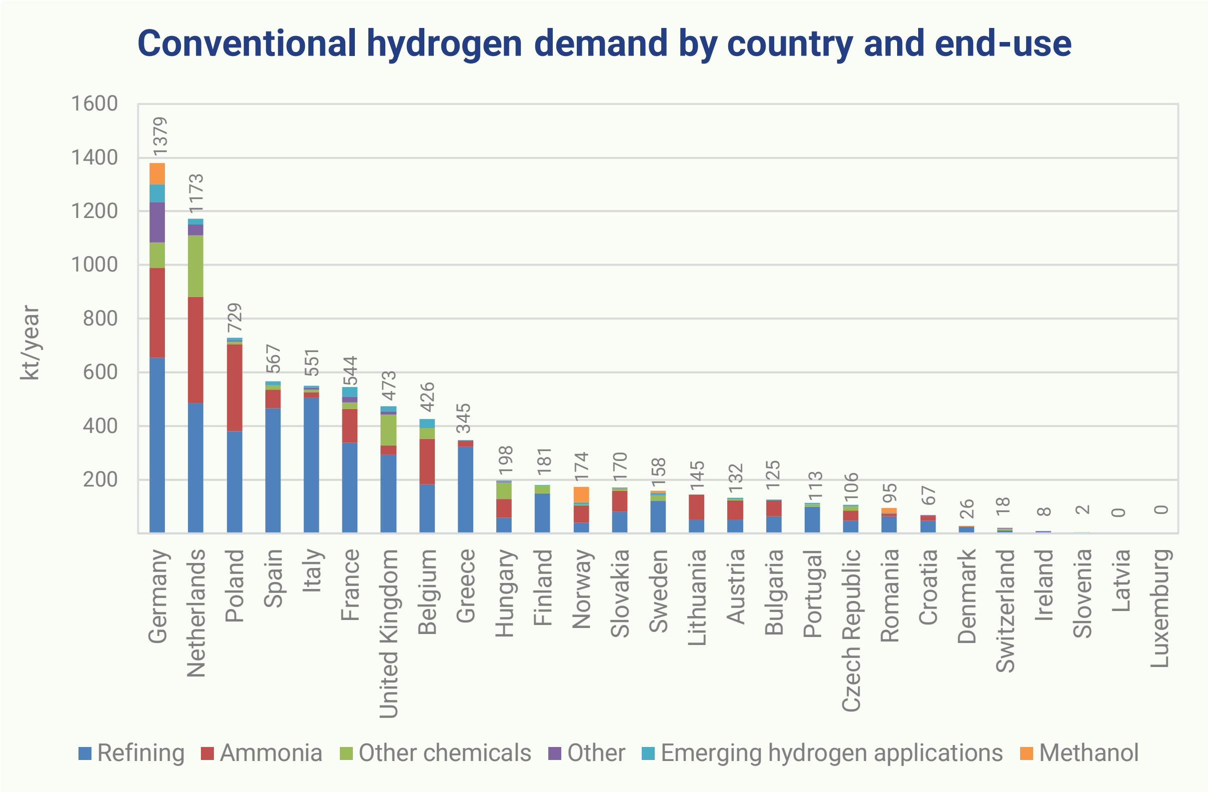

Figure 31.Conventional hydrogen demand by country and end-use[8].

3.2.2.

Clean hydrogen demand

Figure 32 illustrates the distribution of contributions from various sectors to the total clean hydrogen demand in 2023. Clean hydrogen demand in 2023 was estimated at 0.03 Mt, a slight increase of 0.01 Mt from 2022, accounting for 0.3% of the total hydrogen demand.

In the European context for 2023, emerging hydrogen applications (mobility, blending in natural gas pipelines, steel, e-fuels, residential and industrial heat, and power generation) arise as the primary driver of clean hydrogen demand, comprising approximately 54% of the total, equivalent to 14.53 kt. Subsequently, clean hydrogen demand for refining and ammonia production follows, each representing 9% of the overall clean hydrogen demand, amounting to 2.43 kt.

Methanol and other chemicals each account for around 8% of the overall demand, totalling 2.19 kt and 2.02 kt respectively.

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[8] Latvia and Luxemburg report consumption of conventional hydrogen of less than 140 t/y, which are reflected as 0 kt/y.

The category ‘Other’ contributed to a considerable share of the clean hydrogen demand (12%). For this category, no specific end-use could be assigned to the hydrogen that was produced.

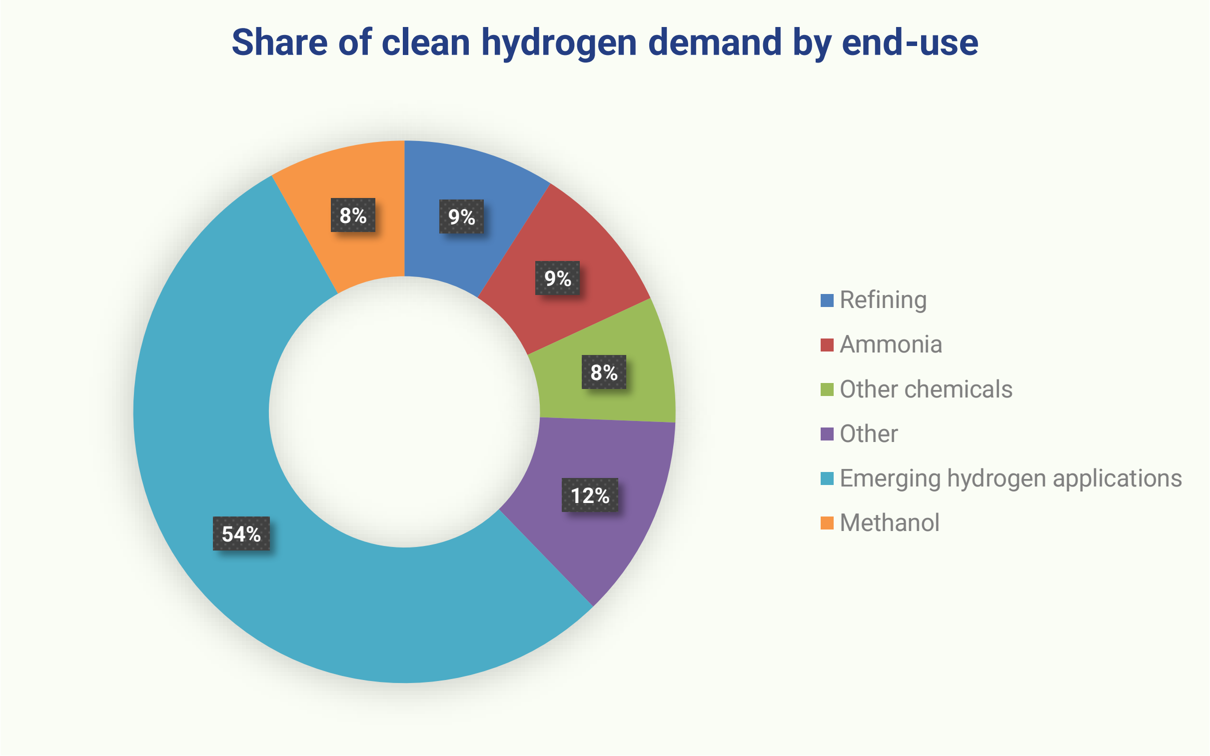

Figure 32. Share of green hydrogen demand by end-use in Europe.

Figure 33 shows the demand for clean hydrogen in various end-use sectors across Europe in 2023.

The clean hydrogen demand across various countries is influenced by different sectors. The emerging hydrogen applications emerge as the predominant driver in most countries. Notably, in countries such as the Netherlands, the United Kingdom, Hungary, Sweden and Austria emerging hydrogen applications account for most of the domestic hydrogen consumption, comprising 100%, 100%, 96%, and 88% of their total clean hydrogen demand, respectively. Notably, in Belgium, Portugal, Romania, and Poland despite negligible demand for clean hydrogen, all hydrogen usage is directed towards emerging applications.

Switzerland leads in clean hydrogen demand for the chemical industry, which constitutes 48% of its total clean hydrogen consumption. In both the Czech Republic and Estonia, while overall demand for clean hydrogen is minimal, all usage is allocated to the chemical sector.

Additionally, various industrial sectors dominate clean hydrogen consumption in specific countries. In the Netherlands, 44% of clean hydrogen demand is driven by the refining industry, while in Spain, 65% is consumed in ammonia production. Methanol production accounts for nearly all clean hydrogen demand in Iceland (99%) and Denmark (95%).

The "Other" category, which represents hydrogen consumption with no specific end-use assignment, is significant in Greece and Finland, where it accounts for 100% and 92% of total clean hydrogen demand, respectively.

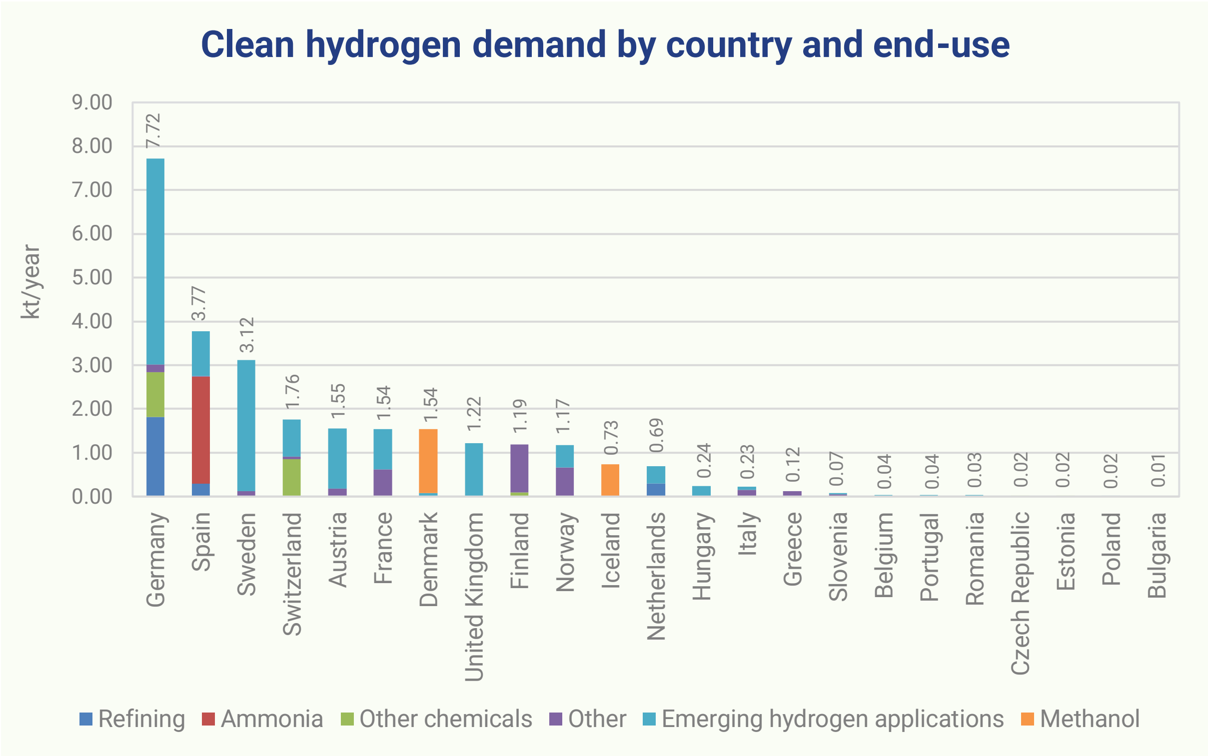

Figure 33. Green hydrogen demand by country and end-use[9].

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[9] Croatia, Ireland, Latvia, Lithuania, Luxemburg and Slovakia report no consumption of clean hydrogen.

3.3.

Hydrogen Fuel Cell Electric Vehicles

3.3.1.

FCEV market evolution

In this section, the Hydrogen fuel cell electric vehicles (FCEV) market evolution in Europe is analysed by looking at the growth in fleet and registration numbers for Europe, followed by a more in-depth analysis of the growth of the different FCEV types (cars, vans, buses, and trucks) and the evolution in national FCEV deployment. Figure 34 illustrates the FCEV market evolution in Europe by depicting the total number of registrations from 2014 to 2023.

A total of **1026 FCEV were registered** in Europe in 2023

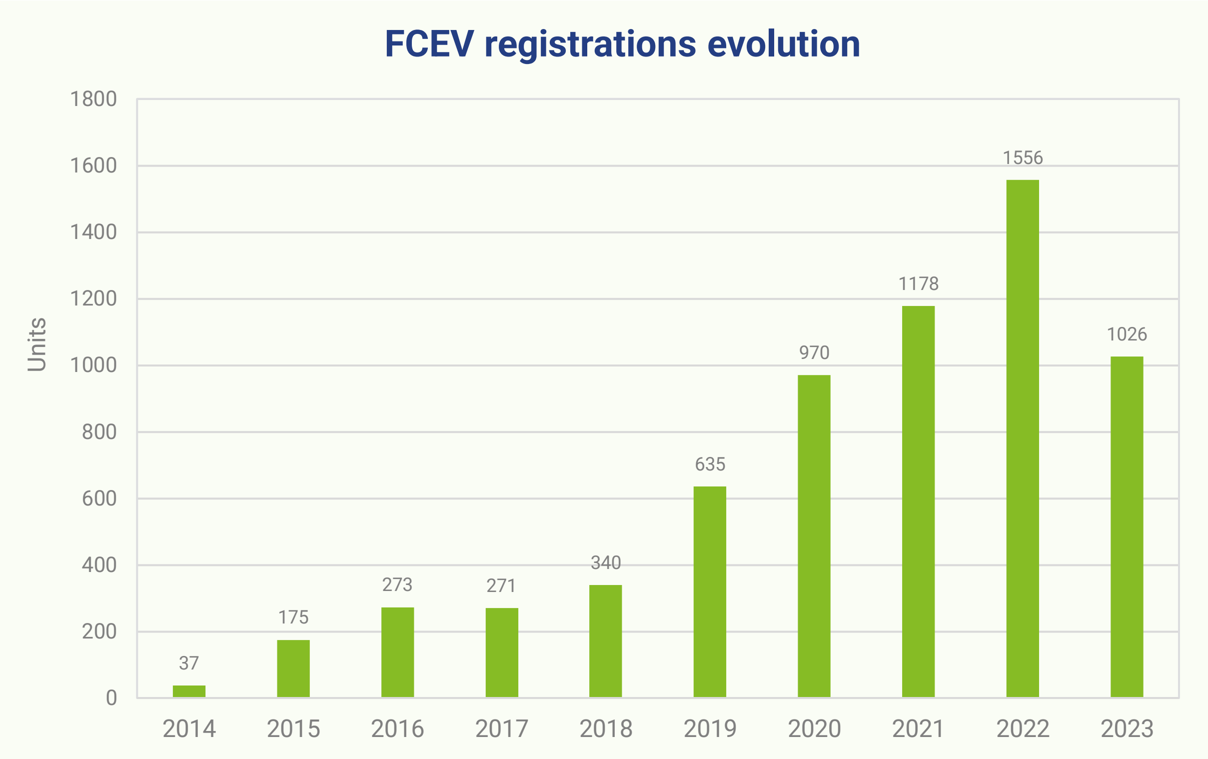

Figure 34. Fuel Cell Electric Vehicles (FCEVs) registrations evolution from 2014 to 2023 in the European market.

Since 2018, the total number of FCEV registrations in Europe has grown at an accelerated pace from 340 to 1537 by 2022 (+352%). However, this was followed by a 34% decline in registrations in 2023.

The trend in registrations also has a clear effect on the evolution of the total FCEV fleet in Europe, which is illustrated in Figure 35 for the period 2014 - 2023.

The FCEV fleet has increased rapidly since 2014 from 78 to 5939 by 2023 (+7514%).

Despite the decline in FCEV registrations from 2022 to 2023, the total FCEV fleet increased by 7% during the same period. This reflects the cumulative effect of high registration rates in prior years, with many vehicles remaining in operation. The growth in the fleet indicates that the number of FCEVs being retired or decommissioned is low, and the existing fleet continues to expand, even as the pace of new registrations temporarily slows.

5939 of FCEV in the European fleet of 2023

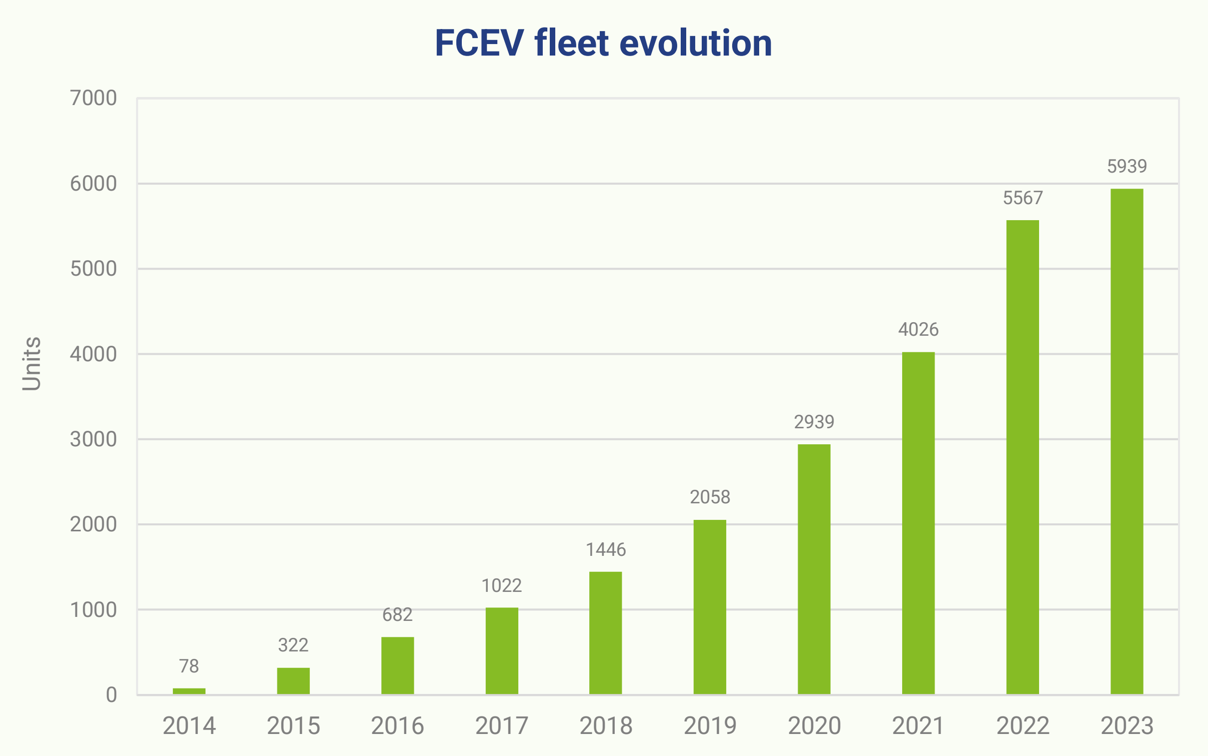

Figure 35. Fuel Cell Electric Vehicles (FCEVs) fleet evolution from 2014 to 2023 in the European market.

3.3.2.

FCEV type evolution

Figure 36 illustrates the evolution of FCEV fleet covering 4 different types of vehicles, including: a) passenger cars (M1), b) vans (N1) c) buses (M2 & M3), and d) trucks (N2 & N3), during the period from 2014 to 2023. For a more comprehensive explanation of the vehicle types, according to EU classification please refer to

Table 3.

Total number of FCEV in the European fleet of 2023

a. **Passenger cars (M1): 4938** *(+2.8% from 2022)*
b. **Vans (N1): 322** *(-0.3% from 2022)*
c. **Buses (M2 & M3): 464** *(+38.9% from 2022)*
d. **Trucks (N2 & N3): 215** *(+97.3% from 2022)*

Table 3. Outline of the terminology employed in this chapter to describe different types of FCEV fleet.

M1	Vehicles used for the carriage of passengers and comprising not more than eight seats in addition to the driver's seat
M2	Vehicles used for the carriage of passengers, comprising more than eight seats in addition to the driver's seat, and having a maximum mass not exceeding 5 tonnes
M3	Vehicles used for the carriage of passengers, comprising more than eight seats in addition to the driver's seat, and having a maximum mass exceeding 5 tonnes
N1	Vehicles used for the carriage of goods and having a maximum mass not exceeding 3.5 tonnes
N2	Vehicles used for the carriage of goods and having a maximum mass exceeding 3.5 tonnes but not exceeding 12 tonnes
N3	Vehicles used for the carriage of goods and having a maximum mass exceeding 12 tonnes

Fuel cell passenger cars showed a continuous increase in the fleet, going from 69 units in 2014 to 4,938 in 2023. The number of fuel cell vans also increased over time, totalling 322 units in 2023. In 2018, however, already 297 fuel cell vans were reported for the total fleet in Europe, and thus it appears that the growth has stabilized since then.

Over time, the number of fuel cell buses experienced a substantial growth, especially in the latest years, going up to 464 by 2023. The fleet of fuel cell trucks only started growing as of

2016. As of 2020, a more substantial growth phase began, resulting in a total of 215 units in 2023. Compared to 2022, the total number of fuel cells increased for all vehicle types, except for vans, which saw a decline. The most significant growth was observed in fuel cell trucks, with an increase of 97.3%.

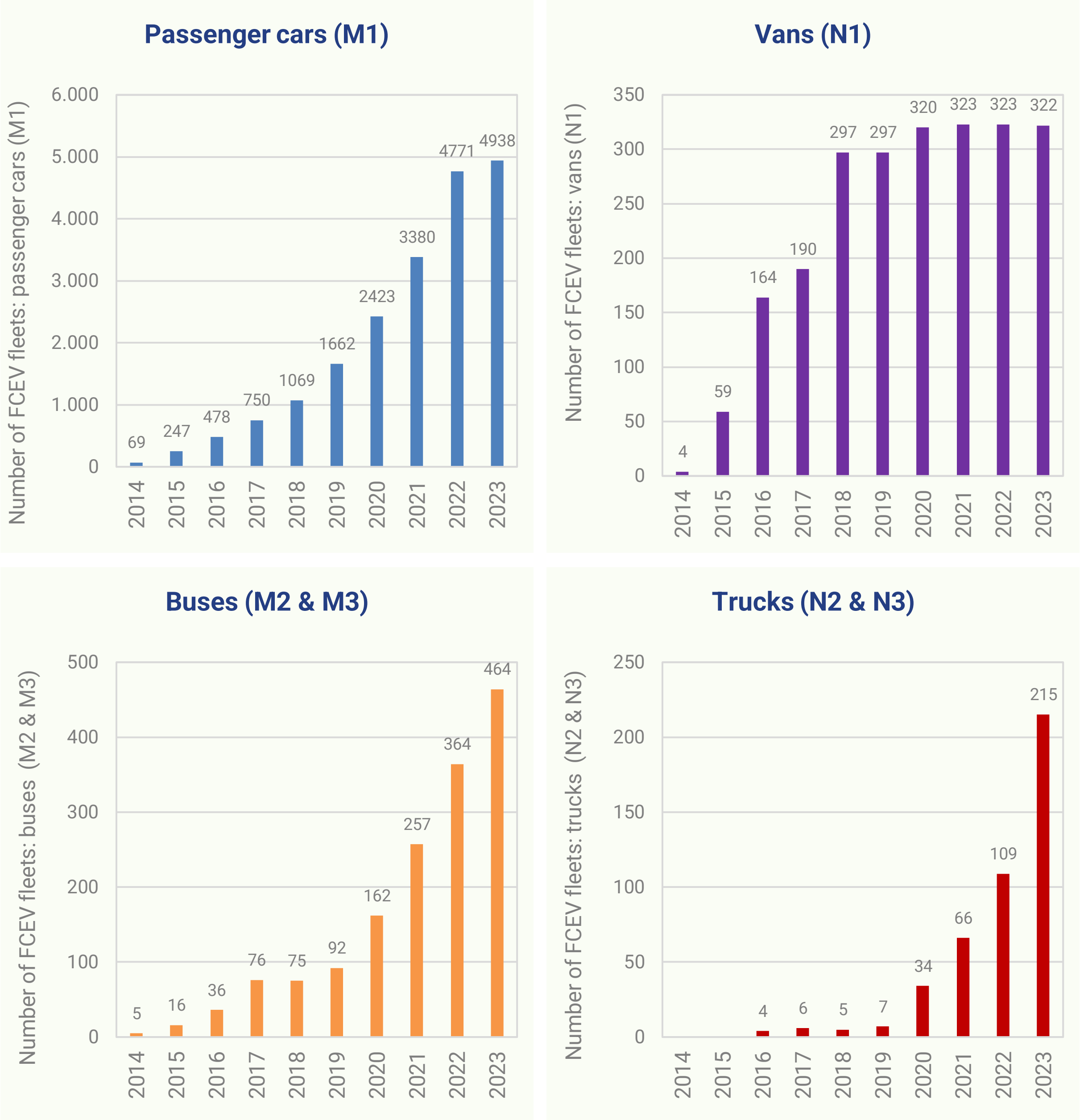

Figure 36. Evolution of FCEV fleet by type of vehicles from 2014 to 2023.

3.3.3.

Evolution in national FCEV deployment

In this section, the evolution in the national deployment of FCEV fleet is analysed covering the 4 different types of vehicles, including: a) passenger cars (M1), b) vans (N1) c) buses (M2 & M3) and d) trucks (N2 & N3), for 2021, 2022 and 2023.

In 2023, Germany remained to have the largest fleet of fuel cell passenger cars with 2,122 units (see Figure 37), constituting 43% of the total number of such vehicles in Europe.

Following Germany are the Netherlands and France, each contributing approximately 12% of the fleet in 2023 with 615 and 614 units, respectively. Also, the UK, Norway, Switzerland, Denmark, Belgium, and Poland have developed a significant fuel cell passenger vehicles fleet, each having above 100 units in 2023.

A noteworthy evolution was observed in Czech Republic, which experienced the most remarkable growth in the number of fuel cell passenger cars, their fleet increased from 9 units in 2021 to 28 units in 2023 (+211%).

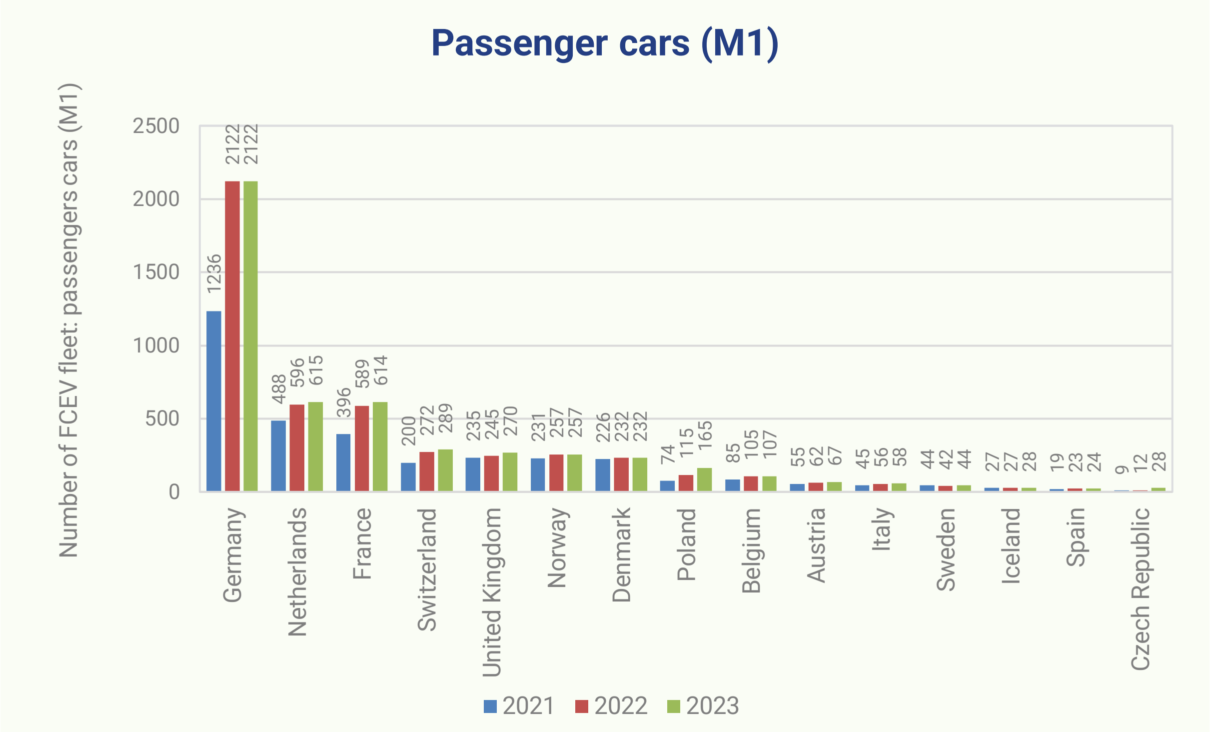

Figure 37. Evolution in national deployment of fuel cell passenger cars (M1).[10]

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[10] Luxembourg, Portugal, Slovakia, Estonia, Finland, Lithuania, Bulgaria, and Latvia were excluded from the graph as their fleet numbers were below 5 in each of the examined years.

In terms of fuel cell vans (Figure 38), France remained the leader in Europe in 2023, representing a substantial 85% of the total number of such vehicles with a fleet of 273 units. The remaining 15% of these vehicles were distributed among several European countries, including Germany, the Netherlands, Switzerland, the United Kingdom, Denmark, and Belgium, with 16, 13, 10, 7, 2, and 1 units of fuel cell vans, respectively.

The fleet of most European countries remains stable, neither experiencing significant increases nor decreases in the number of their fuel cell vans during this period.

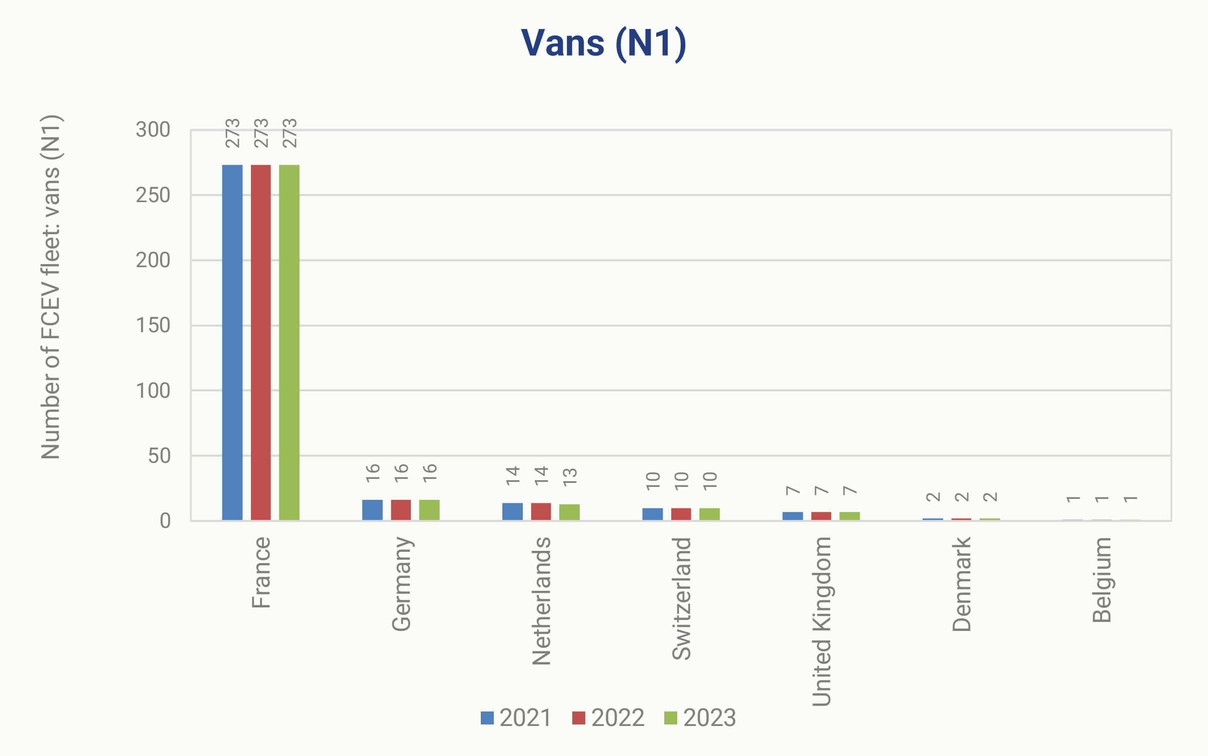

Figure 38. Evolution in national deployment of fuel cell vans (N1).

When looking at the evolution of fuel cell buses in Europe (Figure 39), Germany has emerged to have the largest fleet in 2023, constituting 32% of the total number of such vehicles, with a fleet of 149 units. Following closely were the UK, the Netherlands and Norway each contributing 21%, 14% and 11% to the total fleet of Europe.

Additionally, Norway, the UK, and Latvia have shown remarkable growth in their FCEV fleets in recent years. From 2021 to 2023, the fleet sizes in these countries increased from 10 to 53 in Norway (+430%), from 33 to 98 in the UK (+197%), and from 10 to 22 in Latvia (+120%). Many other European countries, on the other hand, maintained stable numbers of fuel cell buses in recent years. Of particular note is Spain which introduced their first fuel cell buses already having a total of 6 units in 2022.

The fleet of fuel cell trucks has seen a strong increase in recent years in Europe (Figure 40). In

2023, Switzerland remained the leader, representing 27% of the total number of fuel cell trucks, with a total fleet of 57 units. Following closely were the UK and Norway, accounting for 24% and 19% of the total number of fuel cell trucks, totalling 52 and 41 units, in 2023 respectively.

Germany and the UK introduced their first fuel cell trucks into their fleets in 2022, with 27 units in Germany and 1 unit in the UK. The UK and Norway have seen significant growth in their fuel cell truck fleets. The UK expanded from 1 unit in 2022 to 52 units in 2023, while Norway grew from 6 units to 41 units over the same period.

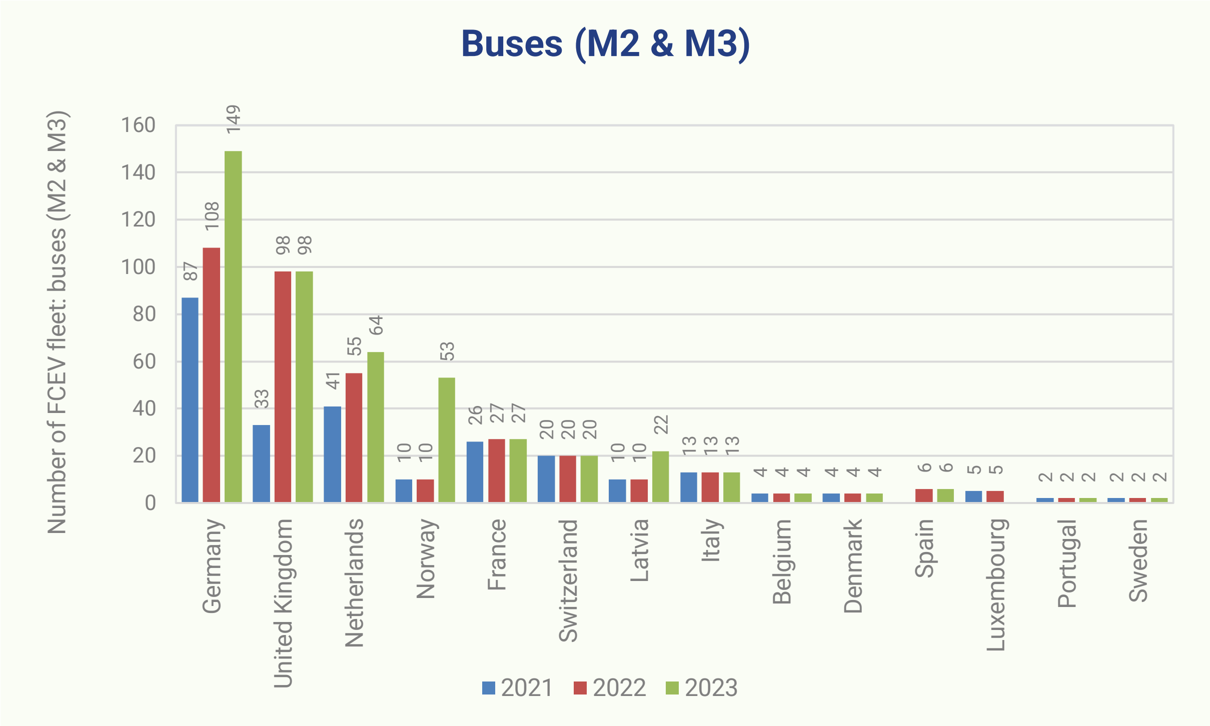

Figure 39. Evolution in national deployment of fuel cell buses (M1 & M2).

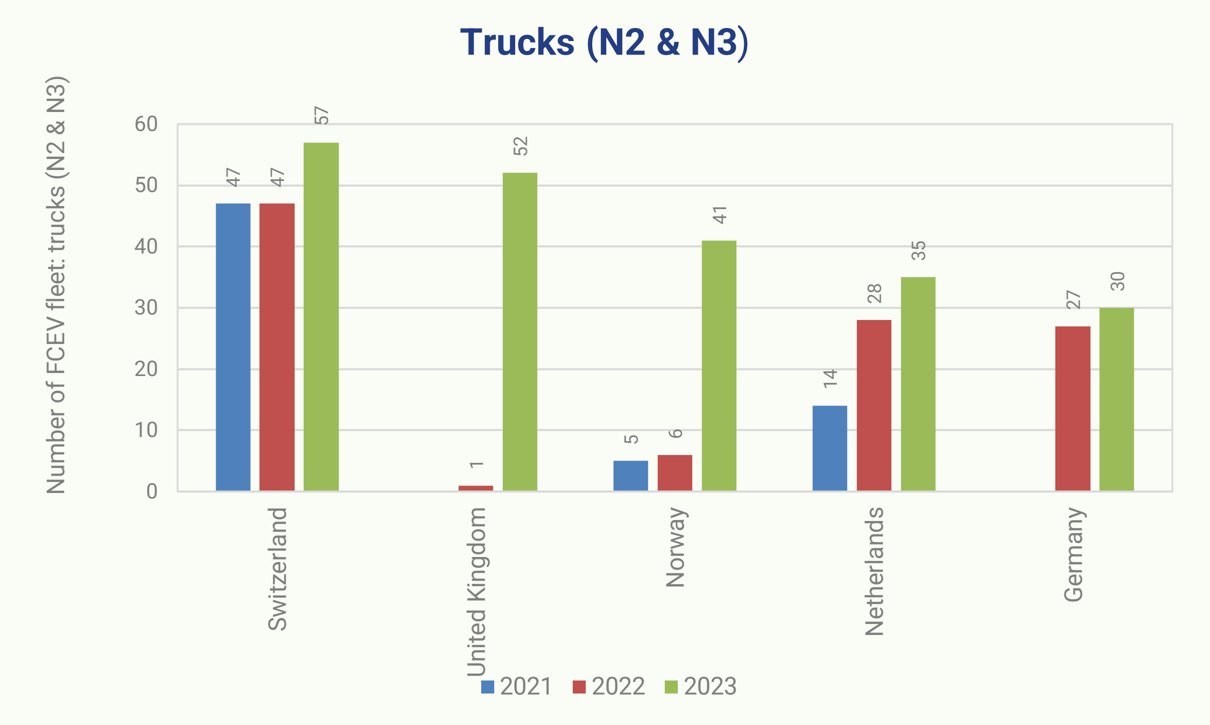

Figure 40. Evolution in national deployment in fuel cell trucks (N2 & N3).

3.4.

Hydrogen demand forecasts

This section investigates and compares the primary scenarios for future hydrogen demand in Europe for the years 2030, 2040, and 2050 across various sectors (industry, transport, buildings, and electricity). In Figure 41, the average hydrogen demand projections of these scenarios are displayed.

The forecasts reveal a projected growth trajectory in the total hydrogen demand in Europe for the coming decades, with a projected 127% surge from 2030 to 2040, followed by a 63% increase from 2040 to 2050. Current hydrogen demand experienced a slight 3% decline since 2022, but a substantial 56% growth is anticipated by 2030.

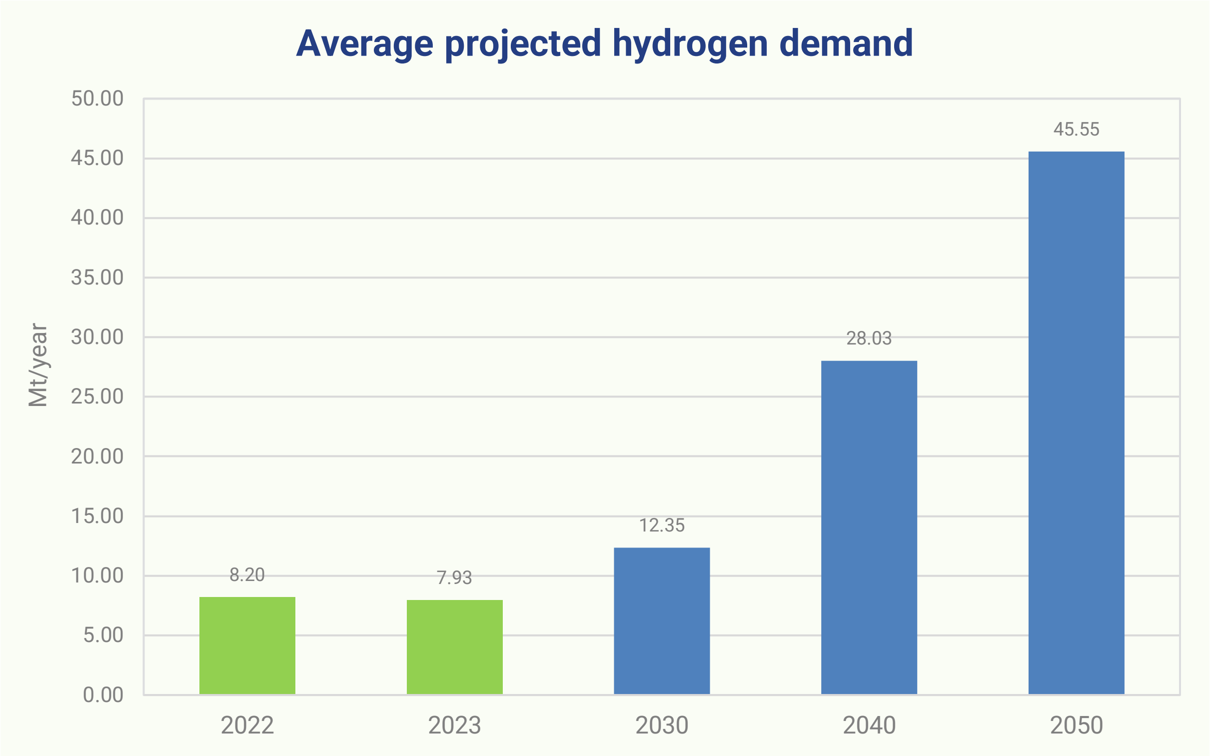

Figure 41. Average hydrogen demand projections of different scenarios in Europe for the years 2030, 2040 and 2050.

A more detailed analysis is depicted in Figure 42, where the projected hydrogen demand is broken down by sector. Throughout the three decades under examination, the industrial sector is projected to maintain its dominance, consistently demonstrating the highest hydrogen demand. This sector is forecasted to witness a steady growth in demand, rising from 9.86 Mt in 2030 to 14.62 Mt in 2040, representing a 48% increase, and further increasing to 16.88 Mt in 2050, which accounts for a 15% growth.

However, despite this growth in absolute demand, the industrial sector's share of the total average hydrogen demand exhibits a progressive decline, decreasing from 78% of the total in 2030 to 37% in 2050. The current hydrogen demand in the industrial sector has experienced a slight 2% decline since 2022; however, a 26% growth is projected by 2030.

The transport sector is anticipated to closely follow, with the second-highest average demand throughout the years, consistently increasing its share of the total average hydrogen demand. Starting with a 15% share in 2030, the transport sector's contribution is projected to grow significantly, reaching 37% by 2050, meeting the industrial demand.

It is also foreseen to have an anticipated growth in the remaining sectors, encompassing building and power, with their shares of total hydrogen demand projected to reach 15% and 11%, respectively by the year 2050, slowly kicking off before 2030, after which they start accelerating.

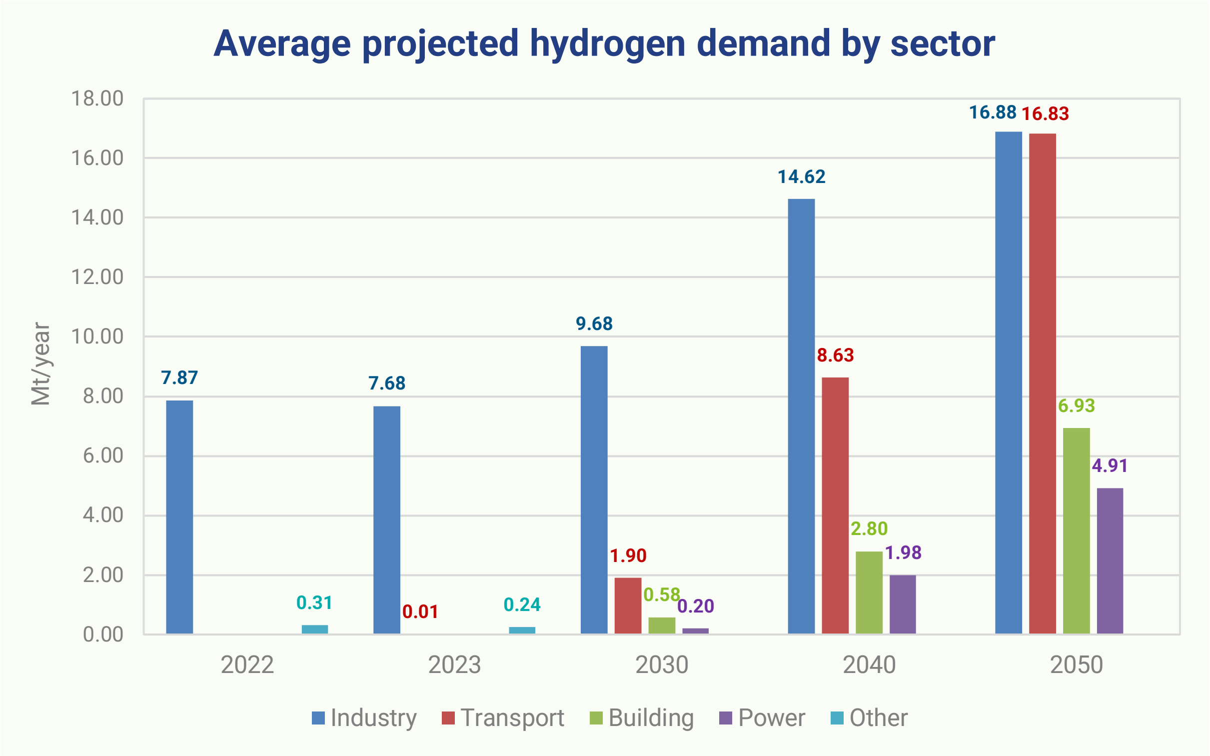

Figure 42. Average projected hydrogen demand of different scenarios by sector for the years 2030, 2040 and 2050.

3.5.

Hydrogen valleys

Hydrogen Valleys

The latest information on Hydrogen Valleys developing hydrogen-based technologies and infrastructures in Europe and in the world can be found in the Mission Innovation Hydrogen Valley Platform. This platform is dedicated to all current and future hydrogen project developers and helps to gather meaningful information from experienced peers and promote collaboration among one another. On top of that, the platform strives to underline the core added value of hydrogen as an energy vector to inform all relevant stakeholders who support the development of hydrogen projects.

On the Hydrogen Valley map, you can click on the pins to learn more about each valley. **In Europe, a total of 75 current and future valleys have been registered by October 2024**, covering most European countries (see figure below). If you would like to get in touch with a project, use the Matchmaking section to contact the Hydrogen Valley directly. If you are interested in a deep dive into the challenges and barriers that Hydrogen Valleys are facing and how they are tackling them, please visit the Best Practices section.

The Hydrogen Valleys have provided detailed information via a comprehensive survey. This information can be consulted based on an aggregate view the Analysis section. This section gives statistics on project status, value chain, preparation, financing, barriers and much more. Based in this analysis, it can be observed **that in Europe 4 valleys are already fully operational and 10 are under construction**. As for the value chain, the following interesting insights can be learned from the analysis for the European Hydrogen Valleys:

- Primary energy source: the Valleys have reported to always make use of renewable electricity, and barely any fossil fuels.
- Hydrogen production technology: most of the Valleys are making use of water electrolysis, with a higher preference for PEM technology (72% of the Valleys).
- End-use applications: Most Valleys are looking into mobility end-uses (84%), followed by industrial use as feedstock (63%).

Figure 43. Current and future hydrogen Valleys in Europe.

04

Cost of production and break-even prices

Introduction

This chapter offers an in-depth examination of the levelised cost of hydrogen (LCOH) production across European countries in 2023. The analysis breakdowns the production costs, distinguishing between capital expenditures (CAPEX) and operational expenditures (OPEX) for the following different hydrogen production technologies:

1. Steam methane reforming (SMR)
2. Steam methane reforming with carbon capture (SMR+CC)
3. Grid-connected electrolysis
4. Electrolysis with direct connection to a renewable energy source (renewable hydrogen)

Data is based on research conducted by Hydrogen Europe, reflecting the situation as of the end of 2023. Data was estimated based on a set of assumptions updated annually and subsequent verification by industry stakeholders. This comprehensive assessment aims to provide valuable insights into the economic considerations and feasibility of these technologies within the European landscape.

Furthermore, an overview on break-even price estimations for renewable hydrogen is presented, illustrating the highest delivery cost at which the adoption of renewable hydrogen becomes economically competitive compared to the fossil fuel-based baseline. This analysis was performed by Hydrogen Europe for four specific end-uses, including oil refining, steel production, heavy-duty trucks and maritime application. The assumptions that were made are listed in Appendix A.2.

Finally, an overview on the different electrolyser cost components is included. The data provides CAPEX (EUR/kW) and OPEX (EUR/kW/year) electrolyser system cost for projects based in Europe. Outputs are presented by technology and by category. The electrolyser system cost data were collected through interviews with developers of electrolytic projects and other industry sources. The data aim to reflect a project of total size of 20 MW_{el} that is under construction or in an otherwise advanced stage. OPEX is expressed as a single value and includes all expenses (including water, insurance, maintenance, stack replacement costs, etc.), except electricity. The CAPEX are divided between stack, balance of plant (BoP), other Engineering, Procurement, and Construction costs (Other EPC), and OPEX (excluding electricity).

Interactive data dashboards and downloadable spreadsheets on the cost of hydrogen production, break-even price of renewable hydrogen and electrolyser cost can be accessed on the European Hydrogen Observatory website.

4.1.

Hydrogen production cost overview

Figure 44 illustrates the average levelised costs of hydrogen production (in €/kg H_2) by technology in Europe in 2023.

For 2023, the levelised production costs of hydrogen produced via SMR in Europe were, on average approximately 3.76 €/kg H_2 (-2.47 €/kg H_2 compared to 2022). However, as SMR plants are already operational (and in many cases long amortized), marginal (not levelised) costs may, in many cases, be a better benchmark. Excluding the impact of CAPEX (amortization) and other fixed costs, estimated SMR hydrogen marginal production costs in Europe in 2023 were around 3.5 €/kg H_2.

With a carbon capture installation, the cost of hydrogen by SMR in Europe increased, on average, to 4.41 €/kg H_2 (-1.97 €/kg H_2 compared to 2022). The hydrogen production costs using grid electricity in Europe in 2023 were estimated in the range of 4.06-17.36 €/kg H_2, with the average for all countries being 7.94 €/kg H_2 (-1.91€/kg H_2 compared to 2022) and a median of 7.53 €/kg H_2.

Hydrogen production costs via electrolysis with a direct connection to a renewable energy source in Europe vary from 4.13 to 9.30 €/kg H_2 of hydrogen, with the average for all countries being 6.61 €/kg H_2 (-0.25 €/kg H_2 compared to 2022) and a median of 6.20 €/kg H_2. Even though hydrogen production via electrolysis with a direct connection to a renewable energy source avoids electricity costs like network costs and taxes, the electrolyser capacity factor is limited by the capacity factor of the renewable source it is connected to. In some cases, this could cause higher production costs.

The evolution of the prices for the different technologies is described in more detail in the following sections.

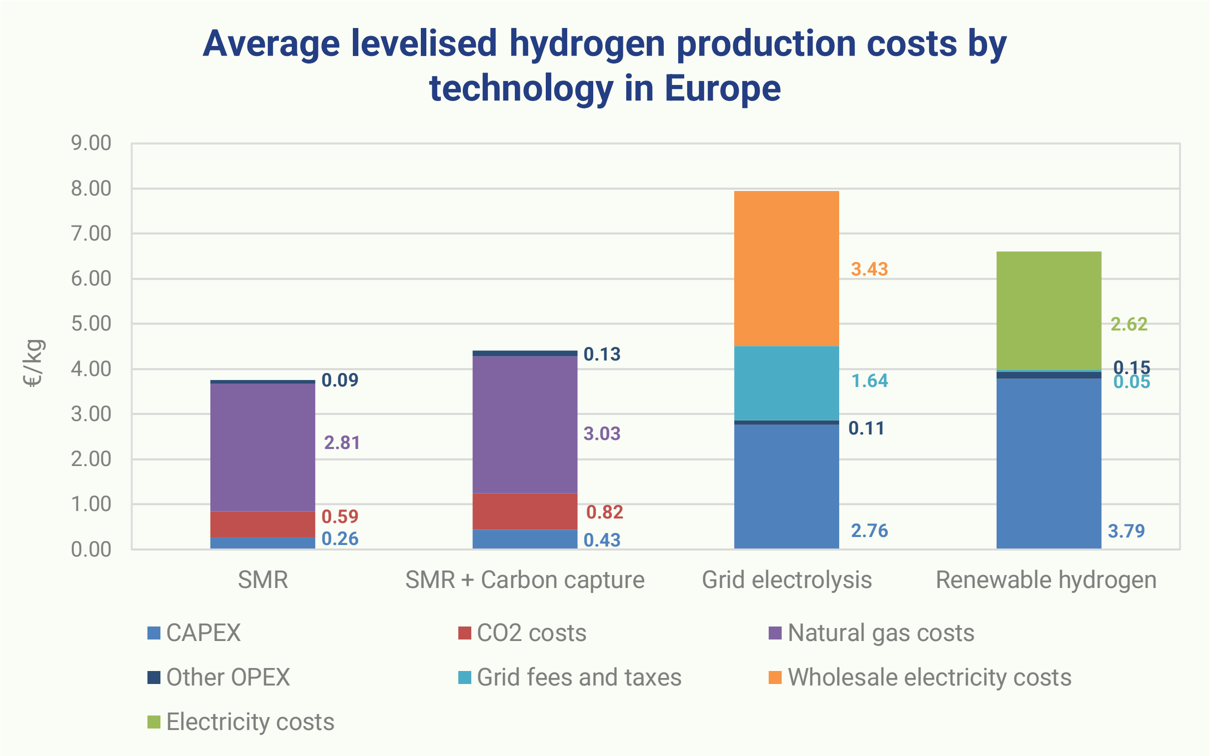

Figure 44. Average levelised hydrogen production costs (€/kg H_2) by technology in Europe in 2023.

4.2.

Hydrogen production cost per production process

4.2.1.

Steam methane reforming (SMR)

The production costs of hydrogen via the steam methane reforming (SMR) method serve as a valuable reference point for pricing in comparison to other production technologies.

The average levelised cost of hydrogen production via SMR in Europe stands at 3.76 €/kg H_2 in 2023, a decrease of 2.47 €/kg H_2 compared to 2022. Marginal costs, which include natural gas, CO_2 expenses, and other operational costs (OPEX), account for 92.8% of the total costs (3.49 €/kg H_2), while the remaining 7.2% is attributed to CAPEX (0.26 €/kg H_2). Compared to 2022, the proportion of marginal costs in the total cost of hydrogen production via SMR has decreased by 4%.

Natural gas costs occupying the largest share, accounting for approximately 75% of the total cost. The remaining 25% of the total costs are allocated to CO_2 costs, CAPEX, and other OPEX, accounting for 16%, 7% and 2% of the total costs, respectively.

Hydrogen production costs via SMR by European country in 2023 (in €/kg H_2) is presented in Figure 46. Luxemburg reported the highest production costs for hydrogen, with an average of 5.57 €/kg H_2. Following closely were Sweden and Slovakia with production costs of 4.77 €/kg H_2, and 4.70 €/kg H_2, respectively. Similarly, the countries demonstrating the cheapest SMR production costs are Belgium and Spain, both maintaining SMR costs below the 3.00 €/kg H_2 of hydrogen threshold.

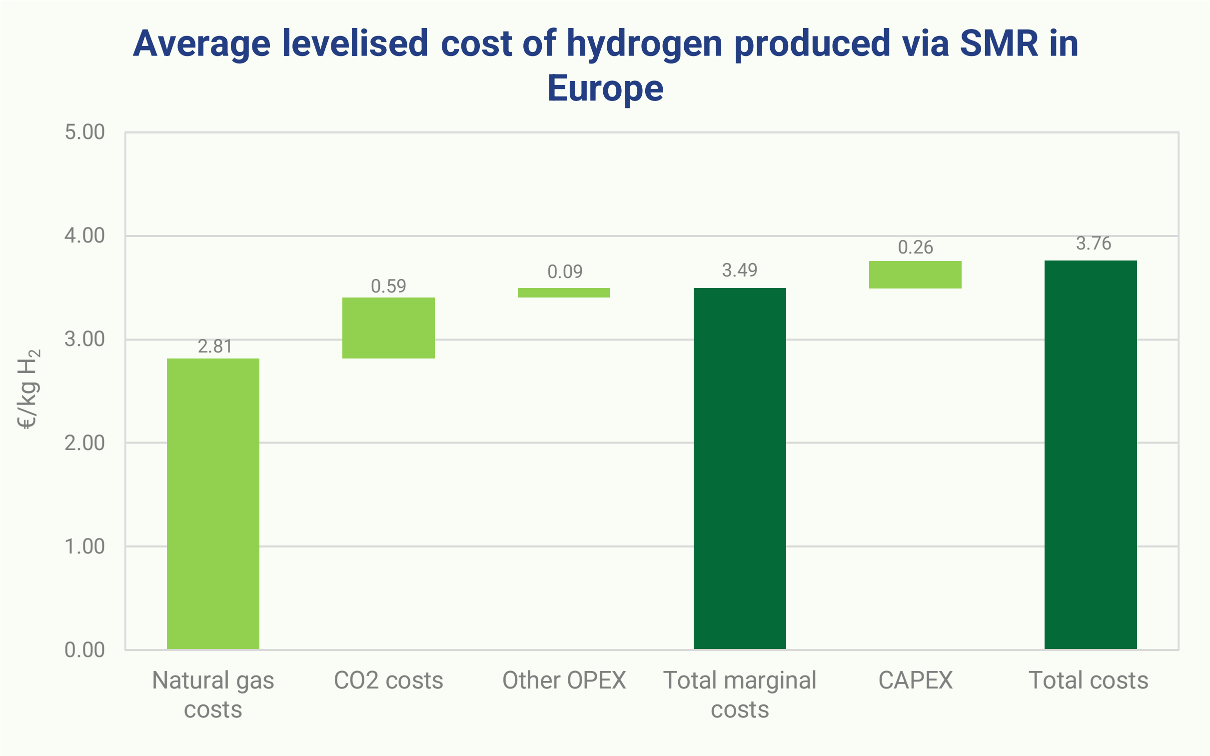

Figure 45. Average levelised cost of hydrogen produced via SMR in Europe (€/kg H_2) in 2023.

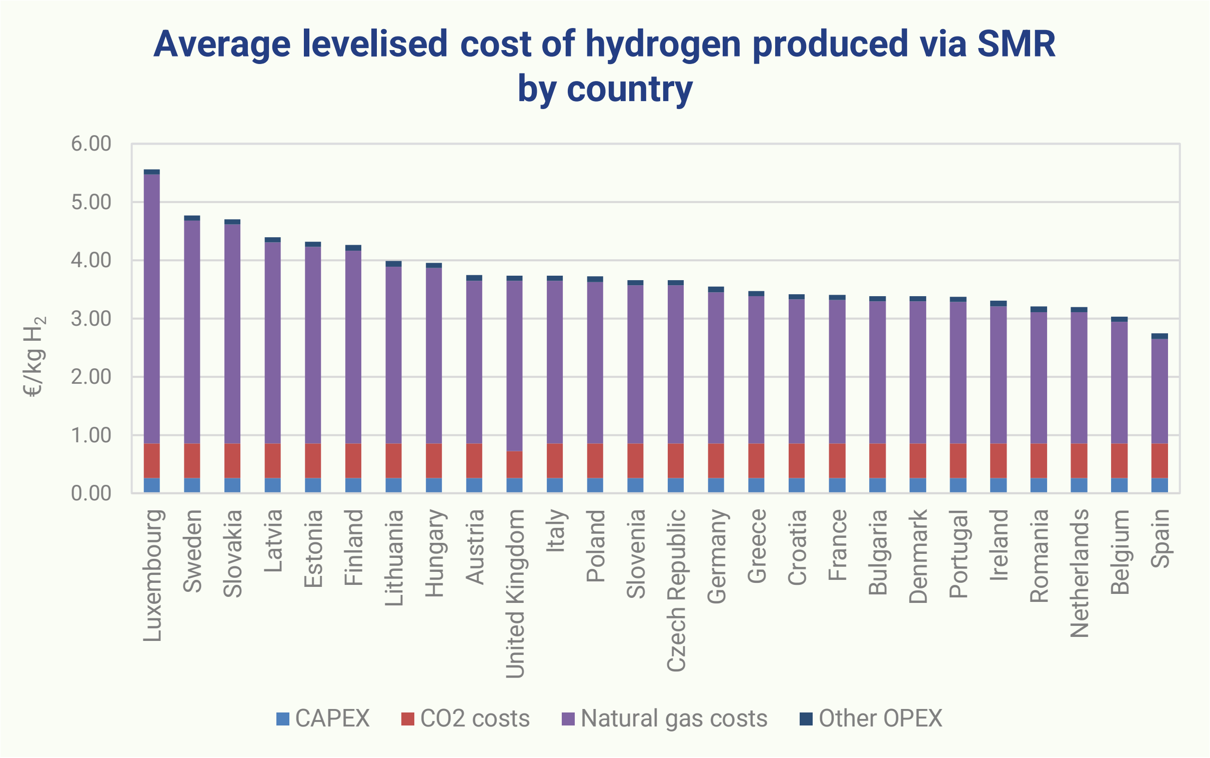

Figure 46. Average levelised cost of hydrogen produced via SMR (in €/kg H2) by country in 2023.

4.2.2.

Steam methane reforming with carbon capture (SMR+CC)

The average levelised cost of hydrogen production through reforming coupled with carbon capture of the emissions (SMR+CC) in Europe in 2023 stands at 4.41 €/kg H_2, a decrease of 1.97 €/kg H2 compared to 2022. Figure 47 gives an overview of the different cost components. Note that the costs of transporting and storing carbon dioxide molecules are not taken into account. The marginal costs account for the largest share (90% of the total costs), which were mostly driven by natural gas costs (approximately 69% of the total). CAPEX on the other hand represents 10% of the overall cost. Compared to 2022, the proportion of marginal costs in the total cost of hydrogen production via SMR+CC has decreased by 4.2%.

Hydrogen production costs via reforming with carbon capture by a European country in 2023 (in €/kg H_2) are presented in Figure 48. The addition of carbon capture to hydrogen production through steam methane reforming leads to an average cost increase of 0.65 €/kg H_2 of hydrogen across all countries.

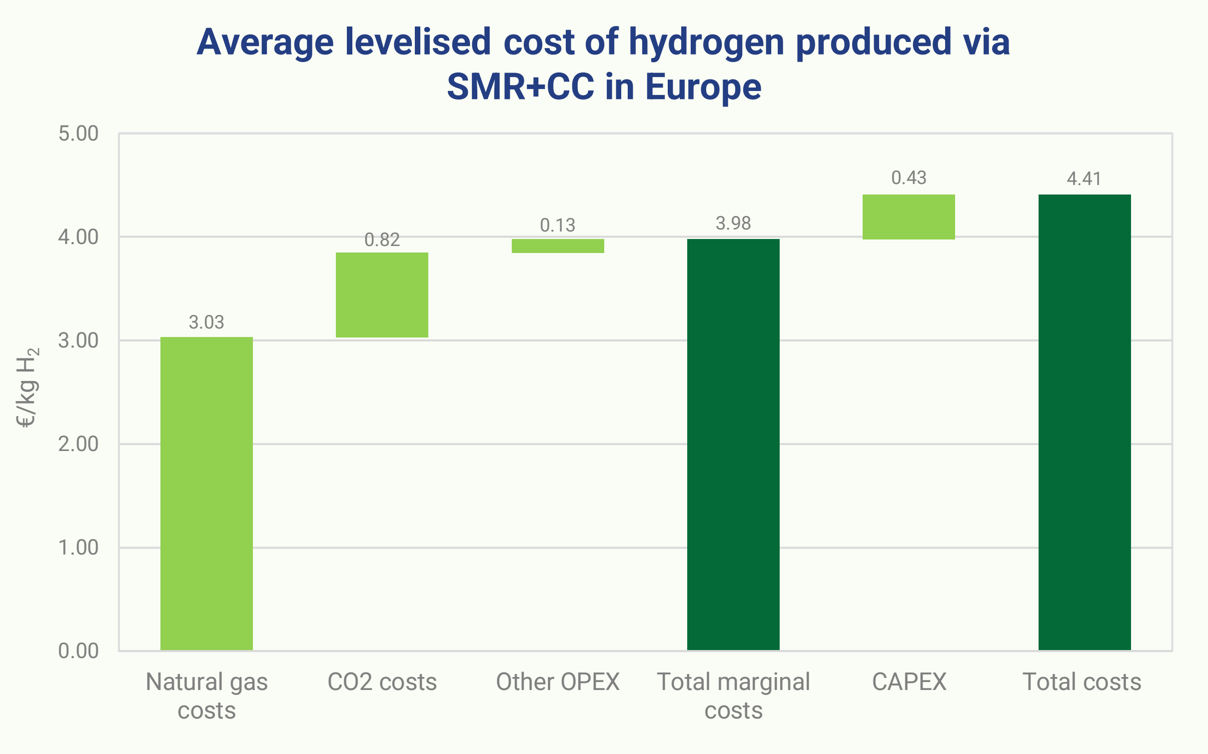

Figure 47. Average levelised cost of hydrogen produced via SMR+CC in Europe (€/kg H_2) in 2023.

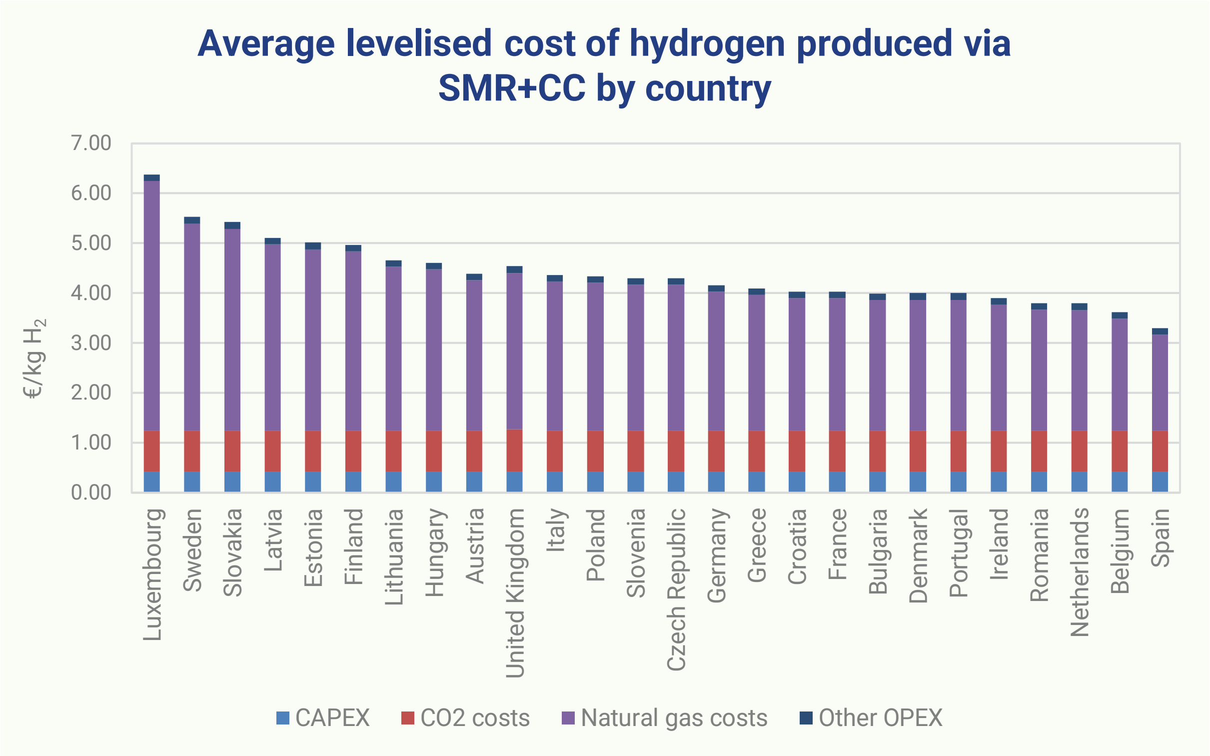

Figure 48. Average levelised cost of hydrogen produced via SMR+CC (in €/kg H_2) by country in 2023.

4.2.3.

Grid electrolysis

The average levelised cost of hydrogen production via grid-connected electrolysis in Europe stands at 7.94 €/kg H_2 a decrease of 1.91 €/kg H_2 compared to 2022. Marginal costs, which include wholesale electricity costs, other OPEX and grid fees and taxes account for 65.2% of the total costs (5.18 €/kg H_2), while the remaining 34.8% is attributed to CAPEX (2.76 €/kg H_2). Compared to 2022, the proportion of marginal costs in the total cost of hydrogen production via grid electolysis has decreased by 22.7%.

Hydrogen production costs via grid-connected electrolysis by European country in 2023 (in €/kg H_2) is presented in Figure 50. The production costs of hydrogen using grid electricity shows variations across European countries. Cyprus reports the highest cost at 17.36 €/kg H_2, followed by Poland Italy and Hungary, with costs of 12.35 €/kg H_2, 10.10 €/kg H_2 and 10.01 €/kg H_2, respectively.

In contrast, Sweden and Finland offer the lowest hydrogen production costs using grid electricity, at 4.43 €/kg H_2 and 4.06 €/kg H_2, respectively. Electricity costs and taxes are key factors in the total production costs of water electrolysis using grid electricity. In 2023, Bulgaria, Greece, Lithuania, and Portugal implemented favourable tax schemes in response to high energy prices, leading to lower overall costs.

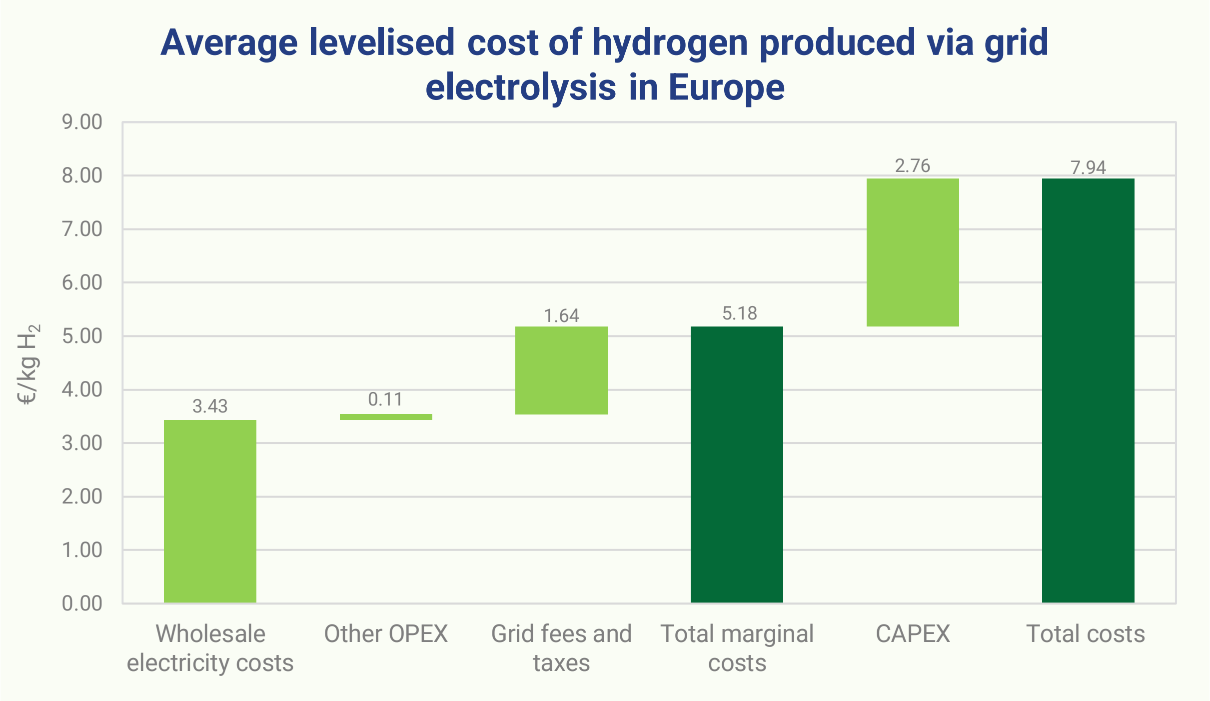

Figure 49. Average levelised cost of hydrogen produced via grid electrolysis (€/kg H2) in Europe in 2023.

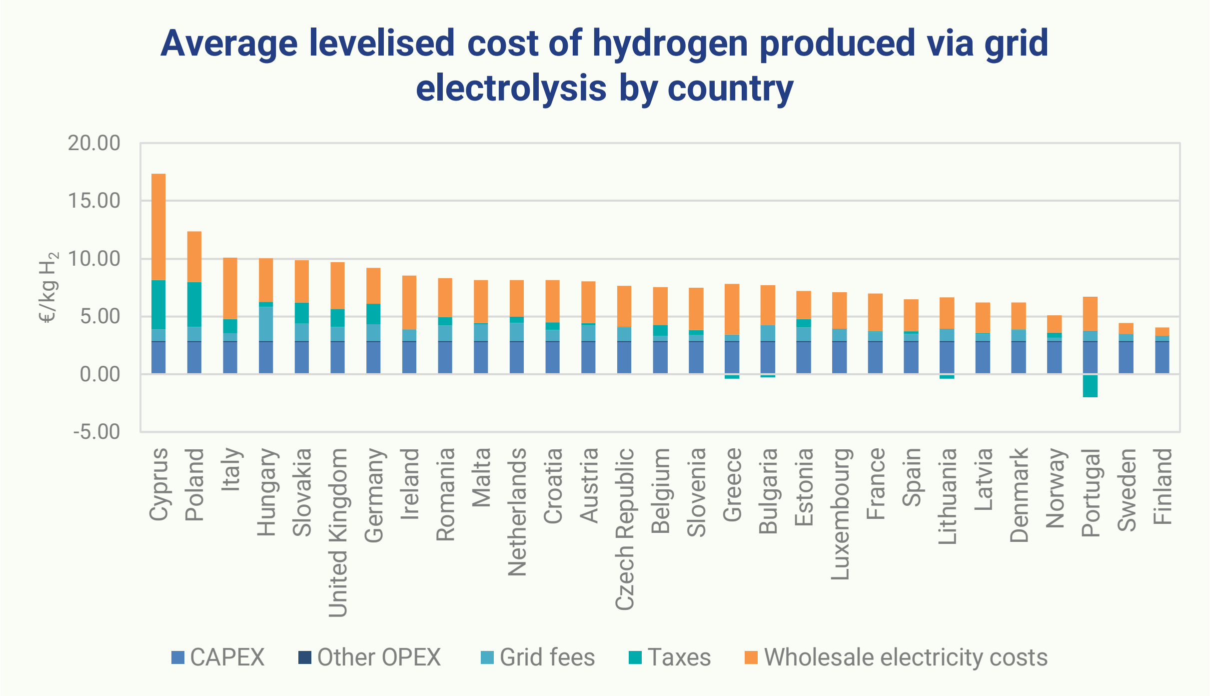

Figure 50. Average levelised cost of hydrogen produced via grid electrolysis (in €/kg H2) by country in 2023.

4.2.4.

Renewable hydrogen

The average levelised cost of renewable hydrogen production, through electrolysis using a direct connection to a renewable energy source, in Europe stands at 6.61 €/kg H_2, a decrease of 0.25 €/kg H2 compared to 2022. Figure 51 provides an overview of the cost components, showing that CAPEX is the largest contributor, representing 57% of the total cost. Marginal costs make up the second-largest share at 43%, with electricity costs being the dominant factor within marginal costs, accounting for approximately 40%. Compared to 2022, the proportion of CAPEX in the total cost of renewable hydrogen production has decreased by 10%.

The average levelised cost of renewable hydrogen falls in 2023 below the price of hydrogen produced via grid electrolysis (7.94 €/kg H_2), even despite a larger contribution of CAPEX costs due to a lower capacity factor of the electrolysis device. The main reasons for this are the high grid electricity prices of 2023 that were impacted by the spike in natural gas prices, in addition to the reduction of grid costs when making a direct connection between the renewable electricity source and the electrolysis device.

The highest reported hydrogen production costs through electrolysis using a direct connection to a renewable energy source are observed in Luxembourg (see Figure 52), where costs reach 9.30 €/kg H_2. This is closely followed by Hungary, and Germany, with respective costs of 8.93 €/kg and 8.87 €/kg H_2.

Conversely, several countries demonstrate relatively low renewable hydrogen production costs. Norway and Ireland are the frontrunners in this regard, with costs of 4.28 €/kg H_2, and 4.13 €/kg H_2, respectively. CAPEX constitutes the largest cost for all the countries, except Belgium where electricity costs are the highest contributor.

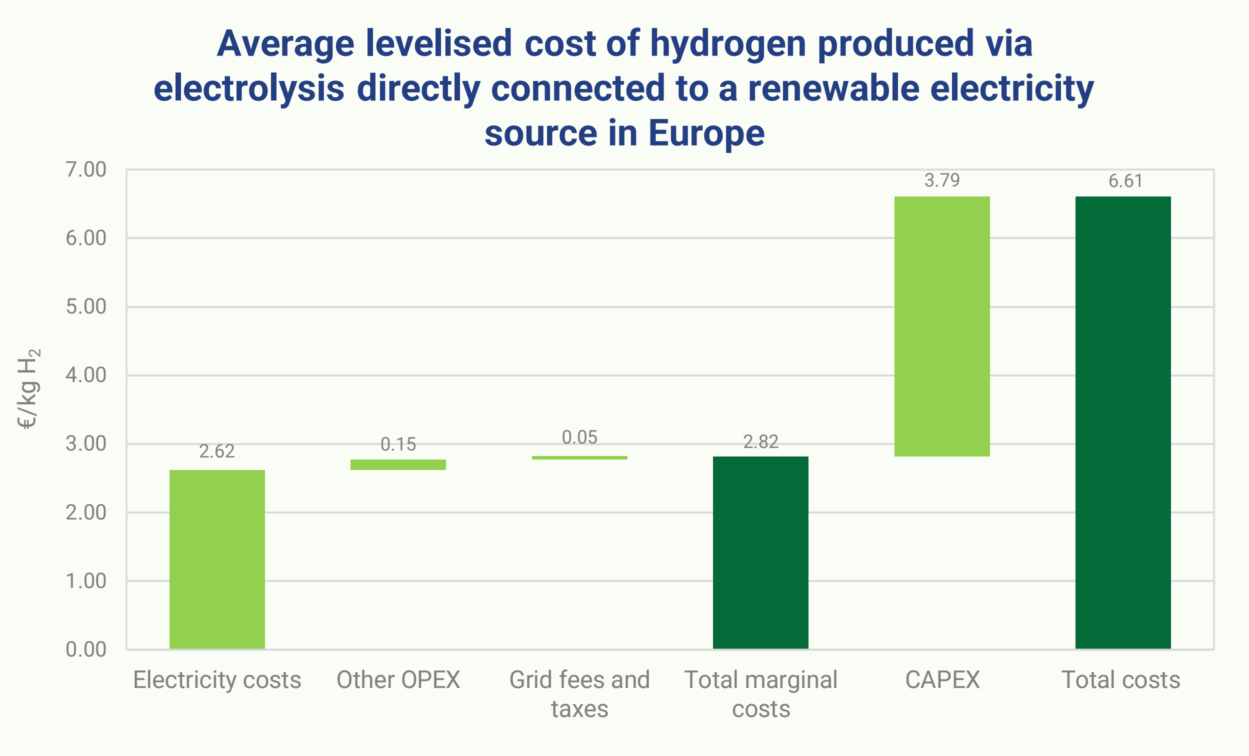

Figure 51. Average levelised cost of hydrogen produced via electrolysis directly connected to a renewable electricity source in Europe (€/kg H_2) in 2023.

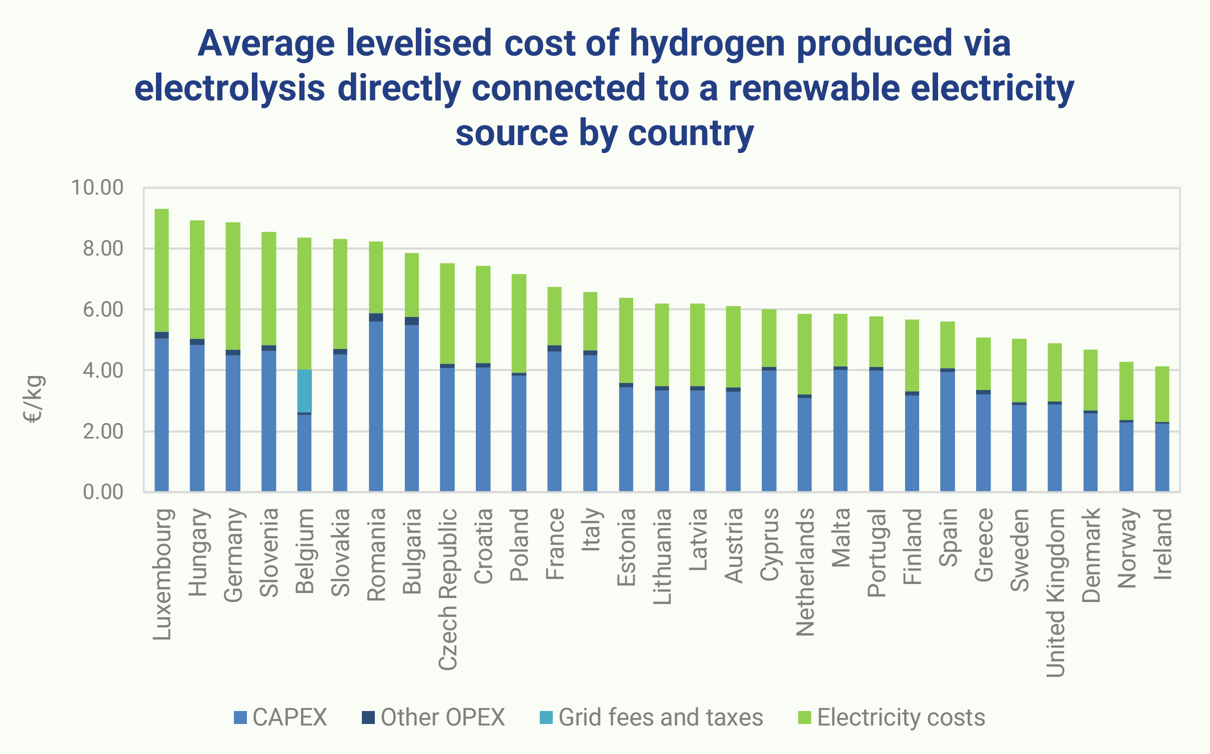

Figure 52. Average levelised cost of hydrogen produced via electrolysis directly connected to a renewable electricity source by country in 2023.

4.3.

Break-even prices for renewable hydrogen

This section presents the break-even price calculations for renewable hydrogen, which refers to the end-use price[11] of renewable hydrogen[12] at which its use, with the corresponding hydrogen end-use technology, reaches cost parity with the fossil fuel benchmark[13]. This assessment was done for a selection of four end-uses: oil refining, primary steel production, heavy-duty trucks and maritime applications. The explanations of the fossil fuel benchmarks are presented in Table 3. All break-even prices are calculated with 2023 numbers.

Based on the 2023 energy prices, the switch to clean hydrogen in oil refining production activities becomes economically competitive in Europe with natural gas-based hydrogen (SMR) as soon as clean hydrogen is available to the off-taker at a price range of 2.7 – 5.6 €/kg (see Figure 53), depending on the country. Correspondingly, the break-even prices for renewable hydrogen adoption in other sectors are as follows: primary steel making at 4.7 €/kg, maritime applications at 1.5 – 2.7 €/kg and heavy-duty trucks at 2.4 – 5.8 €/kg. In 2022, clean hydrogen became competitive at a higher price range for oil refining (€3.9 to €8.1 per kg) and lower for steel making (€3.0 per kg) and maritime applications (€1.2 to €2.2 per kg).

Excluding steel production, where a single value represents the entire EU27, EFTA, and UK, the break-even prices for the remaining three applications are presented in ranges. The subsequent sections provide further explanation on these ranges. A comprehensive list of assumptions for estimating these break-even hydrogen prices is provided in Appendix A2 by end-use. The analysis made for primary steel making is in line with the steel from solar energy report of Hydrogen Europe[14].

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[11] Refers to the cost incurred by the final off-taker, which includes all costs associated with the hydrogen supply chain (i.e., hydrogen production, transportation, distribution and storage).

[12] The assumed renewable hydrogen production process is low-temperature water electrolysis.

[13] Refers to the fossil-based fuel and technology that are most commonly used in the selected end-use applications.

[14] https://hydrogeneurope.eu/wp-content/uploads/2022/06/Steel_from_Solar_Energy_Report_05-2022_DIGITAL.pdf

Table 4. Explanation of the fossil fuel benchmark.

Oil refining	Use of hydrogen as feedstock produced in SMR with natural gas as input
Heavy-duty trucks	Use of diesel in internal combustion engines for long-distance heavy-duty trucks
Primary steel making	Primary steel produced in a blast furnace with basic oxygen furnace with coking coal as the reducing agent
Maritime applications	Use of Very Low Sulfur Fuel Oil (VLSFO) in two or four stroke conventional marine combustion engines

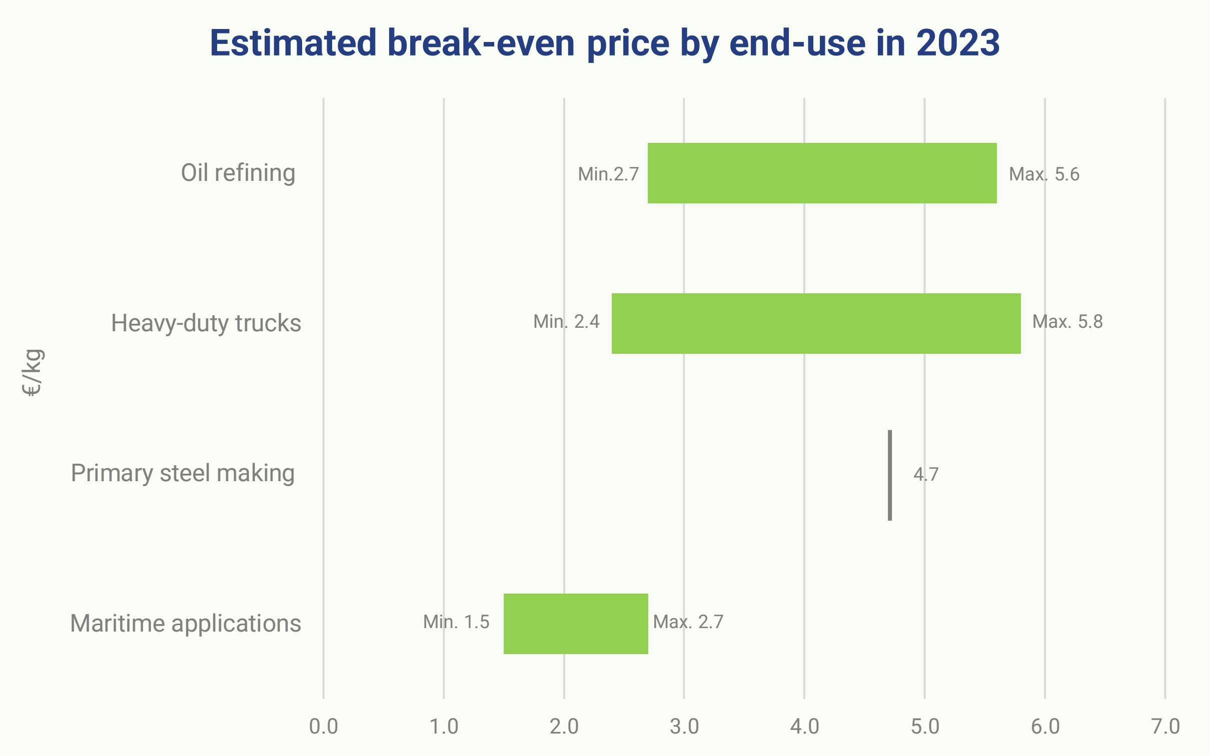

Figure 53. Estimated break-even hydrogen price by end use (€/kg).

4.3.1.

Oil refining

The estimated break-even hydrogen prices for oil refining activities were analysed on a national level for 2023, as illustrated in Figure 54. Among the countries examined, Luxemburg demonstrated the highest break-even price threshold at 5.6 €/kg for clean hydrogen to be economically competitive with natural gas-based hydrogen (SMR) in 2023. Sweden exhibited the second highest break-even price at 4.9 €/kg. In contrast, Belgium and Spain showcased the lowest break-even hydrogen prices for oil refining activities, with thresholds of 3.0 €/kg and 2.7 €/kg, respectively.

These findings highlight significant variations in the economic viability of adopting clean hydrogen in oil refining across different countries, which mainly depends on the natural gas price.

The estimated break-even hydrogen prices are a direct result of the cost of grey hydrogen produced from SMR (as shown in section 4.2.1) and the cost of steam production. Steam is a by-product of SMR that is being used in oil refining processes.

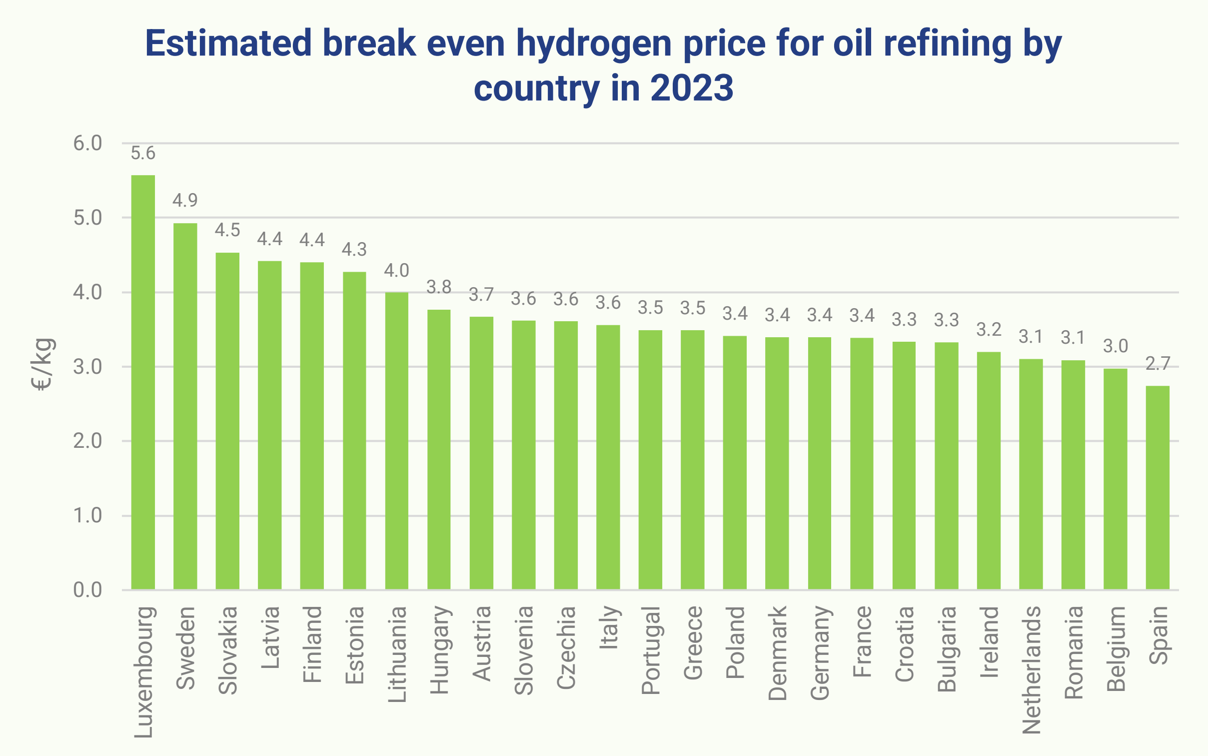

Figure 54.Estimated break-even hydrogen price for oil refining by country.

4.3.2.

Heavy-duty trucks

Figure 55 provides a comprehensive overview of the estimated break-even hydrogen prices for heavy-duty trucks at the national level in 2023. These prices are reflecting the maximum values for renewable hydrogen to be cost competitive with diesel at the pump (refuelling station) and the production point.

The price at the pump includes the costs of fuel conditioning (compression), transportation and refuelling infrastructure, which was estimated at a combined level of 3.26 €/kg. Most of the values required for the analysis were adopted from the JU Fuel Cells Hydrogen Trucks study from

December 2020[15] except for the 2023 energy prices (i.e. prices for the truck, powertrains, hydrogen tank, other equipment, maintenance, taxes and insurance, as well as fuel conditioning, fuel transportation costs and refuelling infrastructure).

Sweden and Finland emerged with the highest break-even prices among European countries at the pump, standing at 5.8 €/kg and 5.4 €/kg, respectively. Conversely, Poland and Malta exhibited the lowest break-even hydrogen prices for heavy-duty trucks, with thresholds at 3.0 €/kg and 2.4 €/kg, respectively. The country differences are mainly a result of the diesel prices.

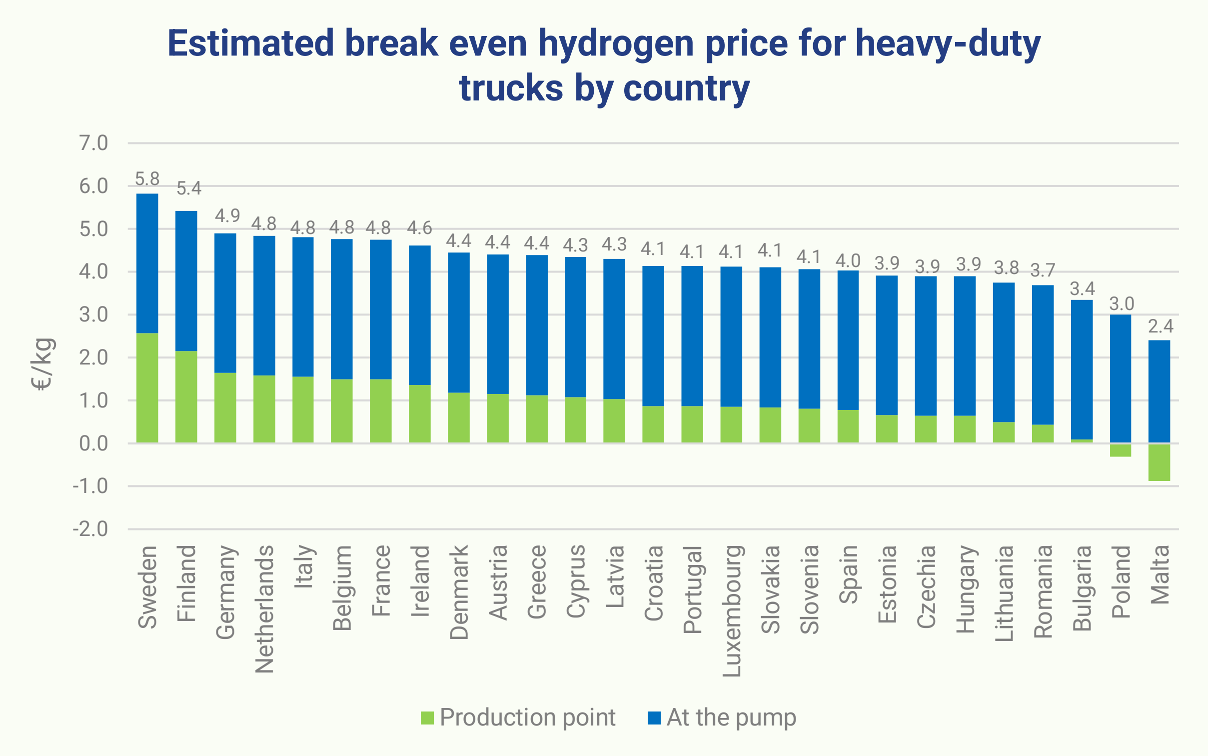

Figure 55. Estimated break-even hydrogen price for heavy-duty trucks by country.

4.3.3.

Maritime applications

Figure 56 presents the estimated break-even hydrogen prices for different maritime applications in 2023. The key operational characteristics for the selected maritime applications are given in Table 4. The analysis follows the same approach as the techno-economic assessment of low-carbon hydrogen technologies for the decarbonisation of shipping

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[15] https://www.clean-hydrogen.europa.eu/media/publications/study-fuel-cells-hydrogen-trucks_en

report written by Hydrogen Europe[16]. The highest break-even hydrogen price is observed for a Ro-Pax ferry (20,000+ GT), with a price threshold for clean hydrogen adoption at 2.7 €/kg, while the lowest one was observed for a large intercontinental containership (12,000-20,000 TEU) with a threshold price of 1.5 €/kg. Correspondingly, the price thresholds for cruise ships (100,000-150,000 GT) and feeder containerships (1,000-1,999 TEU) are 2.3 and 2.5 €/kg, respectively.

Table 5. Assumed key operational characteristics for the selected maritime applications.

Ship type	**Size**	**Avg. DWT[17] (tonnes)**	**Avg. GT[18]**	**Avg. main engine power (kW)**	**Minimum fuel autonomy (NM[19])**
Container	1,000–1,999 TEU[20]	19.051	15.019	12,083	1,000
Container	14,500–19,999 TEU	179.871	177.304	60,202	11,500
Cruise	100,000–149,999 GT	10.935	123.801	67,456	4,000
Ferry – Ro-Pax[21]	20,000+ GT	6.364	31.985	28,255	200

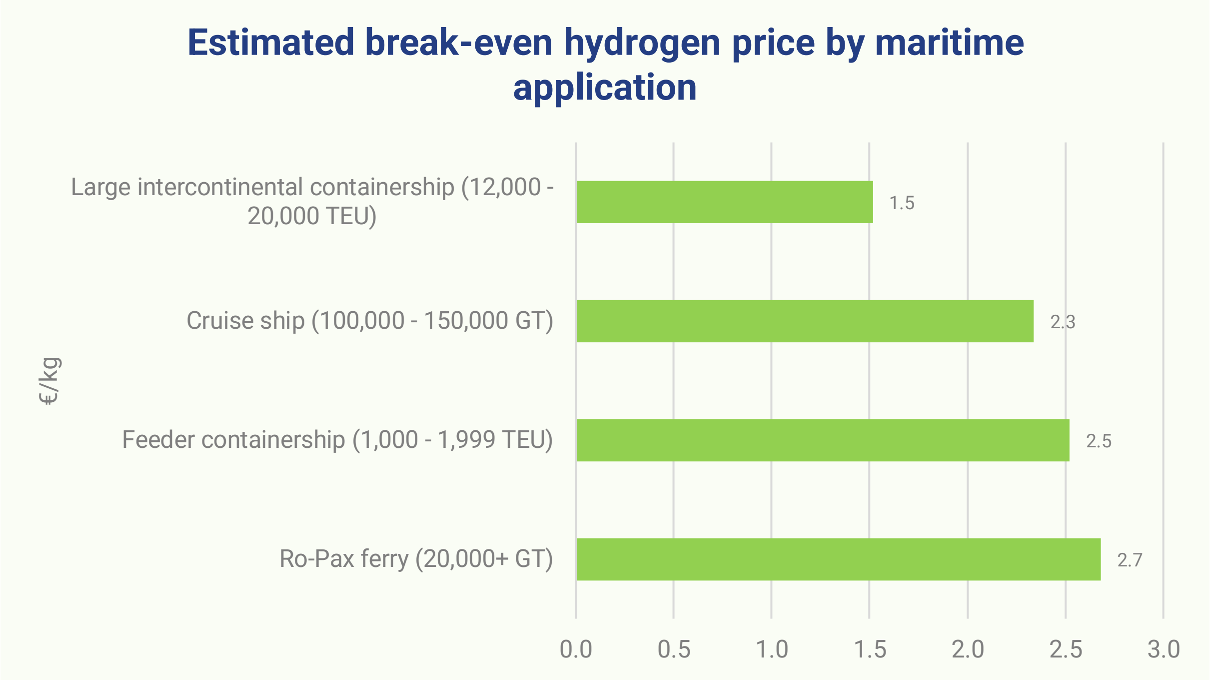

Figure 56.Estimated break-even hydrogen price by maritime application.

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[16] https://hydrogeneurope.eu/wp-content/uploads/2023/11/Maritime-Technical-Paper_Final_HRreduced-vd3ygb.pdf

[17] Deadweight tonnage or tons deadweight (DWT) is a measure of how much weight a ship can carry.

[18] Gross tonnage (GT) is a nonlinear measure of a ship's overall internal volume.

[19] The nautical mile (M, NM or nmi), a unit of length, that is approx. one minute of arc measured along any meridian.

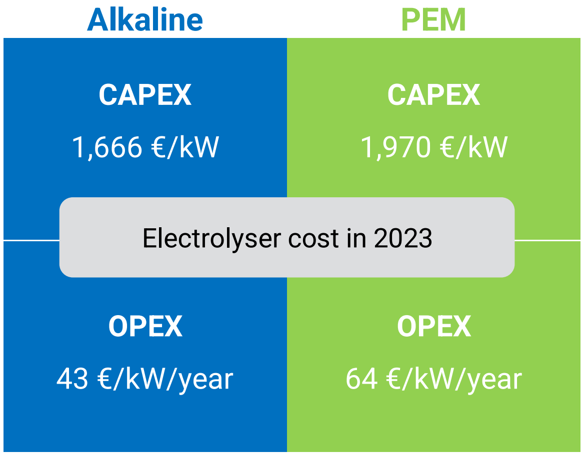
[20] A TEU (twenty-foot equivalent unit) is a measure of volume in units of twenty-foot-long containers.

[21] A ropax ferry (Ro-Pax) combines the features of a cruise ship and night cabins with a roll-on/roll-off ferry.

4.4.

Electrolyser cost

Figure 57 gives an overview of the electrolyser cost, encompassing both capital expenditure (CAPEX) and operational expenditure (OPEX), focusing on two distinct technologies: alkaline and proton exchange membrane (PEM).



	Alkaline	PEM
CAPEX	1,666 €/kW	1,970 €/kW
OPEX	43 €/kW/year	64 €/kW/year

Electrolyser cost in 2023

Figure 57. Total electrolyser cost by technology in 2023

In 2023, the cost assessment of electrolyser technologies in Europe reveals distinct financial profiles. The alkaline electrolyser is estimated to have a Capital Expenditure (CAPEX) of 1,666 €/kW and an Operational Expenditure (OPEX) of 43 €/kW/year. In contrast, the PEM electrolyser demonstrates a comparatively higher cost structure, with an estimated CAPEX of 1,970 €/kW and OPEX of 64 €/kW/year.

In Figure 58, the electrolyser CAPEX cost for the two technologies is divided into three categories including stack, balance of plant (BoP) and other Engineering, Procurement, and Construction costs (Other EPC). The components of these categories are detailed in Table 5.

The total alkaline water electrolyser CAPEX cost in Europe in 2023 is split between 408 €/kW for the stack, 686 €/kW for BoP and 572 €/kW for other EPC. For PEM technologies, the total CAPEX cost is split between 732 €/kW for the stack, 464 €/kW for BoP and 774 €/kW for other EPC. PEM technologies were reported to have a higher CAPEX for the stack and the other EPC, while alkaline technologies had higher CAPEX for the BoP.

Table 6. Explanation of CAPEX categories.

Stack	The stack cost includes all the electrolysis cells and their respective components.
Balance of plant (BoP)	The balance of plant cost includes rectifier, transformer directly connected with the rectifier, gas/liquid separation, water/lye feeding, gas purification, water cooling, water purification, control system and other equipment such as gas container and compressor.
Engineering, Procurement and Construction costs (Other EPC)	The other EPC cost includes equipment installation; civil engineering; project design, procurement, and management; product shipping; and housing at construction site.

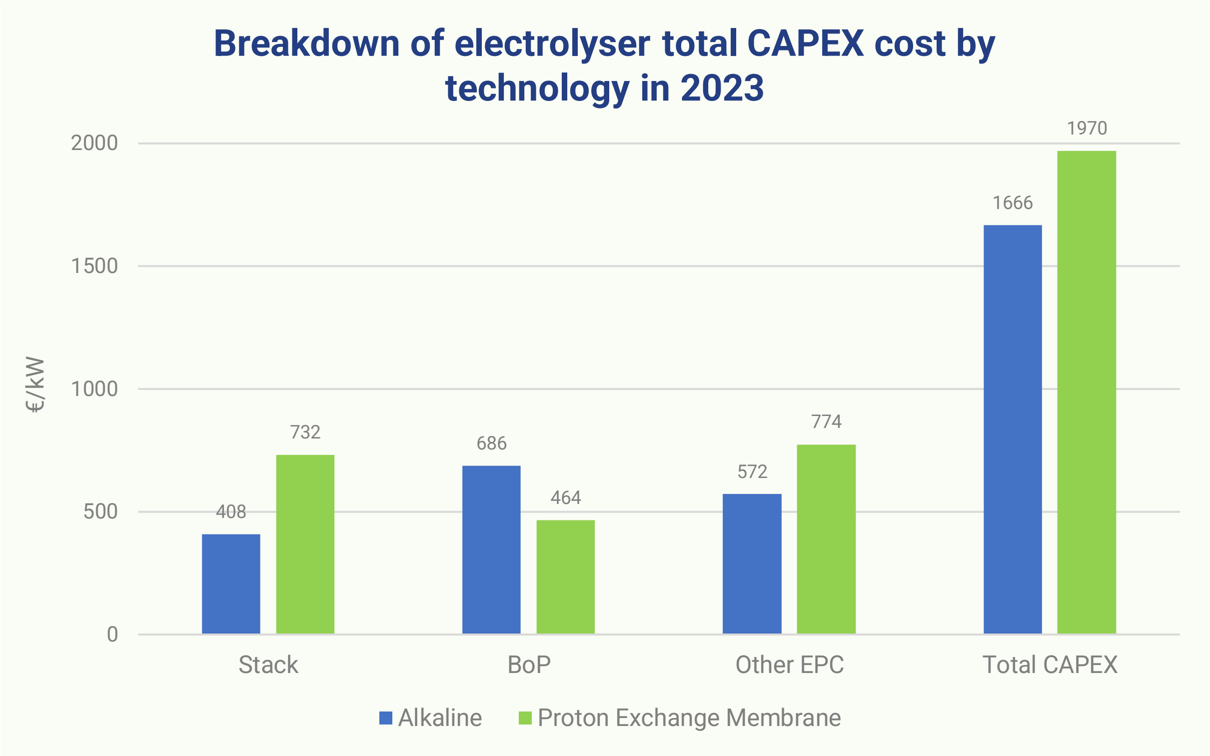


Figure 58. Breakdown of electrolyser total CAPEX cost (€/kW) by technology in 2023.

05

Technologies manufacturing

Introduction

This chapter explores data on European electrolyser manufacturing capacity and electrolyser sales, as well as the European fuel cell deployment.

Electrolyser manufacturing capacity is given in GW for EU27, EFTA and UK based manufacturing facilities. Results are presented by technology and broken down into operational capacity and capacity already under construction or for which a final investment decision (FID) has already been made. Results for planned facilities therefore only include projects whose realization is highly certain in 2024, 2025 and 2026.

The data have been gathered from public sources and verified with companies where appropriate, reflecting the situation as of May 2024. The capacity is the maximum manufacturing capacity on a yearly basis and does not represent the current or future electrolyser production.

Electrolyser sales is given in MW by technology from European electrolyser manufacturers located in EU27, EFTA, and UK. Data has been gathered from public sources.

Moreover, a condensed overview of the European fuel cell deployment is presented in this chapter. Historical data are presented from 2014 – 2022, both in numbers of shipment units and total system megawatts, originating from the ERM Fuel Cell Industry Review 2022.

For a more detailed analysis of the global fuel cell market statistics, we refer to Appendix A.1. This appendix provides fuel cell data by application, fuel cell type and region of integration.

Interactive data dashboards and downloadable spreadsheets on electrolysers manufacturing & sales, and fuel cells can be accessed on the European Hydrogen Observatory website.

5.1.

Electrolyser manufacturing capacity

Current and planned water electrolyser manufacturing capacity in the European countries by 2025 (in GW/year) are presented in Figure 59. By the end of 2024, it is expected that the total water electrolyser manufacturing capacity in Europe will grow to 8.8 GW/year. The operational capacity stands at 5.4 GW/year in May 2024, which increased with 2.29 GW/year compared to May 2023.

By 2026, looking only at projects already under construction or with a final investment decision, the additions will bring total electrolyser manufacturing capacity to 10.5 GW/year.

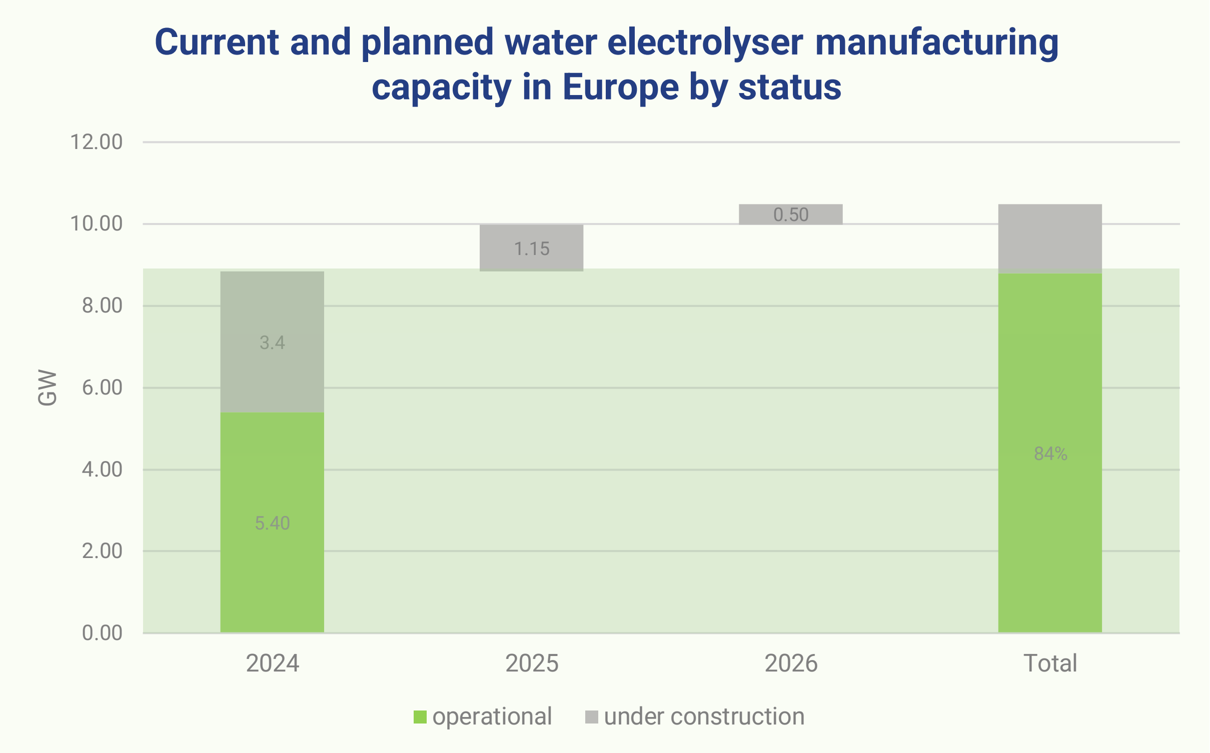


Figure 59. Current and planned water electrolyser manufacturing capacity in the European countries by status.

A breakdown of current and planned water electrolyser manufacturing capacity by technology type in the European countries (in GW/year) is presented in Figure 60.

At the end of 2024, it is expected that alkaline technologies will account for 46% (or 4.09 GW/year) of total operational electrolyser manufacturing capacity in Europe. PEM technologies will represent roughly 53% or 4.70 GW/year. Combined, SO and AEM technologies will represent less than 1% of the total operational electrolyser manufacturing capacity in Europe or 0.04 GW/year.

In 2026, assuming that all projects to increase water electrolyser production capacity materialize, PEM water electrolyser manufacturing capacity would account for 45% of total operational water electrolyser manufacturing capacity in Europe, still 4.70 GW/year. Alkaline technologies would follow closely with 44% or 4.59 GW/year. SO and AEM technologies would represent respectively 8% and 3% or 0.86 GW/year and 0.33 GW/year, representing a significant increase from these technologies' current marginal market share.

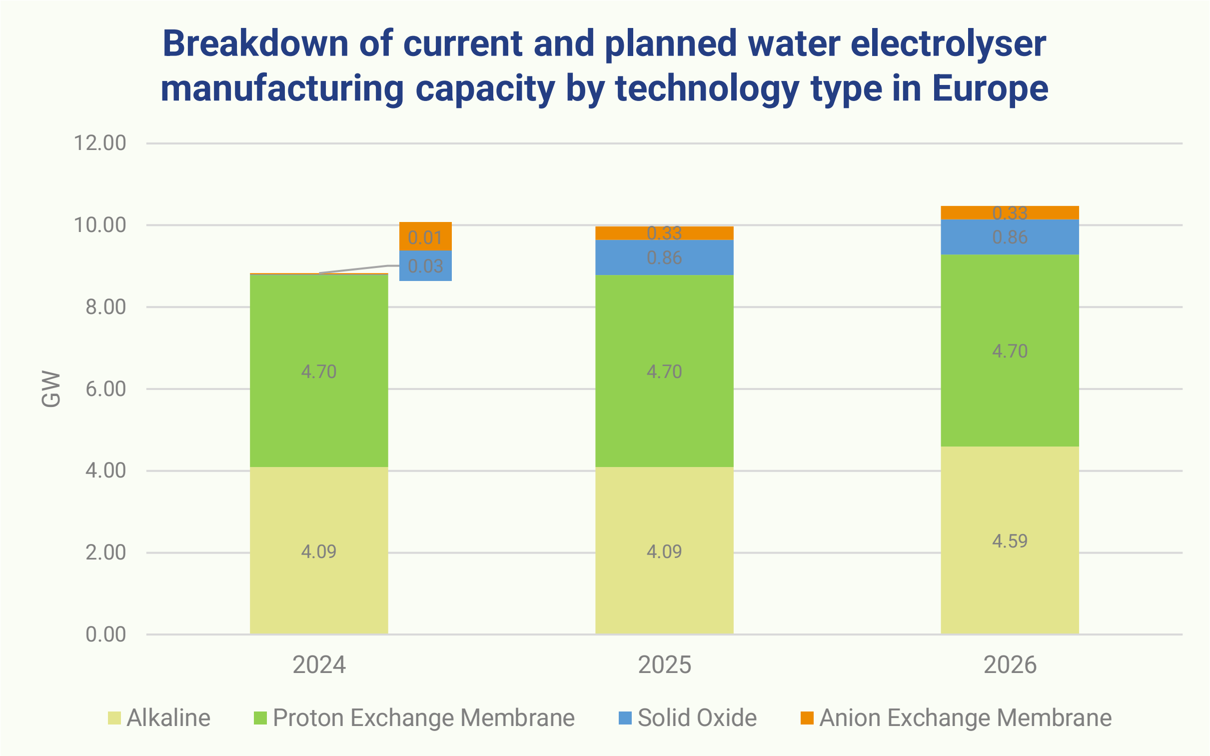


Figure 60. Breakdown of current and planned water electrolyser manufacturing capacity by technology type in the European countries (in GW/year).

5.2.

Electrolyser sales

Annual electrolyser sales in MW by technology from facilities in EU27, EFTA and UK countries are presented in Figure 61.

Approximately 65 MW of water electrolysers were sold by European water electrolyser manufacturers in 2023, a slight increase compared to 2022 (+5%). Technological breakdown of water electrolyser sales shows that alkaline technologies accounted for 43% of total sales or 28.2 MW, while PEM technologies represented 36% of total sales or 23.5 MW. Most of the remaining sales originated from projects where the electrolyser technology is unknown, amounting to 10.5 MW. SO water electrolyser sales accounted for less than 5% or 2.85 MW.

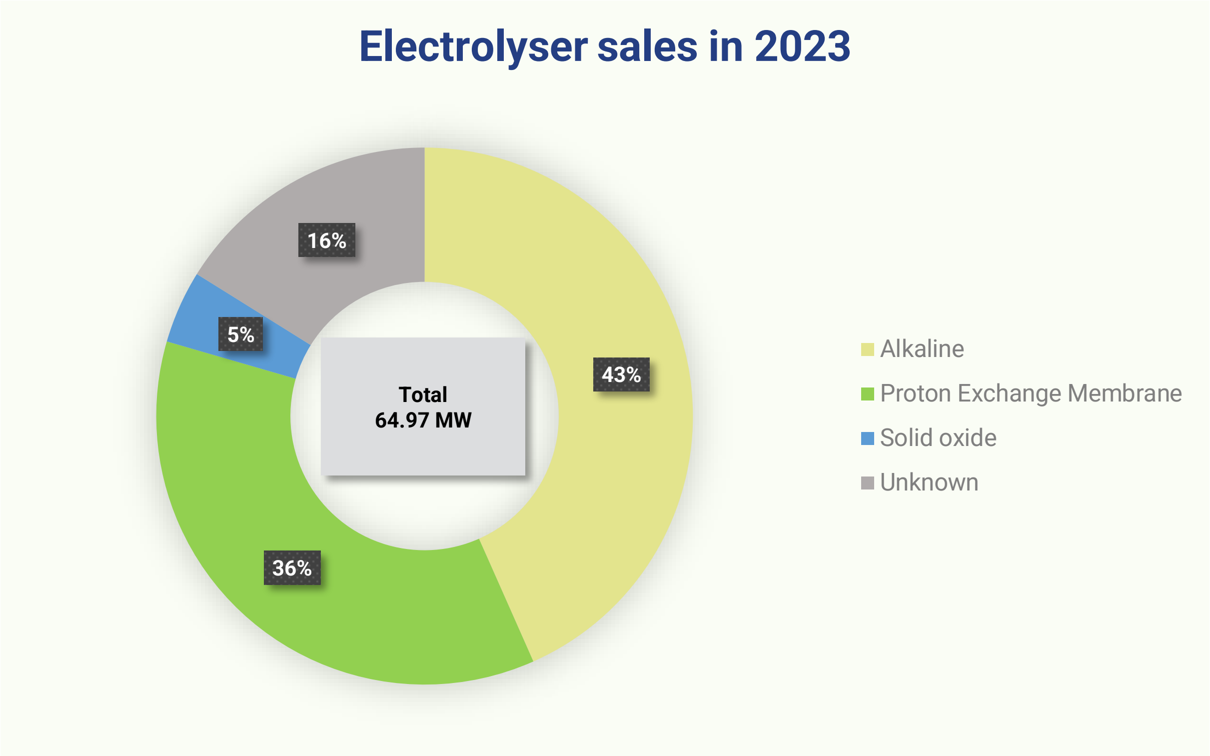


Figure 61. Electrolyser sales by European manufactures by technology in 2023.

5.3.

Fuel cells market

Fuel cell deployment in Europe has showed an increasing trend over the past decade, as can be observed in Figure 62 (number of shipments) and Figure 63 (total capacity). Despite an observed decrease in fuel cell shipments after 2015, a consistent and progressive increase was recorded from 2016 through the end of 2021, reaching approximately 14,000 units. This was followed by a slight decline in 2022, with shipments dropping to around 13,200 units.

The total capacity of fuel cells deployment, had a faster growth from 2014 onwards, compared to the number of shipments, going from 9.9 MW to 228.1 MW in 2022. The capacity of the shipped fuel cells is thus increasing, growing from 1.77 kW/unit to 17.28 kW/unit. The most significant increase in capacity occurred between 2018 and 2022, an addition of 186.9 MW in 4 years of time.

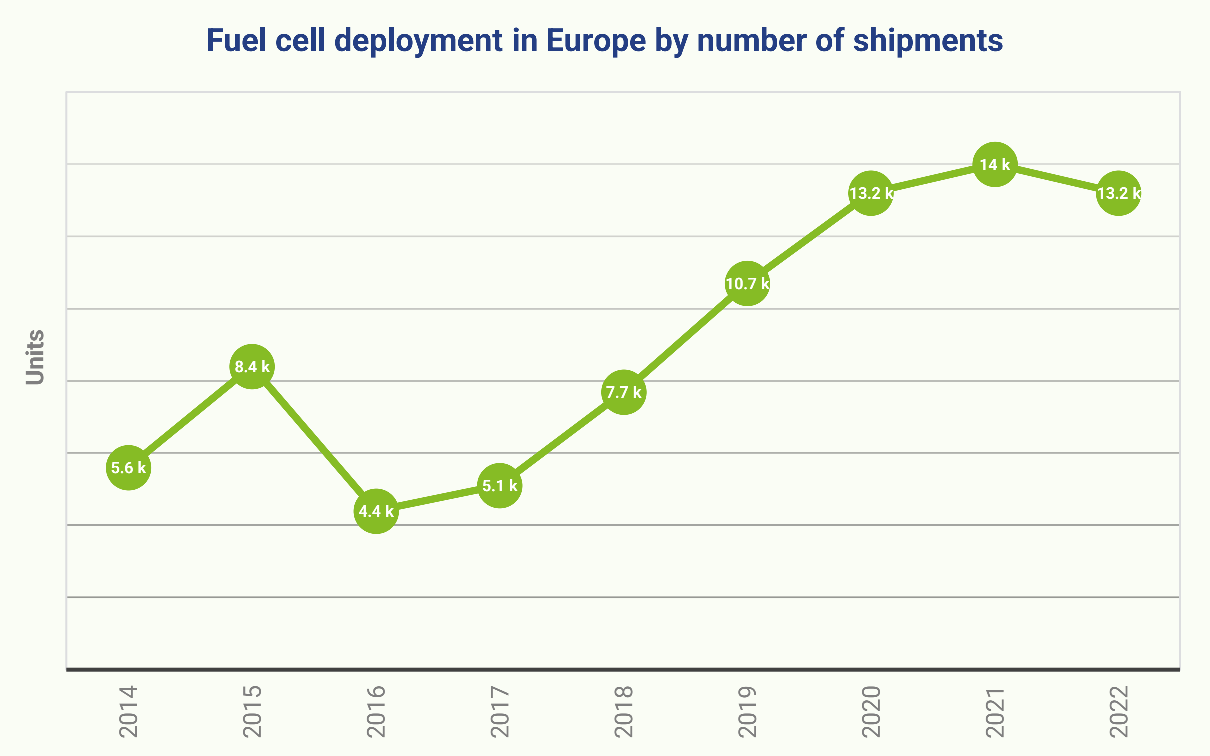


Figure 62. Fuel cell deployment in Europe by number of shipments.

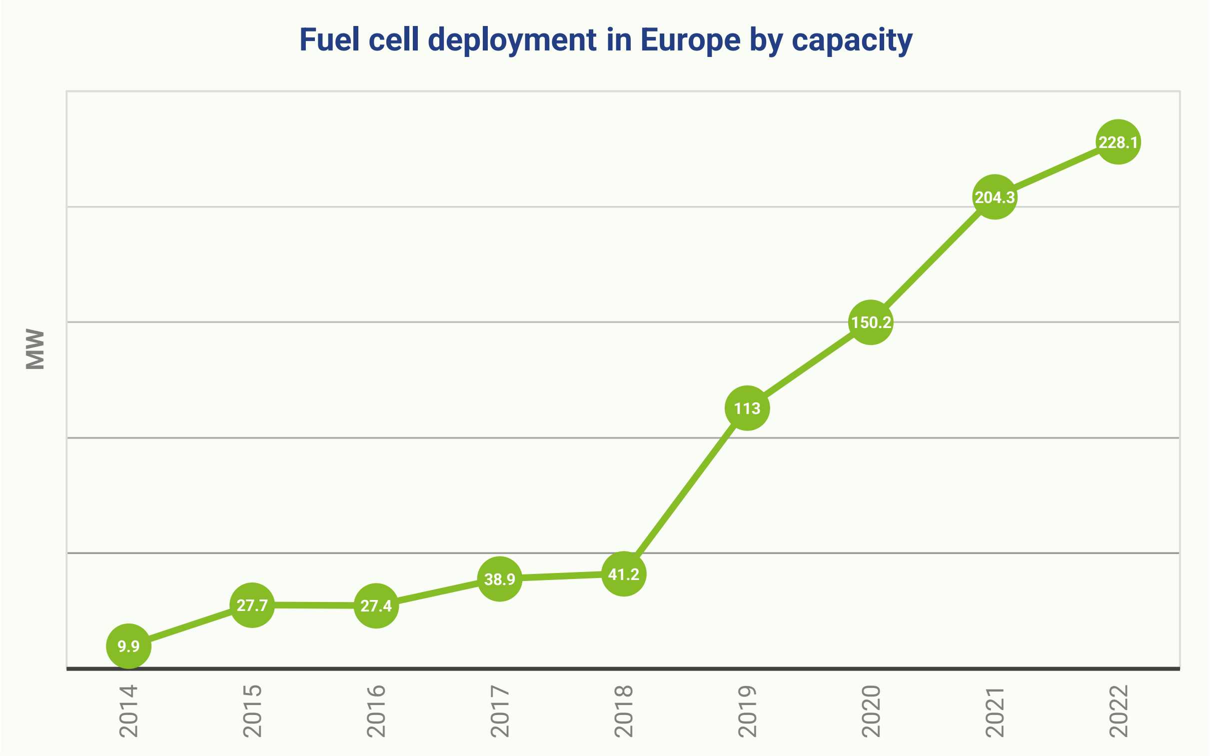


Figure 63. Fuel cell deployment in Europe by capacity.

Conclusions

The purpose of this report is to provide an overview on the latest statistics covering the entire value chain of the European hydrogen market.

Compared to the previous report that analysed the hydrogen market in 2022, the hydrogen production capacity in 2023 remained almost constant compared to 2022 (-1%), with Germany, the Netherlands, Poland, Italy, and France still dominating, representing 50% of Europe's total hydrogen production capacity. In terms of green hydrogen production, as of end of 2023, 44 extra water electrolysis hydrogen production and consumption projects became operational, bringing the total to 141 projects in Europe (88 with a minimum capacity of 0.5 MW). These additions increased the total production capacity by 88.11 MW, reaching 258.39 MW in 2023. When looking at the expected capacity increase of water electrolysis projects that are currently under construction, an even higher raise should follow in the coming years, reaching 2,115 MW by 2026. European electrolyser manufacturers could meet this demand, as they are expected to reach a capacity of 9.99 GW/year by 2025 and 10.49 GW/year by 2026. In 2023, European manufacturers sold approximately 62 MW of water electrolysers, a slight increase compared to 2022 (+5%), with alkaline and PEM technologies making up 43% and 36% of total sales respectively. No significant increase in the number of plants that produce hydrogen from reforming with carbon capture was yet observed, that remained at three.

In terms of hydrogen production capacity allocation, facilities earmarked for on-site captive consumption continued to dominate with the highest share, increased by 1% compared to 2022. Despite the prevailing dominance of captive hydrogen production within Europe, it's noteworthy that thousands of metric tonnes of hydrogen are already being traded and distributed across the continent. These transfers often occur through dedicated hydrogen pipelines or transportation via trucks. In 2023, the total hydrogen traded decreased by 13% compared to 2022, totalling 29,767 tonnes, while the hydrogen flow from Belgium to Netherlands remained the single biggest flow to and between European countries. Belgium and Netherlands remained Europe's leading hydrogen exporter (71% of total exports) and importer (66% of total imports) respectively.

This fast increase in clean hydrogen production is important to meet climate objectives with the aim of decarbonizing the entire hydrogen sector, in addition to supplying hydrogen to many new emerging applications. Based on an average of many different hydrogen demand forecast studies, it is expected that hydrogen demand in Europe could increase from 7.9 Mt in 2023 to 45.5 Mt by 2050.

In 2023, clean hydrogen consumption equalled approx. 27 kt in Europe, an increase of 7 kt from

2022, accounting for 0.34% of the total hydrogen demand. Clean hydrogen consumption was mainly serving new emerging applications, such as mobility, blending with natural gas in pipelines and production of steel. As for mobility, the number of fuel cell electric vehicles is constantly growing, with a 7% increase from 2022 reaching 5,939 vehicles in 2023. To meet this hydrogen demand, the number of operational and publicly accessible hydrogen refuelling stations is also increasing, amounting 187 by summer 2024, showing a 5% increase compared to the summer of 2023. Moreover, more dispensers (+9%) serving both buses and track are available in 2023 in the HRS.

An important element for clean hydrogen production to break through is cost competitiveness. In 2023, the LCOH of renewable hydrogen reached €6.61/kg H_2, reflecting a slight reduction of €0.25/kg H_2 from 2022, where the LCOH stood at 6.86€/kg H_2. Interestingly, in 2022, the cost of hydrogen produced via SMR was €6.23/kg H_2, making it almost comparable with renewable hydrogen. By 2023, the SMR cost decreased sharply to 3.76 €/kg H_2, nearly halving compared to the previous year. This significant reduction can be attributed to the stabilization of energy prices, particularly natural gas, which had spiked dramatically in 2022 due to the combined effects of the COVID-19 pandemic and the geopolitical consequences of the war in Ukraine.

The higher natural gas prices in 2022 also influenced the break-even point for renewable hydrogen in oil refining. In that year, renewable hydrogen would become economically viable at a price range of 3.9 €/kg to 8.1 €/kg, depending on the country. By 2023, with lower natural gas prices, this range decreased to 2.7 €/kg to 5.6 €/kg, decreasing the cost competitiveness of renewable hydrogen.

Appendix

A.1.

Global fuel cells market

This appendix presents the global data of the fuel cell market that is available on the European Hydrogen Observatory website. As referred to in chapter 5, the dataset is originating from the ERM Fuel Cell Industry Review.

Figure A.1.1. provides a visual representation of the trend in the total number of shipped fuel cells and the total capacity of fuel cells (in MW) from 2014 to 2022. In 2014, the total number of shipped fuel cells stood at around 64,000 units.

From 2014 to 2016, there was a slight decrease, resulting in a total of over 63,000 fuel cells in 2016. Subsequently, there was a consistent and progressive increase in the total number of fuel cells, reaching around 89,000 by the end of 2022. The total capacity of fuel cells, however, exhibited a consistent growth from 2014 onwards, going from 185 MW to 2,492 MW in 2022. The capacity of the shipped fuel cells is thus increasing, growing from 2.9 kW/unit to 27.9 kW/unit. The most significant increase in capacity occurred between 2020 and 2021, being a remarkable addition of 979 MW to the total fuel cell capacity, which is a 73% increase.

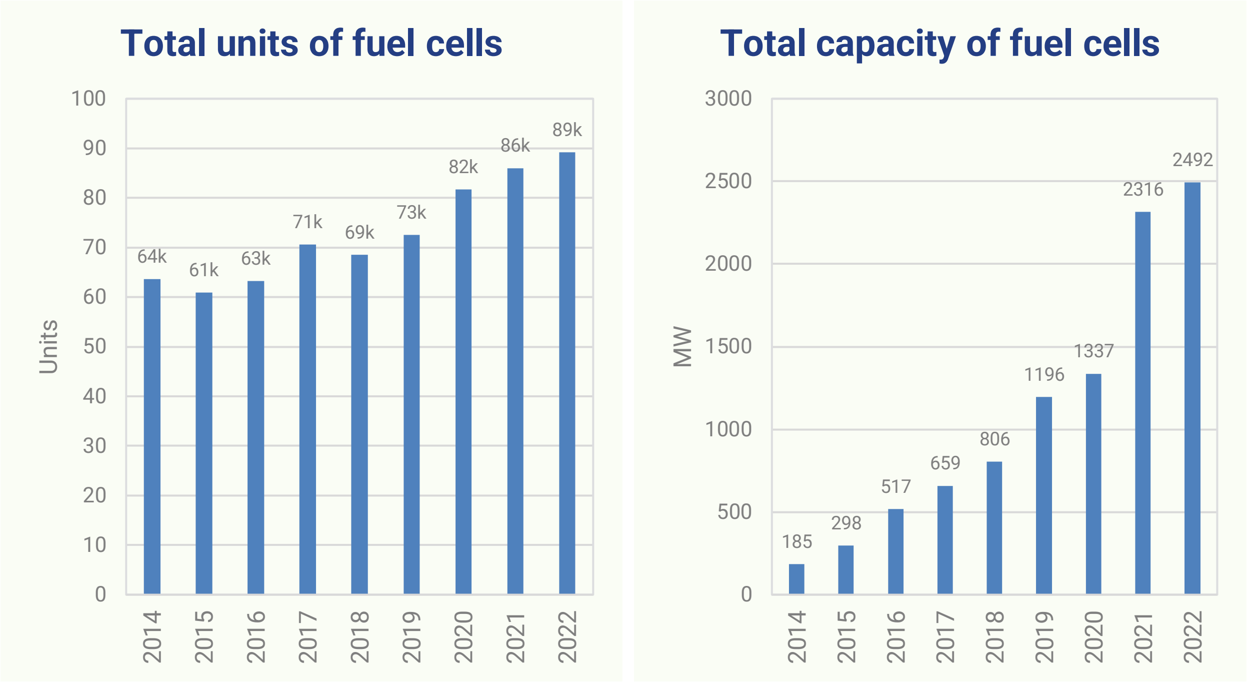


Figure A.1.1. Total units and capacity of fuel cells globally during the period 2014-2022.

A.1.1.

Shipments by application

Figure A.1.2. provides a visual representation of the distribution of fuel cell shipments in terms of the total number of units and the total capacity (in MW) by application from 2014 to 2022.

The dominant application category among shipped fuel cell systems, in terms of units, was stationary fuel cells, accounting for the largest share of total shipments. However, since 2014, there has been a slight decrease in their share of total shipments. In 2014, stationary fuel cells represented 62% of the total shipments, which decreased to 57% in 2022. A similar trend was observed in portable fuel cells, where there was a continuous decline in their share of total shipments. In 2014, portable fuel cells represented 33% of the total shipments, but this percentage decreased to 9% by 2022. In contrast, fuel cells designed for transportation purposes exhibited a notable increase over the years. In 2014, they represented only 5% of the total shipments, but this figure rose significantly to 34% by 2022.

In terms of total capacity, it's worth noting that fuel cells for stationary applications took the lead in 2014, representing a substantial 80% of the total share. However, over the years, there was a significant decline in their share, dropping to a mere 15% by 2022. Conversely, transport-oriented fuel cells accounted for a relatively small share in 2014, representing only 20% of the total capacity. However, they experienced remarkable growth throughout the years and, by 2022, had taken the lead, representing an impressive 85% of the total capacity of fuel cells. In contrast, fuel cells for portable applications remained at consistently low levels throughout the years, accounting for less than 1% of the total capacity.

This data highlights the dynamic shifts in the distribution of total capacity across different fuel cell applications, with transport-oriented fuel cells emerging as the dominant category by 2022.

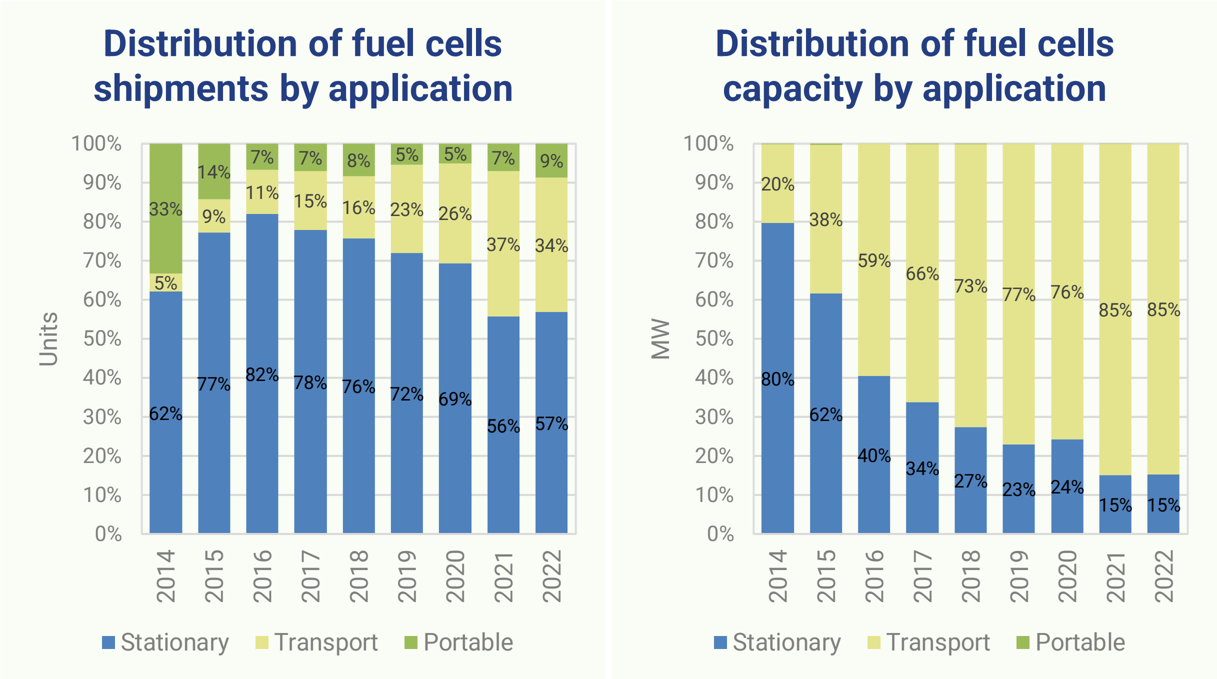


Figure A.1.2. Distribution of fuel cell shipments in terms of the total number of units and the total capacity (in MW) by application in Europe from 2014 to 2022.

The explanation of the different categories of fuel cell systems based on their intended application is presented in Table A.1.1.

Table A.1.1. Outline of the terminology employed in this chapter to describe different categories of fuel cell systems based on their intended application.

Portable	Portable fuel cells are designed to be small, lightweight, and easily transportable. They can be used in applications where mobility is essential, such as powering portable electronic devices (e.g., laptops, smartphones, and cameras), portable generators, and even small vehicles like drones. Portable fuel cells often use hydrogen as a fuel source and can provide a convenient source of power in remote or off-grid locations. The main advantage is that they have a higher energy density compared to batteries.
Stationary	Stationary fuel cells are used to provide electricity and heat to stationary applications, such as homes, businesses, and industrial facilities. Stationary fuel cells are considered for distributed energy generation as a power source or for cogeneration applications since they can efficiently produce electricity and heat at the same time. Common types of stationary fuel cells include proton exchange membrane fuel cells (PEMFCs) and solid oxide fuel cells (SOFCs).
Transport	Transport fuel cells are fuel cell systems designed for use in vehicles, such as cars, buses, trucks, and even trains. They are part of the emerging hydrogen fuel cell vehicle technology, where hydrogen is used as a clean energy source to power electric motors in vehicles. Transport fuel cells are crucial in the development of hydrogen-powered transportation as an alternative to traditional internal combustion engines or battery electric vehicles (BEVs).

A.1.2.

Shipments by fuel cell type

Figure A.1.3. provides a visual representation of the distribution of fuel cell shipments in terms of the total number of units and the total capacity (in MW) by fuel cell type from 2014 to 2022.

The dominant category among fuel cell types, in terms of shipped units, was the proton exchange membrane fuel cell (PEMFC), accounting for the largest share. However, it's worth noting that its share compared to other fuel cell types exhibited a declining trend over the years. In 2014, PEMFCs represented a substantial 92% of the total shipments, but by 2022, this figure had decreased to 61%. Following closely behind were solid oxide fuel cells (SOFC), which, in contrast, increased their share in the total shipments. In 2014, SOFCs accounted for a mere 4% of the total shipments, but by 2022, their share had risen to 30%. Direct methanol fuel cells (DMFC) followed a similar pattern, with a slight increase in their share over the years. In 2014, DMFCs represented 4% of the total shipments, which grew to 9% in 2022. The remaining three types of fuel cells, namely phosphoric acid (PAFC), alkaline (AFC), and molten carbonate (MCFC) fuel cells, collectively constituted less than 1% of the total shipments. This data provides valuable insights into the changing landscape of fuel cell types in our shipments, with PEMFCs still dominating the market but showing a gradual decrease in shipments, while SOFCs and DMFCs are gaining ground.

When considering total capacity, PEMFC emerged as the dominant category, securing the largest share of the total capacity. Its share displayed a steady and significant increase since 2014, surging from a 39% share to an impressive 86% share in 2022. Conversely, SOFC experienced a substantial decrease in its share of the total capacity of fuel cells. In 2014, SOFC represented a 21% share, which dwindled to a mere 10% in 2022. A similar trend was observed for MCFC, which exhibited a considerable decline from a 38% share of the total capacity in 2014 to less than 2% in 2022. PAFC showed fluctuations in its share throughout the years, accounting for 2% in 2014, reaching a peak of 12% in 2017, and subsequently dropping to 2% in 2022.

This data underscores the dynamic shifts in the distribution of total capacity among different fuel cell types, with PEMFC leading the way, while SOFC, MCFC, and PAFC underwent varying trends in their respective shares over the years.

The explanation of the different fuel cell types discussed in this chapter is presented in Table A.1.2.

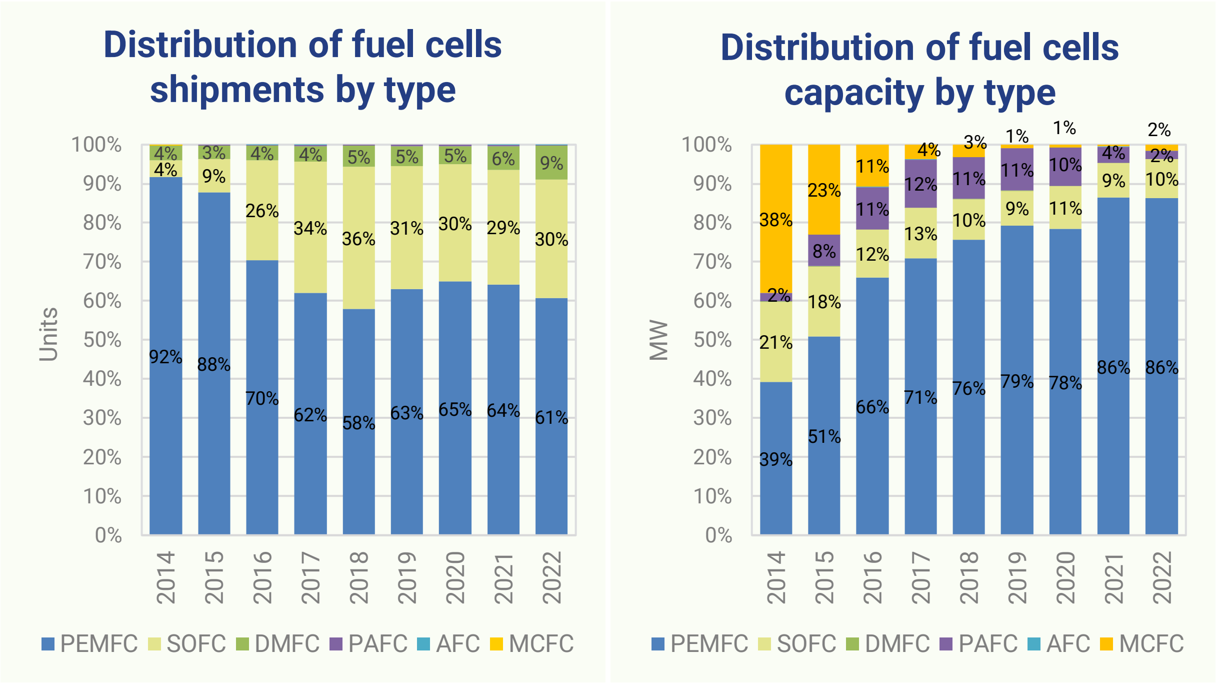


Figure A.1.3. Distribution of fuel cell shipments in terms of the total number of units and the total capacity (in MW) by fuel cell type in Europe from 2014 to 2022.

Table A.1.2. Explanation of the different fuel cell types

AFC	AFC stands for alkaline fuel cell. It is a type of fuel cell technology that generates electricity and heat through an electrochemical process using an alkaline electrolyte, typically potassium hydroxide (KOH) or sodium hydroxide (NaOH). This electrolyte allows for the movement of hydroxide ions (OH^-), creating a low ionic resistance between the anodic and cathodic electrochemical reactions of the fuel cell.
DMFC	DMFC stands for direct methanol fuel cell. This type of fuel cell technology is used for generating electricity directly from methanol, a liquid fuel, without the need for an external reformer to convert the methanol into hydrogen. This direct utilization of methanol simplifies the fuel cell system since it is easier to handle and transport than gaseous or liquefied hydrogen, which is used in many other types of fuel cells.
MCFC	MCFC stands for molten carbonate fuel cell. In MCFCs, the electrolyte is a high-temperature molten carbonate salt, typically a mixture of lithium carbonate (Li_2CO_3) and potassium carbonate (K_2CO_3). This molten carbonate electrolyte allows for the movement of carbonate ions (CO_3^{2-}) between the anode and cathode. MCFCs can operate on a variety of fuels, including natural gas, biogas, and even coal-derived gases. This flexibility makes them suitable for a range of applications and helps reduce dependence on a single fuel source.
PAFC	PAFC stands for phosphoric acid fuel cell. In PAFCs, the electrolyte is typically made in the form of a phosphoric acid-doped polymer membrane. This phosphoric acid electrolyte allows for the movement of ions between the anode and cathode. They operate well at a steady state, making them suitable for stationary and continuous power generation applications.
PEMFC	PEMFC stands for proton exchange membrane fuel cell. The core of a PEMFC is a proton-conducting polymer membrane, typically perfluorosulfonic acid membranes such as Nafion^{TM}. This membrane allows protons (H^+) to pass, while blocking gases and electrons, allowing a compact design.
SOFC	SOFC stands for solid oxide fuel cell. The "solid oxide" in SOFC refers to the type of electrolyte used in the fuel cell, namely a solid oxide or ceramic material. This solid oxide allows for the transport of oxide ions (O^{2-}), which requires high temperatures. The major advantage of the SOFC is that it has a high combined heat and power efficiency.

A.1.3.

Shipments by region

Figure A.1.4. provides a visual representation of the distribution of fuel cell shipments in terms of the total number of units and the total capacity (in MW) by region from 2014 to 2022.

Asia emerged as the predominant region for the deployment of fuel cell units, consistently holding the largest share. In 2014, it accounted for 62% of the total shipments, and this share exhibited a steady increase until 2018 when it reached a peak of 80%. However, in the subsequent years, there was a gradual decline, and by 2022, the share had reverted to approximately 68%. North America followed with a notably lower share, representing 27% of the total shipments in 2014. There was a significant drop to 11% in 2015, but it gradually increased until 2018. Subsequently, there was another drop until 2020, after which it rebounded to a 16% share in 2022. Europe constituted the region with the smallest share, accounting for 9% of the total shipments in 2014. Over the years, Europe experienced fluctuations in its share, ultimately reaching a 15% share of the shipments deployed in 2022.

It is important to note that the remaining fuel cells were distributed among various countries in the rest of the world. This data underscores the dominant position of Asia in fuel cell deployments, with North America and Europe showing variable trends in their respective shares over the years.

The global deployment of fuel cell systems exhibited significant regional variations, with each region showing distinct trends in capacity utilization. Asia emerged as the dominant market for fuel cell system capacity, although it experienced fluctuations over the years. In 2014, it accounted for 56% of the total fuel cell system megawatts (MW) deployed. This share reached its highest points at 70% and 71% in 2020 and 2022 respectively. North America followed with a substantial share of the total capacity deployed in 2014, representing 38%. Its share experienced an upward trajectory, reaching a peak of 53% in 2018. However, it declined to a 19% share by 2022. Europe, on the other hand, consistently had the lowest share of the deployed capacity, also displaying fluctuations over the years. In 2014, it accounted for 5% of the total capacity, with the highest share recorded at 11% in 2020. By 2022, Europe represented 9% of the total capacity.

These regional variations emphasize the dynamic nature of fuel cell system capacity deployment, with Asia taking the lead and North America and Europe demonstrating their distinct patterns.

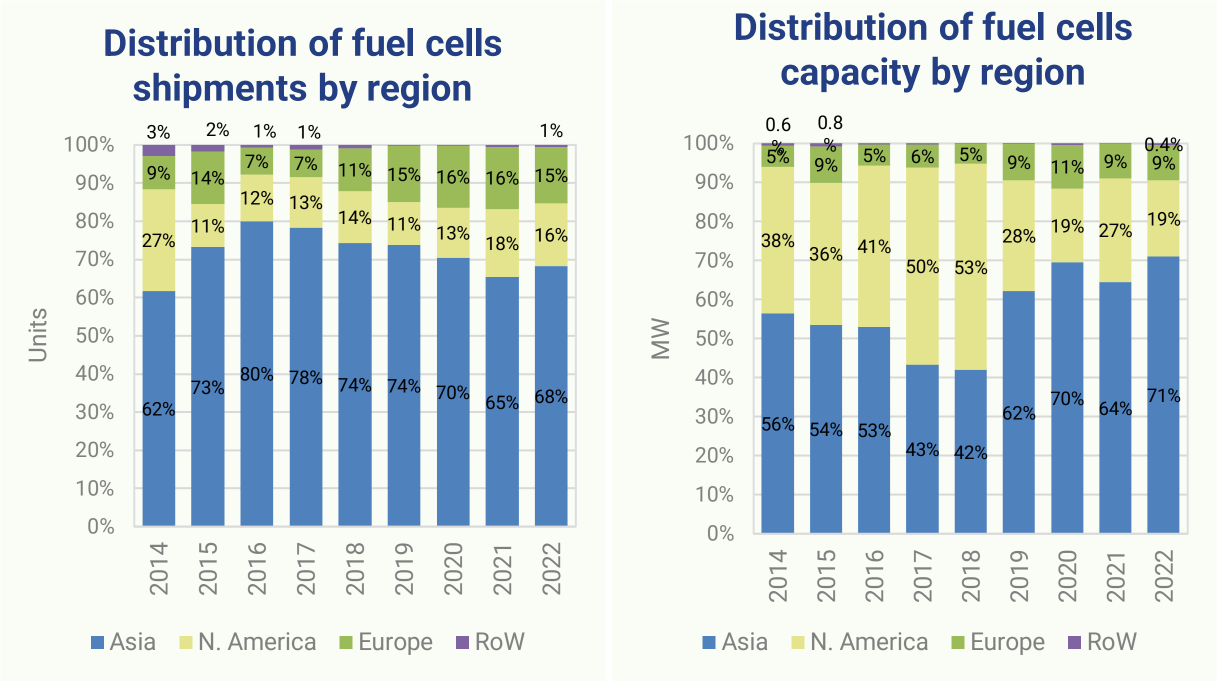


Figure A.1.4. Distribution of fuel cell shipments in terms of the total number of units and the total capacity (in MW) by fuel cell by region of deployment and system integration in Europe from 2014 to 2022.

A.2.

Used assumptions for estimating the break-even prices of renewable hydrogen

Table A.2.1. Assumptions made when estimating break-even hydrogen prices by end use

Oil refining

1. The analysis is based on the assumption that grey hydrogen would be produced using steam methane reforming, using natural gas as feedstock. The only reason why the BEP is not equal to the calculated grey hydrogen production costs is that the SMR unit is producing not only hydrogen but also by-product steam (around 7 MWh per metric ton of hydrogen), which is utilised for other oil refining processes. Therefore, replacing grey hydrogen with renewable hydrogen would create a steam deficit which the refinery would need to supply from other sources. As a result, the BEP for oil refining is set at a level equal to grey hydrogen production costs minus costs of producing additional amount of steam from other sources.

2. For the purpose of the analysis the alternative source of steam was assumed to be combustion of natural gas in a boiler with a 90% efficiency.

3. The assumed renewable hydrogen production process is low-temperature water electrolysis (i.e. no potential benefits from using waste heat from the refinery for high temperature electrolysis were considered).

4. An oil refinery usually has limited use for oxygen. Therefore potential revenues from by-product oxygen from electrolysis have not been included. If valorised oxygen could potentially improve the business case and increase the required BEP by around 0.2 EUR/kg.

Heavy-duty trucks

1. The BEP has been estimated at a level needed to reach cost parity with a diesel 40t 4x2 tractor, with an average daily mileage of 570 km and one shift per day, 250 days per year over a 5 year lifetime.

2. The hydrogen FCEV option assumed 350 bar refuelling.

3. Diesel costs used for the analysis were based on Eurostat data (October 2023), namely the retail prices including fuel taxes and charges, but excluding VAT.

4. Diesel and FCEV trucks, powertrain, equipment, refuelling infrastructure, fuel conditioning and fuel transportation costs were adopted after the JU Fuel Cells Hydrogen Trucks study from December 2020.
5. The potential inclusion of the road transport sector in the ETS system has not been taken into account at this stage.
6. The BEP has been calculated without taking into account any regulatory benefits from the hydrogen contribution towards RED III targets (i.e. no benefit from avoiding penalties or certificate trading were included in the analysis).
7. The BEP reflects the price at the pump and thus includes costs of fuel conditioning (compression), transportation and refuelling infrastructure, which are estimated at a combined level of 3.26 EUR/kg. In case these costs would be higher the hydrogen production costs would have to be lower by a corresponding amount.

Primary steel making

1. The BEP is indicating the maximum price of H2 delivery (i.e. not a production cost) for the H2 DRI-EAF route to reach cost parity with the blast furnace - basic oxygen furnace route which is the market benchmark for primary steel manufacturing in Europe.
2. The analysis includes all the impacts from eliminating blast furnace other than just its crude steel output, but also including loss of blast-furnace-gas and coke-oven-gas outputs, which are currently, in most cases, used for onsite heat and/or power generation.
3. While in the case of onsite electrolysis the by-product oxygen could be used in some of the other processes at a steel plant, this potential benefit was excluded from the analysis to encompass also the case of offsite hydrogen production and delivery via pipeline.
4. The assumed renewable hydrogen production process is low-temperature water electrolysis (i.e. no potential benefits from using waste heat from the steel plant for high temperature electrolysis were considered).
5. As of 2023, the phasing out of free allowances for steel production, following the implementation of CBAM has been incorporated in the business case.

Maritime applications

1. The BEP is indicating the maximum price of H2 delivery for hydrogen fuel to reach cost parity with the benchmark fossil fuel option for 4 selected ship types.
2. The fossil fuel benchmark option in each case was the use of conventional very low sulphur fuel oil (VLSFO), based on fuel prices available in the Port of Rotterdam.
3. Only pure hydrogen options were considered in the analysis (so either compressed or liquefied hydrogen with a fuel cell or ICE - with the final value given for the most profitable from among these options).
4. No synthetic fuels were considered (e-ammonia, e-methanol, e-LNG).
5. The BEP analysis includes cost savings from the participation on the maritime sector in the ETS as of 2023.
6. The BEP has been calculated assuming the ship owner would stay below the FuelEU Maritime targets even without the use of hydrogen (i.e. no benefit from avoiding the FuelEU Maritime penalties have been included in the analysis).
7. The analysis includes the economic impact of using alternative fuels beyond just fuel costs and includes also the impact resulting from lower energy density of the hydrogen fuel, resulting in potential loss of revenues from reduced cargo carrying capacity of the ship.

A.3.

List, sectorial scope and key assumptions & narratives of recent studies on hydrogen demand scenarios by Sector (2030, 2040, 2050)

Table 7 presents an overview of recent, widely recognized studies that propose hydrogen demand scenarios for 2030, 2040, and 2050 across sectors (industry, transport, buildings, and electricity) in Europe. Table 8 highlights the sectoral scope, key assumptions, and narratives of these studies, providing additional context to the projected demand scenarios.

Table 7. List of recent studies on hydrogen demand scenarios by sector (2030, 2040, 2050).

Title of the study	Author(s)	Date of publication	Link to the study
Analysing future demand, supply, and transport of hydrogen	Guidehouse - European Hydrogen Backbone	June 2021	Click here
Study on Hydrogen in Ports and Industrial Coastal Areas	Deloitte - Clean Hydrogen Partnership	March 2023	Click here
Hydrogen roadmap Europe: A sustainable pathway for the European energy transition	FCH JU (now renamed Clean Hydrogen Partnership)	January 2019	Click here
Enabling the European hydrogen economy	Aurora Energy Research	May 2021	Click here
TYNDP 2022 – Scenario Report	ENTSO-G & ENTSO-E	April 2022	Click here
Energy Outlook 2020 edition - Net-zero scenario	BP	2020	Click here
Paris Agreement Compatible Scenarios for Energy Infrastructure (PAC)	Climate Action Network (CAN) Europe	June 2020	Click here
Energy transition outlook (ETO) - Net-zero scenario	DNV	2021	Click here
Transition pathways to a carbon neutral EU28 - Tech scenario	EUCalc	2020	Click here
Achieving the Paris Climate Agreement Goals - 1.5 scenario	IFS	2019	Click here
JRC EU TIMES - Net Zero scenario	Joint Research Centre of the European Commission	2021	Click here
Global Energy and Climate Outlook (GECO) - 1.5°C Differentiated scenario	Joint Research Centre of the European Commission	2021	Click here

Net-Zero Europe: decarbonisation pathways and socioeconomic implications – Cost Optimal and Breakthrough scenarios	McKinsey	2020	Click here
Fit-for-55	European Commission	2022	For 2030: Click here For 2040 and 2050 Click here
REPowerEU	European Commission	2022	Click here
A Clean Planet For All	European Commission	2018	Click here
Impact assessment SWD 176 - MIX	European Commission	2020	Click here

Table 8. Sectorial scope and key assumptions & narratives for some of the most recent and widely recognized studies proposing one or more hydrogen demand scenarios for 2030, 2040 and 2050 by sector in Europe.

Title of the study	Author(s)	Year of publication	Link to the study	Sectorial scope	Key assumptions and narratives
Analysing future demand, supply, and transport of hydrogen	Guidehouse – European Hydrogen Backbone	2021	Click here	• **Industry: Yes**. Includes: Iron & steel; Ammonia for fertilizers; High Value Chemicals (HVCs); Refining & fuel production; Industrial process heat (low, medium and high temperature). • **Transport: Yes**. Includes: Road transport (only heavy-duty road freight), aviation and shipping. • **Power sector: Yes**. • **Buildings: Yes**.	• Policy measures are put in place that prevent relocation of existing industries outside of Europe. • The hydrogen demand for synthetic fuels is categorized under "Industry" and not (as in most of the other studies) under "Transport". • No direct hydrogen or hydrogen derived fuels in the shipping sector. • **See pages 85 to 97 of the study.**
Study on Hydrogen in Ports and Industrial Coastal Areas	Deloitte -Clean Hydrogen Partnership	2023	Click here	• **Industry: Yes**. Includes: Iron & steel; Ammonia for fertilizers; Methanol; High Value Chemicals (HVCs); Refining; Industrial process heat (low, medium and high temperature). • **Transport**: **Yes**. Includes: Road transport (only heavy-duty road freight), international shipping, domestic shipping and port activities (cargo handling and port vessels). Aviation is out of scope. • **Power sector: No**. • **Buildings: Yes**.	• Policy measures are put in place that prevent relocation of existing industries outside of Europe. • **See pages 55 to 68 of the study.**

Hydrogen roadmap Europe: A sustainable pathway for the European energy transition	FCH JU (now renamed Clean Hydrogen Partnership)	2019	Click here	•**Industry: Yes.** Includes: Iron & steel; Ammonia for fertilizers; Methanol; High Value Chemicals (HVCs); Refining; Industrial process heat (low, medium and high temperature). • **Transport**: **Yes**. Includes: Road transport, shipping and aviation. • **Power sector**: **Yes**. • **Buildings: Yes**	• **See page 18 of the study.**
Enabling the European hydrogen economy	Aurora Energy Research	2021	Click here	•**Industry: Yes**. Includes: Iron & steel; Ammonia for fertilizers; Methanol; High Value Chemicals (HVCs); Refining; and Cement • **Transport: Yes.** Includes: Road transport (mainly heavy-duty road freight), shipping and aviation. • **Power sector: Yes.** • **Buildings: Yes.**	• In the "low" scenario, the size of the European industrial sector will "shrink" by 2050. • **See pages 8 and 9 of the study.** • No direct hydrogen or hydrogen derived fuels in the power sector.
TYNDP 2022 –Scenario Report	ENTSO-G & ENTSO-E	2022	Click here	• **Industry: Yes.** Includes: energy use (ex: Iron & steel) and nonenergy use (ex: Ammonia for fertilizers; Methanol; High Value Chemicals (HVCs); Refining). • **Transport: Yes.** Includes: Road transport (heavy-duty trucks, passenger cars, light trucks, buses, rail), shipping and aviation. • **Power sector: Yes.** • **Buildings: Yes.**	• **See pages 12 to 15 of the study** • **All assumptions available here.**

				All numbers available here “Download demand figures (excel)”.	
Energy Outlook 2020 edition -Net-zero scenario	BP	2020	Click here	• **Industry:** **Yes.** Includes: Existing industry feedstock use (ammonia, refineries and methanol and new energy use (ex: Steel) • **Transport: Yes.** • **Power sector: Yes.** • **Buildings: Yes.**	• No direct hydrogen or hydrogen derived fuels in the power sector. • **Note**: Data gathered from JRC Technical Report (2022) “The role of hydrogen in energy decarbonisation scenarios: Views on 2030 and 2050”. For more information, see section “Scenario selection” (page 10-11) & Figure 26 (page 31) of the report here
Paris Agreement Compatible Scenarios for Energy Infrastructure (PAC)	Climate Action Network (CAN) Europe	2020	Click here	• **Industry: Yes.** • **Transport: Yes.** • **Power sector: Yes.** • **Buildings: Yes.**	• No direct hydrogen or hydrogen derived fuels in the power and building sectors. • **Note:** Data gathered from JRC Technical Report (2022) “The role of hydrogen in energy decarbonisation scenarios: Views on 2030 and 2050”. For more information, see section “Scenario selection” (page 10-11) & Figure 26 (page 31) of the report here
Energy transition outlook (ETO) -Net-zero scenario	EUCalc	2020	Click here	• **Industry: Yes.** • **Transport: Yes.** • **Power sector: Yes.** • **Buildings: Yes**	• No direct hydrogen or hydrogen derived fuels in the power sector. • **Note:** Data gathered from JRC Technical Report (2022) “The role of hydrogen in energy decarbonisation scenarios: Views on 2030 and 2050”. For more information, see section

					“Scenario selection” (page 10-11) & Figure 26 (page 31) of the report here
Transition pathways to a carbon neutral EU28 - Tech scenario	EUCalc	2020	Click here	• **Industry:** **Yes.** • **Transport:** **Yes.** • **Power sector:** **Yes.** • **Buildings:** **Yes**	• No direct hydrogen or hydrogen derived fuels in the power and building sectors. • **Note:** Data gathered from JRC Technical Report (2022) “The role of hydrogen in energy decarbonisation scenarios: Views on 2030 and 2050”. For more information, see section “Scenario selection” (page 10-11) & Figure 26 (page 31) of the report here
Achieving the Paris Climate Agreement Goals - 1.5 scenario	IFS	2019	Click here	• **Industry:** **Yes.** • **Transport:** **Yes.** • **Power sector:** **Yes.** • **Buildings:** **Yes**	•**Note:** Data gathered from JRC Technical Report (2022) “The role of hydrogen in energy decarbonisation scenarios: Views on 2030 and 2050”. For more information, see section “Scenario selection” (page 10-11) & Figure 26 (page 31) of the report here
JRC EU TIMES -Net Zero scenario	Joint Research Centre of the European Commission	2021	Click here	• **Industry:** **Yes.** • **Transport:** **Yes.** • **Power sector:** **Yes.** • **Buildings:** **Yes**	• No direct hydrogen or hydrogen derived fuels in the power sector. • No direct hydrogen or hydrogen derived fuels in the building sector in 2050 (small quantities in 2030/2040). • **Note:** Data gathered from JRC Technical Report (2022) “The role of hydrogen in energy decarbonisation scenarios: Views on 2030 and 2050”.

					For more information, see section "Scenario selection" (page 10-11) & Figure 26 (page 31) of the report here
Global Energy and Climate Outlook (GECO) - 1.5°C Differentiated scenario	Joint Research Centre of the European Commission	2021	Click here	• **Industry: Yes.** • **Transport: Yes.** • **Power sector: Yes.** • **Buildings: Yes**	• No direct hydrogen or hydrogen derived fuels in the power sector. • **Note:** Data gathered from JRC Technical Report (2022) "The role of hydrogen in energy decarbonisation scenarios: Views on 2030 and 2050". For more information, see section "Scenario selection" (page 10-11) & Figure 26 (page 31) of the report here
Net-Zero Europe: decarbonization pathways and socioeconomic implications –Cost Optimal And Breakthrough scenarios	McKinsey	2020	Click here	• **Industry: Yes.** • **Transport: Yes.** • **Power sector: Yes.** • **Buildings: Yes**	• **Note**: Data gathered from JRC Technical Report (2022) "The role of hydrogen in energy decarbonisation scenarios: Views on 2030 and 2050". For more information, see section "Scenario selection" (page 10-11) & Figure 26 (page 31) of the report here
Fit-for-55	European Commission	2022	For 2030: Click here For 2040 and 2050: Click here	• **Industry: Yes.** Includes: Iron & steel; Ammonia for fertilizers; Refining; Industrial heat. • **Transport: Yes.** Includes: Road transport (Transport); Aviation (synthetic fuels); Maritime (bunker fuels) • **Power sector: Yes.** • **Buildings: Yes.**	• **For 2030: see page 27 of the document** • **Note for 2040 and 2050:** Data gathered from JRC Technical Report (2022) "The role of hydrogen in energy decarbonisation scenarios: Views on 2030 and 2050". For more information, see section "Scenario selection" (page 10-11) & Figure 26

					(page 31) of the report here.
REPowerEU	European	2022	Click here	• **Industry:** **Yes.** Includes: Iron & steel; Ammonia for fertilizers; Refining; Industrial heat. • **Transport:** **Yes.** Includes: Road transport (Transport); Aviation (synthetic fuels); Maritime (bunker fuels) • **Power sector:** **Yes.** • **Buildings:** **Yes.**	• **See page 27 of the document** • REPowerEU allocates 4 Mt (133 TWh) of hydrogen demand in the form of ammonia (or other hydrogen derivatives) import, without specifying in which sectorial application this hydrogen could be used. It is therefore assumed that the 4 Mt are evenly split in the 4 demand categories (resulting in an additional 1 Mt, or 33 TWh, for industry, transport, power and buildings.
A Clean Planet For All	European Commission	2018	Click here	• **Industry:** **Yes.** • **Transport:** **Yes.** • **Power sector:** **Yes.** • **Buildings:** **Yes**	• **Key assumptions and narrative available pages 56 and 324-326 of the document.** • Note: Data gathered from European Commission Report (2018) "A Clean Planet for all". For more information, see Figure 32 (page 30) of the report here.
Impact assessment SWD 176 - MIX	European Commission	2020	Click here	• **Industry:** **Yes.** • **Transport:** **Yes.** • **Power sector:** **Yes.** • **Buildings:** **Yes**	• Note: Data gathered from aggregation and consolidation effort performed in Guidehouse (2021)'s analysis. For more information, see Figure 21 (page 52) of the report here.