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Historical Analysis of Clean Hydrogen JU Fuel Cell Electric Vehicles, Buses and Refuelling Infrastructure Projects

Evaluation of Contribution towards the State of the Art

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Contents

Abstract

This technical report provides a comprehensive historical analysis of the Clean Hydrogen Joint Undertaking (JU) projects focused on Fuel Cell Electric Vehicles (FCEVs), Fuel Cell Electric Buses (FCEBs), and associated Hydrogen Refueling Stations (HRS) within the European Union. The FCEV, FCEB and HRS demonstration activities of Clean Hydrogen JU projects aim to prove that hydrogen-powered vehicles and HRS are capable of substituting conventional vehicles, offering climate benefits. Their ultimate goal is to accelerate the entrance of fuel cell technology in the European car and bus manufacturing industry by showcasing market readiness and creating competitive cost refuelling networks with positive business cases. Anchored in the EU's commitment to the Paris Agreement and the Glasgow Climate Pact, the report delves into the policy context, strategic initiatives, and recent developments that have shaped the EU's approach to hydrogen as a pivotal component of its energy transition, particularly within the transport sector. The report outlines the methodology used for the historical analysis, detailing the data sources, key performance indicators (KPIs), and performance assessment approach. The achievements of these demonstrations over the years, and their implications for the wider rollout of hydrogen mobility across the EU, are discussed, tracking the relevant KPIs progress for each technology. The conclusions and recommendations highlight the pivotal role that the Clean Hydrogen JU and its predecessors played in advancing hydrogen mobility, while also addressing challenges and offering key recommendations to foster the growth of hydrogen mobility in Europe. The findings underscore the potential of hydrogen mobility in achieving ambitious decarbonization targets and building a resilient, efficient, and low-carbon future for European transport.

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1 Introduction

The transition to a sustainable and low-carbon future is a prominent global challenge that has been embraced with determination by the European Union. Anchored in its commitment to the Paris Agreement and the Glasgow Climate Pact, the EU has undertaken a series of ambitious policy initiatives aimed at greenhouse gas emissions (GHG) reduction and the fostering of renewable energy sources. Key among these initiatives is the strategic focus on hydrogen as an integral part of the EU's energy transition, particularly within the transport sector, which includes Fuel Cell Electric Vehicles (FCEVs), Fuel Cell Electric Buses (FCEBs), and the development of Hydrogen Refuelling Stations (HRS).

This report delves into the historical analysis of the Clean Hydrogen Joint Undertaking (JU) projects that have been pivotal in advancing these hydrogen-based transport solutions. It offers a comprehensive overview of the projects involving FCEVs, FCEBs and HRS, the State of the Art (SoA) of these technologies, the deployment and state of implementation of the FCEV and FCEB projects, and the critical role played by the Clean Hydrogen JU in fostering these technologies.

1.1 EU Policy Context and the Push for Hydrogen

The EU's policy landscape sets the backdrop for this historical analysis. The European Union, as a signatory to the Paris Agreement (COP21), has made significant strides in climate action, with a renewed commitment highlighted in the Glasgow Climate Pact (COP26) and the recent agreements from COP28. The last ones focused on transitioning away from fossil energy by 2050, tripling the global renewable energy capacity and doubling the rate of energy efficiency improvements by 2030.

Legislative frameworks, such as the 2030 Climate & Energy Framework (European Commission, 2021), the Clean Energy for all Europeans package (European Commission, 2019), and the European Green Deal (European Commission, 2019), have laid the groundwork for a comprehensive approach to achieving ambitious greenhouse gas emissions (GHG) reduction targets. The emergence of the Fit for 55 package (European Commission, 2019), in particular the Alternative Fuels Infrastructure Regulation (European Union, 2023), and the Hydrogen and Gas Markets Decarbonisation package (European Commission, 2021) has further sharpened the focus on alternative fuels, including hydrogen.

In response to geopolitical shifts and the imperative for energy security, the REPowerEU Plan presented by the European Commission in May 2022 amplifies these efforts, setting even loftier goals for renewable energy production and the integration of hydrogen into the energy mix (European Commission, 2022). The establishment of the NextGenerationEU (European Commission, 2022) and the European Hydrogen Strategy (European Commission, 2020) underscores the EU's commitment to fostering a robust hydrogen economy that will contribute to the decarbonisation of various sectors, including transportation.

1.2 Recent Developments on the Role of Hydrogen in Climate Policies: Road Transport

Hydrogen's potential as a versatile energy carrier and its role in the decarbonisation of the EU's energy system cannot be overstated. From its current primary use in the chemical industry to its promise as a renewable energy source, hydrogen stands at the cusp of a transformative shift. The EU's strategies and action plans reflect a concerted effort to scale up the production and application of clean hydrogen, particularly in hard-to-decarbonize sectors like heavy transport. The Fit-for-55 package and the REPowerEU Plan further delineate the role of hydrogen, setting specific targets for its production and use in the EU.

The Fit-for-55 package contains a set of interconnected proposals designed to make the EU's climate, energy, land use, transport and taxation policies in line with the targets set by the European Green Deal. The following proposals relevant to hydrogen road transport applications passed through the trilogue legislative process and have been approved by the Council and the Parliament in 2023:

- The Alternative Fuels Infrastructure Regulation (AFIR) provides specific deployment targets for 2025 and 2030, replacing and completing the original Directive of 2014. While the previous Alternative Fuels Infrastructure Directive (AFID) was only foreseeing voluntary Member States adoption of hydrogen solutions for mobility, the AFIR now sets minimal requirements for hydrogen refuelling stations serving both cars and trucks, which must be deployed from 2030 onwards in all urban nodes and every 200 km along the TEN-T core network. The Regulation has been published in the EU's official journal on the 23rd September 2023 (European Union, 2023).

- The revision of the EU Emissions Trading System (EU-ETS) package has been approved in May 2023 (European Union, 2023): Among other provisions, the revision extends the ETS to buildings, road transport and the maritime sectors. To ensure a fair transition, it introduces as well a Social Climate Fund to address the social impacts of the new system on vulnerable groups affected by energy or mobility poverty. The Carbon Border Adjustment Mechanism (CBAM) Regulation is part of this package (European Union, 2023). The CBAM aims at levelling the price of carbon between domestic products and imports and ensure that the EU's climate objectives are not undermined by production relocating to countries with less ambitious policies. The targets set on hydrogen supply of the REPowerEU plan imply the necessity of including hydrogen imports into the CBAM. Therefore, among the products initially covered by CBAM are iron and steel, fertilisers, electricity and hydrogen.

Through the financing of the REPowerEU Plan, it strengthens all previous hydrogen-related policies by increasing the deployment targets by means of its Hydrogen Accelerator Pillar (European Commission, 2022). Directly relevant to the hydrogen road transport applications is the increasing Clean Hydrogen Joint Undertaking's budget by 200 million EUR to double the number of Hydrogen Valleys from 23 to 46 by 2025.

1.3 The Role of the Clean Hydrogen Joint Undertaking and its predecessors

The ambitious plan for the gradual roll-out of clean hydrogen technologies needs to be supported by research and innovation actions to increase their technology readiness level, reduce their costs and allow their demonstration. The EU has been supporting research and innovation for hydrogen technologies for many years, starting through traditional collaborative projects under Framework Programmes (FP4, FP5 and FP6), and subsequently since 2008 with the Fuel Cell and Hydrogen Joint Undertakings (FCH JU and FCH 2 JU), under FP7 and Horizon 2020 (H2020) respectively.

The Clean Hydrogen JU is the continuation of FCH JU and took over all activities of its predecessors. In line with all policy developments described above, it is crucial that the Clean Hydrogen JU continues to support its existing projects and further develop technology solutions that will help materialise the benefits of hydrogen technologies in support of the high-level EU policy agenda. It has the leading role in research activities related to hydrogen, collaborating closely with most of the end-use European partnerships on hydrogen applications in the relevant sectors.

The European Commission Joint Research Centre's Directorate for Energy, Transport and Climate (JRC) supports the Clean Hydrogen JU on hydrogen research and technology monitoring and assessment, among other activities. As a part of the knowledge management activities of the Clean Hydrogen JU, the JRC has been commissioned to perform a series of historical analyses by topic area in order to assess the impact of funded projects and the progression of the FCH JU Multi-Annual Work Plan (MAWP) towards its objectives.

These reports consider the performance of projects against the overall Programme Targets for specific technologies, using Key Performance Indicators (KPI) for assessment. The purpose of such an exercise is to see whether and how the programme has enhanced the state of the art and to identify potential Research and Innovation gaps for the future.

Reports assessing progress of two technologies have been published, and the Clean Hydrogen JU has requested that the next report of the series will focus on FCEVs, FCEBs and their associated refuelling infrastructure. This report will cover a historical analysis from 1998 to 2022 on the progress of the FCEV and FCEB technologies.

The report will highlight the crucial contributions of the Clean Hydrogen JU in supporting research, innovation, and the deployment of hydrogen technologies. The evolution of the JU from its inception under the FP7 program to its current iteration under Horizon Europe will be detailed, showcasing its pivotal role in advancing the technological readiness of hydrogen solutions and its alignment with high-level EU policy objectives.

In summary, this report aims to provide a thorough historical analysis of the Clean Hydrogen JU projects on FCEVs, FCEBs, and HRS, set against the backdrop of the EU's evolving policy landscape and its pursuit of a sustainable and resilient energy future.

1.4 Report Structure

This report aims to provide an historical overview and an assessment of the Clean Hydrogen JU projects in the field of FCEVs, FCEBs, and associated refuelling infrastructure. The purpose of this historical review is to assess whether and how the Clean Hydrogen Joint Undertaking projects have contributed to the advancement of the state of the art.

First, the methodology followed throughout the historical analysis is thoroughly described in Chapter 2. Chapter 3 contains the whole analysis of the Clean Hydrogen JU projects. It starts with a brief funding overview of the Clean Hydrogen JU projects and an analysis of the organisations and Member States (MS) participating. A comparison is drawn between the organisations and MS participating within the overall 35 projects reviewed (1998-2022) and the participation within the 17 Clean Hydrogen JU projects (2010-2022).

The Chapter 3 is then splitted into two main sections, one dedicated to FCEV projects (Section 3.1) and one dedicated to FCEB projects (Section 3.2). Both sections followed the same structure. First, an historical overview of projects preceding the Clean Hydrogen JU projects is provided (Section 3.1.1 for FCEVs and Section 3.2.1 for FCEBs). Secondly, an overview of the Clean Hydrogen JU demonstration projects is detailed (Section 3.1.2 for FCEVs and Section 3.2.2 for FCEBs). Next, the State of the Art (SoA) for each technology is outlined, with particular attention given to technical development, manufacturing and deployment (Section 3.1.3 for FCEVs and Section 3.2.3 for FCEBs). Following this, the progress against the SoA in Europe is evaluated (Section 3.1.4 for FCEVs and Section 3.2.4 for FCEBs). The following section focuses on presenting the Key Performance Indicators (KPIs) and targets (Section 3.1.5 for FCEVs and Section 3.2.5 for FCEBs). Then, the performance evaluation of the projects in Europe is discussed (Section 3.1.6 for FCEVs and Section 3.2.6 for FCEBs) and summarised (Section 3.1.7 for FCEVs and Section 3.2.7 for FCEBs).

Finally, conclusions and recommendations based on the analysis of the SoA and the performace of the Clean Hydrogen projects are provided in Chapter 4. Following Chapter 4, references, a list of abbreviations, a list of figures and a list of tables are provided.

In the report the terms “Clean Hydrogen JU”, “Fuel Cell Hydrogen JU (FCH JU)” and “Fuel Cell Hydrogen 2 JU (FCH 2 JU)” will be used indiferently to refer to the Clean Hydrogen Joint Undertaking and its predecessors.

2 Methodology

The objective of this historical review is to assess whether and how the Clean Hydrogen Joint Undertaking projects have contributed to the advancement of the state of the art in the field of Fuel Cell Electric Vehicles (FCEVs), Fuel Cell Electric Buses (FCEBs), and related refuelling infrastructure (HRS). The primary focus was to use Key Performance Indicators (KPIs) for both FCEVs and FCEBs to demonstrate how funded projects have performed against the State of the Art (SoA) and overall Programme Targets. To achieve this, several steps were taken.

First, the evolution of the SoA for both FCEV and FCEB technologies was reviewed. This was accomplished by integrating various information sources, including a study commissioned to PriceWaterhouseCoopers (PWC) by the Clean Hydrogen JU and the JRC. The aim of this study was to examine the technological advancements in hydrogen mobility for FCEVs, FCEBs, and HRS worldwide from 2008 to 2020. Publicly available data was collected from various sources, such as IHS Markit and energy agency publications, and in some cases, paid research publications previously accessible to the contractors. The data was then analysed and presented in the PWC study. The information from this study and other publicly available sources were reviewed and integrated in this report in its different sections to follow the evolution of the SoA of these technologies from the early 2000s until today. KPIs and targets were drawn from the analysis of SoA to evaluate the performance of the Clean Hydrogen JU projects with their respective KPIs. The purpose of such an exercise is to see whether and how the programme has enhanced the SoA, and to identify potential research and innovation gaps for the future.

As the next step, European projects involving FCEV and FCEB technologies were identified through CORDIS database. A total of 35 projects were reviewed in this report (including projects preceding the Clean Hydrogen JU). The online software TIM (Tools for Innovation Monitoring) developed by the JRC was used to provide an overview of the organisations and Member States participating in these projects.

For each technology an overview of both, the pioneering projects mainly from Framework Programmes 4, 5 and 6 (FP4, FP5 and FP6), and the Clean Hydrogen JU projects (FP7 and H2020) was provided. However, the core of this report centred on the analysis of the Clean Hydrogen JU projects. These projects belonged to the FCH JU Panel 1 category (Trials and Deployment of Fuel Cell Applications – Transport), now the Clean Hydrogen JU Pillar 3 category (Transport). These are a total of 17 projects focusing on the large-scale demonstration of FCEVs and FCEBs in Europe. For these projects, the primary sources for the project KPIs was the final report (which is generally submitted within 3 months of the end of the project). The full methodology outlined below was performed for these projects in two sections, one for FCEV projects and another for FCEB projects.

Templates were created for each technology (FCEV and FCEB). These contain a set of deployment parameters and a series of KPIs, based on the list of programme targets given in the Addendum to the Multi-annual Work Program (MAWP) from 2018 (Fuel Cells and Hydrogen 2 Joint Undertaking (FCH JU), 2018). These are supplemented by additional KPIs from the TRUST database (Technology Reporting Using Structured Templates), which was set up by the FCH 2 JU to collect quantitative data from FCH 2 JU projects, and is now part of the required reporting process for ongoing projects.

Additional KPIs were included where the reported values were given in a different form to those identified in the MAWP. For example, for some projects durability was often not reported but hours of operation were so an analysis on the "hours of operation" parameter was included. Additional parameters were also included if they were repeatedly required in order to calculate the KPIs identified in the MAWP.

In the final step, the KPI template was filled in for each project, using data obtained from the following sources, in order of priority:

- Project Final Report (if available)
- The latest update of the TRUST database
- Intermediate Project Reports
- Other source documents

As mentioned, it was often necessary to re-calculate the KPI values in order to include them in a standard form or unit, and qualifying comments are provided within the template provided for each project. This comments section is also used to give details of the conditions under which particular KPIs were obtained in the instance that they differ from and are additional to those in the MAWP.

For each KPI included in the template, the following fields were completed:

- The parameter (KPI)
- The definition of the parameter in TRUST
- The definition of the parameter according to the MAWP
- Unit of the parameter
- Value achieved
- Comments (the conditions under which the particular performance was achieved and, if it had been calculated, then from which values)
- Source (report, page number)
- Dissemination level (Confidential or Public) of the report in which the KPI value was found.

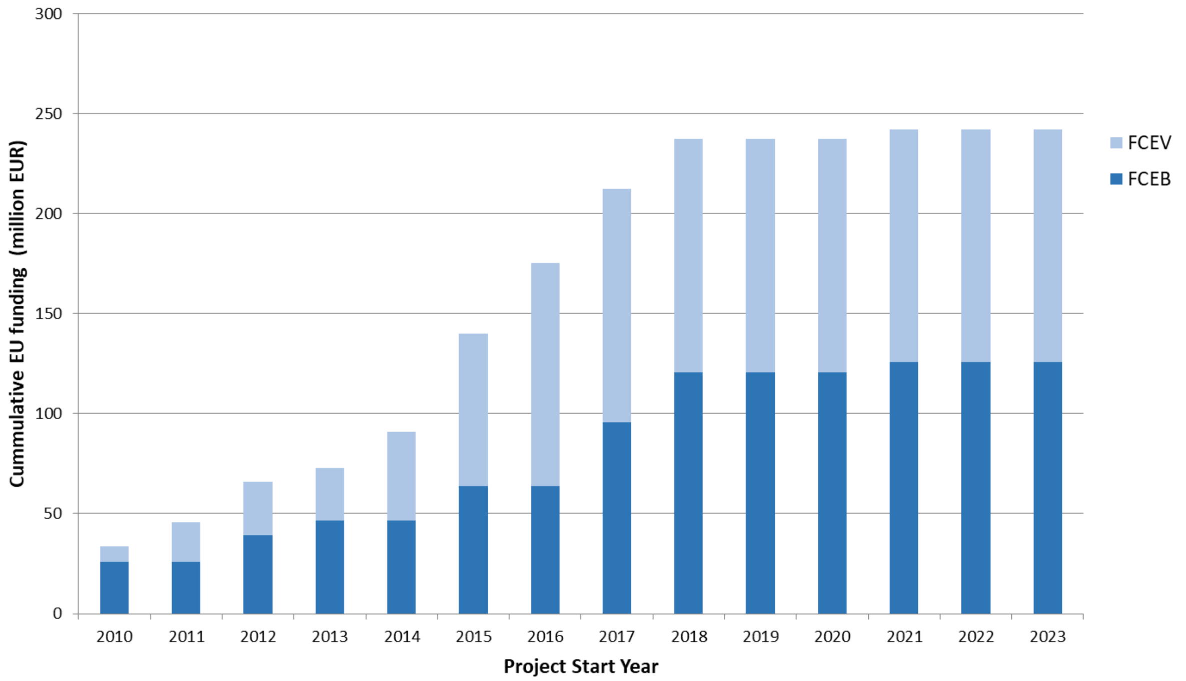
It should be noted that in many cases it was not possible to determine all the KPI values for a particular project. The reasons for this vary from project to project, but may either be due to the project not addressing all the KPIs listed in the templates (i.e. the performance parameter was not part of the project scope) or where the responsible has not reported the KPI value. It should further be mentioned that the MAWP programme targets were only published in the Addendum to the MAWP in 2018 whereas prior to this time projects were responding to other KPIs in Annual Work Programmes or had set their own project targets. Therefore, early FCH JU projects may not necessarily have been fully aligned with the current targets of the programme.

The deployment parameters and KPI values obtained for the relevant projects were then plotted against the SoA and target values to identify trends and draw conclusions in this report.

3 Analysis of Clean Hydrogen JU FCEV, FCEB and HRS projects

The Clean Hydrogen JU (previously known as FCH JU and FCH 2 JU) has been funding projects on the demonstration of Fuel Cell Electric Vehicles (FCEVs), Fuel Cell Electric Buses (FCEBs), and Hydrogen Refuelling Stations (HRS) since 2010. In Figure 1, the cumulative level of EU funding from the Clean Hydrogen JU towards FCEV, FCEB and the associated HRS demonstration projects is shown. The demonstration projects are those aiming at large-scale FCEV, FCEB and corresponding HRS deployment and performance monitoring. The value given in the plot is the cumulative EU funding value against the project start year. The EU funding value in the plot has been split into FCEV and FCEB categories (HRS deployment is contained within these two categories since they were funded as part of the projects on FCEV and FCEB). It can be seen that in the early years (2010-2013) the most funding has been applied to FCEB projects whilst lower levels of funding have been directed at FCEV projects. However, from 2014 onwards the level of funding of FCEV has equiparated to that of FCEB. As of 2023, the cumulative EU funding value for FCEB was close to 126 million EUR while the cumulative funding dedicated to FCEV demonstration project was 116 million EUR, approximately.

Figure 1. Cumulative level of Clean Hydrogen JU funding versus project start year for FCEV, FCEB and HRS technologies



Source: JRC based on data from Clean Hydrogen JU, 2023.

The online software TIM (Technology Innovation Monitoring) developed by the JRC has been used to provide an overview of organisations that have taken part in the 35 projects reviewed in this report (including projects preceding the Clean Hydrogen JU). Figure 2 (a) shows the organisations that are involved in all 35 projects relevant to FCEV, FCEB and HRS from 1998 until 2022 whilst Figure 3 (a) shows only those organisations involved in the 17 Clean Hydrogen JU demonstration projects covering the period from 2010 until 2022, looking at large-scale FCEV, FCEB and HRS deployment and performance monitoring.

In the plots, the size of the nodes (circles) is proportional to the number of projects a partner has been involved in whilst the thickness of the lines is proportional to the number of links (i.e. the number of projects partners have been involved in together). TIM uses a particular algorithm to cluster related items into a "Community".

Each community has a different colour. [1] Basically, the coloured clusters identified by TIM are formed by partners that collaborate more frequently with each other because they share participation in the same projects.

In both figures, a number of key partners that are common to a number of projects can be identified. For example, vehicle manufacturers such as Bayerische Motoren Werke AG (BMW) and Honda are connected in a community/cluster with HRS developers such as ITM Power in Figure 2 (a) referring to overall projects. Another example is Mercedes-Benz group and Hyundai connected in a cluster with hydrogen supplier Air Products in Figure 3 (a) referring to recent projects. This shows the strong link between vehicle and infrastructure deployment in the projects over the years. The top ten organisations in terms of project participation can also be observed in both figures and it is notable that most of the organisations involved in the early FCEV, FCEB and HRS initiatives are also involved in the most recent demonstration projects funded by the Clean Hydrogen JU (17 projects).

The organisations that participated the most in projects covering the whole studied period (1998-2022) were Air Liquide SA (gas technologies company, hydrogen supplier and HRS manufacturer), followed by Element Energy LTD (energy consultancy with a role on project coordination) and Mercedes-Benz group (vehicle manufacturer). This shows the importance of the different types of organisation in the demonstration projects: 1) hydrogen refuelling infrastructure developers, which are common for FCEV and FCEB deployment proyects, 2) consultancy companies coordinating projects, also common for FCEV and FCEB deployment projects, and 3) vehicle manufacturers, FCEV or FCEB depending on the project.

If we focus only in the recent projects (Figure 3 (a)), we can observe some similarities. The organisations with major participation in the FCEV, FCEB and associated HRS demonstration projects funded by the Clean Hydrogen JU (2010-2022) were again Element Energy LTD, followed by London Bus Services LTD (bus operator) and Air Liquide SA. The evolution of the participation of organisations and shifts observed over the years will be studied more thoroughly and separately for FCEV and FCEB in sections 3.1 and 3.2, respectively.

In the plot shown in Figure 2 (b) and Figure 3 (b), the size of the circles represents the number of projects that contain at least one consortium member from that EU member state. The thickness of the links between the circles shows the number of projects in common.[2] This plot shows that the countries that are active in the greatest number of projects tend to be the larger European economies of Germany, the UK and France. Belgium, The Netherlands, Italy and Denmark ranked also very high in project participation. The member state that participated in the most projects covering the period 1998-2022 was Germany, followed by the United Kingdom and Belgium (Figure 2 (b)).

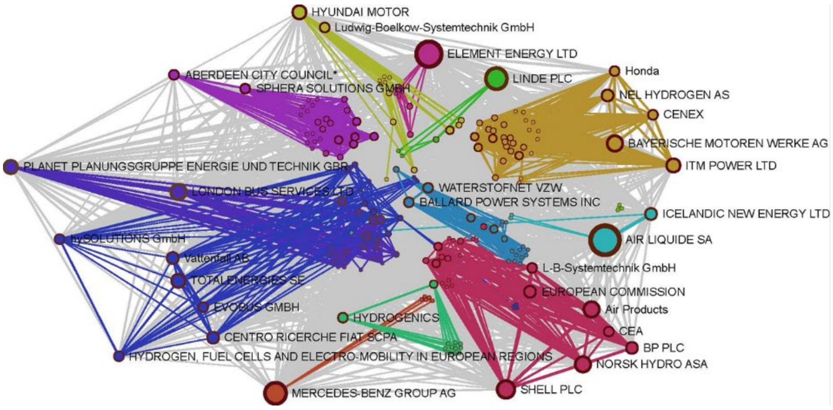
If we only consider the FCEV, FCEB and HRS demonstration projects funded by the Clean Hydrogen JU (2010-2022), the United Kingdom was the state that participated in the most projects followed by Germany and Belgium (Figure 3 (b)).

(1) The size of the node represents the number of projects a partner is involved in, whilst the thickness of the links represents the number of projects in common between the linked partners. The coloured groupings are potential clusters identified by TIM's algorithm. The table shows the top 10 participants from the plot.

(2) The size of the node represents the number of projects that has at least one participating organisation from that member state. The thickness of the links between the nodes is proportional to the number of projects those member states have in common. The United Kingdom does not appear in the graph as it is not a current EU member state. The table shows the top 10 countries represented, including the United Kingdom for comparison.

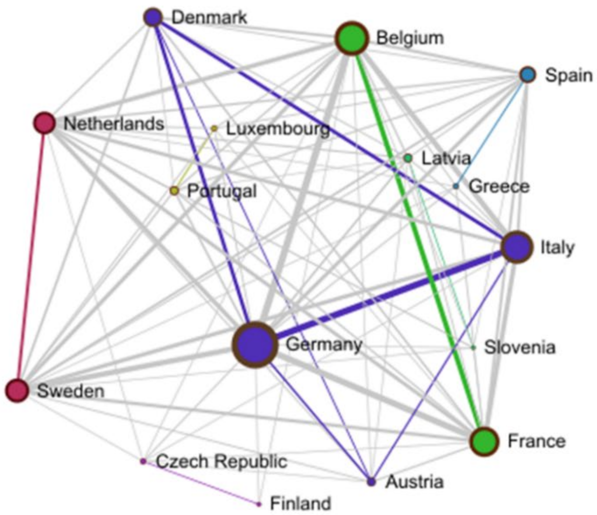
Figure 2. TIM plots showing (a) the participants for all projects considered in this report (35 projects covering the period 1998-2022)[3][4]. (b) EU member state participation for all projects considered (35 projects covering the period 1998-2022).[5]

a)



Organisation	Number of Projects
AIR LIQUIDE SA	14
ELEMENT ENERGY LTD	12
MERCEDES-BENZ GROUP AG	10
LINDE PLC	10
EUROPEAN COMMISSION	9
SHELL PLC	8
Air Products	7
BAYERISCHE MOTOREN WERKE AG	7
NORSK HYDRO ASA	7
LONDON BUS SERVICES LTD	7

b)



Member State	Number of Projects
Germany	29
United Kingdom	23
Belgium	22
France	18
Netherlands	17
Italy	17
Norway	15
Denmark	14
Spain	10
Sweden	9

Source: JRC (TIM) based on data from CORDIS and Clean Hydrogen JU, 2022.

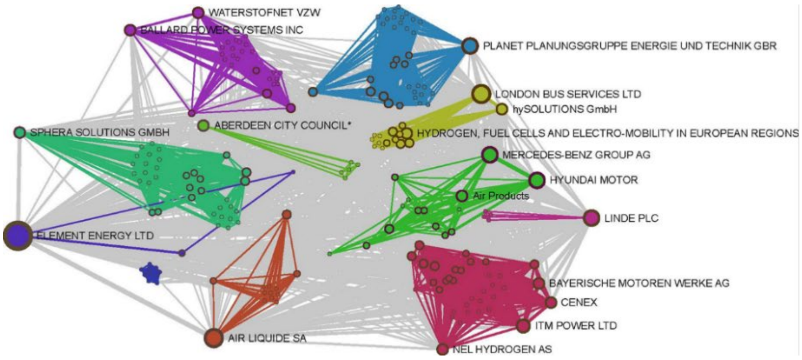
3 The size of the node represents the number of projects a partner is involved in, whilst the thickness of the links represents the number of projects in common between the linked partners. The coloured groupings are potential clusters identified by TIM's algorithm. The table shows the top 10 participants from the plot.

4 The organisation described as "European Commission" encompasses participation from the following sub-institutions found in CORDIS: "DG JRC", "Hydrogen Fuel Cells and Electro-Mobility in European Regions", and "Commission of the European Communities".

5 The size of the node represents the number of projects that has at least one participating organisation from that member state. The thickness of the links between the nodes is proportional to the number of projects those member states have in common. The United Kingdom does not appear in the graph as it is not a current EU member state. The table shows the top 10 countries represented, including the United Kingdom (an EU member state when the project was awarded) for comparison.

Figure 3. TIM plots showing (a) the participants for Clean Hydrogen JU demonstration projects (17 projects in the 2010-2022 period).[6][7] (b) EU member state participation for Clean Hydrogen JU demonstration projects (17 projects in the 2010-2022 period).[8]

a)



Organisation	Number of Projects
ELEMENT ENERGY LTD	11
LONDON BUS SERVICES LTD	7
AIR LIQUIDE SA	7
PLANET PLANUNGSGRUPPE ENERGIE UND TECHNIK GBR	6
MERCEDES-BENZ GROUP AG	6
Europe GmbH	6
LINDE PLC	6
ITM POWER LTD	5
NEL HYDROGEN AS	4
EUROPEAN COMMISSION	4

b)

Member State	Number of Projects
United Kingdom	16
Germany	15
Belgium	15
Denmark	11
Netherlands	9
France	9
Italy	9
Norway	8
Sweden	5
Spain	5

Source: JRC (TIM) based on data from Clean Hydrogen JU, 2022.

6 The size of the node represents the number of projects a partner is involved in, whilst the thickness of the links represents the number of projects in common between the linked partners. The coloured groupings are potential clusters identified by TIM's algorithm. The table shows the top 10 participants from the plot.

7 The organisation described as "European Commission" encompasses participation from the following sub-institutions found in CORDIS: "DG JRC", "Commission of the European Communities" and "Hydrogen Fuel Cells and Electro-Mobility in European Regions".

8 The size of the node represents the number of projects that has at least one participating organisation from that member state. The thickness of the links between the nodes is proportional to the number of projects those member states have in common. The United Kingdom does not appear in the graph as it is not a current EU member state. The table shows the top 10 countries represented, including the United Kingdom (an EU member state when the project was awarded) for comparison.

3.1 Fuel Cell Electric Vehicles Projects

3.1.1 Historical overview of FCEVs projects preceding the Clean Hydrogen JU projects

The following table contains a summary of all the early FCEV relevant projects that paved the way for the development of the FCEV technology (mainly in FP4, FP5 and FP6). These projects constituted the founding stone for the demonstration projects that were developed in later FPs (FP7 and H2020). These projects focused on the harmonization of regulations, licensing, approval, public acceptance and early demonstration of FCEVs. The table includes the project acronym, the corresponding FP, the duration (start/end year), the project metrics (number of FCEVs deployed, number of HRSs deployed, participant cities, project total costs and corresponding EU funding), and a short description of the original project objectives.

Table 1. Summary of the historical FCEV projects (early FCEV initiatives, mainly from FP4, FP5 and FP6).

Project	FP	Start/End	Project in numbers	Project Title and Summary of original Project Objectives
EIHP	FP4	1998-2000	n/a n/a n/a n/a n/a	*European Integrated Hydrogen Project.* This project was the first internationally integrated activity for the harmonization of rules, regulations and safety requirements jointly involving technology companies, vehicle operators and licensing authorities in the field of hydrogen technologies. It provided the basis for global harmonization initiatives in the field of hydrogen technologies. It contributed to the dissemination and formation of acceptability in Europe, making use of already developed European prototype technology and of initially available approval experience, available from only very few operators, authorities and technology companies at the time.
EIHP2	FP5	2001-2004	n/a n/a n/a 4.9 M€ 2.4 M€ (48%)	*European Integrated Hydrogen Project 2.* This project was the phase 2 of the previous EIHP project. Its goals were: 1) Development of a worldwide-harmonised regulation for hydrogen fuelled road vehicles; 2) Development of procedures for periodic vehicle inspections (roadworthiness); and 3) Development of a worldwide standard or regulation and of periodic inspection procedures for the relevant refuelling infrastructure, subsystems or components.
ACCEPTH2	FP5	2003-2005	n/a n/a London (UK) Luxemburg (LU) Munich (DE) 0.4 M€ 0.4 M€ (100%)	*Public Acceptance of Hydrogen Transport Technologies* This project aims to achieve a better understanding of the acceptance of hydrogen technologies to enable the introduction of hydrogen vehicles with a clear strategy towards public acceptance. The work compares public attitudes in London, Luxemburg, Munich, Perth and Oakland.

Project	FP	Start/End	Project in numbers	Project Title and Summary of original Project Objectives
ZERO REGIO	FP6	2004-2009	n/a n/a Rhein-Main (DE) Lombardia (IT) 18.7 M€ 7.5 M€ (40%)	*Lombardia & Rhein-Main towards Zero Emission: Development & Demonstration of Infrastructure Systems for Alternative Motor Fuels (Bio-fuels and Hydrogen)* This project aims to use hydrogen as an alternative motor fuel, produced as primary or waste stream in a chemical plant or via on-site production facilities. The specific goals of this project are: 1) Development of infrastructure systems for alternative motor fuels (bio-fuels & hydrogen) and integrating them in conventional refuelling stations; 2) Adaptation and demonstration of 700 bar refuelling technology for hydrogen; 3) Demonstration of high blends of bio-fuels in fuel flexible vehicles; 4) Demonstration of alternative fuels via. automobile-fleet field tests at two different urban locations in the EU, Rhein-Main, Germany and Lombardia, Italy; and 5) Showing ways and prospects for faster penetration of low-emission alternative motor fuels in the market at short and medium term.
HARMONHY	FP6	2005-2006	n/a n/a n/a 0.5 M€ 0.5 M€ (95%)	*Harmonisation of Standards and Regulations for a Sustainable Hydrogen and Fuel Cell Technology* This project aims to make an assessment of the activities on hydrogen and fuel cell related regulations and standards on a worldwide level. On this basis gaps will be identified and propositions to solve fragmentation will be made. The goal is to render European collaboration in the field as effective as possible and to increase its contribution at the worldwide level. Additionally, the result of the discussions could also serve as basis for further projects to be set up as response to the last call series of FP6.
HYLIGHTS	FP6	2006-2008	n/a n/a n/a 3.4 M€ 3.2 M€ (93%)	*A Coordination Action to Prepare European Hydrogen and Fuel Cell Demonstration Projects* This project focuses on performing an assessment of concluded/ongoing H_2/FC demonstration projects and recommendations for the preparation of HyCOM/Lighthouse Projects LP. Although HyLights's assessment focuses on transport, stationary and portable H_2 applications will be considered if synergies become apparent. The project comprises 3 phases: 1) Methodology definition and assessment; 2) Gaps analysis and development of recommendations; and 3) Continuous monitoring.
HYCHAIN MINI-TRANS	FP6	2006-2011	158 FCEV n/a Grenoble (FR) Modena (IT) Soria (ES) Emscher Lippe (DE) 37.6 M€ 17 M€ (45%)	*Deployment of Innovative Low Power Fuel Cell Vehicle Fleets to Initiate an Early Market for Hydrogen as an Alternative Fuel in Europe* This project has the objective to deploy fleets of innovative fuel cell vehicles in four regions in Europe (France, Germany, Spain and Italy) operating on Hydrogen as an alternative fuel. The fleets are based on similar modular technology platforms in a variety of applications with the main objective to achieve a large enough volume of vehicles (180) to justify an industrial approach to lower costs and overcome major cross-sectional barriers.

Project	FP	Start/End	Project in numbers		Project Title and Summary of original Project Objectives
NEXTHYLIGHTS	FP7	2010-2010		n/a	*Supporting Action to Prepare Large-Scale Hydrogen Vehicle Demonstration in Europe* This project will directly contribute to the FCH JU activities regarding the preparation of the next calls on hydrogen large-scale vehicle demonstration. It will use the Multi Annual Implementation Plan (MAIP) as the basis and will help to detail it taking the ambitions and opportunities of all stakeholders into account. The concept of the project is to develop a strategy (Master Plan) on how to bridge the gap between today's demo projects and the start of market introduction by building upon existing knowledge from various activities including: HFP & FCH JU (implementation plans), HyWays, R2H, HyLights (methods, instruments and databases), HyFleet:CUTE, ZERO REGIO, HYCHAIN and other demo projects.
				n/a	
				n/a	
				1.1 M€	
				0.5 M€ (44%)	

Source: JRC based on information from CORDIS, 2022.

Figure 4 (a) shows the organisations participating at the early FCEV initiatives described in Table 1, covering 9 projects in the period from 1998 until 2010, using the online software TIM. As mentioned before, the size of the nodes (circles) is proportional to the number of projects an organisation has been involved in whilst the thickness of the lines is proportional to the number of links (i.e. the number of projects partners have been involved in together). TIM uses a particular algorithm to cluster related items into a "Community" or "Cluster". Each community has a different colour. Basically, the coloured clusters identified by TIM are formed by partners that collaborate more frequently with each other because they share participation in the same projects.

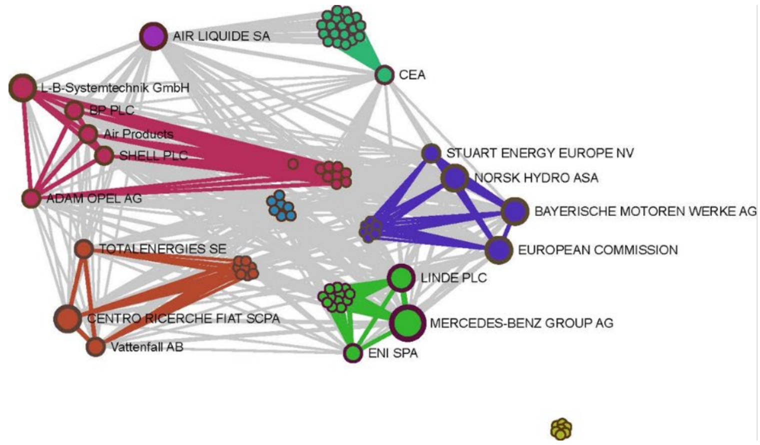
It can be noticed in Figure 4 (a) that a number of specific partners are common to a number of projects forming coloured clusters. Some of these clusters have a vehicle manufacturer and a hydrogen supplier/HRS developer, for example vehicle manufacturer Mercedes Benz with gas company Linde PLC sharing a number of projects. This is also observed in another cluster which includes BMW (vehicle manufacturer) with Stuart Energy (now Canadian Hydrogenics, hydrogen supplier). This shows a strong collaboration between FCEV manufacturers and HRS developers. It is also observed another type of cluster formed by gas companies/HRS components manufacturers such as Shell PLC, BP PLC, Air products, etc.). This shows an effective collaboration among the hydrogen supply / HRS companies, sharing projects. The organisations that participated in the most FCEV projects covering the period 1998-2010 were Mercedes-Benz group (vehicle manufacturer), L-B Systemtechnik GmbH (energy consultancy) and the European Commission (research institution).[9]

Figure 4 (b) shows that the countries that were active in the greatest number of FCEV projects during this period tend to be the larger European economies. The size of the circles represents the number of projects that contain at least one consortium member from that EU member state. The thickness of the links between the circles shows the number of projects in common. The member state that participated in the most projects was Germany, followed by The Netherlands and Italy.

[9] The organisation described as "European Commission" refers mainly to European Commission DG JRC.

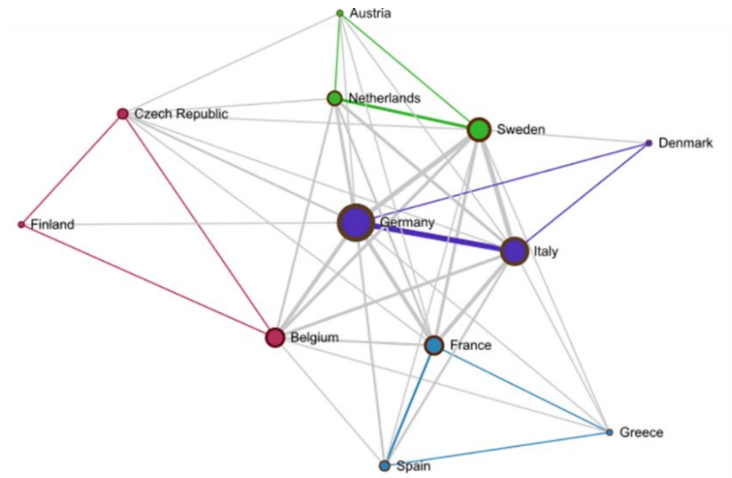
Figure 4. TIM plots showing (a) the participants for all 9 projects considered in Table 1 (early FCEV initiatives 1998-2010).[10][11] (b) EU Member State participation for all 9 projects considered in Table 1 (early FCEV initiatives 1998-2010).[12]

a)



Organisation	Number of Projects
MERCEDES-BENZ GROUP AG	4
L-B-Systemtechnik GmbH	3
EUROPEAN COMMISSION	3
AIR LIQUIDE SA	3
BAYERISCHE MOTOREN WERKE AG	3
NORSK HYDRO ASA	3
LINDE PLC	3
CENTRO RICERCHE FIAT SCPA	3
Air Products	2
ADAM OPEL AG	2

b)



Member State	Number of Projects
Germany	8
Netherlands	5
Italy	5
Belgium	4
United Kingdom	4
Norway	4
France	4
Sweden	3
Spain	3
Czech Republic	2

Source: JRC (TIM) based on data from CORDIS, 2022.

([10]) The size of the node represents the number of projects a partner is involved in, whilst the thickness of the links represents the number of projects in common between the linked partners. The coloured groupings are potential clusters identified by TIM's algorithm. The table shows the top 10 participants from the plot.

[11] The organisation described as "European Commission" encompasses participation from the following sub-institutions found in CORDIS: "DG JRC", "Commission of the European Communities" and "Hydrogen Fuel Cells and Electro-Mobility in European Regions".

([12]) The size of the node represents the number of projects that has at least one participating organisation from that member state. The thickness of the links between the nodes is proportional to the number of projects those member states have in common. The United Kingdom does not appear in the graph as it is not a current EU member state. The table shows the top 10 countries represented, including the United Kingdom (an EU member state when the project was awarded) for comparison.

3.1.2 Overview of Clean Hydrogen JU FCEVs demonstration projects

The following table contains a summary of all the relevant FCEVs demonstration projects that have provided input values used in this report (Table 2). These projects belong to the FCH JU Panel 1 category (Trials and Deployment of Fuel Cell Applications – Transport) and focus on the large-scale demonstration of the FCEV in Europe (deployment and performance monitoring). The table includes the project acronym, the corresponding FP, the duration (start/end year), the project metrics (number of FCEVs deployed, number of HRSs deployed, participant cities, project total costs and corresponding EU funding), and a short description of the original project objectives. These projects belong now to the Clean Hydrogen JU Pillar 3 category (Transport).

Table 2. Summary of all Clean Hydrogen JU FCEV demonstration projects analysed in this report (2010-2023).

Project	FP	Start/End	Project in numbers		Project Title and Summary of original Project Objectives
H2movesSCANDINAVIA	FP7	2010-2012		19 FCEV 1 HRS DK NO 18.7 M€ 7.7 M€ (41%)	*H2moves.eu Scandinavia.* First EC funded European Lighthouse Project (LHP) for FCEVs, a cluster of European demonstration projects on hydrogen for transport. A state-of-the-art HRS is to be integrated in a conventional refuelling station in Oslo. The objective is to provide hydrogen in a normal retail setting with a fully integrated purchase interface and in an urban environment. 10 Mercedes-Benz B-class F-CELL cars and 2 Alfa Romeo MiTo FCEVs from Centro Ricerche FIAT are to be provided for daily operation in Oslo, southern Norway and the Scandinavia region. Additionally, 5 city cars from H2 Logic driving within Oslo are to complete the fleet (BEV with FC range extender). 2 FCEVs are to be employed at 5 European hydrogen demonstration tours and a safety study to identify certification gaps to accelerate full commercialisation of FCEVs and HRS is to be performed.
HYTEC	FP7	2011-2015		30 FCEV 4 HRS DK NO UK 29.3 M€ 11.9 M€ (41%)	*Hydrogen Transport in European Cities.* Create 2 new European hydrogen passenger vehicle deployment centres in London and Copenhagen. The objective is to implement stakeholder inclusive vehicle demonstration programmes that specifically address the challenge of transitioning hydrogen vehicles from running exemplars to fully certified vehicles utilised by end-users. 25 new FCEVs in the hands of real customers (5 taxis and 19 passenger cars) are to be demonstrated. Additionally, FC hybrid scooters are to be demonstrated as proof of concept in London and Ride and Drive events. New HRS are to support these FCEVs deployments leading to 2 new city based networks for hydrogen refuelling: 1) on-site production in Copenhagen and 2) hydrogen delivery in London. A well to wheels life cycle analysis of the FCEVs and HRS is to be performed.
SWARM	FP7	2012-2018		34 FCEV 3 HRS BE DE UK 15.3 M€ 6.7 M€ (44%)	*Demonstration of Small 4-Wheel fuel cell passenger vehicle Applications in Regional and Municipal transport* Establish a demonstration fleet of small passenger FCEVs that builds on and expands existing hydrogen refuelling infrastructure. Three European regions participate: the UK (the Midlands and Wales), Belgium (the Brussels area and Wallonia), and North Rhine Westphalia Germany (Cologne/Weser Ems). 3 new hydrogen refuelling sites are to be added to develop continuous 'hydrogen highways' from Scotland via the Midlands to London, connecting to Brussels and on to Cologne and Hamburg/Scandinavia/Berlin. 34 FCEVs are to be deployed by 3 organisations. These FCEVs are to be driven in a variety of real-life operating environments. An extensive data monitoring exercise is to be performed throughout the demonstration phase to evaluate the FCEVs reliability and make recommendations for the improvement of fully commercial vehicle designs.

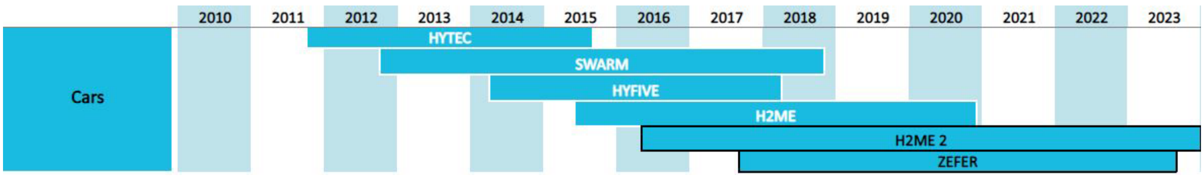
Project	FP	Start/End	Project in numbers		Project Title and Summary of original Project Objectives
HYFIVE	FP7	2014-2018		145 FCEV	*Hydrogen for innovative vehicles* Aims to deploy 185 FCEVs from 5 global automotive companies (BMW, Daimler, Honda, Hyundai and Toyota). Refuelling stations configured in viable networks will be developed in three distinct clusters by deploying 6 new stations linked with 12 existing stations. The project will tackle the final technical and social issues, which could prevent the commercial roll-out of hydrogen vehicle and refuelling infrastructure across Europe.
				6 HRS	
				AT DE DK IT SE UK	
				39.1 M€	
				18 M€ (46%)	
H2ME	H2020	2015-2020		357 FCEV	*Hydrogen Mobility Europe* Hydrogen Mobility Europe (H2ME) brings together 4 national initiatives on hydrogen mobility (Germany, Scandinavia, France and the UK). The project will expand their developing networks of HRS and the fleets of fuel cell vehicles (FCEVs) operating on Europe's roads, to significantly expand the activities in each country and start the creation of a pan-European hydrogen fuelling station network. This will include trialling a large fleet of 325 FCEVs in diverse applications across Europe and deploying 29 refuelling stations.
				27 HRS	
				DE DK FR IS NO SE UK	
				62.3 M€	
				32 M€ (51%)	
H2ME 2	H2020	2016-2023		560 FCEV	*Hydrogen Mobility Europe 2* This project will address the innovations required to make the European hydrogen mobility sector truly ready for market. The project will perform a large-scale market test of hydrogen refuelling infrastructure, passenger and commercial fuel cell electric vehicles operated in real-world customer applications and demonstrate the system benefits generated by using electrolytic hydrogen solutions in grid operations. H2ME 2 will deploy 1,230 new hydrogen fuelled vehicles trebling the existing fuel cell fleet in Europe.
				12 HRS	
				CH DE DK FR IS NL NO SE UK	
				108.4 M€	

Project	FP	Start/End	Project in numbers	Project Title and Summary of original Project Objectives
			35 M€ (32%)	
ZEFER	H2020	2017-2023	180 FCEV 3 HRS DK FR UK 13.7 M€ 5 M€ (36%)	*Zero Emission Fleet vehicles For European Roll-out* ZEFER will demonstrate viable business cases for captive fleets of Fuel Cell Electric Vehicles in operations which can realise value from hydrogen vehicles, for example by intensive use of vehicles and HRS, or by avoiding pollution charges in city centres with applications where the refuelling characteristics of FCEVs suit the duty cycles of the vehicles. ZEFER aims to drive sales of FCEVs in these applications to other cities, thereby increasing sales volumes of FCEVs and improving the business case for HRS serving these captive fleets. ZEFER will deploy 180 FCEVs in Paris, Brussels and London (Brussels replaced by Copenhagen). 170 FCEVs will be operated as taxi or private hire vehicles, and the remaining 10 will be used by the police.

Source: JRC based on information from the Clean Hydrogen JU, 2023.

Figure 5 shows the timeline of the 7 FCEVs demonstration projects assessed in this report covering the period from 2010 until 2022.

Figure 5. Timeline of all FCEV demonstration projects analysed in this report



Source: Clean Hydrogen JU, 2023

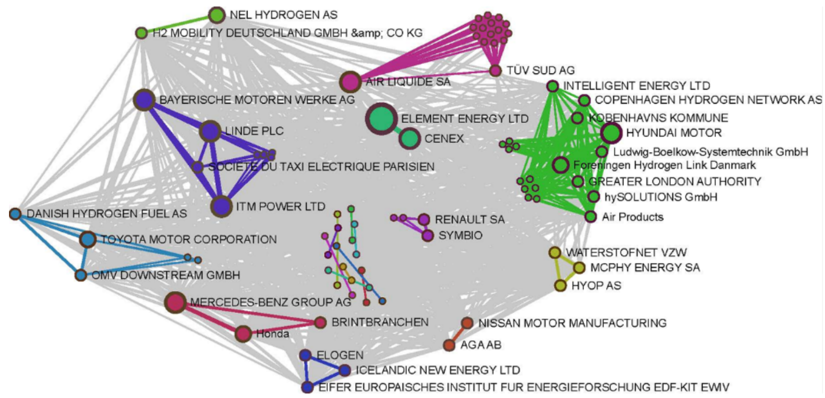
TIM visualisation was also employed to analyse the trends on organisations and countries participating on these 9 projects. Figure 6 (a) shows organisations involved in the Clean Hydrogen JU FCEV demonstration projects. We can observe many clusters formed among the same type of companies, i.e. vehicle manufacturers (cluster formed by Mercedes-Benz group and Honda), energy consultancies (cluster formed by Element Energy and Cenex), etc. However, other clusters usually include vehicle manufacturers, gas companies/HRS developers and transport companies (taxi operators). This is the case of the cluster formed by BMW (vehicle manufacturer), Linde PLC (gas company/hydrogen supplier), ITM Power (hydrogen supplier) and Societé du Taxi Electric Parisien (taxi operator's society). The inclusion of taxi operators in the clusters that were traditionally formed by vehicle manufacturers and HRS developers is a positive shift showing the creation of business cases with FCEVs. Other organisations complementing the different clusters are fuel cell companies and research institutions. The organisations that participated in the most FCEV projects covering the period 2010-2022 were Element Energy LTD (energy consultancy), Mercedes-Benz group (vehicle manufacturer) and Hyundai Motor Europe GmbH (vehicle manufacturer).

Comparing the organisations participating in previous FCEVs projects from FP4 to FP6 (Figure 4 (a)) with the Clean Hydrogen JU FCEV demonstration projects (Figure 6 (a)), it is observed an historical shift from early projects composed of vehicle manufacturers, HRS developers, FC providers and scientific institutions to new projects mainly composed of FCEV manufacturers, HRS developers, FCEV operators/cities and consultants (data collection, coordination). This is showing the evolution from new technology developments to commercialisation and use of FCEVs for captive fleets.

Figure 6 (b) shows that the trend observed on participating countries from the FCEV early initiatives (see Figure 4 (b)) continues with the Clean Hydrogen JU FCEV demonstration projects. The country that was active in the greatest number of FCEV projects is again Germany. However, differing from the early FCEV initiatives it is Belgium and the United Kingdom that followed in project participation in the 2010-2022 period.

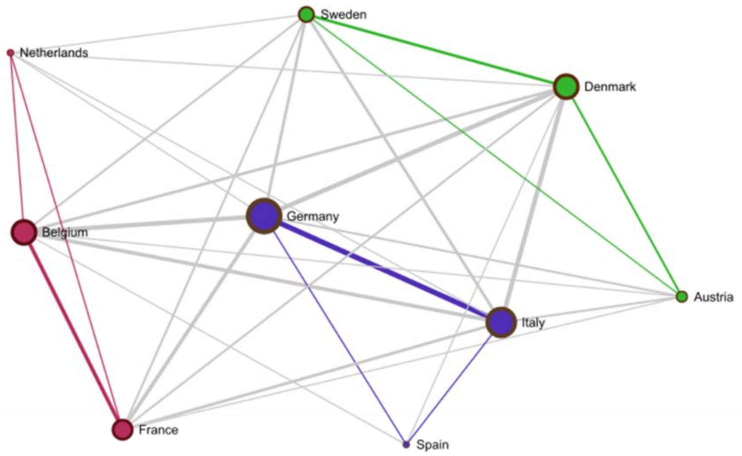
Figure 6. TIM plots showing (a) the participants for the 9 Clean Hydrogen JU FCEV demonstration projects (2010-2022).[13] (b) EU member state participation for the 9 Clean Hydrogen JU demonstration projects (2010-2022).[14]

a)



Organisation	Number of Projects
ELEMENT ENERGY LTD	6
MERCEDES-BENZ GROUP AG	4
Europe GmbH	4
Centre of Excellence	4
AIR LIQUIDE SA	4
LINDE PLC	4
ITM POWER LTD	4
BAYERISCHE MOTOREN WERKE AG	4
Foreningen Hydrogen Link Danmark	3
NEL HYDROGEN AS	3

b)



Member State	Number of Projects
Germany	7
Belgium	6
United Kingdom	6
Denmark	5
Italy	4
France	4
Norway	3
Sweden	3
Austria	3
Iceland	2

Source: JRC (TIM) based on data from Clean Hydrogen JU, 2022.

It is worth mentioning that the Clean Hydrogen JU funded additional projects that further contributed to the demonstration of the FCEV technology. These projects belong to FCH JU Panel 5 (Hydrogen for Sectoral Integration) and intend to develop hydrogen valleys in which the use of FCEVs is not the main objective, hence

([13]) The size of the node represents the number of projects a partner is involved in, whilst the thickness of the links represents the number of projects in common between the linked partners. The coloured groupings are potential clusters identified by TIM's algorithm. The table shows the top 5 participants from the plot.

([14]) The size of the node represents the number of projects that has at least one participating organisation from that member state. The thickness of the links between the nodes is proportional to the number of projects those member states have in common. The United Kingdom does not appear in the graph as it is not a current EU member state. The table shows the top 10 countries represented, including the United Kingdom (an EU member state when the project was awarded) for comparison.

these projects were not included in the analysis. A summary of the hydrogen for sectoral integration projects that include deployment of few FCEVs is contained in Table 3.

Table 3. Summary of Clean Hydrogen projects on hydrogen sectorial integration with FCEVs deployment.

Project	FP	Start/End	Project in numbers	Project Title and Summary of original Project Objectives
BIG HIT	H2020	2016-2021	5 FCEVs 1 HRS Orkney Islands (UK) 7.7 M€ 5 M€ (64%)	*Building Innovative Green Hydrogen systems in an Isolated Territory: a pilot for Europe.* This project aims to create a replicable hydrogen territory in Orkney (Scotland) by implementing a fully integrated model of hydrogen production, storage, transportation and utilisation for heat, power and mobility. The project will use the energy from two wind turbines and tidal turbines on the islands of Eday and Shapinsay, to produce 50 t pa of hydrogen with a 1.5MW PEM electrolyser. This will be used to heat two local schools, and transported by sea to Kirkwall in 5 hydrogen trailers, where it will be used to fuel a 75kW fuel cell (which will provide heat and power to the harbour buildings, a marina and 3 ferries when docked), and a refuelling station for a fleet of 10 fuel cell vehicles.
HEAVENN	H2020	2020-2025	4 FCEVs n/a Eemshaven (NL) Delfzijl (NL) Zuidwending (NL) Emmen (NL) Hoogeveen (NL) Groningen (NL) 96.2 M€ 20 M€ (21%)	*Hydrogen Energy Applications for Valley Environments in Northern Netherlands.* This is a sizeable demonstration project aimed at the development of a methodology to design a fully integrated and functioning 'hydrogen valley'. By bringing together the central elements of hydrogen production, distribution, storage and local-end use, the goal is to demonstrate how this hydrogen valley could (through the use of green hydrogen across the value chain) reduce carbon emissions as well as potentially benefit businesses along its value chain. The hydrogen produced will be used as: 1) Storage medium to manage intermittent renewable inputs in the electricity grid; and 2) Energy vector for the decarbonisation across other energy sectors beyond electricity, namely industry, heat and transportation.
GREEN HYSLAND	FP7	2012-2025	10 FCEVs 5 FCEBs 1 HRS Mallorca island (ES) 20.4 M€ 10 M€ (48.9%)	*Deployment of a H2 Ecosystem on the Island of Mallorca* This project aims at deploying a fully-integrated and functioning H_2 ecosystem in the island of Mallorca, Spain. The project brings together all core elements of the H_2 value chain i.e. production, distribution infrastructure and end-use of green hydrogen across mobility, heat and power. The goal is the integration of 6 deployment sites in the island of Mallorca, including 7.5MW of electrolysis capacity connected to local PV plants and 6 FCH end-user applications, namely buses and cars, 2 CHP applications at commercial buildings, electricity supply at the port and injection of H_2 into the local gas grid. The intention is to facilitate full integration and operational interconnectivity of all these sites.

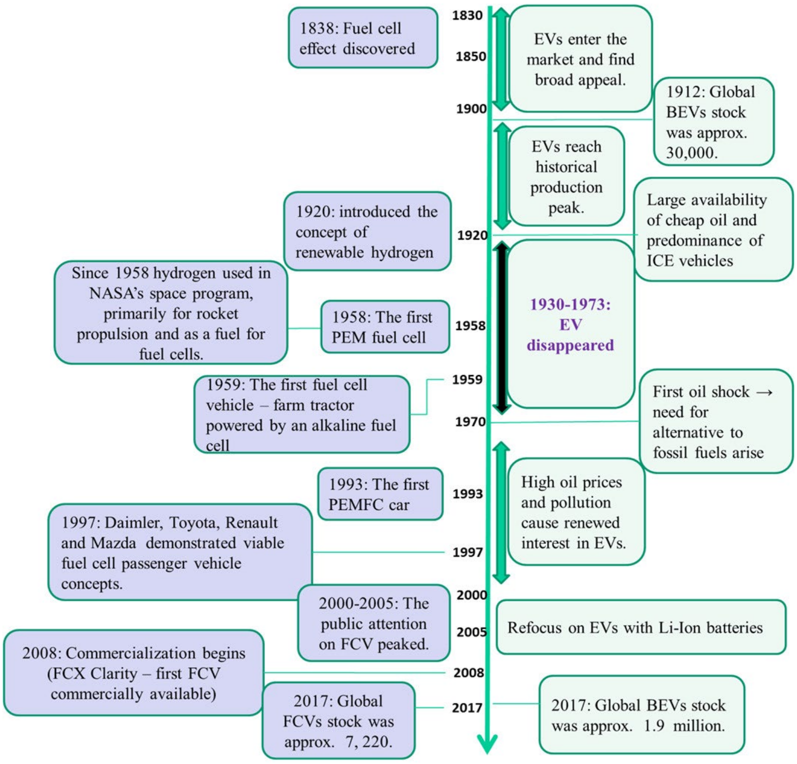
Source: JRC based on information from the Clean Hydrogen JU, 2023.

3.1.3 State of the Art

3.1.3.1 Technical development

The development of FCEV dates back to 1838 when fuel cells and their effects were discovered. Figure 7 shows the FCEV development timeline compared to the battery electric vehicles (BEV) timeline (Ajanovic and Haas, 2019). It can be noticed that since the oil crises of the 1970s, FCEV development intensified. That crisis launched interest in hydrogen fuel cells in the absence of adequate batteries for electric vehicles.

Figure 7. Major steps in the development of FCEVs compared to BEVs.



Source: Ajanovic and Haas, 2019

As seen in Figure 7, the global development and commercialisation of FCEV can be understood in four stages (Luo et al., 2021). The first stage covers the period before the year 2000 when major automobile manufacturers launched their own FCEV prototypes. The second stage comprises the decade 2000-2010. In this period the key technologies of FCEVs were developed, demonstrated, tested, and validated. Technical advances made during the development of the prototype/concept cars led to the launch of newer models reaching the highest technological readiness level (TRL9). The third stage covers the period 2010-2015 where FCEVs were partially commercialised in specific areas of the world. The fourth and last stage continues from 2015 until today with the main FCEV manufacturers entering a production phase. Table 4 shows the models that entered the production phase and were commercially available. By the end of 2021, the global hydrogen vehicle stock (FCEV, FCEB and trucks) was more than 51.000, up from about 33.000 in 2020, representing the largest annual deployment of hydrogen vehicles since they became commercially available in 2014 (International Energy Agency, 2023). This translates to a 42,000 FCEV stock by the end of 2021.

Table 4. FCEVs that entered production phase and were commercially available

Honda	Toyota	Hyundai	Mercedes Benz
FCX Clarity	Mirai I	Hyundai ix35/Tucson Fuel Cell	GLC F-Cell
Clarity Fuel Cell	Mirai II	Nexo	

Source: PwC data aggregation from publicly available data from various manufacturers

The technical specifications from the vehicles that entered the production phase can be observed in Table 5. The technical specifications of the vehicles (fuel cell power capability, storage capacity, range, and hydrogen consumption) have clearly improved globally over the last few years. This can be observed in detail in Figure 8. In terms of fuel cell power rating, the latest models (Hyundai Nexo and Toyota Mirai II) surpassed the initial power capability of the earlier models (Honda FCX Clarity, Hyundai ix35 and Toyota Mirai I). However, the highest FC power capability was the one installed in the Daimler (Mercedes-Benz) GLC model, now discontinued, with 155 kW. Another significant trend is the rising power density in the powertrains of newer models.

Looking at storage capacities, the newest models (Hyundai Nexo and Toyota Mirai II) have increased their storage capacity by 12% in comparison to their predecessors (Hyundai ix35 and Toyota Mirai I, respectively). The largest storage capacity has been achieved by the Hyundai Nexo with 6.33 kg of hydrogen. This translates in a drive range increase with Hyundai Nexo and Toyota Mirai II leading the charts with 666 and 650 km, respectively.

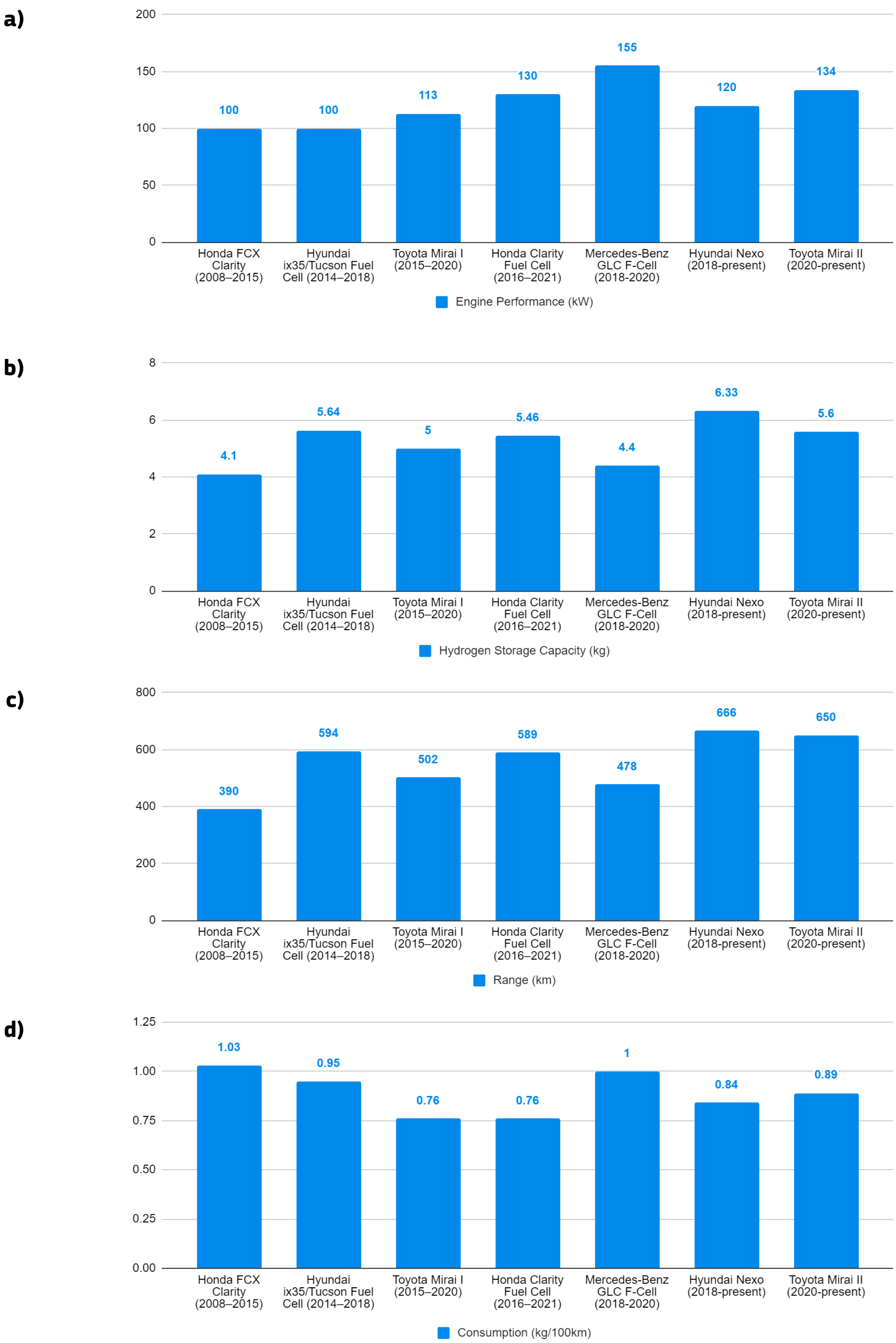
Regarding hydrogen consumption, the newest models (Hyundai Nexo and Toyota Mirai II) have managed to decrease it significantly, compared to the earlier models (Honda FCX Clarity and Hyundai ix35). However, the lowest hydrogen consumption (so higher fuel efficiency) was achieved by the Toyota Mirai I and Honda Clarity Fuel Cell. It must be noted that these values of Toyota Mirai I and Honda Clarity Fuel Cell were measured under the New European Drive Cycle (NEDC) and the measurements in the newest models are done accordingly with the Worldwide Harmonized Light Vehicles Test Procedure (WLTP), influencing slightly the values.

Table 5. Specifications of FCEVs that were mass produced and were commercially available

Model	Honda FCX Clarity	Hyundai ix35/Tucson Fuel Cell	Toyota Mirai I	Honda Clarity Fuel Cell	Mercedes-Benz GLC F-Cell	Hyundai Nexo	Toyota Mirai II
Year	2008–2015	2014–2018	2015–2020	2016–2021	2018-2020	2018-present	2020-present
Price	Leasing only US$600	60,181€ - 80,611€ Leasing - 625€	73,261€ (new)	60,839€	Full service rental model in Germany	60,703€	51,523€ - 63,900€
Fuel cell stack	100 kW Honda Vertical Flow (V Flow) hydrogen fuel cell stack (Proton Exchange Membrane Fuel Cell)	100 kW (136 ps) Hyundai cell stack	FCA110 Toyota Fuel Cell System, 370 cells, 113 kW output	103 kW, 358 cells, 33 l volume, 52 kg weight	Daimler subsidiary NuCellSys polymer electrolyte fuel cells, 155 kW stack	95 kW 440 cells 3.1 kW/l power density @ 0.6 V 60% system efficiency	330 cells, 102 g cell weight, 128 kW max. output, 5.4 kW/l volume power density, 5.4 kW/kg mass power density, 29 L volume / 32 kg weight
Volumetric Power Density	n/a	1.35 kW/L	3.1 kW/L	3.12 kW/L	n/a	3.1 kW/L	5.4 kW/L
Storage capacity	4.1 kg at 345 Bar	5,64 kg at 700 Bar	122.4 L (front tank: 60.0L / rear tank: 62.4L) 5kg	700 bar, 5.46 kg hydrogen 141 L overall capacity, 2 tanks, 24 L and 117 L	2 carbon fibre tanks (Daimler subsidiary NuCellSys) 700 bar, 4,4 kg	6.33 kg hydrogen 156.6 L overall capacity, 3 tanks, each 52.2 l	700 bar working pressure, 875 bar max. filling pressure, 5.6 kg fuel capacity 24 kg weight, 3 tanks
Engine	Fuel cell-powered 100 kW (130 hp) AC synchronous electric motor (permanent magnet)	Electric engine rated at 100 kW (134 hp)	4JM Permanent magnet synchronous motor 113 kW, 154 bhp	AC permanent magnet synchronous motor, 130 kW power output, 300 Nm max. torque	Electric motor, powered by fuel cell and 13.5kWh battery 155 kW; 208 hp 365 Nm	Permanent magnet motor 120 kW power output 395 Nm. max. torque	Permanent magnet, synchronous 134 kW max. power 300 Nm max. torque
Range	390 km NEDC	594 km NEDC	502 km NEDC	589 km NEDC	478 km	666 km WLTP, 756 km NEDC	650 km WLTP
Consumption	1,03 kg/100 km (NEDC)	0,95kg/100km (NEDC)	0.76kg/100km (NEDC)	0.76 kg/100 km (NEDC)	1kg/100 km (0.34kg/100km in Hybrid mode)	095 kg/100 km (WLTP)	0.89 kg/100 km combined (WLTP)
Battery type	Lithium-Ion Battery	24 kW Lithium-Ion Battery	Sealed nickel-metal hydride (NI-MH), 34 battery cell modules	Lithium-Ion Battery	lithium-Ion Battery	Lithium-Ion Battery	Lithium-Ion Battery
Battery capacity	n/a	0.95 kWh	1.6 kWh	1.7 kWh	13.5 kWh	1.56 kWh	1.2 kWh
Hydrogen storage max pressure	350 bar Type III	700 bar Type IV	700 bar Type IV	n/a	700 bar Type IV	700 bar Type IV	n/a

Source: PwC, Study on State of the Art of FCEV, FCB and HRS

Figure 8. Evolution of fuel cell power (kW), storage capacity (kg), range (km) and hydrogen consumption (kg/100)



Source: PwC, Study on State of the Art of FCEV, FCB and HRS

Looking at fuel cell range extender vehicles (FC REEVs), there has been significant developments in Europe. These vehicles, also known as fuel cell plug-in hybrid vehicles, use a battery as the primary source of power. The battery can be charged from the grid, like a typical electric vehicle, and provides power for most driving. The hydrogen fuel cell is used as a range extender to provide additional driving range. When the charge of the battery gets low, the fuel cell kicks in to generate electricity and recharge the battery, allowing the vehicle to drive further than it could on battery power alone. Symbio (joint venture formed by Faurecia and Michelin) has produced hydrogen fuel cell systems which were integrated in the Renault Kangoo ZE converting the original car in a range extender (dual energy) vehicle. Renault-Symbio has already deployed more than 700 fuel cell range extender vans in Europe, while participating in Clean Hydrogen JU projects such as H2ME, H2ME 2 and BIG HIT. The technical specifications from the Renault Kangoo ZE Hydrogen can be observed in Table 6. Additionally, some smaller manufacturers have developed two-wheel and four-wheel fuel cell range extender vehicles such as the Riversimple car deployed in the project SWARM.

Table 6. Specifications of fuel cell range extender vehicles commercially available in Europe

Model	**Kangoo ZE Hydrogen**
Year	2019
Price	48,300€
Fuel cell stack	Symbio "StackPack" 5kW
Volumetric Power Density	n/a
Storage capacity	Model 350 Bar: 74 L at 350 Bar Model 700 Bar: 74 L at 700 Bar
Engine	Electric motor rated at 44 kW (60 hp)
Range	370 km (WLTP)
Consumption	0,9 kg/100km
Battery type	33 kWh Lithium-Ion Battery
Hydrogen storage max pressure	Model 350 Bar: 350 Bar Type IV Model 700 Bar: 700 Bar Type IV

Source: (Renault Press, 2019)

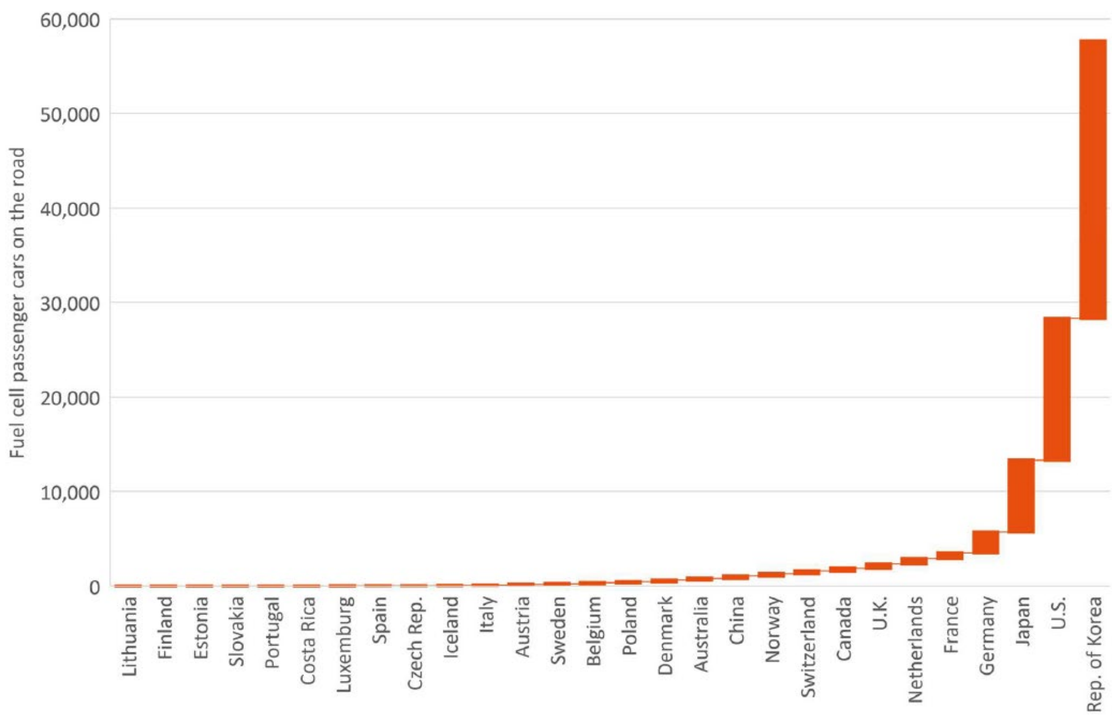
3.1.3.2 Manufacturing

From the analysis performed by PWC on FCEV manufacturing and sales data from 2008 to 2020 based on the IHS Markit, it can be concluded that the Republic of Korea and Japan are the two largest manufacturers of commercial FCEV vehicles. The Asian region has surpassed the European market, and the currently available models (Toyota Mirai II, Hyundai Nexo) are dominating the global market taking up 89.52% of all FCEV production (commercially available). The vehicles that were initially produced by European manufacturers (i.e. GLC F-Cell by Daimler/Mercedes-Benz) seemed to have stopped production due to high manufacturing costs. However, European manufacturers continue developing FCEV concept cars and prototypes (i.e. BMW iX5 Hydrogen). Looking at fuel cell engine manufacturing, Japanese and Korean manufacturers are the leading players again, with China taking the second position with less than 4% of the production and installation of the above mentioned two countries.

3.1.3.3 Deployment

According to recent data, the worldwide fleet of FCEV (passenger cars) has surpassed 57,000 units by the end of 2022, see Figure 9 (Can and Rex, 2023) (International Energy Agency, 2023). The Republic of Korea is leading the deployment of FCEV with 51% of the worldwide fleet (29,337 FCEVs), followed by the United States (26%; 14,979 FCEVs), Japan (13%; 7619 FCEVs), and Germany (4%; 2201 FCEVs).

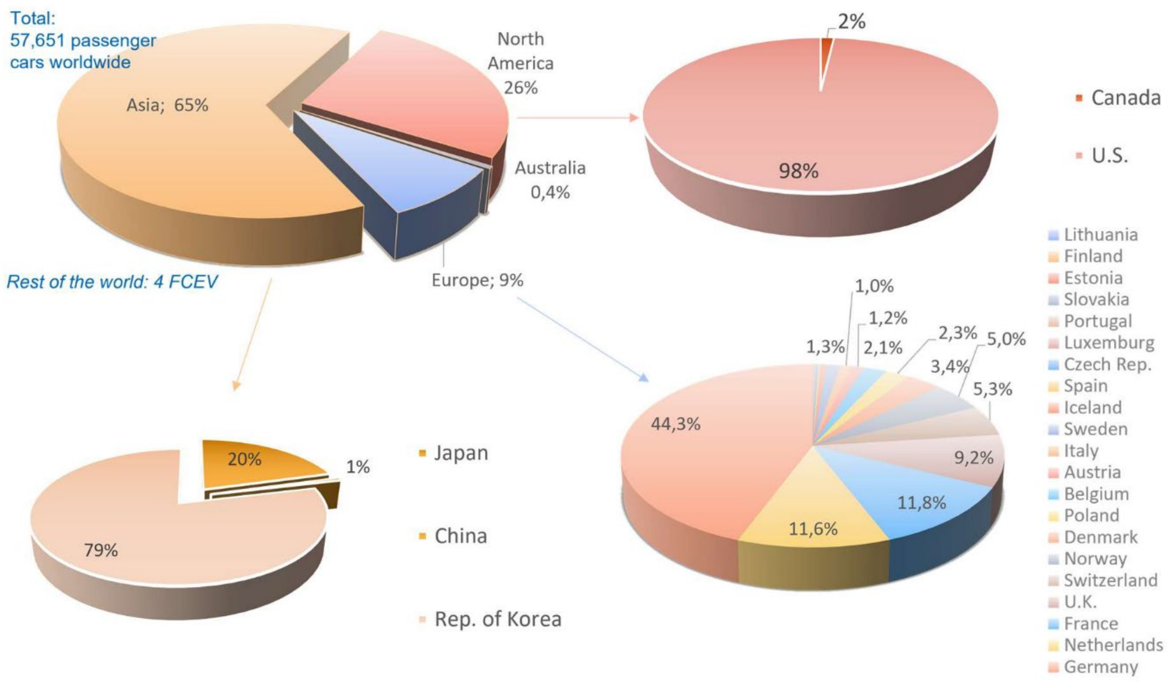
Figure 9. Waterfall diagram showing the breakdown of FCEV (passenger cars) worldwide



Source: (Can and Rex, 2023)

Figure 10 shows that the Asian region is leading the deployment of FCEV with 65% of the fleet, followed by North America (26%) and Europe (9%). Within the regions, the Republic of Korea takes the lead in Asia (79%) followed by Japan (20%) and China (1%). US has the majority of the fleet in North America (98%), followed by Canada (2%). Germany tops the charts in Europe (44.3%), followed by France (11.8%) and The Netherlands (11.6%).

Figure 10. Shares of FCEV (passenger cars) over continents, detailing the contributions within Asia, America and Europe.



Source: (Can and Rex, 2023)

There have been numerous developments on the fuel cell vehicles sector worldwide in recent years. Regarding passenger vehicles, Jaguar Land Rover disclosed the trial of a passenger fuel cell vehicle prototype in June 2021 (Jaguar Land Rover, 2021). This venture was partially sponsored by the UK government. Riversimple revealed a hydrogen fuel cell car prototype in February 2022 (Riversimple, 2022), followed by Changan's launch of a fuel cell variant of their large sedan model in July 2022 (Energy News, 2022). This marked the first-ever mass-produced hydrogen fuel cell car in China. BMW set a goal to manufacture a small series of the iX5 Hydrogen fuel cell vehicle by late 2022, having successfully completed winter weather tests (BMW, 2022). The BMW iX5 Hydrogen pilot fleet was finally launched early 2023 (BMW, 2023). Aditionally, Great Wall Motors launched a high-end brand specialising in hydrogen fuel cell passenger cars end of 2022 (Fuel Cell Works, 2022). Renault has also disclosed plans for an electric concept car featuring a hydrogen fuel cell range extender, set to be revealed in 2024 (Renault, 2023).

Regarding vans, Hyundai is expanding its selection of fuel cell vehicle models and has declared intentions to release a fuel cell multi-functional vehicle (TopElectricSUV, 2023). In Japan, joint development of light-duty commercial trucks is planned by Hino Motors, Isuzu, Toyota and Commercial Japan Partnership Technologies Corporation (Hino, 2022). Meanwhile, in Europe, several Stellantis brands, including Citroën, Peugeot and Opel, have started introducing hydrogen light commercial vehicles, which have been available since 2023 (Stellantis, 2023).

3.1.4 Progress against the State of the Art

3.1.4.1 Early FCEVs initiatives (2000-2010)

The early projects under Framework Programme 4, 5 and 6 (FP4, FP5 and FP6) made significant strides in harmonizing regulations, streamlining licensing processes, and fostering public acceptance. These initiatives were part of a larger European Union strategy aimed at promoting sustainable and clean energy technologies.

Each of these projects played a crucial role in shaping the future of FCEVs, see Table 1. For instance, the EIHP and its successor EIHP2 project worked on the harmonization of codes and standards for hydrogen refuelling infrastructure. The ACCEPTH2 project focused on public acceptance and awareness of hydrogen-based technologies. ZERO REGIO was a demonstration project showcasing the use of hydrogen in transport and energy systems.

Meanwhile, HARMONHY and HYLIGHTS aimed at drafting regulations for hydrogen vehicles and infrastructure, while the HYCHAIN MINI-TRANS project worked on deploying fleets of small hydrogen vehicles for urban transport. NEXTHYLIGHTS, on the other hand, aimed to prepare for the next generation of hydrogen light-duty vehicles.

These early projects under FP4, FP5, and FP6 established a solid foundation for the Clean Hydrogen JU demonstration projects under the Seventh Framework Programme (FP7).

Building upon the regulatory, licensing, and public acceptance groundwork laid by the earlier programmes, the projects under FP7 were designed to demonstrate the real-world viability and benefits of FCEVs and hydrogen technologies. This included a focus on the performance, durability, and efficiency of these technologies, as well as their potential for integration into existing transport and energy systems.

Collectively, the efforts of these projects across FP4, FP5, FP6, and FP7 have been instrumental in propelling the development and acceptance of FCEVs and clean hydrogen technologies, paving the way towards a more sustainable and clean energy future.

3.1.4.2 Clean Hydrogen JU projects (2011-2023)

The focus of the Clean Hydrogen JU in the FCEV area has been the demonstration, progress and validation of the FCEV technology and its refuelling infrastructure. The aim was accelerating the market penetration of fuel cell technology for vehicles deployed in Europe, demonstrating market readiness as well as developing the necessary infrastructure (refuelling networks) at a competitive cost. The projects funded by the Clean Hydrogen JU from 2010 onwards have also allowed the collection of a significant amount of FCEVs performance data which facilitated the assessment of MAWP KPIs (Multi-Annual Work Plan of the Fuel Cells and Hydrogen 2 Joint Undertaking).

Early Clean Hydrogen JU FCEV projects (2011-2014)

Early Clean Hydrogen JU FCEV projects under FP7 (H2MOVES SCANDINAVIA, HYTEC, SWARM and HYFIVE) mainly focused on the deployment of the state-of-the art HRS and FCEV fleets at different European sites, validating and monitoring the progress of the FCEV technology.

H2MOVES SCANDINAVIA project was the first Clean Hydrogen JU project showcasing the reliability and market preparedness of FCEVs, testing them under harsh climate conditions (Oslo and Copenhagen sites). H2MOVES SCANDINAVIA had also a pioneering role in developing links and collaborations between different industry stakeholders.

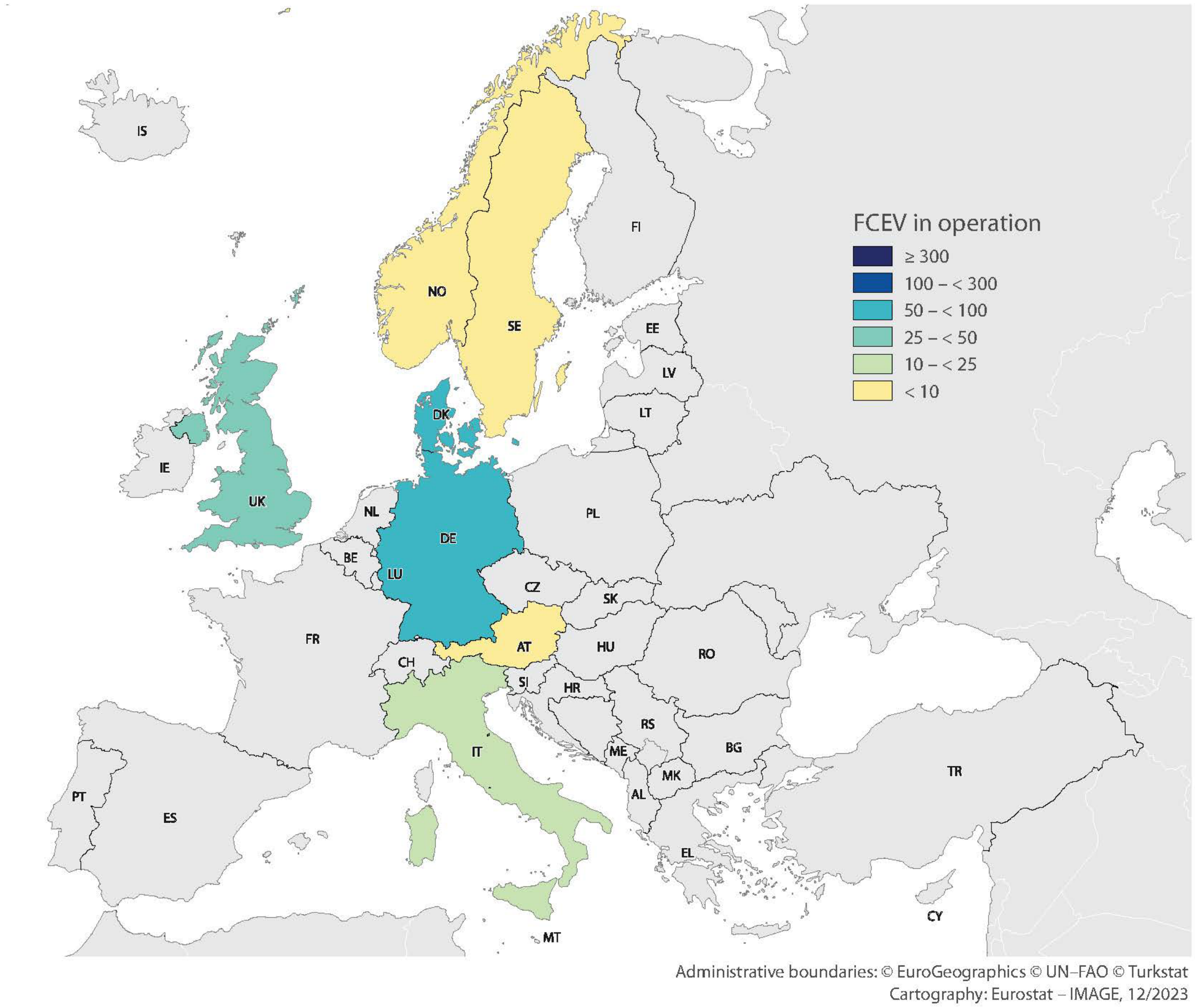
HYTEC project continued the H2MOVES SCANDINAVIA efforts by expanding the existing European network of hydrogen demonstration sites in Denmark and the United Kingdom. The overall achievement of this project was to successfully implement a demonstration programme that specifically addressed the challenge of transitioning hydrogen vehicles from prototypes to fully commercial vehicles, used by a range of drivers in real-world conditions. Another major achievement of the project was the construction of a network of HRS in the two main deployment centres of Copenhagen and London.

The SWARM project expanded on the European FCEV demonstration activities. The project aimed to establish demonstration FCEV fleets (90 vehicles) supporting and expanding the existing hydrogen refuelling infrastructure across three clusters: British Midlands, Brussels and Wallonia, and the Weser-Ems region in northwest Germany. While the ambitious objectives of the project were not fully achieved during the active project period (only 34 FCEV were deployed), the contribution from SWARM to the development of the European hydrogen mobility sector was significant. The lessons learnt in SWARM were applied to the successor Clean Hydrogen JU FCEV projects (HYFIVE, H2ME, H2ME2 and ZEFER).

HYFIVE continued the FCEV demonstration activities in Bolzano, Copenhagen, Innsbruck, London, Munich and Stuttgart. It aimed to deploy a large FCEV fleet (initially 185 vehicles but revised in 2016 to 110) and six new HRS integrated within the existing European HRS infrastructure. Finally, a total of 145 FCEVs were deployed by the end of the project. The major achievements of this project were: 1) the fact that the vehicles deployed demonstrated and exceeded the technical performance; 2) the development of best practises in systems to support FCEVs (i.e. commercial ready support service on maintenance, servicing, spare parts acquisition, etc.); 3) task forces development to understand the progress on solutions to technical issues in HRS; 4) the assessment of the challenges of using electrolysers at HRS with dynamic operation; and 5) the understanding of the impact of developing a refuelling infrastructure operated by different suppliers and the buying characteristics of early FCEV adopters. Additionally, the experience gained across the member states, the different FCEV manufacturers and the HRS operators participating in the project resulted in the development of recommendations on best practises for hydrogen regulations, codes and standards.

Figure 11 shows the deployment of FCEVs in Europe from the early Clean Hydrogen JU FCEV projects during the 2011-2014 period, including data from the H2MOVES SCANDINAVIA, HYTEC, SWARM and HYFIVE projects. The total FCEV fleet deployed in Europe during this period amounted to 200.

Figure 11. FCEVs in operation in Europe from 2011 to 2014. Projects: H2MOVES SCANDINAVIA, HYTEC, SWARM and HYFIVE



Source: Clean Hydrogen JU, 2023

Recent Clean Hydrogen JU FCEV projects (2015-2023)

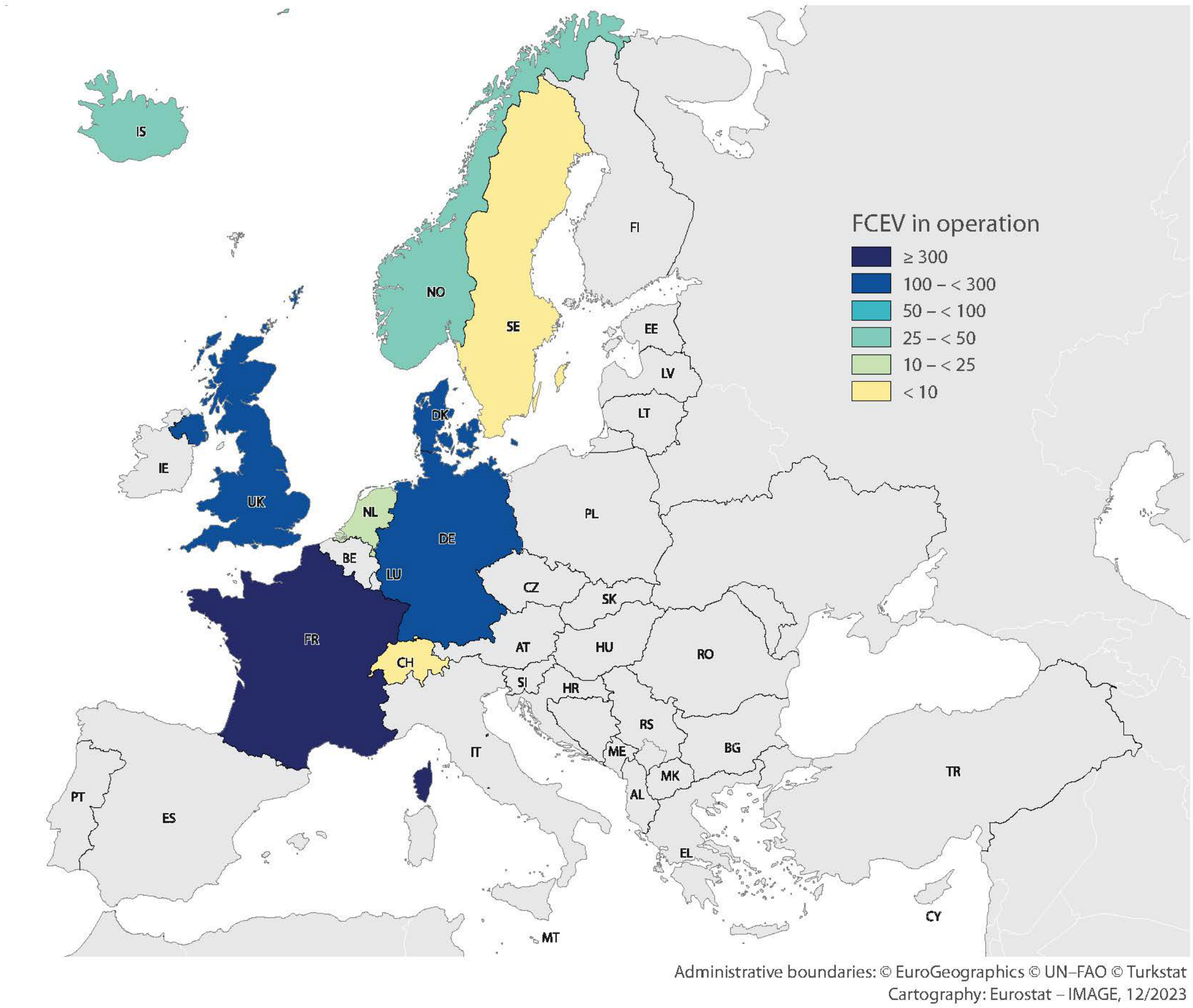
Recent Clean Hydrogen JU FCEV projects (H2020) focused on accelerating the market penetration of FCEVs deployed in Europe, demonstrating market readiness and identifying business cases as well as developing the necessary refuelling infrastructure at a competitive cost.

H2ME and H2ME2 both aimed at the expansion of the deployment of FCEVs and refuelling infrastructure across Europe; however, H2ME focused on car OEMs whilst H2ME2 focused on end-users. Additionally, H2ME2 placed emphasis on grid balancing activities using on-site electrolysers. The H2ME initiative (H2ME and H2ME2 projects) is the largest European deployment to date for hydrogen mobility, planning to deploy more than 1400 vehicles in 9 countries and 50 HRS from 10 suppliers in 6 countries (Element Energy, 2022). The technical data accumulated in the H2ME so far has greatly supported the analysis on market and customer readiness. By March 2023, 917 vehicles were deployed under the H2ME initiative from which 727 were reporting data through 2023. From these 727 vehicles, 472 were passenger cars from a variety of manufacturers (Daimler, Honda, Hyundai and Toyota) and 255 were fuel cell range-extended electric vehicles (FC REEVs) from Symbio. Additionally, a total of 39 HRS were deployed by Air Liquide, ITM Power, Linde (including its subsidiaries AGA and BOC), McPhy and NEL Hydrogen Fuelling (Element Energy, 2022).

The aim of project ZEFER was to demonstrate viable business cases for captive fleets of FCEVs (taxi, private hire and police services). The 180 FCEVs planned are already in operation (60 in Paris, 60 in London and 60 in Copenhagen). ZEFER is upgrading three HRS (Zaventem, Paris, and London) and at the same time it makes use of H2ME stations for refuelling operations. The deployment of FCEV taxi fleets within H2ME and ZEFER has helped to improve the business case of FCEVs and HRS. Fleet vehicles are subjected to large mileages and typically refuel at a centralized hydrogen fuelling station at the depot. This makes, on the one hand, a favourable business case for the HRS. On the other hand, intensive use of vehicles and HRS is expected to prove their readiness for heavy-duty applications in the near future.

Figure 12 illustrates the deployment of FCEVs in Europe from the recent Clean Hydrogen JU FCEV projects during the 2015-2023 period, including data from the H2ME, H2ME2 and ZEFER projects. The total FCEV fleet deployed in Europe during this period amounted to 1102.

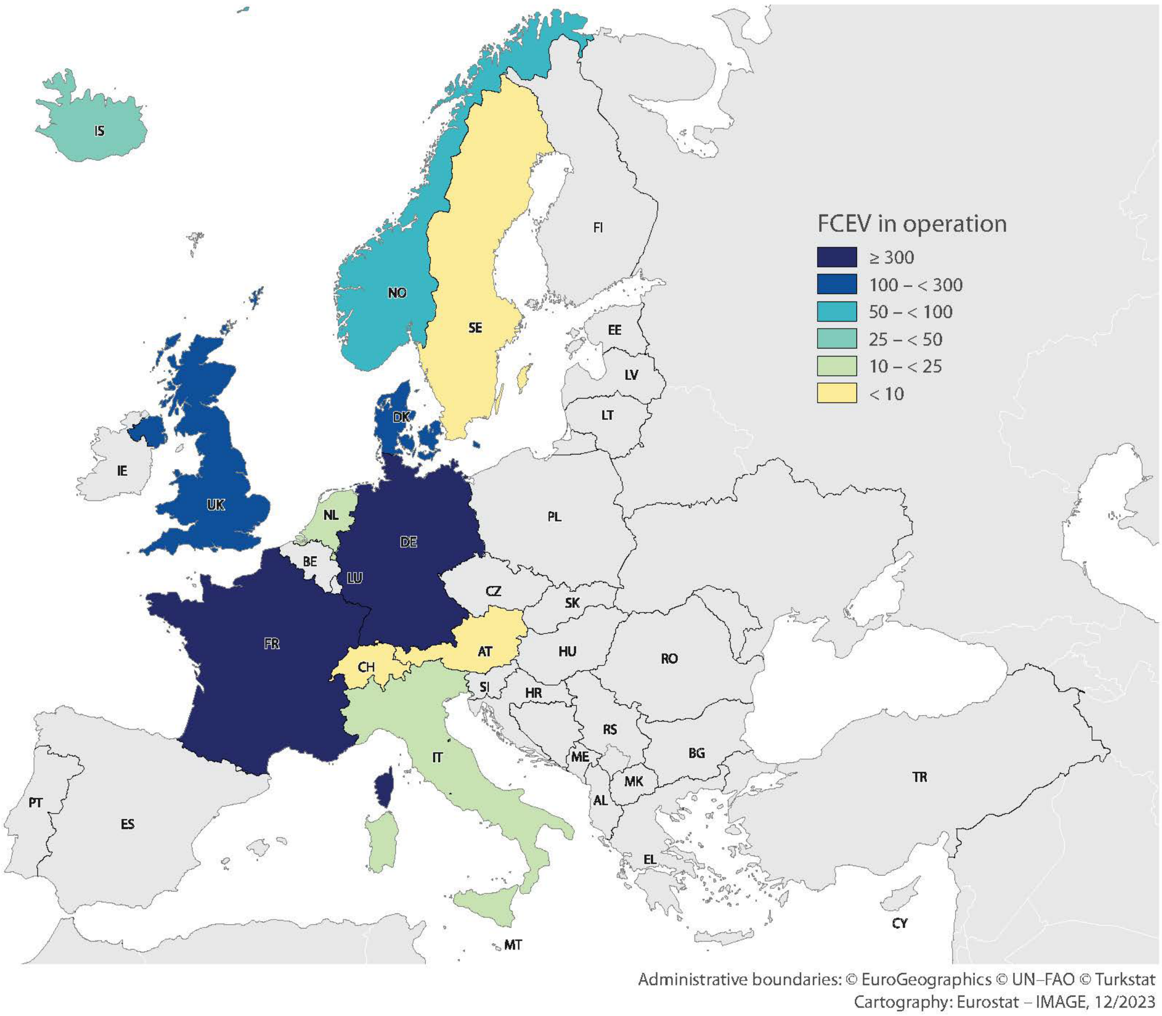
Figure 12. FCEVs in operation in Europe from 2015 to 2023. Projects: H2ME, H2ME2 and ZEFER



Source: Clean Hydrogen JU, 2023

The activities of the Clean Hydrogen JU, deploying hundreds of fuel cell hydrogen cars and vans along with the associated refuelling infrastructure, can be considered a pioneering initiative. Figure 13 illustrates the total FCEV fleet rolled out across Europe from 2010 to 2023, encompassing data from H2MOVES SCANDINAVIA, HYTEC, SWARM, HYFIVE, H2ME, H2ME2 and ZEFER projects. The total number of FCEVs deployed during this timeframe has crossed the 1300-unit benchmark. These projects have laid the foundation for the first genuinely pan-European network, and aided in the establishment of the world's most extensive network of hydrogen refuelling stations.

Figure 13. FCEVs deployed in Europe from 2010 to 2023. Projects: H2MOVES SCANDINAVIA, HYTEC, SWARM, HYFIVE, H2ME, H2ME2 and ZEFER.



Source: Clean Hydrogen JU, 2023

The success of these FCEVs demonstration projects is evidenced by the fact that various project partners have plans to scale-up their FCEVs fleets. Positive business cases have been demonstrated by H2ME2 and ZEFER projects. FCEVs showed an operational advantage against other zero-emission mobility solutions in high mileage and high required availability applications, such as taxi fleets. Comprehensive learnings have been achieved on customer acceptance, the business case for fuel cell vehicles and the technical performance of HRS and fuel cell vehicles under high utilisation.

Additional outputs from these projects worth mentioning are: 1) the significant amount of data collected, relevant for KPIs assessment and improvement of Well-to-Wheel (WTW) analysis and Total Cost of Ownership (TCO) models; and 2) the advancement of integrated solutions through collaborations between powertrain manufacturers, automotive manufacturers, and hydrogen providers is promoting the rapid development of hydrogen mobility in Europe. Nevertheless, there are still obstacles that need to be addressed.

FCEVs face challenges in competing with battery electric vehicles due to the latter's lower operational costs and increasing range capabilities, driven by advancements in battery development. This situation has been accentuated through 2022 as the energy crisis impacted the hydrogen prices at the pump, affecting the operational costs. Moreover, there is a fragile supply chain for components used in hydrogen mobility applications. The primary problem lies in manufacturers' tendencies to respond to demand, resulting in limited flexibility to expand spare parts inventory. Consequently, the ability to boost manufacturing capacity and optimize costs is restricted. Additionally, there is a lack of validated WTW data, specially adapted to the most recent models of FCEV passenger cars.

3.1.5 Key Performance Indicators and Targets

The targets originating from the Addendum to the MAWP of the Fuel Cells and Hydrogen 2 Joint Undertaking (Fuel Cells and Hydrogen 2 Joint Undertaking (FCH JU), 2018) for fuel cell light duty vehicles are summarised in Table 7.

This table also includes SoA values for 2012 and 2017. The values provided in this table originate from agreement between the FCH 2 JU and a panel of industry experts. The parameters considered as KPIs for the purpose of the programme are:

1. *Fuel cell system durability (h)*. Durability of the fuel cell system until 10% power degradation.
2. *Hydrogen consumption (kg/100)*. Hydrogen consumption for 100 km driven under real life operation using exclusively hydrogen feed.
3. *Availability (%)*. Percent of time that the vehicle is able to operate versus the overall time that it is intended to operate, assuming only FC related technical issues.
4. *Maintenance (EUR/km)*. Costs for spare parts and labour for the drivetrain maintenance per km travelled over the vehicle's complete lifetime of 6,000 to 7,000 hours.
5. *Fuel cell system cost (EUR/kW)*. Cost of the fuel cell system - excluding overheads and profits, assuming 100.000 systems/year as cost calculation basis.
6. *Areal power density (W/cm^2)*. Power per cell area @ 0,66V: Ratio of the operating power of the fuel cell to the active surface area of the fuel cell.
7. *PGM loading (g/kW)*. Overall loading in Platinum Group Metals at cathode + anode.
8. *Cell Volumetric power (kW/l)*. Power for single cell (cathode plate, MEA, anode plate) per unit volume, ref: Autostack-core Evo 2 dimensions: cell pitch 1,0mm and cell area: 595cm^2

Table 7. State-of-the-art and future targets for fuel cell light duty vehicles (Fuel Cells and Hydrogen 2 Joint Undertaking (FCH JU), 2018)

No.	Parameter	Unit	State of the art		Clean Hydrogen JU target		
			2012	2017	2020	2024	2030
1	Fuel cell system durability	h	2,500	4,000	5,000	6,000	7,000
2	Hydrogen consumption	kg/100	n/a	1.2	1.15	1,1	1
3	Availability	%	95	98	98	99	>99
4	Maintenance	EUR/km	n/a	0.04	0.03	0.02	0.01
5	Fuel cell system cost	EUR/kW	500	100	60	50	40
6	Areal power density	W/cm^2	n/a	1.0	1.5	1.8	2.0
7	PGM loading	g/kW	n/a	0.4	0.17	0.08	0.05
8	Cell Volumetric power	kW/l	n/a	5.0	7.3	9.3	10.0

Source: Addendum to the Multi-annual Work Plan of the FCH 2 JU (Fuel Cells and Hydrogen 2 Joint Undertaking (FCH JU), 2018)

Notes:

1) Durability of the fuel cell system until 10% power degradation. The typical vehicle lifetime requirement is 6,000-7,000 h of operation.

2) Hydrogen consumption for 100 km driven under real life operation using exclusively hydrogen feed.

3) Percent of time that the vehicle is able to operate versus the overall time that it is intended to operate, assuming only FC related technical issues.

4) Costs for spare parts and labour for the drivetrain maintenance per km travelled over the vehicle's complete lifetime of 6,000 to 7,000 hours.

5) Actual cost of the fuel cell system - excluding overheads and profits, assuming 100.000 systems/year as cost calculation basis.

6) Power per cell area @ 0,66V: Ratio of the operating power of the fuel cell to the active surface area of the fuel cell.

7) Overall loading in Platinum Group Metals at cathode + anode. (To be only used as guidance, not as a development target).

8) Power for single cell (cathode plate, MEA, anode plate) per unit volume, ref: Autostack-core Evo 2 dimensions: cell pitch 1,0mm and cell area: 595cm^2

Additionally, the following parameters related to the deployment of fuel cell buses have also been studied to assess the progress of Clean Hydrogen JU projects:

1. *Number of vehicles deployed (units)*. Number of vehicles of the same model in deployment during the reference period in the reference location by the end date of the present reporting exercise.
2. *Number of vehicles deployed, cumulative (units)*. Cumulative number of vehicles deployed during the reference period in the reference location by the end date of the present reporting exercise.
3. *Distance driven (km)*. Yearly distance driven by the vehicles over the timeframe of this data collection exercise.

4. *Distance driven, cumulative (km)*. Total distance driven by the vehicles within the project, until the end date of this data reporting exercise.

3.1.6 Performance evaluation of FCEV projects in Europe

In this section, the performance of the reviewed projects versus a series of specific KPIs will be assessed. The KPI values from each project were extracted from Final Reports, the TRUST database (Technology Reporting using Structured Templates) and other sources of information. The TRUST database was set up by the Clean Hydrogen JU to collect quantitative data from Clean Hydrogen JU projects, and it is now part of the required reporting process for ongoing projects.

The information obtained from this study has then been used to review how the programme is progressing against its overall targets, and to suggest future modifications to the research programme and associated targets. This will be put into context regarding the scale of the project and the conditions under which the particular performance was achieved. The obtained data comes from the following demonstration projects:

H2MOVES SCANDINAVIA, HYPE, SWARM, HYFIVE, H2ME, H2ME2, ZEFER.

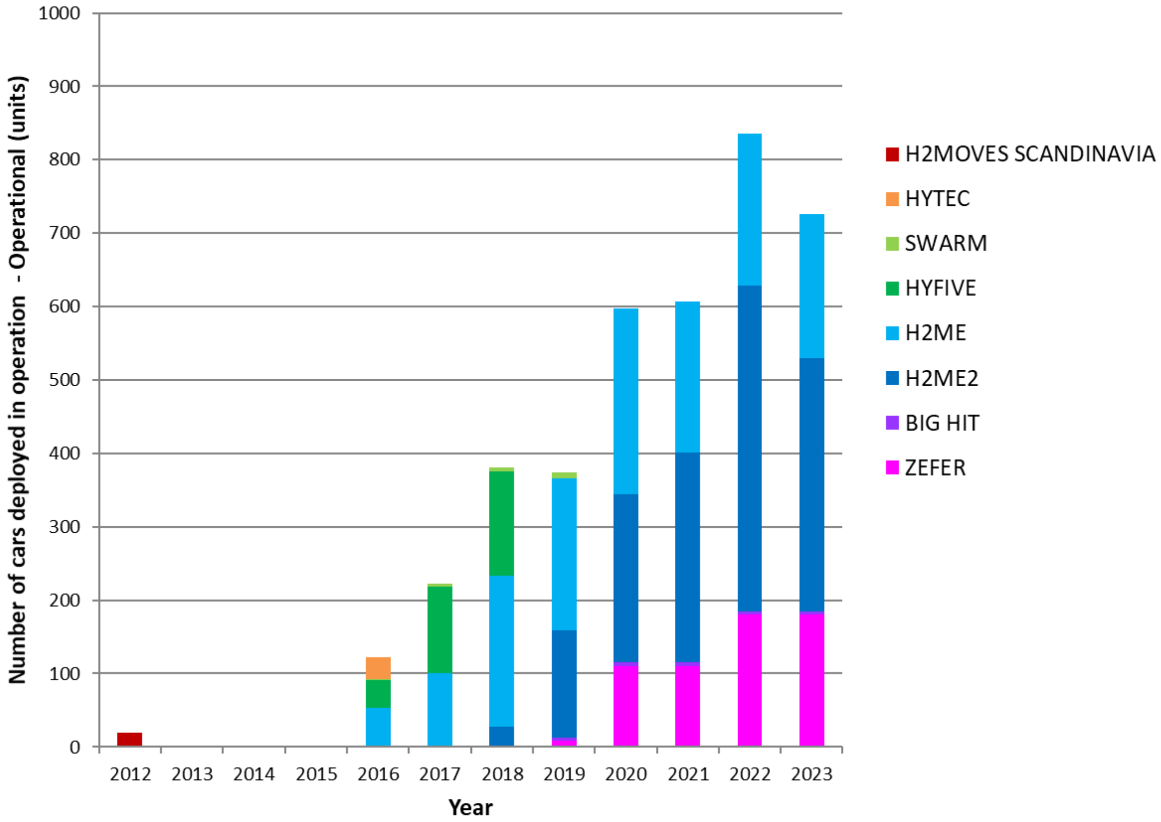
It should be noted that the values obtained should be provided under standard boundary conditions applying to all system KPIs (as defined in Table 7). In general, it has not been possible to establish whether all data has been given under these standard conditions. Adding to this remark, the plug-in vehicles (Symbio Hykangoo) have been excluded from the KPI analysis as they present a different powertrain architecture which would prevent a fair comparison. However, they have been included in the vehicle deployment and distance driven analysis and for this the project BIGHIT was also considered.

3.1.6.1 Number of vehicles deployed in operation (units)

Figure 14 shows the number of FCEV deployed in operation over the years by the Clean Hydrogen JU projects. In this figure all FCEVs deployed were considered (passenger cars in which the FC is the primary element of the powertrain and plug-in vans).

It is noticed that the early deployments that started with the H2MOVES SCANDINAVIA, HYTEC, SWARM and HYFIVE projects have seen a significant growth with the H2ME initiative (H2ME and H2ME2) and the ZEFER project. In 2022, 835 FCEVs were in operation from H2ME, H2ME2, ZEFER and BIG HIT projects in Europe. In 2023, 726 FCEVs were in operation, slightly lower number than 2022 due to the H2ME project finalisation. It is worth mentioning that the gap observed between 2013 and 2015 is an artificial one due to lack of data reporting over that period. HYTEC, SWARM and HYFIVE projects were deploying vehicles over the 2013-2015 period and we can observe the cumulative deployment from these projects in 2016.

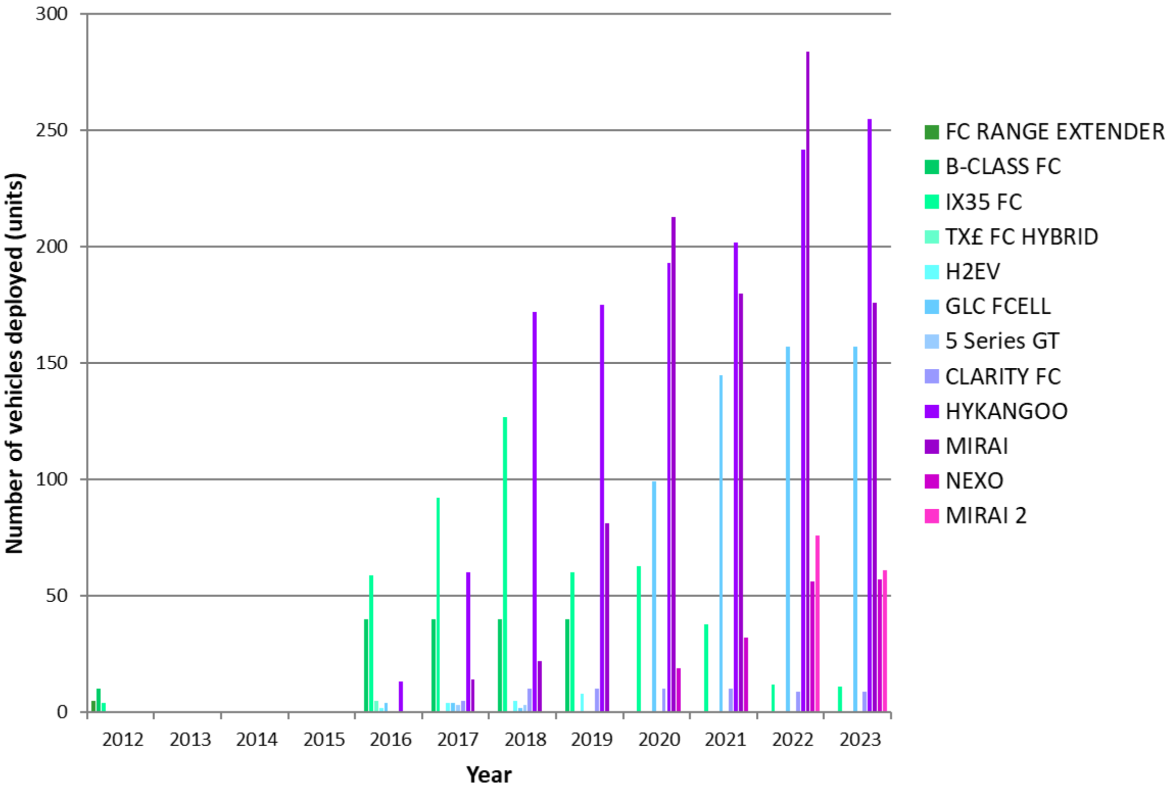
Figure 14. Number of FCEVs deployed and in operation per project versus year



Source: JRC based on data from Clean Hydrogen JU, 2023.

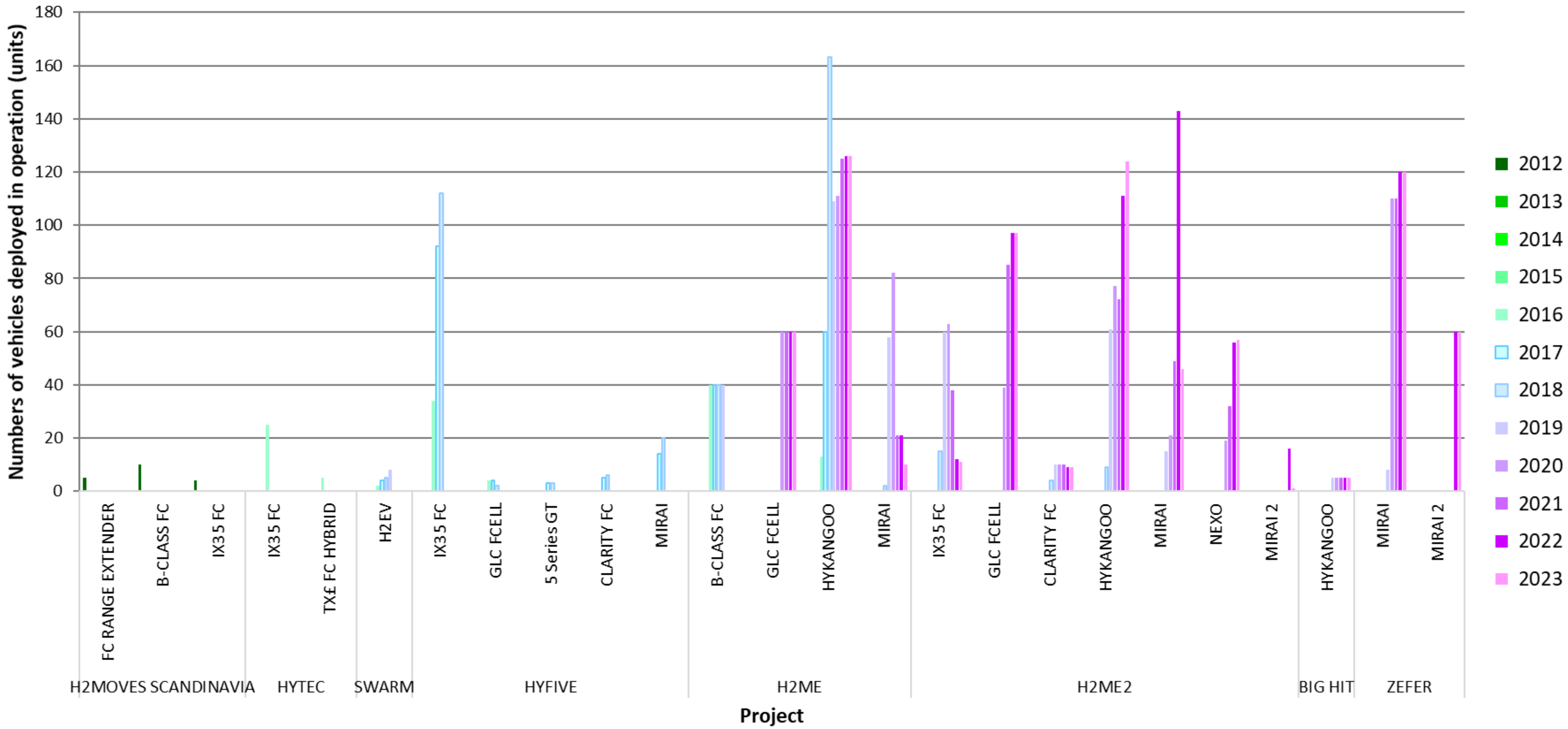
Figure 15 and Figure 16 show a detail of the FCEV models deployed over the years and the models deployed within the projects over the years, respectively. The models deployed came from a variety of manufacturers: Daimler (now Mercedes-Benz group), Hyundai, Th!nk, Intelligent Energy, Microcab, Toyota, BMW and Honda. A total of 11 different FCEV models were deployed over the years in the different projects. The deployment followed the international state of art with the latest models launched being deployed. In some cases, prototype/concept cars were also deployed and tested within the projects timeframe. Figure 16 details the FCEV models deployed within each project. We can observe that the models most deployed for each project were: 1) Daimler B-Class FC for H2MOVES SCANDINAVIA with 10 units, 2) Hyundai ix35 FC for HYTEC with 25 units, 3) Microcab H2EV for SWARM with 8 units, 4) Hyundai ix35 FC for HYFIVE with 112 units, 5) Renault Symbio HyKangoo for H2ME with 163 units, 6) Toyota Mirai for H2ME2 with 143 units and 7) Toyota Mirai for ZEFER with 120 units.

Figure 15. Number of deployed vehicles in operation from each model versus year for FCEV projects



Source: JRC based on data from Clean Hydrogen JU, 2023.

Figure 16. Number of deployed vehicles in operation from each model per year over the different FCEV projects

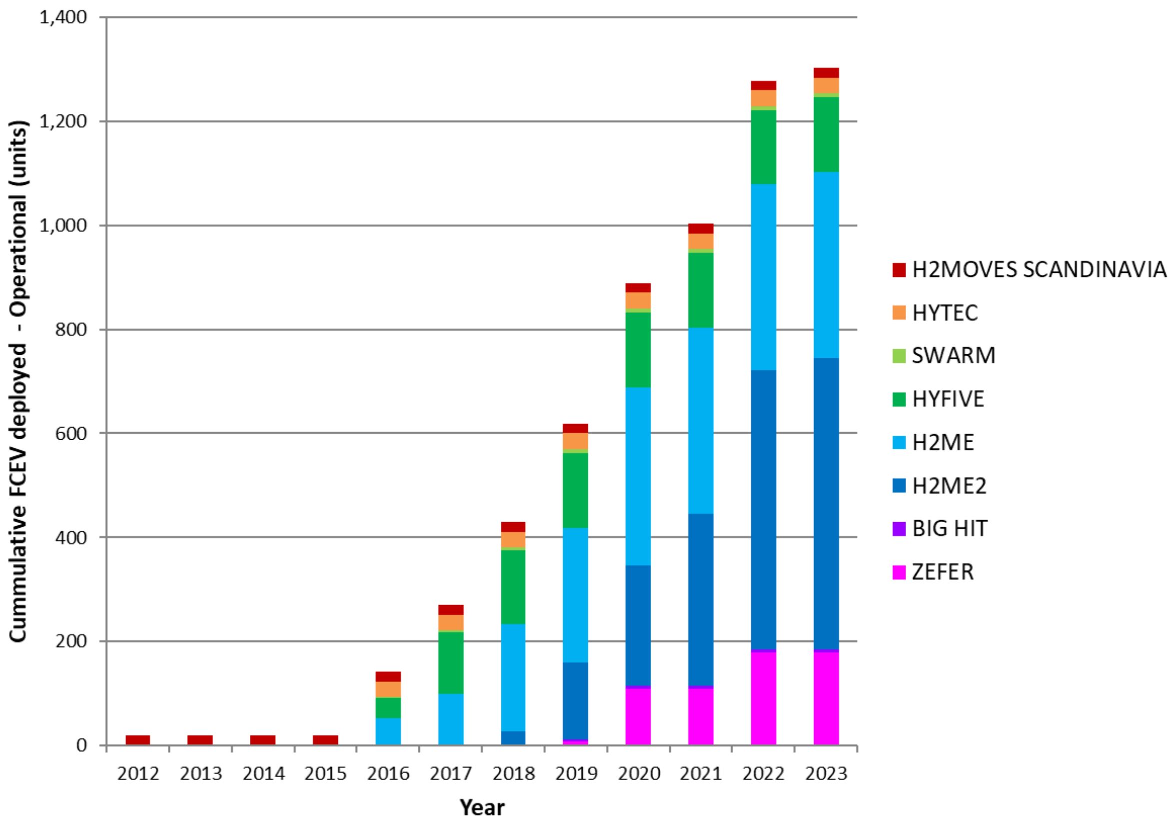


Source: JRC based on data from Clean Hydrogen JU, 2023.

3.1.6.2 Number of vehicles deployed, cumulative (units)

Figure 17 illustrates the cumulative FCEVs deployed over the years by the different projects. There has been a linear growth in deployment numbers from 2016 onwards. This growth has been intensified by the H2ME inititiative (H2ME + H2ME2). The H2ME inititiative has become a flagship European project deploying hundreds of fuel cell hydrogen cars, vans and their associated refuelling infrastructure. The total FCEV fleet deployed over the 2012-2023 period surpasses the 1300-unit milestone.

Figure 17. Cumulative FCEVs deployed per project versus year

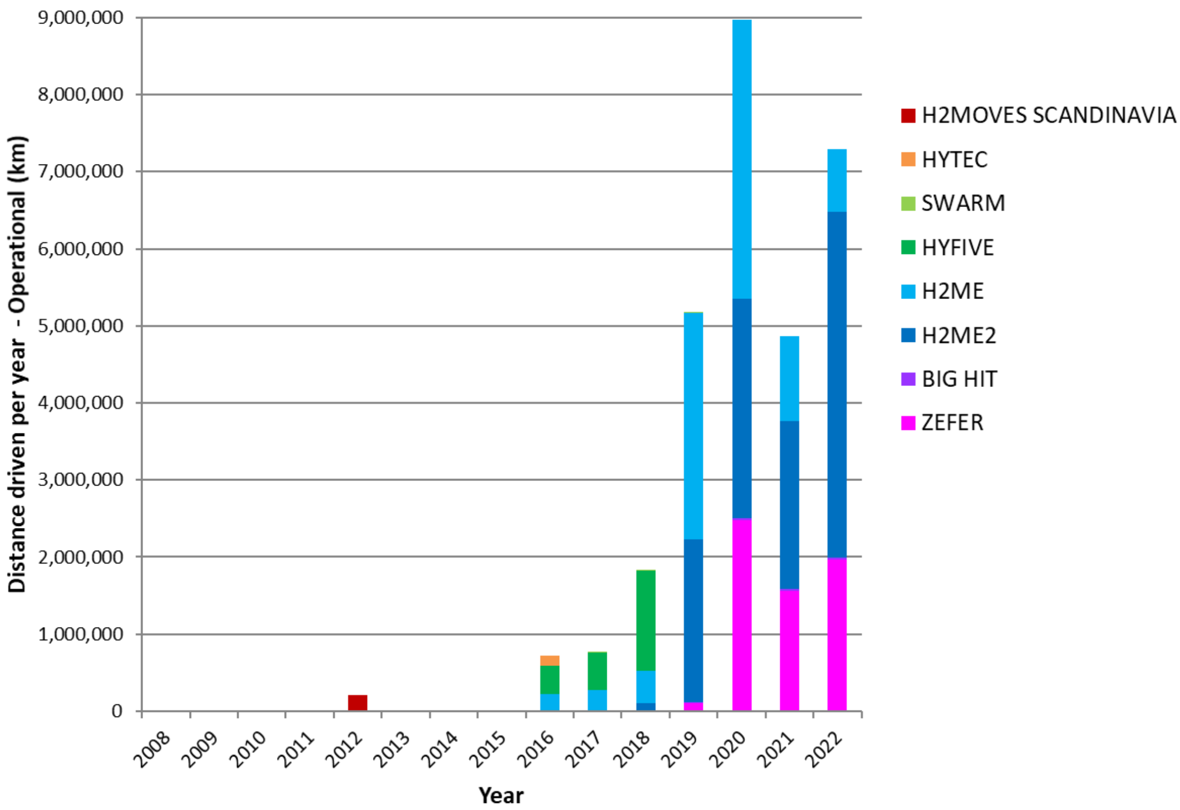


Source: JRC based on data from Clean Hydrogen JU, 2023

3.1.6.3 Distance driven (km)

Figure 18 shows the yearly distance driven by the vehicles deployed in each project per year. It is observed that the distance driven by the FCEVs per year was growing exponentially until 2020 with 9 million of km driven per year by the total fleet in operation. The effect of the lock-downs from the COVID-19 pandemic is noticeable in the data collected in 2021. However, a recovery in distance driven is shown in the data collected in 2022. It is worth mentioning that the gap observed between 2012 and 2016 is an artificial one due to lack of data reporting over that period. HYTEC, SWARM and HYFIVE projects were deploying vehicles over the 2013-2015 period and we can observe the cumulative distance driven from these projects in 2016.

Figure 18. Yearly distance driven by the vehicles versus year of data collection

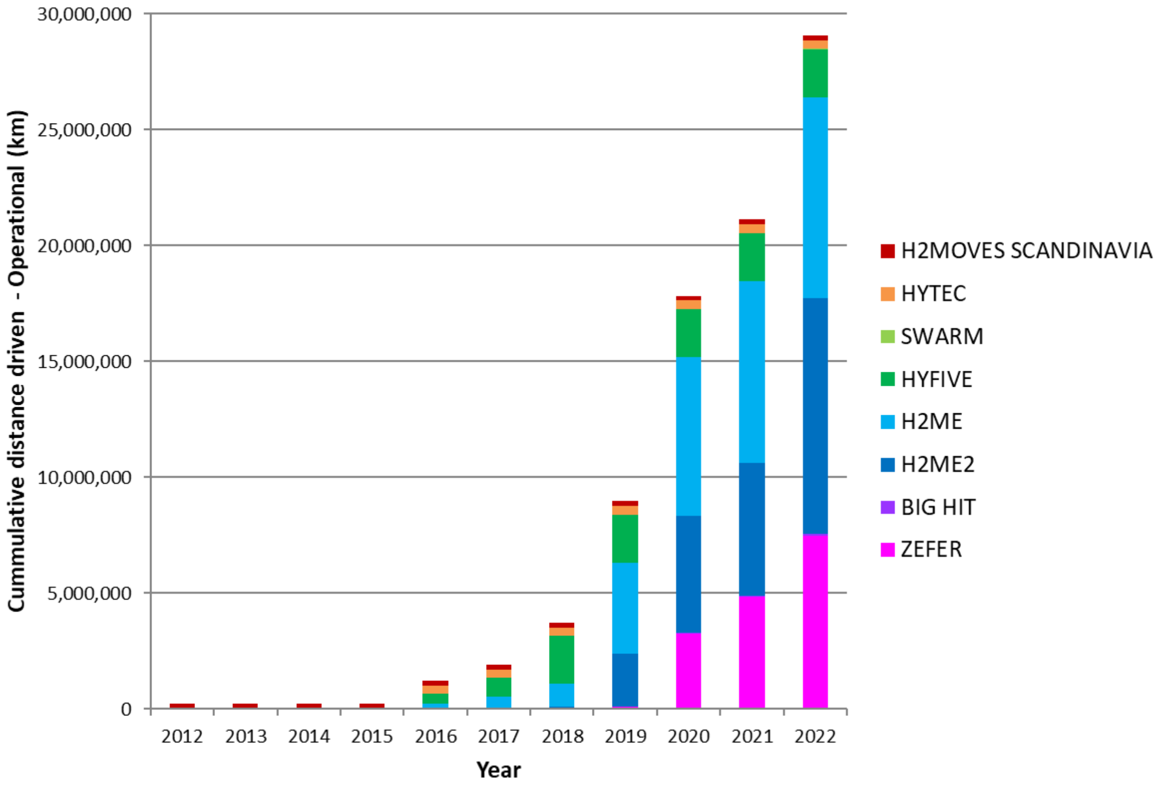


Source: JRC based on data from Clean Hydrogen JU, 2022.

3.1.6.4 Distance driven, cumulative (km)

Figure 19 shows the cumulative distance driven by the FCEVs of all the projects. The FCEVs deployed over the 10 year period (2012-2022) have accumulated a mileage of more than 29 million km, demonstrating the FCEV technology.

Figure 19. Total distance driven by the vehicles within the project duration, until the end date of this data reporting exercise versus year



Source: JRC based on data from Clean Hydrogen JU, 2022.

3.1.6.5 Fuel Cell System Durability (h)

It is important to make the distinction between the three different parameters that have been analysed to assess the fuel cell system durability of the FCEVs in the reviewed projects from the TRUST database.

- Fuel Cell System Durability - Descriptive: Durability of the fuel cell system as rated by the manufacturer - Indicative End of Life criterion: 10% stack power degradation.
- Fuel Cell System Durability - Operational: Only if at least one of the stacks reached their EoL (10% power degradation)[15] during the timeframe of this exercise: Total hours of operation (since they were first put in operation) at the time they are taken out of service
- Hours of operation – Operational: Total hours of operation without considering the EoL criterion of 10% power degradation.

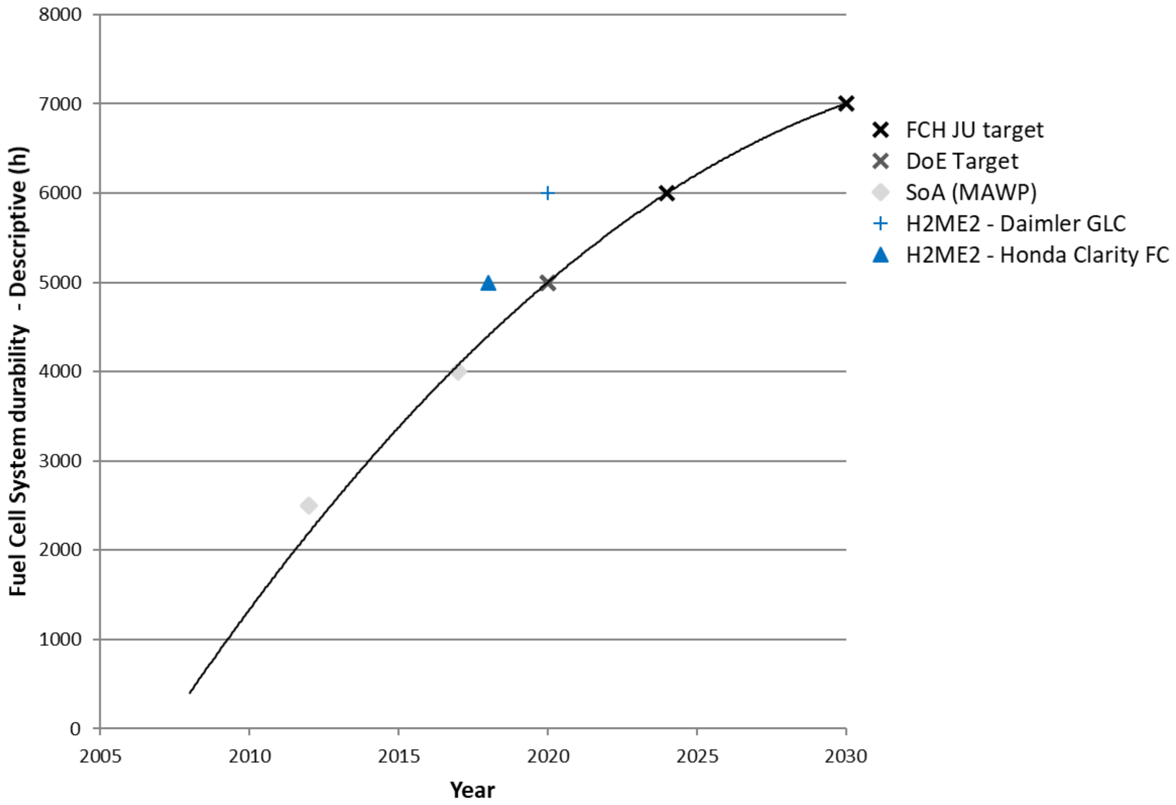
Figure 20 shows the descriptive fuel cell system durability versus the year of the data collection. The target values from the Multi-annual Work Programme of the Clean Hydrogen JU and the US Department of Energy are shown for comparison as FCH JU target and DoE target, respectively. These targets are denoted in the figures by "X" markers. Two sets of targets, defined in the 2015 and 2017 updates of the MAWP, are also included to show the State of Art (SoA). The SoA points will be denoted in the figures by diamond markers. Square markers will be use to depict average values of the project, each project with an associated colour. Other

[15] Average for all stacks

type of markers (cross, triangle, sphere, etc.) will be use to differentiate between vehicle models and their colour will refer to the associated project. The projects are ordered in the legend according to start date, with the earliest first. This format will be used for all subsequent figures regarding KPIs.

Unfortunately, there is not much data reported by the projects on the rated fuel cell system durability. The only data reported for this parameter was by the H2ME2 project for the Honda Clarity FC and the Daimler/Mercedes-Benz GLC models, both surpassing the trend line (polynomial approximation based on targets) set by the Clean Hydrogen JU and the US DoE targets with 5000 and 6000 h, respectively.

Figure 20. Descriptive fuel cell system durability (h) versus year for FCEV projects

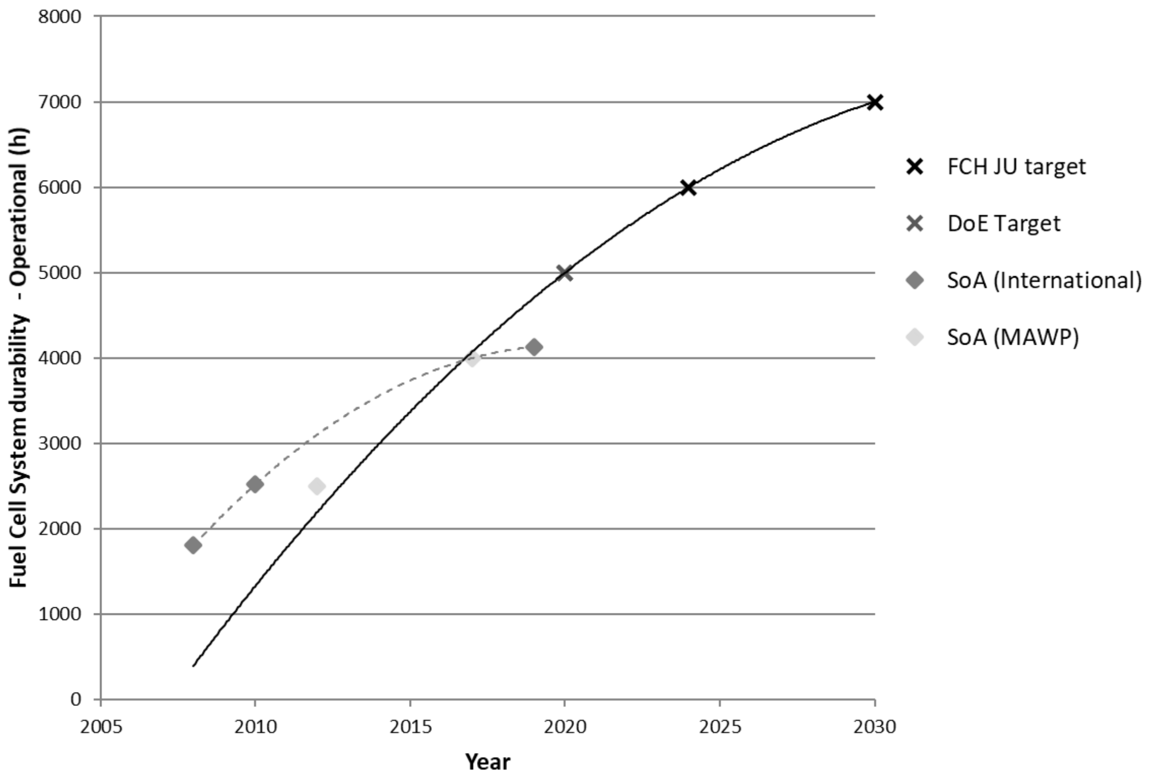


Source: JRC based on data from Clean Hydrogen JU, 2022.

Figure 21 shows the operational fuel cell system durability versus the year of the data collection. The values for the international state of the art are included as SoA (International) with a dotted trend line, alongside the FCH JU and DoE target trend lines for comparison. The two sets of targets, defined in the 2015 and 2017 updates of the MAWP, are also included in the figure. The SoA (International) data points come from a NREL study in which operational data was collected for a fleet of vehicles (Kurtz et al., 2018). The operational hours reached the targeted 5000 hours before 2020, however some of the vehicles in the fleet had already reached a 10% voltage degradation when the data was collected. Considering the EoL criterion of 10% power degradation, a more conservative data point was reported with 4130 hours before the degradation threshold occurs.

Values for the operational fuel cell system durability have been only provided by two projects (H2ME and H2ME2) for the Daimler/Mercedes-Benz models. The Daimler B-Class FC model reported that no stack replacement was needed in 45,297 h cumulative for the 40 vehicles. However, this value only accounts for hours of operation during the project and not for the total operational durability of the fuel cell as the vehicles were still in operation when the project finished. The operational fuel cell system durability of the Daimler GLC model was reported from H2ME and H2ME2 projects to be 6000 h in 2020. However no information on degradation was gathered so it is not possible to determine whether the degradation threshold was respected or not. Additionally, the value provided is the same as the descriptive durability value (6000 h) so it is assumed that during the length of the project no stack replacement was required. Other manufacturers have reported that they have not changed the fuel cell stack during the timeframe of the projects in which their cars were operating and similar fuel cell system durabilities to the durabilities of conventional cars were achieved. However, no information on fuel cell stack degradation was provided (Private Communication with Toyota Motor Europe). Therefore, these data points are not included in Figure 21 as they do not reflect the operational durability (only if at least one of the stacks reached their EoL (10% power degradation) during the timeframe of this exercise).

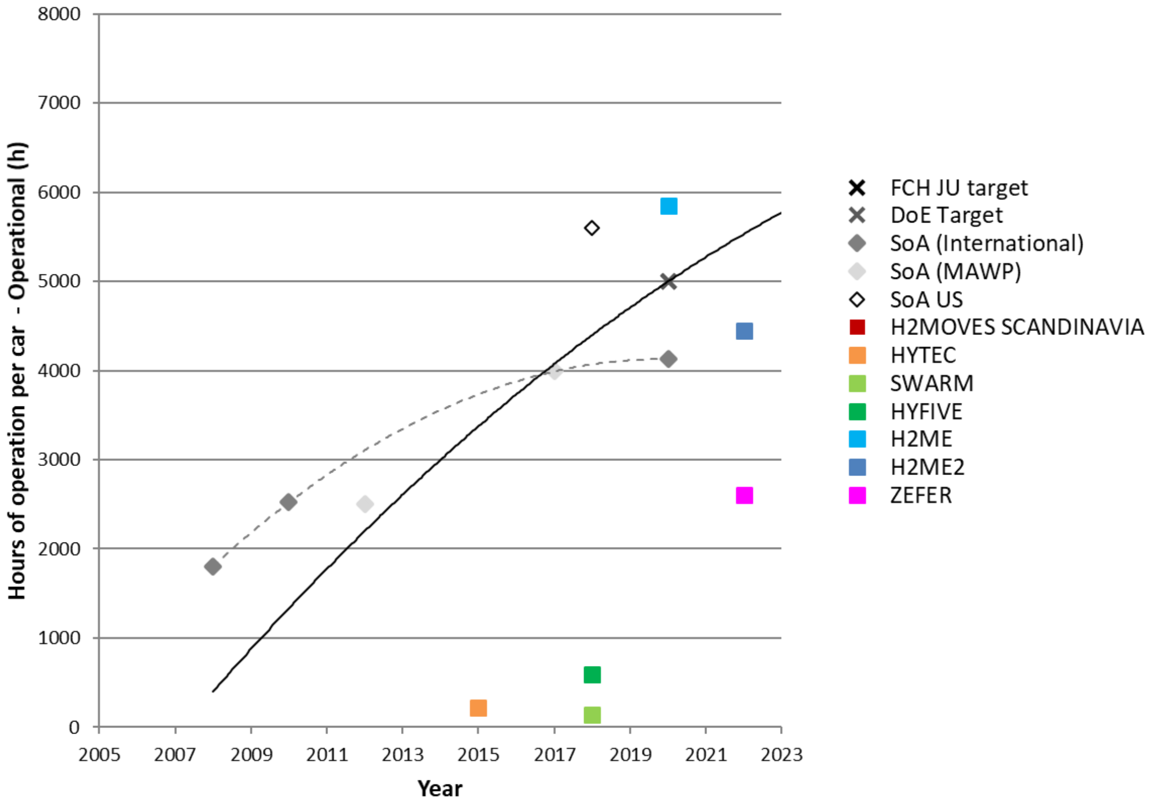
Figure 21. Operational Fuel Cell System Durability (h) versus Year for FCEV projects



Source: JRC based on data from Clean Hydrogen JU and NREL, 2022.

Figure 22 shows the cumulative hours of operation of the best performing FCEV (the car that operated the most hours in the timeframe of the project) versus the final year of the project. Additionally, the operational data point of the NREL fleet has also been added as SoA US (Kurtz et al., 2018). The figure shows that the early projects (HYTEC, SWARM and HYFIVE) accumulated the least amount of operational hours, below the trend line of the international state of the art. This can be easily explained by the short duration of these early projects. The cars were only operating during a short timeframe and therefore not accumulating enough operation hours to be able to demonstrate the durability. That does not mean that the durability of these cars was limited to the operation hours recorded in the project timeframe. H2ME has been operating for the longest timeframe and the best performing FCEV of the project has surpassed the FCH JU targets. In the case of H2ME2 and ZEFER, the projects have been running for less time than H2ME and therefore have not accumulated yet the sufficient amount of hours to be compared with the best performing FCEV from H2ME. It is also worth mentioning that the lock-downs during the COVID-19 pandemic have had an effect on the total hours of operation recorded. This effect can be observed for H2ME2 and ZEFER projects.

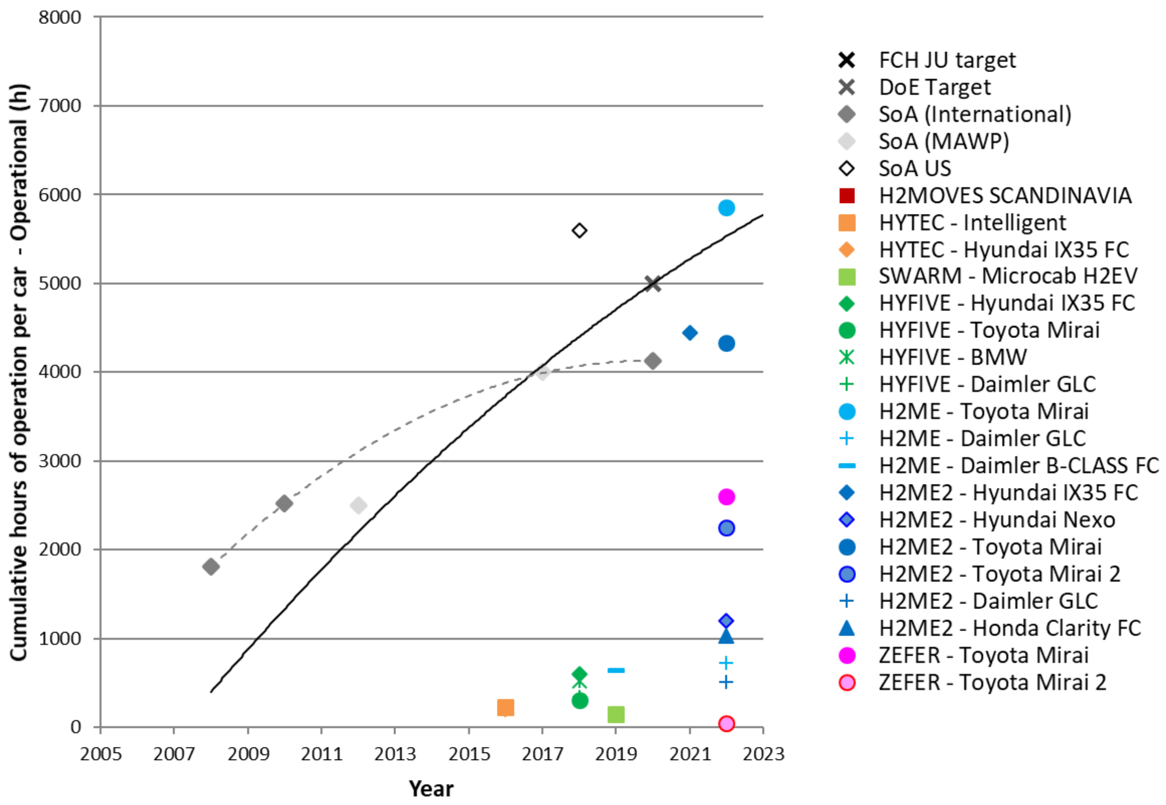
Figure 22. Total hours of operation of the best performing car (h) versus final year of the project or final year of the data collection if the project is still active.



Source: JRC based on data from Clean Hydrogen JU and NREL, 2022.

Figure 23 shows the cumulative hours of operation of the best performing FCEV for each model and for each project (the car that operated the most hours in the timeframe of the project) versus the final year of the data collection. Please note that the data points collected for 2022 are indicative because the projects are not yet finished. The improvement on hours of operation recorded from the early projects until the H2ME project is significant. The best performing H2ME FCEV (Toyota Mirai) has surpassed in operation hours the FCH JU and DoE targets. However, it is not known if the fuel cell degradation has surpassed the threshold stated in the MAWP. FCEV models operating under H2ME2 and ZEFER have accumulated less hours due to the fact that these projects have started later than H2ME and are still active. Recent models like the Toyota Mirai II in ZEFER project have been operating only for a year. Additionally, the lock-downs during the COVID-19 pandemic would have a negative impact (recording less hours than in normal years).

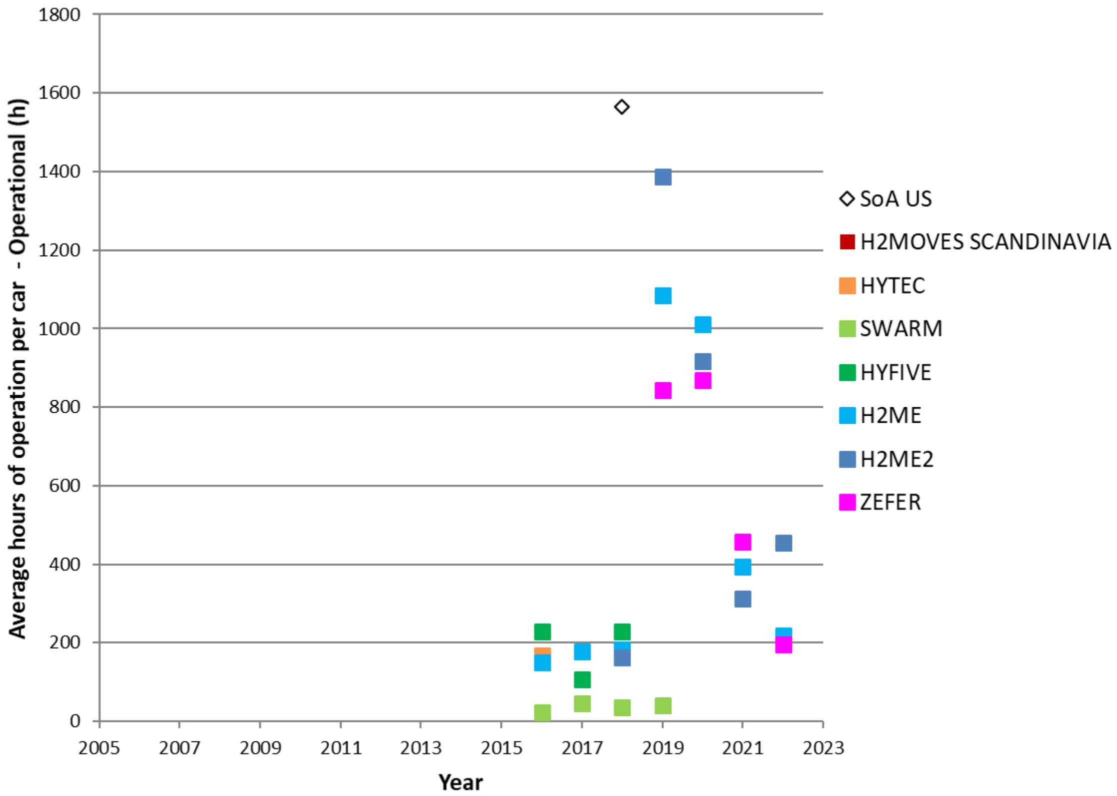
Figure 23. Total hours of operation of the best performing car from each model (h) versus final year of the project or final year of the data collection if the project is still active



Source: JRC based on data from Clean Hydrogen JU and NREL, 2022.

Figure 24 shows the average operation hours per car recorded per project per year. This figure gives an insight on the evolution of the use of FCEVs in the Clean Hydrogen JU projects over the years. It can be observed that the amount of operation hours per year has increased significantly from the early projects (HYTEC, SWARM, HYFIVE) to the H2020 projects (H2ME, H2ME2, ZEFER). However, the impact of the lock-downs during the COVID-19 pandemic are visible in the later years with the projects recording less hours of operation. This is noticeable in particular for the data points of H2ME, H2ME2 and ZEFER in 2021 and 2022 where part of their fleet was off service. This is also the case of the FCEVs deployed in Paris. Taxis in Paris were off road from March 2020 to July 2021. Additionally, a legal dispute between the 2 taxi companies from August 2021 to October 2022 severely altered the FCEVs operation.

Figure 24. Average hours of operation per car per year versus year for FCEV projects



Source: JRC based on data from Clean Hydrogen JU and NREL, 2022.

3.1.6.6 Hydrogen consumption (kgH_2/100km)

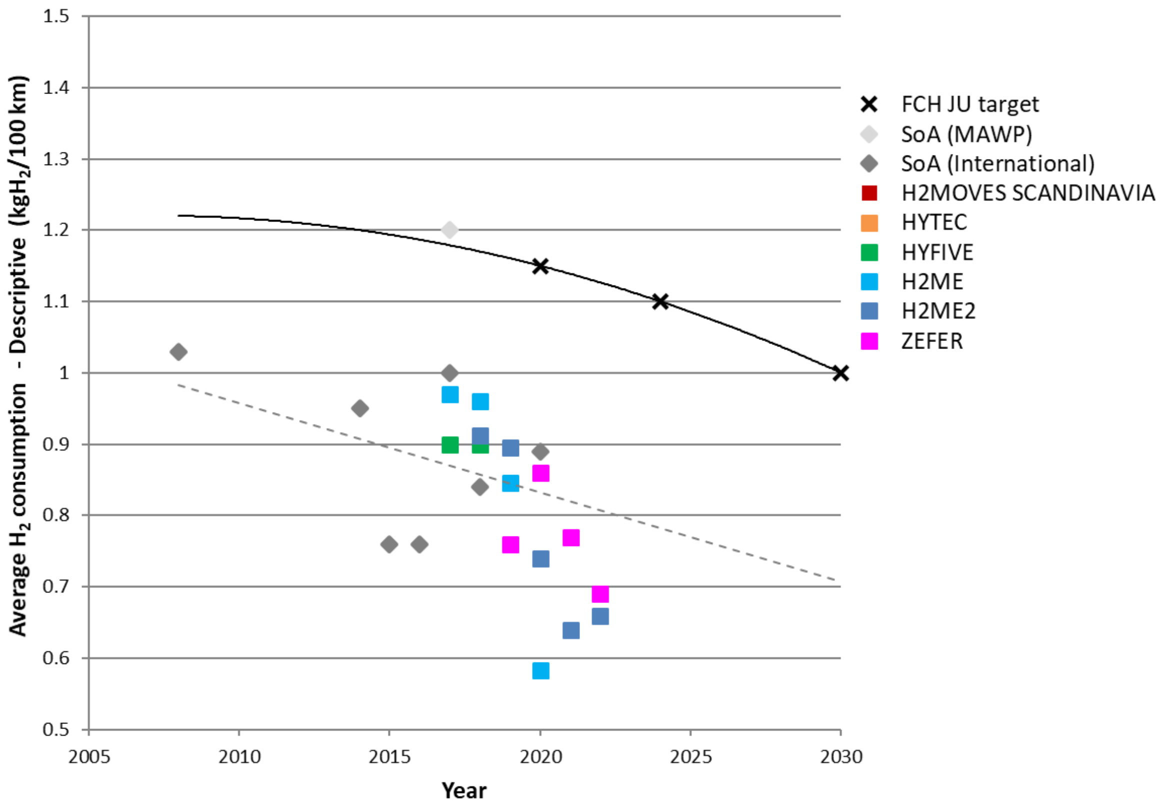
It is important to make the distinction between the two different parameters that have been analysed to assess the hydrogen consumption of the FCEVs in the reviewed projects from the TRUST database.

- Hydrogen Consumption - Descriptive: Hydrogen tank to wheel (TTW) consumption for 100 km driven according to the New European Driving Cycle (NEDC) rated by the manufacturers.
- Hydrogen Consumption - Operational: Hydrogen consumption for 100 km driven under real operation conditions, measured in the projects.

Figure 25 shows the average hydrogen consumption of the FCEVs deployed per project rated by the manufacturers (descriptive) over the years. The diamond markers representing the SoA fluctuate because each new model launched on the market has a specific rated consumption. Although the general trend is downward, indicating better consumption efficiency, some newer models have higher rated consumption than older ones. This is why the trendline is useful to observe the overall downward evolution of FCEV consumption.

It is observed that all projects show a potential hydrogen consumption significantly below the FCH JU targets, demonstrating fuel efficiency which is really positive. The figure also shows that the FCEVs deployed over the last years (H2ME2 and ZEFER) have a rated consumption lower than the average international state of the art. This shows that the models deployed in H2ME2 and ZEFER (mainly Toyota Mirai, Toyota Mirai II and Hyundai Nexo) are at the forefront of the FCEV technology.

Figure 25. Descriptive average hydrogen consumption for 100 km driven versus year for FCEV

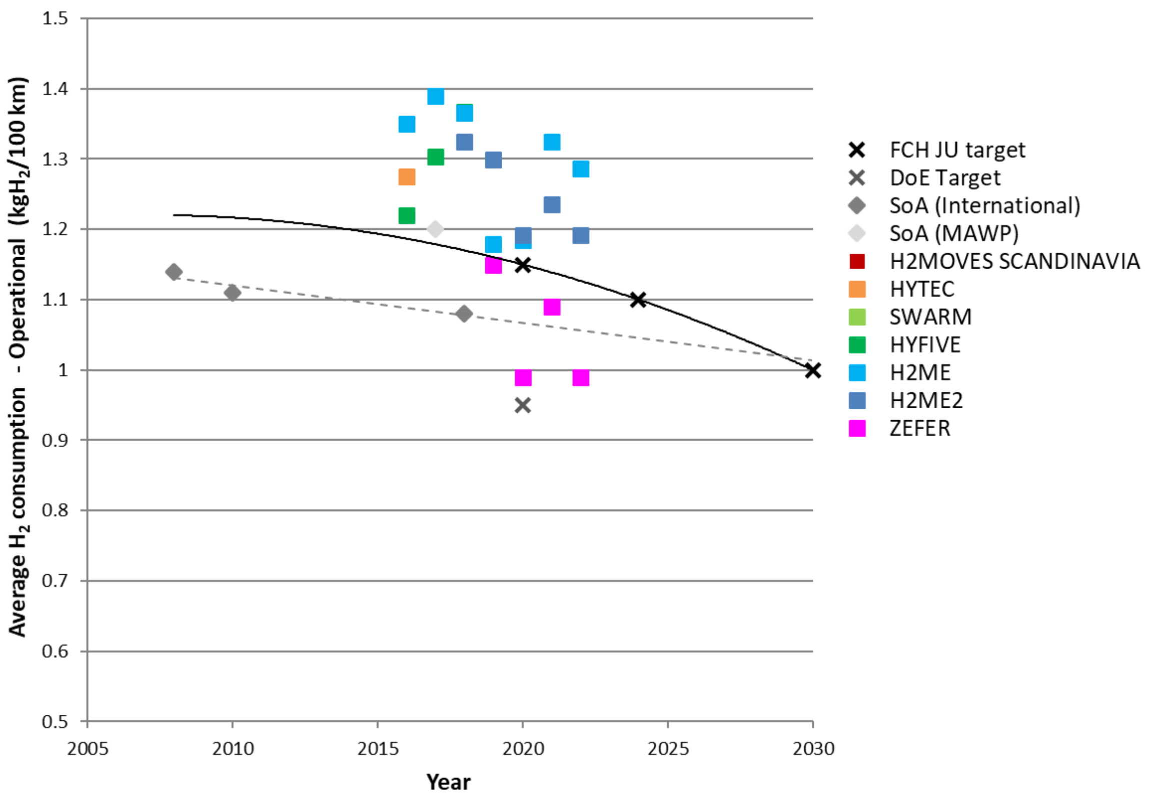


Source: JRC based on data from Clean Hydrogen JU, 2022.

Figure 26 shows the average hydrogen consumption of the FCEVs deployed per project measured in operational conditions over the years, along with the FCH JU and DoE targets for comparison (with DoE target being more ambitious). The diamond markers representing the International SoA refer to the US SoA, showing the average values of fleets operating in US according to NREL reports.

It is observed that only the ZEFER project achieves an average hydrogen consumption below the trend line of the FCH JU targets and in some cases below the international state of the art. This means that the real conditions in which the cars operated differed from the testing conditions used by manufacturers (New European Driving Cycle). It is worth noting that the geographical conditions of each deployment site will also differ, these have an influence on the fuel consumption reported. Another reason for the improved fuel efficiency in ZEFER is the training on "eco-driving" given to the taxi drivers participating in the project.

Figure 26. Operational average hydrogen consumption for 100 km driven versus year for FCEV projects



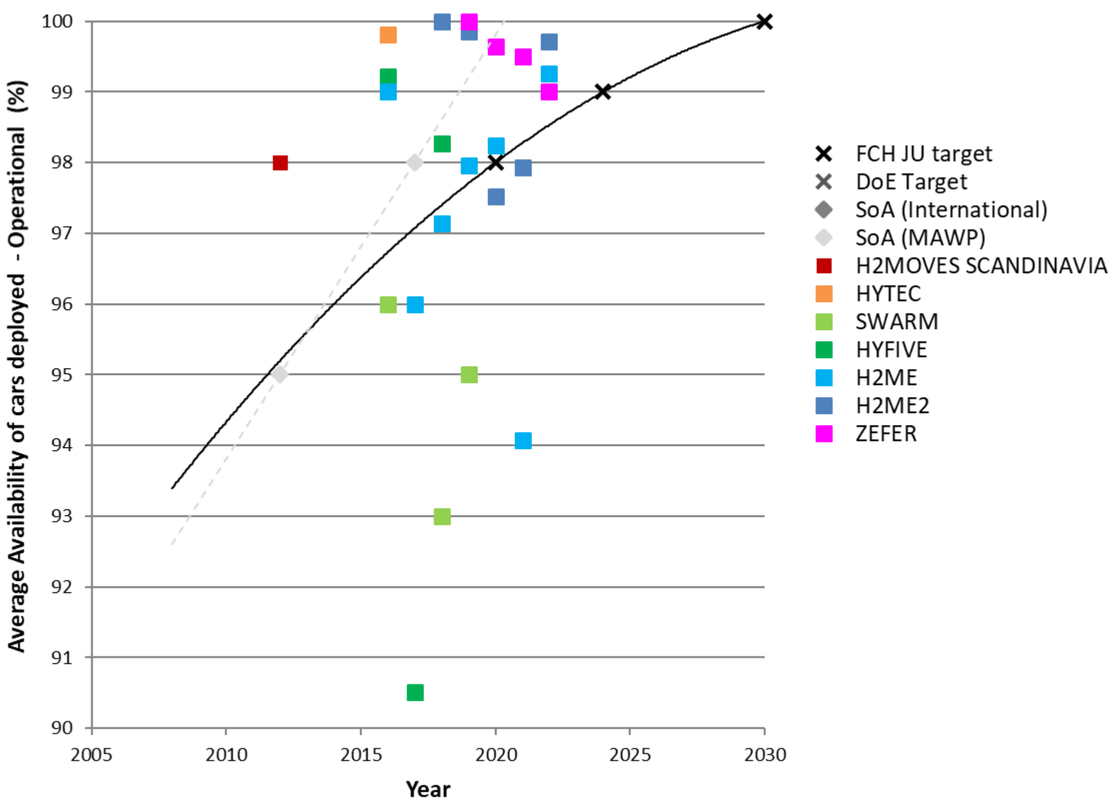
Source: JRC based on data from Clean Hydrogen JU, 2022.

3.1.6.7 Availability (%)

Figure 27 shows the average availability of the FCEVs deployed per project over the years. The availability is defined in the TRUST database as the percentage of time that the vehicles were able to operate versus the overall time that they were intended to operate during the timeframe of this data collection exercise, assuming only fuel cell related technical issues.

From the data analysis we can observe that most of the projects have met or surpassed the trend line of the FCH JU target over the years. The exceptions have been observed for early projects such as SWARM and HYFIVE. In the case of H2ME the average availability has surpassed or closely met the FCH JU targets over the years with the exception of the year 2021. The cause for a lower average availability that year was the low availability reported by the Daimler GLC models (92%). Nevertheless, these models reported a 100% availability the following year. H2ME2 shows higher average availabilities meeting and surpassing the FCH JU target trend line. ZEFER FCEVs have excelled every year in terms of the availability, surpassing the FCH JU targets.

Figure 27. Average availability of the cars deployed per project versus year for FCEV projects



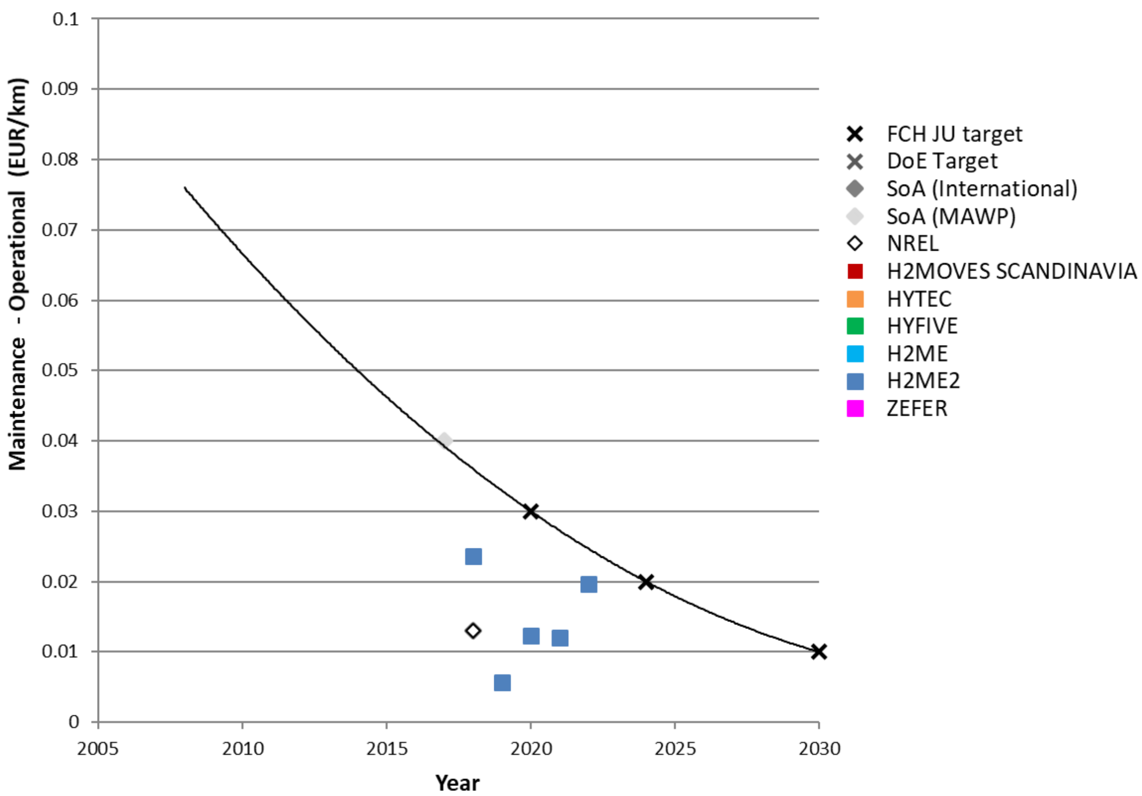
Source: JRC based on data from Clean Hydrogen JU, 2022.

3.1.6.8 Maintenance (EUR/km)

Final project reports and the TRUST database were consulted to gather yearly maintenance costs (spare parts and labour for the drivetrain maintenance in EUR/km). Very few vehicles reported reliable information on maintenance costs. These vehicles belonged to the H2ME2 project.

Figure 28 shows the average yearly maintenance costs for this project. On average, H2ME2 showed very low maintenance costs, below the FCH JU targets and in line with the costs reported by NREL in their study (Kurtz et al., 2018). In the case of ZEFER the maintenance costs were included in the leasing contract so they are not reported in the TRUST database and cannot be included in the figure. It is worth mentioning that project participants pointed out that one of the major factors of variability in the maintenance costs were the differences in labour costs among countries.

Figure 28. Average maintenance costs (spare parts and labour) of each project versus year

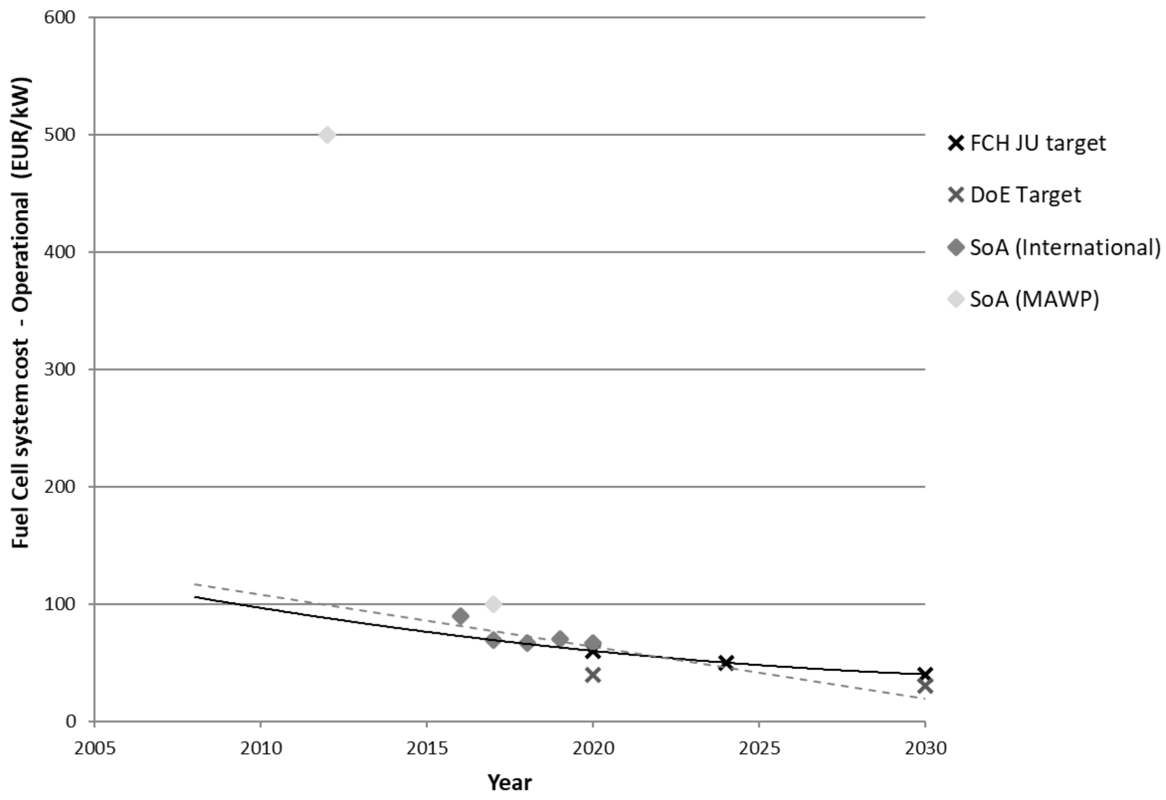


Source: JRC based on data from Clean Hydrogen JU and NREL, 2022.

3.1.6.9 *Fuel cell system cost (EUR/kW)*

There is not enough data reported on fuel cell system costs in the final project reports or TRUST database to conduct an in-depth analysis. The projections on fuel cell system costs from the US DoE show a value of 66.65 EUR/kW for 2020, see SoA (International) dotted line (US Department of Energy, 2021). The FCH JU target was 60 EUR/KW for 2020. The data found in TRUST is really scarce, available only from some FCEV models of the projects HYFIVE, H2ME and H2ME2. The costs reported by those projects significantly surpassed the FCH JU target for 2020 and are not included in Figure 29 due to confidentiality concerns. Further efforts are required to lower the fuel cell system costs.

Figure 29. Operational fuel system costs (EUR/kW) versus year for FCEV projects



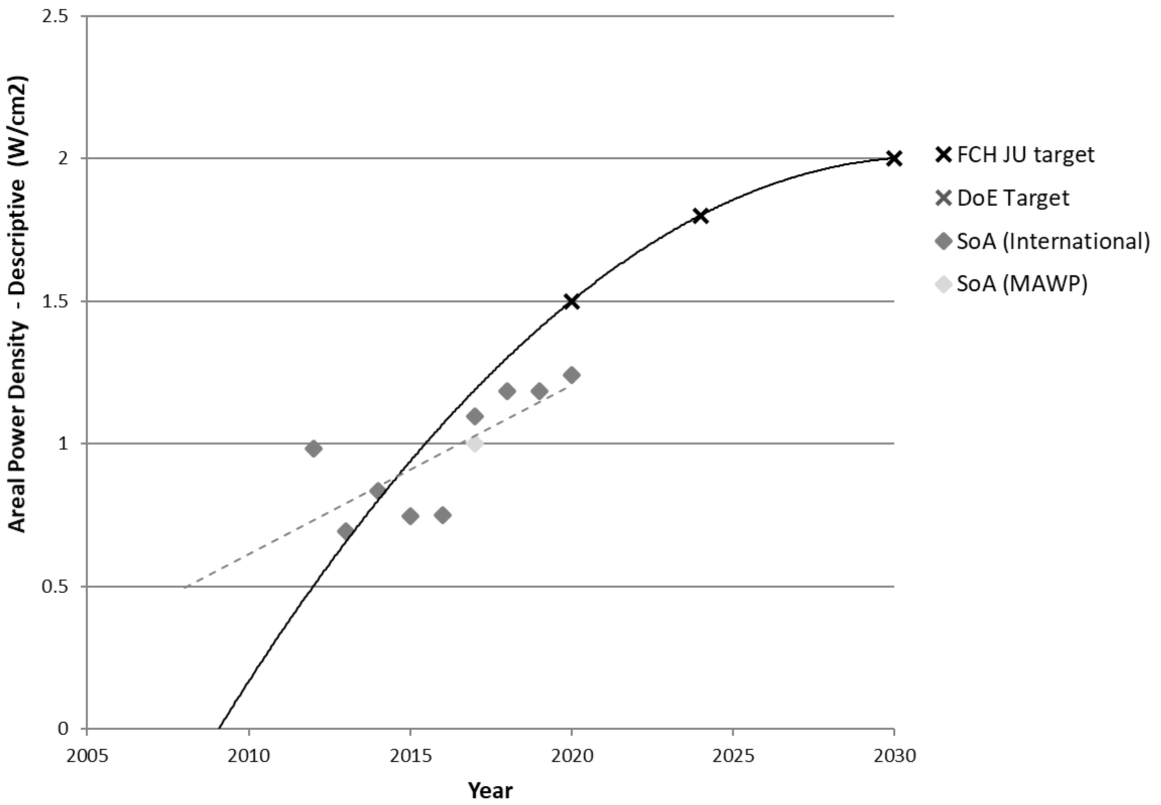
Source: JRC based on data from Clean Hydrogen JU, 2022.

3.1.6.10 *Areal power density (W/cm^2)*

Areal power density data is sensitive for FCEV manufacturers. Therefore, no data was provided to assess the areal power density of the fuel cell from the cars deployed in the Clean Hydrogen JU projects.

Figure 30 shows the FCH JU targets and the data observed for the international state of the art coming from the US DoE (US Department of Energy, 2016), (US Department of Energy, 2021). It is observed that the international state of the art falls short on the areal power density target. Further efforts are required to increase the areal power density of the fuel cells employed in FCEVs. However, it is also observed that the targets are too optimistic, doubbling the 2017 SoA areal power density value by 2030. This target has been reviewed for mobility applications in the Strategic Research and Innovation Agenda (SRIA) (Clean Hydrogen JU, 2021). There are not specific targets for FCEVs but there are targets for building blocks of FC trucks (fuel cell stacks) which can be applicable. For high TRL projects the targets for power densities are 1 W/cm^2 in 2024 and 1.2 W/cm^2 in 2030. The best heavy-duty Clean Hydrogen JU funded project has achieved 1 W/cm^2 and therefore it is assumed to be the current state-of-art for trucks (high power fuel cell stacks).

Figure 30. Descriptive areal power density (W/cm^2) versus year



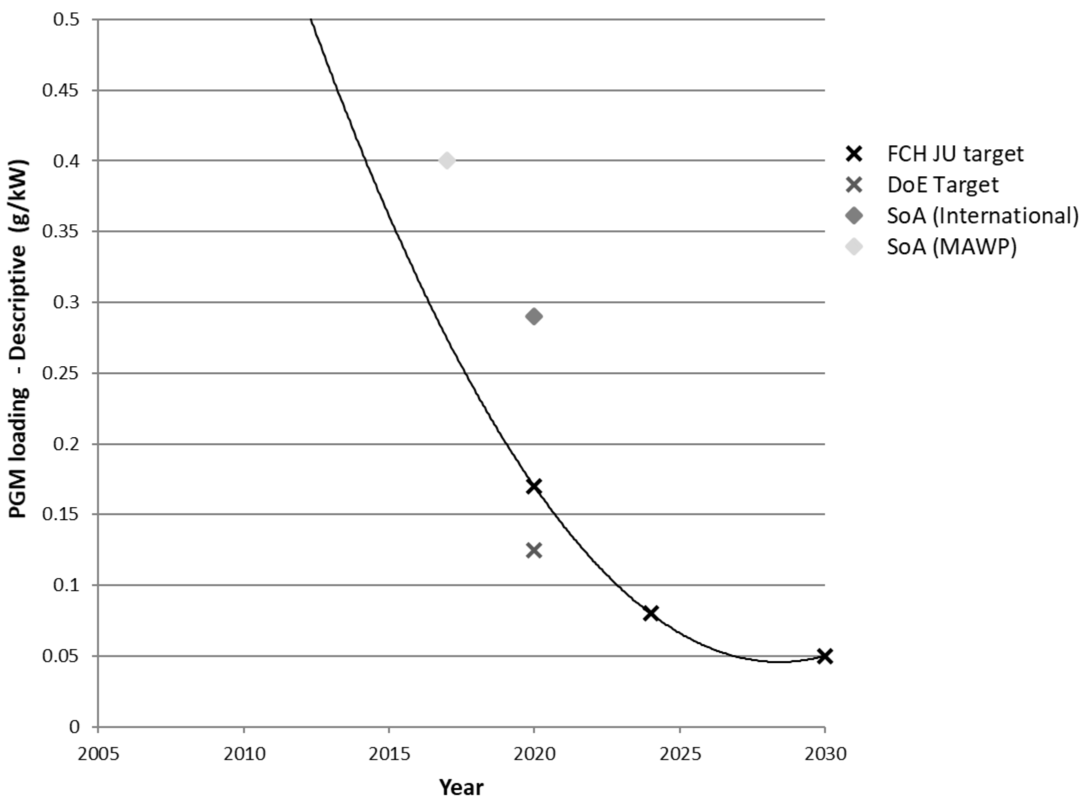
Source: JRC based on data from Clean Hydrogen JU and US DoE, 2022.

3.1.6.11 PGM loading (g/kW)

Platinum group metals (PGM) loading is another sensitive parameter for FCEV manufacturers, hence, no data was reported to assess the PGM loading of the fuel cells from the cars deployed in the Clean Hydrogen JU projects.

Figure 31 shows the FCH JU targets and the data observed for the international state of the art (US Department of Energy, 2020). Again the FCH JU target was optimistic foreseeing that the PGM loading could be reduced by an order of magnitude in 15 years (2015 – 2030). This target has also been reviewed for mobility applications in the SRIA (Clean Hydrogen JU, 2021). There are not specific targets for FCEVs but there are targets for building blocks of FC trucks (fuel cell stacks) which can be applicable. For high TRL projects theses targets are 0.35 and 0.3 g/kW for 2024 and 2030, respectively. The best heavy-duty Clean Hydrogen JU project has currently achieved the 2024 target.

Figure 31. Descriptive PGM loading (g/kW) versus year



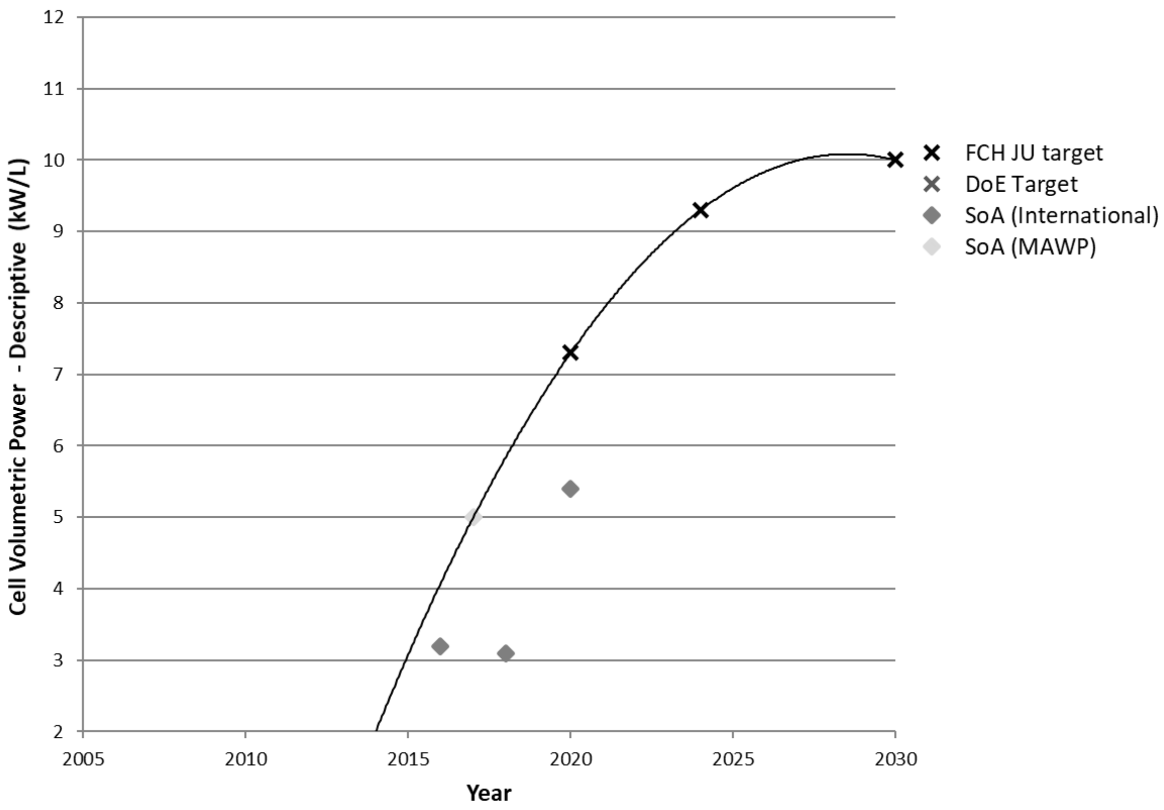
Source: JRC based on data from Clean Hydrogen JU and US DoE, 2022.

3.1.6.12 Cell Volumetric power (kW/l)

Cell volumetric power is also sensitive for FCEV manufacturers. No data was reported from the cars deployed in the Clean Hydrogen JU projects.

Figure 32 shows the FCH JU targets and specifications of some FCEV models as international state of the art values. The international state of the art data indicates that the technology is falling behind the targets stated by the Clean Hydrogen JU in terms of cell volumetric power.

Figure 32. Descriptive cell volumetric power (kW/L) versus year



Source: JRC based on data from Clean Hydrogen JU, 2022.

3.1.7 Summary

This section provides a summary and conclusions for Section 3.1. A complete list of recommendations is provided in Chapter 4.

- FCEV projects generally use commercial or near-commercial vehicle models.
- FCEVs deployment in Europe has seen a significant growth with the Clean Hydrogen JU projects, especially with H2ME and H2ME2 projects. The total FCEV fleet deployed over the 2005-2023 period surpasses the 1300-unit milestone.
- The FCEVs deployed in Europe over the 17 year period (2005-2022) accumulated a mileage of more than 29 million km, demonstrating the readiness of the FCEV technology.
- Not all relevant data is submitted to the TRUST database due to commercial sensitivity, particularly regarding fuel cell system durability, fuel cell system costs, maintenance costs, and fuel cell characteristics like areal power density, PGM loading, and cell volumetric power.
- To assess fuel cell system durability, parameters like FCEV cumulative operation hours have been analysed alongside the limited durability data from projects.
- Initial projects such as H2MOVES SCANDINAVIA, HYTEC, SWARM, and HYFIVE had durations too short to assess vehicle and fuel cell system durability. This issue was addressed with H2020 projects like the H2ME initiative, where FCEVs could accumulate enough operational hours to demonstrate durability.
- Although cumulative operational hours surpassed the FCH JU target on durability, fuel cell degradation was not measured. It should be reported for better assessment of fuel cell system durability.
- The criterion on degradation set in the MAWP (10% power degradation) should be better defined, including standard operation procedures on how fuel cell degradation should be measured. More attention should be given to degradation rates under dynamic operating conditions.
- Despite falling short on some KPIs like fuel cell durability, data shows that technology advancement should enable fuel cell stacks to meet the target within 2–4 years (Kurtz et al., 2018), given the rate of improvement since initial demonstrations
- Reported values for hydrogen consumption (descriptive and operational) meet the FCH JU target and show consistent improvement over time.
- It would be beneficial for projects to submit both descriptive KPI hydrogen consumption values (as rated by manufacturers) and a separate operational value reflecting performance in real conditions (measured in the projects).
- Recent projects have excelled every year in terms of the availability, surpassing the FCH JU targets.
- From the limited information available on fuel cell system costs, it can be inferred that costs significantly exceed the FCH JU target, although there has been considerable improvement over the years. This also applies to data from international state of the art, where costs are reported to exceed the target by 10%.
- Little information has been reported on maintenance costs, but available data largely complies with the FCH JU target and shows a downtrend.
- No project data was reported on fuel cell specifications. International data indicates that reported values for areal power density, PGM loading and cell volumetric power of state-of-the-art fuel cells fall short of the FCH JU target.

3.2 Fuel Cell Electric Buses Projects

3.2.1 Historical FCEBs Projects

Table 8 contains a summary of all the early FCEB relevant projects that contributed to the initial development of the FCEB technology (mainly in FP4, FP5 and FP6). These projects constituted the foundation for the demonstration projects that were developed in later FPs (FP7 and H2020). These projects focused on the assessment and harmonization of regulations and standards, and the early demonstration and technological improvements of FCEBs with the necessary refuelling infrastructure. The table includes the project acronym, the corresponding FP, the duration (start/end year), the project metrics (number of FCEBs deployed, number of HRSs deployed, participant cities, project total costs and corresponding EU funding), and a short description of the original project objectives.

Table 8. Summary of the historical FCEB projects (early FCEB initiatives, mainly from FP4, FP5 and FP6).

Project	FP	Start/End	Project in numbers	Project Title and Summary of original Project Objectives
DEVELOPMENT OF FULL SIZE ELECTRIC BUS WITH SECOND GENERATION FUEL CELLS STACKS	FP4	1996-2001	n/a n/a n/a n/a n/a	*Development of Full Size Electric Bus with Second Generation Fuel Cells Stacks.* This project aims to develop a pre-commercial fuel cell powered electric bus with high energy efficiency, autonomous and without range limitation. A 35-50 kW PEM hydrogen/air fuel cell is to be installed in hybrid combination with an energy buffer, allowing energy recovery when slowing or braking.
FUEL CELL BUS	FP5	2000-2003	n/a n/a Berlin (DE) Copenhagen (DK) Lisbon (PT) n/a n/a	*Fuel Cell Bus Project Berlin, Copenhagen, Lisbon.* This project has three objectives: 1) Development, construction and implementation of the electrical storage system to support the fuel cell system; 2) Development, construction and implementation of a stationary hydrogen filling station; and 3) Demonstration of the bus in an inner-city environment and of the filling station infrastructure.
FUEL CELL BUS II	FP5	2000-2004	n/a 1 HRS Berlin (DE) Copenhagen (DK) Lisbon (PT) 5.2 M€ 1.8 M€ (35%)	*Fuel Cell Bus Project Berlin, Copenhagen, Lisbon II* This project was the phase 2 of the previous FUEL CELL BUS project. This project is aimed at demonstrating the innovative fuel cell propulsion system, different energy storage systems and a stationary hydrogen refilling infrastructure. Its main goal is completing the demonstration approach of the first European fuel cell bus using liquefied hydrogen in an inner city application.

Project	FP	Start/End	Project in numbers	Project Title and Summary of original Project Objectives
ECTOS	FP5	2001-2005	3 FCEBs 1 HRS Reykjavik (IS) 6.9 M€ 2.9 M€ (41%)	*Ecological City Transport System. Demonstration, Evaluation and Research Project of Hydrogen Fuel Cell Bus Transportation System of the Future* This project aims to perform a real scale comparative assessment of the effect of changing the transport energy base from fossil fuel to hydrogen with a consortium of leading European companies on hydrogen production and distribution and vehicle manufacturers. The project will perform research, demonstration and evaluation of a hydrogen infrastructure and fuel cell buses in Reykjavik.
CUTE	FP5	2001-2006	27 FCEBs 9 HRS Amsterdam (NL) Barcelona (ES) Hamburg (DE) London (UK) Luxemburg (LU) Madrid (ES) Porto (PT) Stockholm (SE) Reykjavik (IS) 52.4 M€ 18.5 M€ (35%)	*Clean Urban Transport for Europe* This project aims to develop a transport system including the necessary accompanying energy infrastructure based on hydrogen. The goal is to achieve 250,000 hours of fuel cell operation with 27 FCEB project has three objectives: 1) Operationalise the concept of sustainable mobility in the transport sector; 2) Perform an integrated assessment of the elements in the CTP and other policy measures; and 3) Create cost-effective policy packages for reducing transport's contribution to CO_2 emissions.
HYFLEET:CUTE	FP6	2006-2009	33 FCEBs 9 HRS (former CUTE) Amsterdam (NL) Barcelona (ES) Hamburg (DE) London (UK) Luxemburg (LU) Madrid (ES) Porto (PT) Reykjavik (IS) 43 M€ 19 M€ (44%)	*Hydrogen for Clean Urban Transport in Europe* This project will continue operating the FCEB fleets from the former CUTE and ECTOS projects (27). Additionally, the project aims to develop and demonstrate a new FC hybrid pre-prototype and also to develop and demonstrate a fleet of 14 hydrogen powered internal combustion engine (ICE) buses in regular service in Berlin with the required hydrogen infrastructure.

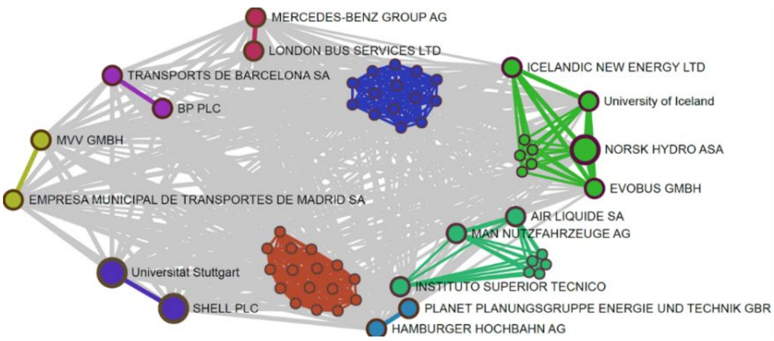
Source: JRC based on information from CORDIS, 2023.

Figure 33 (a) shows the organisations participating at the early FCEB initiatives described in Table 8 covering the period from 1996 until 2010. It can be noticed that a number of specific partners are common to a number of projects, forming clusters. These clusters aggregate different types of organisations, commonly a university or research centre, some HRS components manufacturers and a bus manufacturer or bus operator company (e.g. cluster formed by University of Iceland, Norsk Hydro ASA, Icelandic New Energy LTD and Evobus GmbH). The organisations that participated in a greater number of FCEB and associated HRS projects covering the period 1996-2010 were Universität Stuttgart, Norsk Hydro ASA, Shell PLC and Evobus GmbH, participating in 3 projects out of the 6 projects detailed in Table 8. All other organisations in Figure 33 (bus operators, bus manufacturers, research centres and other HRS components manufacturers) participated in at least 2 of the 6 projects detailed in Table 8. Many bus manufacturers and bus operators are present in these early initiatives, with Evobus GmbH, Icelandic New Energy LTD, London Bus Services, MVV GmbH, Hamburger Hochbahn AG, Empresa Municipal de Transportes de Madrid SA, Transports de Barcelona SA and MAN Nutzfahrzeuge AG participating in at least 2 of the 6 projects detailed in Table 8. In terms of HRS components manufacturers and HRS operators, Shell PLC, Norsk Hydro ASA, BP PLC and Air Liquide are present in most of these FCEB projects since there were not so many HRS component manufacturers and HRS operators at the time.

Figure 33 (b) shows the countries that were active in the greatest number of FCEB and associated HRS projects during this period. The member state that participated in the greatest number of projects was Germany with 4, followed by Norway, The Netherlands and Portugal with 3 projects.

Figure 33. TIM plots showing (a) the participants for all projects considered in Table 8 (early FCEB initiatives 1996-2010).[16] (b) EU Member State participation for all projects considered in Table 8 (early FCEB initiatives 1996-2010).[17]

a)

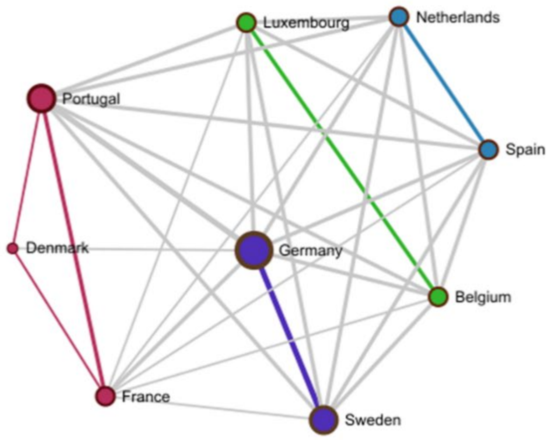


Organisation	Number of Projects
Universität Stuttgart	3
NORSK HYDRO ASA	3
SHELL PLC	3
EVOBUS GMBH	3
University of Iceland	2
ICELANDIC NEW ENERGY LTD	2
PLANET PLANUNGSGRUPPE ENERGIE UND TECHNIK GBR	2
LONDON BUS SERVICES LTD	2
MVV GMBH	2
MERCEDES-BENZ GROUP AG	2

(16) The size of the node represents the number of projects a partner is involved in, whilst the thickness of the links represents the number of projects in common between the linked partners. The coloured groupings are potential clusters identified by TIM's algorithm. The table shows the top 10 participants from the plot.

(17) The size of the node represents the number of projects that has at least one participating organisation from that member state. The thickness of the links between the nodes is proportional to the number of projects those member states have in common. The United Kingdom does not appear in the graph as it is not a current EU member state. The table shows the top 10 countries represented, including the United Kingdom (an EU member state when the project was awarded) for comparison.

b)



Member State	Number of Projects
Germany	4
Norway	3
Netherlands	3
Portugal	3
Iceland	2
Sweden	2
Luxembourg	2
United Kingdom	2
Belgium	2
Spain	2

Source: JRC (TIM) based on data from CORDIS, 2022.

3.2.2 Overview of Clean Hydrogen JU FCEBs demonstration projects

The following table contains a summary of all the relevant FCEBs demonstration projects that have provided most of the input values used in this report (Table 9). These projects, corresponding to FP7 and H2020, belong to the FCH JU Panel 1 category (Trials and Deployment of Fuel Cell Applications – Transport). They focus on the large-scale demonstration of the FCEB in Europe (deployment and performance monitoring). The table includes the project acronym, the corresponding FP, the duration (start/end year), the project metrics (number of FCEBs deployed, number of HRSs deployed, participant cities, project total costs and corresponding EU funding), and a short description of the original project objectives. These projects belong now to the Clean Hydrogen JU Pillar 3 category (Transport).

Table 9. Summary of all Clean Hydrogen JU FCEB demonstration projects analysed in this report (2010-2022).

Project	FP	Start/End	Project in numbers	Project Title and Summary of original Project Objectives
CHIC	FP7	2010-2016	58 FCEBs 7 HRS Aargau (CH) Berlin (DE) Bolzano (IT) Cologne (DE) Hamburg (DE) London (UK) Milan (IT) Oslo (NO) 82 M€ 25.9 M€ (32%)	*Clean Hydrogen in European Cities* The goal of this project is the advance towards the commercialisation of hydrogen powered fuel cell buses via operating a minimum of 26 fuel cell buses (FCEB) in medium sized fleets in normal city bus operation, whilst enlarging hydrogen infrastructure in 5 European regions. It will also embed the knowledge and experiences of previous projects operating FCEB (CUTE and HyFLEET:CUTE). A life cycle assessment of the use of H2FC buses will also be performed. Additional objectives are: 1) the identification of advantages, improvement potential and synergies of FCEB compared with conventional and alternative technologies, and 2) build a critical mass of public support for the benefits of green hydrogen powered transport.

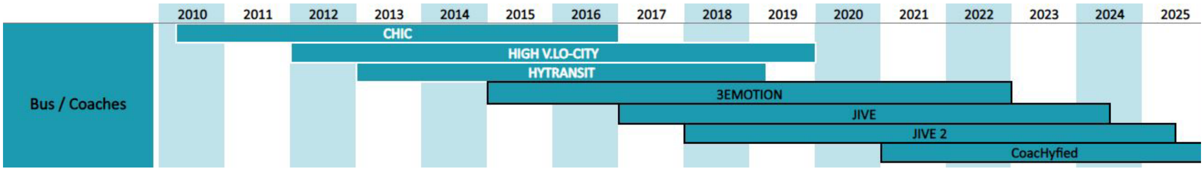
Project	FP	Start/End	Project in numbers	Project Title and Summary of original Project Objectives
HIGH V.LO-CITY	FP7	2012-2019	14 FCEBs 4 HRS Aberdeen (UK) Antwerp (BE) Groningen (NL) San Remo (IT) 30.5 M€ 13 M€ (43%)	*Cities Speeding up the Integration of Hydrogen Buses in Public Fleets.* This project aims at increasing the "velocity" of integrating FCEB on a larger scale in European bus operations by implementing technical improvements that increase efficiency and reduce costs, as well as introducing a modular approach to hydrogen refuelling infrastructure deployment. The technical improvements to increase efficiency and reduce cost of ownership will be directed to: 1) decrease hydrogen consumption to 7-9 kg H_2/100km, 2) integrating latest drive trains and battery technologies, 3) maintaining an availability of 90% without permanent support, 4) go beyond 12000 h of operation and decrease additional warranty cost, 5) increase key components lifetime (FC and batteries) and 6) reduce investment costs beyond 1.3 million EUR. Efforts are also directed to reduce the cost of hydrogen supply.
HYTRANSIT	FP7	2013-2018	6 FCEBs 1 HRS Aberdeen (UK) 17.7 M€ 7 M€ (39%)	*European Hydrogen Transit Buses in Scotland* The project will trial a fleet of 6 hybrid fuel cell buses in daily fleet services, together with one state of the art hydrogen refuelling station in Aberdeen (Scotland) for over three years. This project aims to advance the commercialisation of hydrogen buses in Europe by: 1) bringing together a European industrial consortium, 2) develop 6 A330 hybrid fuel cell buses specifically modified for long sub-urban routes, 3) operate the fleet under similar conditions to diesel buses (14h and 270 km/day) and 4) build a state of the art HRS to serve the bus fleet.
3EMOTION	FP7	2015-2022	29 FCEBs 5 HRS Aalborg (DK) London (UK) Pau (FR) Rotterdam (NL) Versailles (FR) 88.8 M€ 32 M€ (36%)	*Environmentally Friendly, Efficient Electric Motion* The project aims to overcome technical and economic barriers as well as significantly increasing the number of bus operators involved with FCEB. The main technical goals are: 1) decrease H_2 consumption below 9 kgH_2/km, 2) integrating latest drive trains and battery technologies, 3) maintaining an availability of >90% without permanent support, 4) go beyond 15000 h of operation and decrease additional warranty cost, and 5) reduce investment costs to 850 K EUR for a 13 m FCEB. To achieve these targets the consortium will operate 27 FCEB in 5 EU cities: London, Pau, Versailles, Rotterdam, and Aalborg (8 already existing) and develop 3 new HRS.
NEWBUSFUEL	H2020	2015-2017	n/a n/a n/a 2.5 M€ 2.4 M€ (99%)	*New Bus ReFuelling for European Hydrogen Bus Depots* The main goal of the project is to resolve a significant knowledge gap around the technologies and engineering solutions required for the refuelling of a large number of buses at a single bus depot. The project will focus on improving: 1) scale (throughputs in excess of 2000kg/day), 2) ultra-fast reliability (ensure close to 100% availability), 3) short refuelling window, 4) footprint and 5) volume of hydrogen storage (exceeding 10 t per depot).

Project	FP	Start/End	Project in numbers	Project Title and Summary of original Project Objectives
JIVE	H2020	2017-2024	138 FCEBs 9 HRS Aberdeen (UK) Birmingham (UK) Cologne (DE) Gelderland (NL) London (UK) Pau (FR) Rotterdam (NL) South Tyrol (IT) Wiesbaden (DE) Wuppertal (DE) 88 M€ 32 M€ (36%)	*Joint Initiative for Hydrogen Vehicles across Europe* JIVE will pave the way to bus commercialisation through the deployment of 142 fuel cell buses across 9 locations, more than doubling the number of FC buses operating in Europe. JIVE will use coordinated procurement activities to unlock the economies of scale which are required to reduce the cost of the buses. JIVE will also test new hydrogen refuelling stations with the required capacity to serve fleets in excess of 20 buses.
JIVE 2	H2020	2018-2025	119 FCEB 10 HRS Auxerre (FR) Barcelona (ES) Brighton (UK) Cologne (DE) Emmen (NL) Groningen (NL) London (UK) South Holland (NL) Wuppertal (DE) 90 M€ 25 M€ (28%)	*Joint Initiative for Hydrogen Vehicles across Europe 2* JIVE 2 is the successor of JIVE and is Europe's most ambitious FCEB project to date: 152 buses in 14 cities across seven countries. JIVE 2 involves regions with experience of the technology scaling up fuel cell bus fleets (e.g. Cologne), and those seeking to build their knowledge and experience by demonstrating FC buses in small fleets for the first time. The JIVE and JIVE 2 projects together will see the deployment and operation of nearly 300 FC buses in 22 European cities/regions, thus providing a sound basis for further development of this sector.
CoacHyfied	H2020	2021-2025	n/a n/a n/a 7.3 M€ 5 M€ (68%)	*Coaches with Hydrogen Fuel Cell Powertrains for Regional and Long-Distance Passenger Transport with Energy Optimised Powertrains and Cost Optimised Design.* The project will introduce two coach solutions to solve the challenges of longer driving distances of regional and long-distance coaches, more stringent packaging constraints, less favourable driving patterns and higher auxiliary powers.

Source: JRC based on information from the Clean Hydrogen JU, 2023.

Figure 34 shows the timeline of the FCEBs demonstration projects assessed in this report covering the period from 2010 until 2022.

Figure 34. Timeline of all FCEB demonstration projects analysed in this report



Source: Clean Hydrogen JU, 2023

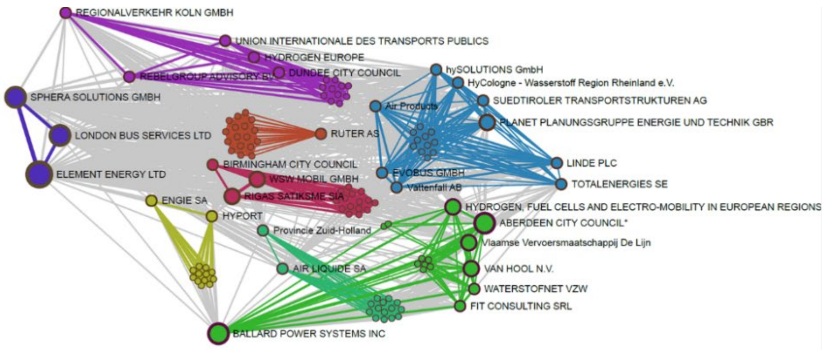
TIM visualisation was also employed to observe the trends on organisations and countries participating on these projects. Figure 35 (a) shows organisations involved in the Clean Hydrogen JU FCEB demonstration projects with a table listing the top ten in project participation. It can be observed that a number of specific partners are common to a number of projects, forming clusters. These clusters aggregate different types of organisations, usually a bus manufacturer, a bus operator company (commonly a municipal transport company), some HRS components manufacturers and a university, research centre or consultancy. This is the case of the cluster in light blue in Figure 35: Evobus GmbH (bus manufacturer), HyCologne Wasserstoff Region Rheinland / Suedtiroler Trasportstrukturen AG (bus operator companies), Air Products, Vattenfall AB, HySolutions GmbH, Linde PLC, TotalEnergies SE (HRS components manufacturers) and Planet Planungs Gruppe Energie und Technik GbR (consultancy). The organisations that participated in a greater number of FCEB and associated HRS projects covering the period 2010-2022 were Aberdeen City Council (bus operator) and Element Energy LTD (consultancy). These organisations participated in 4 projects out of the 8 projects detailed in Table 9. Following them with participation in at least 3 projects were Ballard Power Systems INC (fuel cell manufacturer), Rigas Satiksme SIA (bus operator), Sphera Solutions GmbH (HRS component manufacturer) and WSW Mobil GmbH (bus operator).

Comparing the organisations participating in previous FCEBs bus projects from FP4 to FP6 (Figure 33a) with the Clean Hydrogen JU FCEB demonstration projects (Figure 35a), it is observed the historical shift from early projects composed of scientific institutions, FC providers, and bus OEM to new projects mainly composed of FCEB operators/authorities/cities and consultants (data collection, coordination). FC providers, bus OEM are not often partners in the newest projects. This is showing the evolution from new technology developments to commercialisation and access to an open FCEB market.

Figure 35 (b) shows that the trend observed on participating countries in the FCEB early initiatives (see Figure 33 (b)) continues with the Clean Hydrogen JU FCEB demonstration projects. This means that the countries involved in the earlier FCEB initiatives (1996-2010), participated in the greatest number of FCEB projects in the 2010-2022 period. The country that was the most active was the United Kingdom with participation in 6 projects, followed by Germany, Denmark, and Belgium, participating in 5 projects.

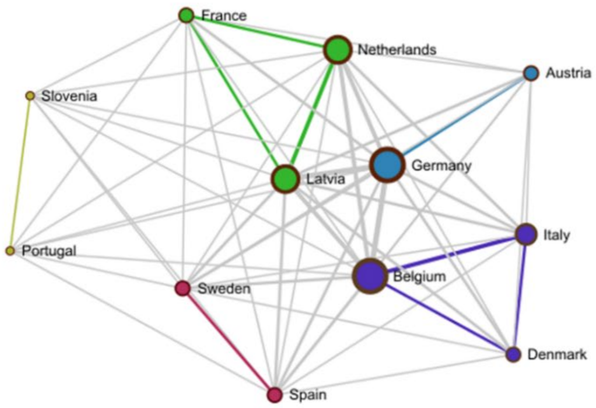
Figure 35. TIM plots showing (a) the participants for Clean Hydrogen JU FCEB demonstration projects (2010-2022). [18] (b) EU member state participation for Clean Hydrogen JU demonstration projects (2010-2022). [19]

a)



Organisation	Number of Projects
ABERDEEN CITY COUNCIL*	4
ELEMENT ENERGY LTD	4
BALLARD POWER SYSTEMS INC	3
RIGAS SATIKSME SIA	3
SPHERA SOLUTIONS GMBH	3
WSW MOBIL GMBH	3
HYDROGEN, FUEL CELLS AND ELECTRO-MOBILITY IN EUROPEAN REGIONS	2
Vlaamse Vervoersmaatschappij De Lijn	2
VAN HOOL N.V.	2
PLANET PLANUNGSGRUPPE ENERGIE UND TECHNIK GBR	2

b)



Member State	Number of Projects
United Kingdom	6
Denmark	5
Belgium	5
Germany	5
Netherlands	4
Latvia	4
Italy	3
Austria	2
France	2
Spain	2

Source: JRC (TIM) based on data from Clean Hydrogen JU, 2022.

It is worth mentioning that the Clean Hydrogen JU funded additional projects that further contributed to the demonstration of the FCEB technology. These projects belong to FCH JU Panel 5 (Hydrogen for Sectoral Integration) and intend to develop hydrogen valleys in which the use of FCEBs is not the main objective, hence these projects were not included in the analysis. A summary of the hydrogen for sectoral integration projects that include deployment of few FCEBs is contained in Table 3.

(18) The size of the node represents the number of projects a partner is involved in, whilst the thickness of the links represents the number of projects in common between the linked partners. The coloured groupings are potential clusters identified by TIM's algorithm. The table shows the top 5 participants from the plot.

(19) The size of the node represents the number of projects that has at least one participating organisation from that member state. The thickness of the links between the nodes is proportional to the number of projects those member states have in common. The United Kingdom does not appear in the graph as it is not a current EU member state. The table shows the top 5 countries represented, including the United Kingdom (an EU member state when the project was awarded) for comparison.

3.2.3 State of the Art

3.2.3.1 Technical development

Hydrogen fuel cell buses have undergone significant technological evolution since they were first developed in the early 1990s. At that time, hydrogen was primarily used in buses with internal combustion engines. However, bus developers are now concentrating almost entirely on fuel cell electric buses (FCEB). The primary advantage of FCEBs is their ability to produce electricity on-board with a high level of efficiency, providing zero-emissions transportation with a range of up to 300 to 500 km. Fuel cell buses draw their energy from the fuel cell system (composed of two fuel cell stacks for some FCEBs models, each with an output of around 100 kW). They also have a relatively small traction battery and are able to recover brake energy. In addition, they carry approximately 30 to 50 kg of compressed hydrogen on board, which is usually stored in pressure tanks at 350 bar.

The main FCEB manufacturers worldwide are Toyota Motors Corporation, Hyundai Motor Company, Daimler AG (now Mercedes-Benz Group), Van Hool NV and Wrightbus International Limited. These companies have been at the forefront of developing and deploying fuel cell technology in transportation, and particularly in urban buses. Other relevant FCEB manufacturers are New Flyer, VDL, Safra Bus, Solaris and Caetano Bus. They have been involved in various projects and initiatives worldwide aimed at reducing carbon emissions by promoting the use of hydrogen fuel cell-powered buses. As of 2019, the most deployed hydrogen fuel cell bus models per region were the Van Hool A330 FC in Europe, the New Flyer XHE60 in the US, the Hyundai Fuel Cell Electric Bus in the Republic of Korea, the Toyota Sora in Japan and the Yinlong Fuian Golden Dragon hydrogen fuel cell bus in China (International Energy Agency, 2019). The technical specifications from these and other frequently deployed models can be observed in Table 10.

Looking at the technical specifications we can observe that Ballard fuel cell technology is used by the many of FCEB models examined in Table 10, with 5 out of 11 FCEB manufacturers using their fuel cell stacks. This makes it the most commonly used fuel cell technology. Three other FCEB manufacturers use Toyota fuel cells, and there is no available information for the other models. The most widely used Ballard model is the FCvelocity-HD85, followed by the earlier developed FCvelocity-HD6. The power output of the fuel cells ranges between 60 kW to 228 kW, irrespective of the model. The majority of batteries used in these FCEBs are of the Li-ion type, with a few exceptions. Toyota utilises Ni-metal-hydride and Caetano Li-Ti-oxide (LTO) batteries. The battery capacity varies significantly from the lowest 11 kWh used by ENC model, to the highest one at 230 kWh used by Toyota Sora.

The range of fuel cell buses also varies greatly; Toyota Sora has the shortest range at 200 km, while New Flyer, Wright, Yinlong and Geely buses have a range of over 450 km. However, greater ranges are observed in new model prototypes, e.g. Temsa intercity Hydrogen bus with a range of up to 1000 km (TEMSA, 2023). The majority of the FCEB models displayed in Table 10 can travel a range of more than 340 km. There is no clear correlation between newer models deployed and range increase, and data on their reliability and operation is limited, as they are still quite recent. Hydrogen storage in these buses generally ranges between 27 kg to 50 kg, and the majority of FCEBs use a large hydrogen tank with lower storage pressure, typically at 350 bar. Buses in Asia present a higher storage pressure, at 700 bar, while buses in Europe and America have a storage pressure of 350 bar.

In terms of bus cost, the Wright bus shows the lowest cost per bus at 570 000 EUR, whereas ENC can cost more than three times that, at 1 963 000 EUR, owing the lower cost of the Wright bus to technological advantages and component cost reductions of newer models. There is a correlation of price reduction with the newer models. The average fuel consumption is approximately 8 kg per 100 km, ranging from 6 to 11 kg. This gives FCEBs an energy efficiency advantage of around 40% as compared with diesel buses. The operational data of newer models is limited, with only three out of eleven FCEB manufacturers reporting data on availability. These newer models have achieved an availability that ranges 75 – 89%.

Table 10. Specifications of the most commonly deployed FCEB models in Europe, US, Japan, Republic of Korea and China.

Bus Manufacturer	**Van Hool**	**ENC**	**New Flyer**	**Wright**	**Solaris**	**Toyota**	**Hyundai**	**Caetano**	**Foton**	**Yinlong**	**Geely**
Country of origin	Belgium	US	US	UK	Poland	Japan	Rep. of Korea	Portugal	China	China	China
Model	A330 FC	Axess	XHE40	STREETDECK FCEV Hydroliner	Urbino 12 hydrogen	Toyota FC Bus / Sora	Elec City Fuel Cell	H2.City Gold	BJ6123FCEVCH	Fuian Golden Dragon	F12
Start of Production	2019	2017	2018	2020	2020	2017	2020	2020	n/a	n/a	n/a
Fuel cell OEM	Ballard	Ballard	Ballard	Ballard	Ballard	Toyota	n/a	Toyota	Toyota	n/a	n/a
Model FC	FCvelocity-HD85	FCvelocity-HD6	FCvelocity-HD85	FCvelocity-HD85	n/a	Toyota FC Stack	n/a	Toyota FC Stack	SinoHytec	n/a	n/a
Power (kW)	210	150	85	85	120	228	180	60	n/a	120	n/a
Design	FC dominant	FC dominant	Hybrid (Battery dominant)	FC dominant	FC dominant	Hybrid (Battery dominant)	FC dominant	n/a	n/a	n/a	n/a
Battery type	Li-ion	Li-ion	Li-ion	Li-ion	Li-ion	Ni-metal hydride	Li-ion	Li-titan oxide	n/a	n/a	n/a
Battery capacity	17.4 kWh	11 kWh	100 kWh	27.4kWh	29.2 kWh	230 kWh	78.4 kWh	n/a	65 kWh	n/a	n/a
Range	350-400 km	418 km	482 km	450 km	350 km	200 km	343 km	400 km	n/a	500 km	500 km
Storage	38.5 kg	50 kg	37.5 kg	27kg	1560 L	600L	34.5 kg	37.5 kg	n/a	n/a	n/a
Pressure	350 bar	350 bar	350 bar	350 bar	350 bar	700 bar	700 bar	350 bar	350 bar	n/a	n/a
Hydrogen storage type	Type III	Type III	Type IV	N/A	Type IV	Type IV	Type IV	Type IV	n/a	n/a	n/a
Price (Thousand EUR)	650	1,718 - 1,963 *	1,039*	570*	650	762*	n/a	n/a	n/a	n/a	n/a
Fuel Consumption in 100 km	9-11 kg	10 kg	6.9 kg	n/a	<10 kg	n/a	6.9 kg	>6 kg	n/a	n/a	7.5 kg
Availability	83-89%	75%	75,6%	No data	n/a	n/a	n/a	n/a	n/a	n/a	n/a

Source: PwC, Study on State of the Art of FCEV, FCB and HRS

Other relevant European FCEBs manufacturers who have recently launched FCEB models and are not included in Table 10 are: Safra with Businova and its new H2City model, TEMSA with is intercity Hydrogen bus model, Skoda with its H'City model, IVECO Bus with its E-WAY H2 model, Mercedes Benz with its e-CITARO fuel cell model (using a fuel cell as a range extender), Karsan with its e-ATA hydrogen model, Otokar with its KENT C Hydrogen model and Irizar with its i6S Hydrogen model (Bus World Europe, 2023).

The use of fuel cells and hydrogen in municipal buses has made a substantial contribution to the technical and economic development of this drive technology in road transport. For that reason, the use of fuel cell technology and hydrogen in buses is also regarded as a model which can be transferred to other commercial vehicles (coaches, MD and HD vehicles). However, FCEBs also face some challenges. The cost of manufacturing and maintaining fuel cell buses is high, though it is expected to decrease as production volume increases. They also need hydrogen refuelling stations, which are not widely available yet. This lack of infrastructure is a major hurdle for the wider adoption of hydrogen fuel cell buses, and it is likely to contribute to slower growth than their battery electric counterparts.

Despite these challenges, FCEBs are regarded as a key component of sustainable transport solutions, particularly in urban areas. This is because they do not produce any harmful emissions, providing cleaner air to residents in cities where air pollution is often a significant problem. Demonstration projects with large fleets in long-term use are accelerating the market penetration, with FCEB fleets in Europe reaching between 300 and 400 vehicles in 2020. In comparing FCEBs with other zero-emissions transport solutions, battery electric buses (BEBs) are often considered the main competitor. BEBs are more affordable in the short term, with lower vehicle and refuelling costs, and with battery technology improving rapidly the difference in range is gradually closing.

In conclusion, fuel cell buses have undergone significant technological evolution in the last few decades. They represent a key component of sustainable transportation solutions in urban areas, but their high manufacturing and maintenance costs, as well as the lack of hydrogen refuelling infrastructure, are important challenges. They do, however, provide key advantages compared to battery electric buses in extended range and short refuelling times.

3.2.3.2 Manufacturing

From the analysis performed on FCEB manufacturing and sales data from 2016 to 2020 based on the IHS Markit, it can be concluded that the quantity of FCEBs manufactured varied significantly by region. The majority of FCEBs (88%) were manufactured in China, almost reaching 2500 units over the four years. During the same time period, European production accounted for approximately 123 buses, 4.5% of the global production. Japan and Republic of Korea followed with 92 and 81 units, respectively. The US came in last with 32 FCEBs (1.2% of the global production). Regarding fuel cell production for FCEBs, the largest fuel cell manufacturer was Ballard. Other main fuel cell system manufacturers for MD and HD vehicles are Cummings/Hydrogenics, Loop Energy, Nuvera, Plug Power, PowerCell and US Hybrid. Most fuel cell manufacturers offer a wide power range, typically 30 - 100 kW, producing fuel cells for both range extender and primary power applications (US Department of Energy). Toyota and Hyundai use similar fuel cell technology in their FCEBs as in their FCEVs but sized accordingly for the power needs of the FCEBs.

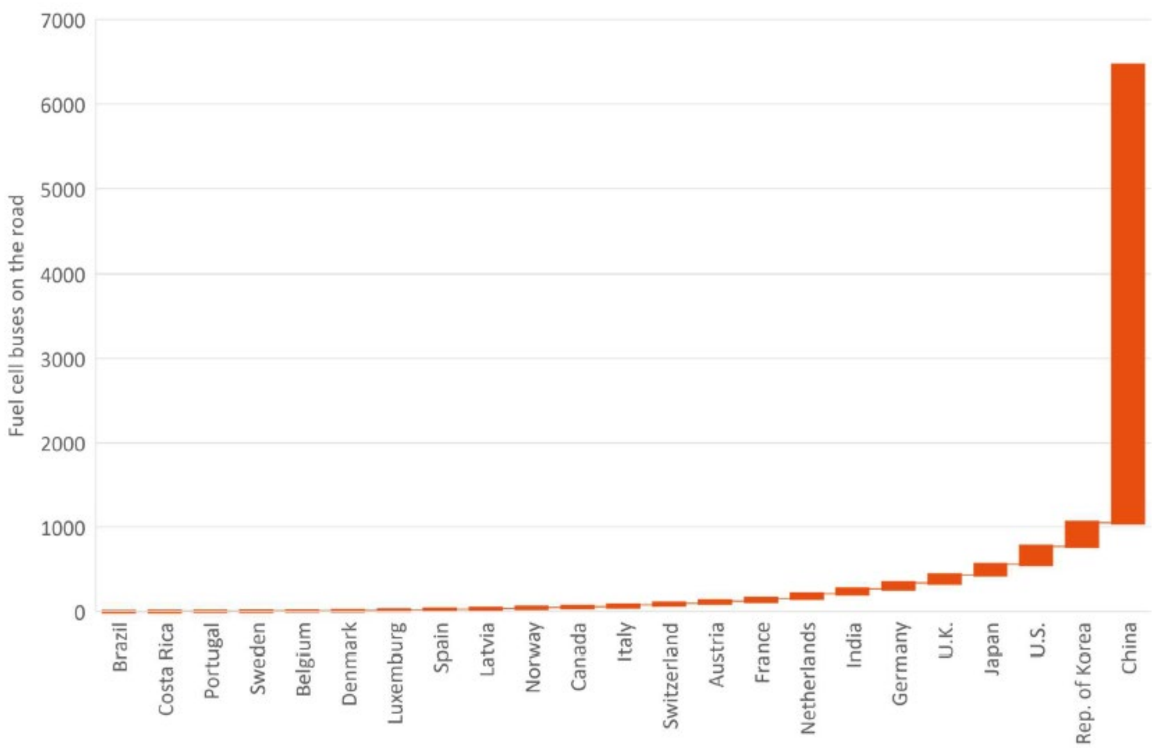
China has the largest bus and coach market globally, with the largest FCEB fleet. However, information on Chinese manufacturers is limited. The data shows that Chinese FCEBs tend to be smaller in size, with fuel cell modules between 40 kW - 70 kW. These manufacturers heavily depend on imported fuel cell technology since the primary fuel cell producers have joint ventures or own factories in China.

3.2.3.3 Deployment

As of June 2023, there were around 7000 fuel cell buses in operation worldwide, mostly in China, which accounts for over 85% of global deployment (International Energy Agency, 2023). Other regions such as Europe, Republic of Korea, the United States and Japan are also developing fuel cell bus fleets, although at a slower pace. Figure 36 shows the breakdown of FCEBs deployment per country as of the end of 2022. The Republic of Korea (281) and The United States (211) follow China (5410) in second and third place. Japan (124), The United Kingdom (98), Germany (68), India (58) and The Netherlands (54) are further countries with more than 50 units

(Can and Rex, 2023). Other countries that also operate fuel cell buses in the double digits are France (33), Austria (25), Switzerland and Italy (20 each). Other European countries, such as Norway, Latvia, Spain, Luxemburg, Denmark, Belgium, Portugal and Sweden are the remaining countries that operate fuel cell buses, with one to nine units each. Europe as a whole had 364 fuel cell buses in operation at the end of 2022, being the most active region deploying hydrogen buses after China.

Figure 36: Waterfall diagram showing country-based distribution of FCEBs on the road as of the end of 2022



Source: (Can and Rex, 2023)

There have been developments on fuel cell buses worldwide throughout 2022 and 2023. For example, Kansai Airport (Japan) launched a hydrogen fuel cell shuttle bus service in 2022 (VINCI Airports, 2022). In Europe, Polish manufacturer Solaris announced in September 2022 plans to unveil an 18-metre fuel cell bus with the first deliveries scheduled for the second quarter of 2023 (Solaris, 2022). Solaris has delivered nearly 100 of their 12-metre fuel cell buses to European customers since 2019. Additionally, Wright Bus will supply up to 60 fuel cell buses to the city of Cologne (Germany) (Belfast Telegraph, 2022), and Solaris will provide up to a further 20 fuel cell buses with deliveries beginning in 2023 (Solaris, 2022). A hundred and twenty-four new fuel cell buses will be also deployed in The United Kingdom's West Midlands, adding to the existing fleet of 20 buses (Express & Star, 2022). Caetano Bus, part of Toyota Caetano Portugal, has also announced plans to deploy 60 FCEBs in 2024 (Toyota Motor Corporation, 2023). In 2022, Safra launched a new fuel cell bus model at the European Mobility Expo held in Paris. The Hycity 12 will be the successor to their previous Businova H2 model, launched in 2011. In 2023, Germany has witnessed a significant uptake of FCEBs, with notable stakeholders like Deutsche Bahn, the cities of Weimar and Frankfurt, embracing this technology. For instance, Deutsche Bahn has approved the purchase of 60 FCEBs (Fuel Cell Works, 2023), while Weimar (Fuel Cell Works, 2023) and Frankfurt (Hydrogen Fuel News, 2023) have also shown their support for FCEBs. Similar developments are taking place in Liverpool, where the introduction of the first of 20 planned FCEBs took place in 2023 (H2-view, 2023). Additionally, Higer, a Chinese manufacturer, is currently conducting trials for FCEBs in Brazil and Uruguay (Fuel Cell Works, 2023). Notably, the Republic of Korea has made substantial strides in this area, with plans to deploy 700 FCEBs in Incheon by the end of 2024 (Hydrogen Central, 2023) and a staggering 1300 in Seoul by 2030 (Hydrogeninsight, 2023), partly supported by a subsidy program (Fuel Cell Works, 2023).

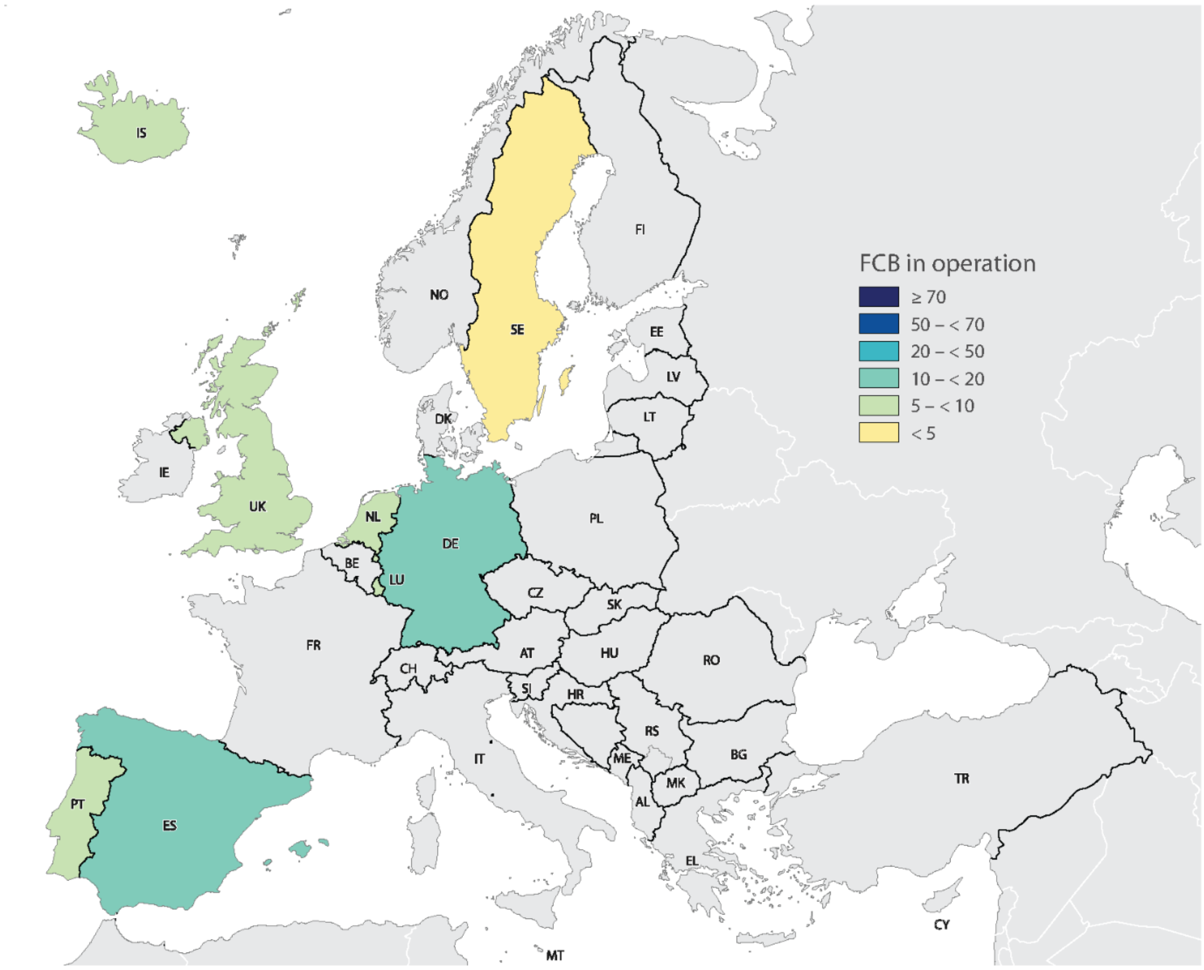
3.2.4 Progress against the State of the Art in Europe

3.2.4.1 Early FCEBs initiatives (2000-2010)

The early initiatives carried out during the implementation of FP4, FP5 and FP6 marked the start of the demonstration activities on FCEBs and its associated refuelling infrastructure in Europe. The projects “Development of Full Size Electric Bus with Second Generation Fuel Cells Stacks”, FUEL CELL BUS and FUEL CELL BUS II focused on the development and optimisation of pre-commercial fuel cell bus powertrains and its implementation in buses for inner city transport. Following these, ECTOS, CUTE and HIGH:FLEET CUTE projects led the way on the demonstration of the FCEB technology, deploying the first FCEB fleets in Europe, ahead of the Clean Hydrogen JU projects. Figure 37 illustrates the deployment of Fuel Cell Electric Buses (FCEBs) in Europe during the 2005-2010 period, including data from the CUTE and HIGH:FLEET CUTE projects. When considering the FCEBs deployed by the previous ECTOS project, the total European FCEB fleet amounted to 63.

Overall, these projects played a significant role in the development and commercialization of fuel cell buses. Through their research, demonstration and evaluation of fuel cell buses, these projects were able to demonstrate the potential of fuel cell technology for sustainable and efficient urban transportation, which helped to encourage the adoption and investment in fuel cell buses in the following years. These projects were also instrumental in establishing the first examples of hydrogen refuelling infrastructure for the urban transport sector, which was crucial for wider adoption of fuel cell buses in following projects.

Figure 37. FCEBs in operation in Europe from 2005 to 2010. Projects CUTE and HYFLEET:CUTE.



Administrative boundaries: © EuroGeographics © UN–FAO © Turkstat
Cartography: Eurostat – IMAGE, 09/2023

Source: Clean Hydrogen JU, 2023

3.2.4.2 Clean Hydrogen JU FCEB projects (2011-2023)

The projects funded by the Clean Hydrogen JU (FP7 and H2020) were focused on the wider demonstration, progress and validation of FCEB technology and its refuelling infrastructure. The ultimate goal was to accelerate the entrance of fuel cell technology in the European bus manufacturing industry by showcasing market readiness and creating competitive cost refuelling networks. Additionally, these projects assisted in the gathering of substantial FCEB and HRS performance data. This data proved to be useful in evaluating the performance of the deployed fleets and HRS against the MAWP KPIs.

Early Clean Hydrogen JU FCEB projects (2011-2019)

Early Clean Hydrogen JU FCEB projects under FP7 (CHIC, HIGH V.LO-CITY, HYTRANSIT and 3EMOTION) mainly centred on the deployment of the state-of-the art HRS and FCEB fleets at different European sites, validating and monitoring the progress of the FCEB technology. These bus demo projects provided further positive evidence on the performance and functionality of hydrogen fuel cell buses and associated refuelling infrastructure, steadily reducing barriers for their commercialisation in the short term. This was mainly achieved through major progress in fuel cell lifetime (exceeding the expectations) and increasing the availability of high-capacity refuelling systems. Operational experience was acquired with different bus drive trains and with different means of hydrogen production.

CHIC continued the demonstration efforts from the former CUTE project. CHIC was the first Clean Hydrogen JU project demonstrating FCEB reliability by operating 54 hydrogen fuel cell buses and 4 hydrogen powered internal combustion engine buses in 9 cities in Europe and Canada. The buses were delivered by 5 different bus manufacturers and had fuel cells from two different suppliers. Additionally, it contributed to enlarge the hydrogen refuelling infrastructure in Europe. The progress in the refuelling infrastructure was also demonstrated with more reliability, higher availability and shorter filling times. The refuelling stations operated with an average availability of more than 94% over the entire project lifetime, and at greater than 98% for half the sites in the latter half of the project. Meeting the demanding daily operational requirements of public transport operations in a number of diverse cities across Europe and Canada was the most significant achievement. This, combined with the step change, generational improvement in performance, including fuel consumption, and availability cemented the FCEB technology in urban transport.

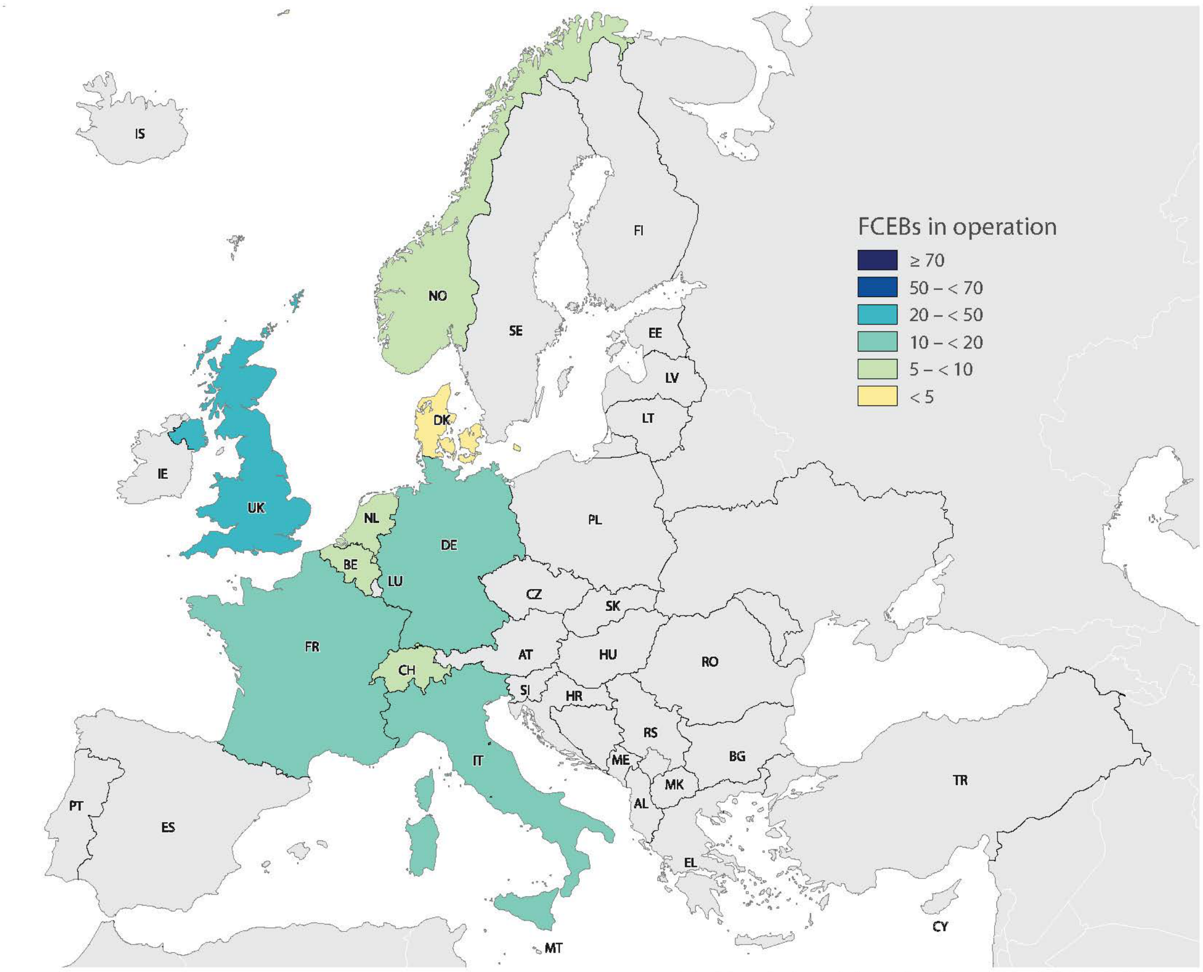
HIGH V.LO-CITY project accelerated the integration of a new generation of FCEBs. 14 FCEBs were operated in Scotland (UK), Liguria (IT), Flanders (BE) and Groningen (NL) in the public transport system. These buses were operated in fleets demonstrating the technical and operational quality. The project showcased their value in creating a clean and highly attractive public transport service and facilitated the modular shift that local transport policies were envisioning. By effectively linking previous (CHIC) and future demonstration sites (3EMOTION and JIVE), the project sought to further broaden and consolidate a network of successful fuel cell bus operators able to widen the dissemination of fuel cell bus operations in Europe. During the project lifetime, all 14 buses and 3 planned HRSs (and 1 additional HRS) were delivered and operated in the 4 European regions, under a wide range of geographical-, climate- and operational conditions. The buses drove more than 1 million km throughout the project, consuming between 9 - 13 kg H_2/100km. The refuelling times were kept in the 10 - 12 min interval at the project HRSs with an average availability of 96.8%. This led to the achievement of avoiding more than 1000 t of CO_2 emissions.

HYTRANSIT project deployed a fleet of six FCEBs and one state-of-the-art HRS in Aberdeen, Scotland. Throughout the project, the Aberdeen Kittybrewster HRS demonstrated some of the highest utilisation and availability figures observed across hydrogen projects in Europe. Over the four years of operation, an average availability of 99.5% was achieved, with over 147,000 kg of hydrogen dispensed in 5400 successful refills. This high level of performance was attributed to two main factors: the innovative station design which factored in great levels of redundancy into the station, and a dedicated on-site technical engineer who visited and monitored the site every day to assess performance and conduct pre-emptive maintenance. Based on the success of the station, the HRS was upgraded in 2018 to include a 700-bar refueller on-site. This opened the station to passenger cars and other smaller goods vehicles, increasing the utilisation of the facility and expanding Aberdeen City Council's (ACC) potential for hydrogen deployments. Through rigorous operation, the FCEBs demonstrated that the technology can meet many of the operational requirements of an equivalent diesel bus, especially when considering the range and refuelling time of the technology. However, when placed in comparison with their diesel counterparts, the availability of the FCEB was a challenge for the bus operator averaging 80% across the project period, excluding the teething period of the FCEBs and the HRS. Despite these availability challenges, the 6 HYTRANSIT buses operated impressively in the project, driving approximately 1.4 million kilometres and transporting over 1.3 million passengers. As a result, the consortium was able to compile a detailed dataset which has facilitated the development of a new generation of FCEBs capable of matching the full operational requirements of a conventional diesel bus.

3EMOTION deployed all the 29 buses it originally aimed at: 10 buses in London, 6 in Rotterdam and the South Holland province, 7 in Versailles, 3 in Pau and 3 in Aalborg. The project demonstrated the operability of buses from four different manufacturers with two different fuel cells systems. Additionally, 3EMOTION succeeded in gathering operational data throughout the project and in sharing operational experiences, attracting new cities, regions and operators to hydrogen buses. The project has also shown good synergies with other projects (JIVE initiative), other funding calls such as H2 Bus Europe (CEF) and bus manufacturers (Van Hool, Toyota Motor Europe and Caetano Bus) by participating in meetings and sharing experiences and lessons learned. Additionally, four peer-reviewed scientific publications were developed under the project duration, mainly on hydrogen refuelling aspects related to buses. It is worth mentioning that the project also created spill-over effects and new activities not originally targeted. An example of this is that the bus concepts developed and tested in the project (range extender trailers) led to the development of the first VDL hydrogen truck, which used the same module on a fuel cell heavy duty truck. A more integrated system for trucks (H2Haul project) evolved from the initial concepts tested in 3EMOTION with further development. The buses in some sites of 3EMOTION met the targets on Hydrogen Consumption (average of 8 kg H_2/100 km), Warranty Time (15 000 h) and Bus Cost (< 850 000 EUR) but fell behind slightly on Availability. The cumulative distance covered by the 3EMOTION buses through the project duration was close to 4 million km. Overall, the project met its targets in terms of deployment and KPIs. The main difficulties experienced throughout the project were related to delays due to replacement of project sites or due to regulatory and permitting issues (homologation of new bus concepts). Another major issue was the impact of COVID-19 on the operation of the buses in the different sites. However, full operation of the project sites was achieved during 2022.

Figure 38 shows the deployment of FCEBs in Europe from the early Clean Hydrogen JU FCEB projects during the 2011-2019 period, including data from the CHIC, HIGH V.LO-CITY, HYTRANSIT and 3EMOTION projects. The total FCEB fleet deployed in Europe during this period amounted to 107.

Figure 38. FCEBs in operation in Europe from 2011 to 2019. Projects: CHIC, HIGH V.LO-CITY, HYTRANSIT and 3EMOTION.



Administrative boundaries: © EuroGeographics © UN–FAO © Turkstat
Cartography: Eurostat – IMAGE, 12/2023

Source: Clean Hydrogen JU, 2023

Recent Clean Hydrogen JU FCEB projects (2020-2023)

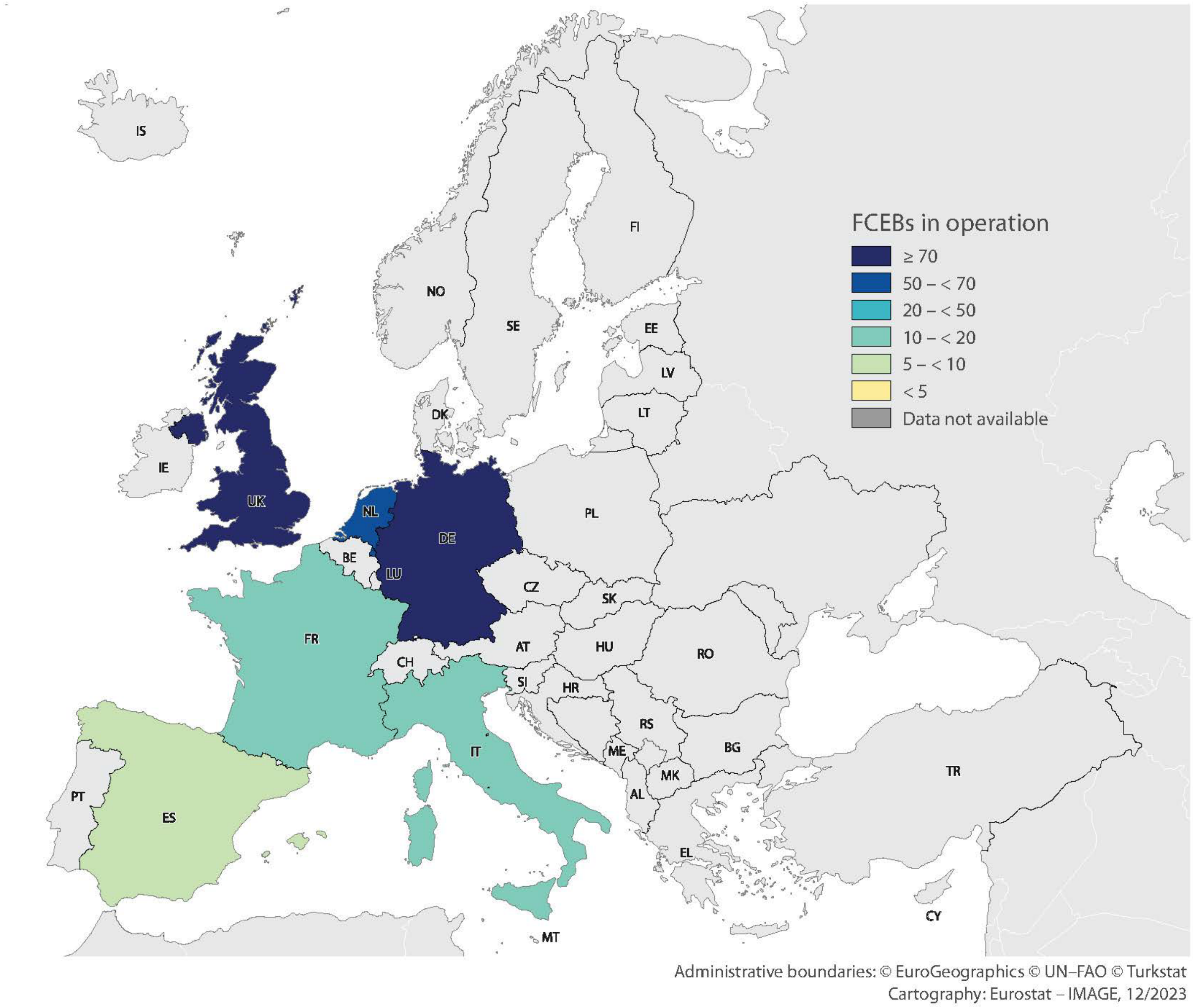
Recent Clean Hydrogen JU FCEB projects under H2020 (NEWBUSFUEL, JIVE and JIVE2) focused on accelerating the market penetration of FCEBs deployed in Europe, demonstrating market readiness and identifying business cases as well as developing the necessary refuelling infrastructure at a competitive cost. JIVE and JIVE2 both aimed at the expansion of the deployment of FCEBs and refuelling infrastructure across Europe while NEWBUSFUEL focused on techno-economic aspects of FCEB and associated infrastructure.

Within the NEWBUSFUEL project engineering studies were conducted for 13 different large scale hydrogen refuelling station designs at 12 different sites in seven European countries, taking into account the individual boundary conditions and constraints of the individual projects. These comprised numerous challenges with respect to local conditions such as topography and climate, the situation of the bus operator, e.g. the existing bus depots, or the national regulatory framework. Despite the large variation of requirements, suitable HRS solutions could be developed for all case studies within the project. This was achieved by close cooperation between the bus operators and infrastructure suppliers. All solutions considered components and technologies that were available, proving that there were no technological limits related to hydrogen infrastructure. The project also focused on the economic performance of the hydrogen infrastructure. Three case studies following different HRS technology concepts achieved the hydrogen target cost range of 4 – 6 €/kg H_2. For those case studies missing the target cost range, the most relevant reasons and obstacles were identified. Recommendations from the experiences and insights that were generated among the project participants were proposed for the three main stakeholder groups (bus operators, hydrogen infrastructure suppliers and policy makers). These aimed for further technical and economic improvements of the HRS technologies, and consequentially for improving the cost-competitiveness of operating hydrogen fuel cell buses.

Combined JIVE and JIVE 2 are deploying over 300 fuel cell buses in 16 cities across Europe, the largest deployment in Europe to date. The local fleets range from 5 to 50 FCEBs, typically 10 to 20. As of 2022, JIVE has ordered all the 142 planned buses and 132 are in operation, while JIVE 2 has ordered 122 buses out of the 156 planned, has 98 buses in operation and expects to have the committed fleet delivered by mid-2024. These two projects have suffered considerable delays over the pandemic period and had to be extended. One city from JIVE and another city from JIVE2 do not yet have their buses operational, although they are expected to be operational by the summer 2023 and November 2024, respectively. Considering these two projects and 3EMOTION, 258 Clean Hydrogen JU buses were in operation and reporting data throughout 2022 in 17 cities. Considering the bus demonstration projects that were reporting in TRUST between 2016 and 2022, a total distance of over 14.8 million km was accumulated, with almost 6.9 million km accumulated in 2022 alone. In the last six years, over 1.4 million tonnes of hydrogen have been consumed, of which 44% in 2022.

Figure 39 illustrates the deployment of FCEBs in Europe from the recent Clean Hydrogen JU FCEB projects during the 2020-2023 period, including data from the JIVE and JIVE2 projects. The total FCEB fleet deployed in Europe during this period amounted to 257.

Figure 39. FCEBs in operation in Europe from 2020 to 2023. Projects: JIVE and JIVE2.

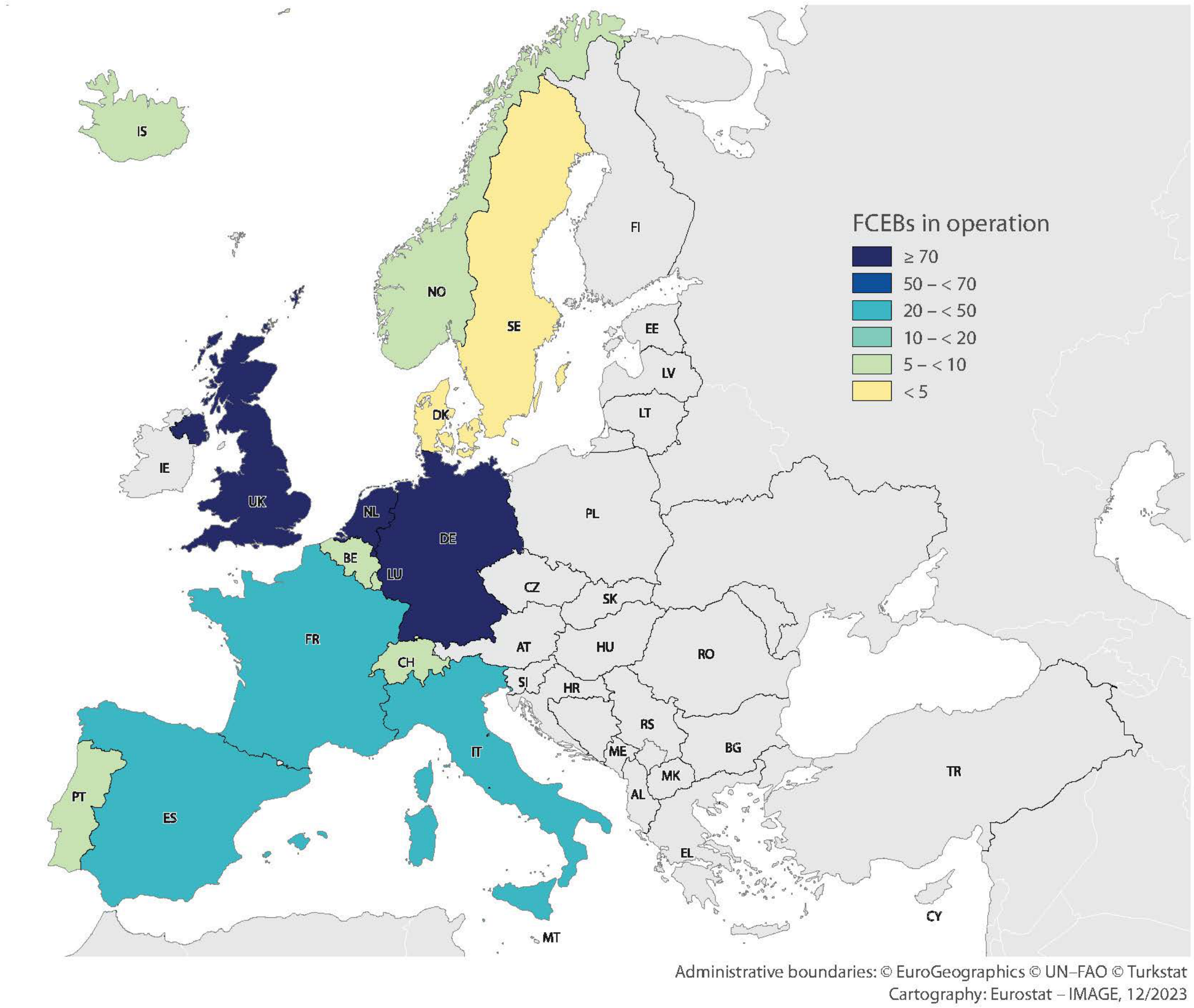


Source: Clean Hydrogen JU, 2023

A major advantage for FCEBs is the longer distance range they can achieve in comparison to battery electric buses. The COACHYFIED project, which started in January 2021, is aiming to demonstrate coaches with fuel cell powertrains in regional and long-distance passenger transport. The project focuses on the evolution of the fuel cell city bus drive systems into the coach sector, taking into account the special challenges for electrification of coaches regarding range, speed, comfort (air conditioning) and luggage space. The project is addressing two coach types, both for the medium range Regional Coaches (M3 class II) for regional or intercity transport as well as the Long-Distance Coaches (M3 class III) for tourist transport. The demonstration comprises 6 coaches from two European coach manufacturers, with FC technology from two leading FC manufacturers and applies two standard compressed hydrogen tank solutions. The vehicles are to be demonstrated in two different European regions representing a bandwidth of different geography, climate and operational profiles.

At a European level, the Clean Hydrogen JU bus deployment activities can be considered as a flagship. Figure 40 shows the total European FCEB fleet deployed from 2005 to 2023, including data from CUTE, HIGH:FLEET CUTE, CHIC, HIGH V.LO-CITY, HYTRANSIT, 3EMOTION, JIVE and JIVE2. The number of deployed FCEBs during this period surpasses the 400-unit milestone. The success of bus demo projects is demonstrated by the fact that in different cities, bus operators have joined the projects after their start. This evidences a growing involvement of regions and a steadily increase in private contribution to the financing of the demo projects.

Figure 40. FCEBs deployed in Europe from 2005 to 2023. Projects: CUTE, HIGH:FLEET CUTE, CHIC, HIGH V.LO-CITY, HYTRANSIT, 3EMOTION, JIVE and JIVE2.



Source: Clean Hydrogen JU, 2023

Additional outputs from these projects worth mentioning are: 1) the significant amount of data collected, relevant for KPIs assessment and improvement of WTW analysis and TCO models; 2) the collaboration with city councils for dissemination to the public, site visits and dissemination to attract new customers; and 3) the development of integrated solutions offered by partnerships among powertrain manufacturers, bus manufacturers and hydrogen providers, promoting the acceleration of the development of hydrogen mobility in Europe. However, there are still barriers to be overcome.

FCEBs encounter difficulties competing against the cheaper costs of battery electric buses. This situation has been accentuated through 2022 as the energy crisis impacted the hydrogen prices at the pump, affecting the financial viability of the projects. Maintenance and operational costs for the buses have become too high for some operators to commit to the project, especially due to the high hydrogen prices observed in 2022. The high hydrogen price has been a significant unforeseen challenge and is still to be resolved. Improvements are expected, but uncertainties persisted at the end of 2022. Additionally, FCEB mass production is still not available and manufacturing times are long with 12 to 18 months between FCEB order and delivery. The 'chicken and egg problem' for refuelling infrastructure is slowly improving but there are still few providers for "package solutions" including hydrogen production, storage and dispensing, with operation and maintenance of the HRS. Another barrier to be considered is the weak supply chain of components for hydrogen mobility applications in general. The main issue is that manufacturers tend to follow demand and there is little flexibility to increase the stock of spare parts. The increase of manufacturing capacity and cost optimisation are therefore limited.

3.2.5 Key Performance Indicators and Targets

The targets originating from the Addendum to the Multi-Annual Work Plan (MAWP) of the FCH JU 2 (Fuel Cells and Hydrogen 2 Joint Undertaking (FCH JU), 2018) for fuel cell electric buses were employed to assess the performance of the FCEB projects. These targets are summarised in Table 11.

This table also includes SoA values for 2012 and 2017. The values provided in this table originate from agreement between the FCH 2 JU and a panel of industry experts. The parameters considered as KPIs for the purpose of the programme are:

1. *Fuel cell system durability (h)*. Durability of the fuel cell system until 10% power degradation.
2. *Hydrogen consumption (kg/100)*. Hydrogen consumption for 100 km driven under real life operation using exclusively hydrogen feed.
3. *Availability (%)*. Percent of time that the bus is able to operate versus the overall time that it is intended to operate.
4. *Yearly operation cost (EUR/year)*. Costs for spare parts and labour for the drivetrain maintenance.
5. *Fuel cell system cost (EUR/kW)*. Cost of the fuel cell system - excluding overheads and profits.
6. *Bus cost (Thousand EUR)*. Cost of manufacturing the vehicle.

Table 11. State-of-the-art and future targets for fuel cell buses (Fuel Cells and Hydrogen 2 Joint Undertaking (FCH JU), 2018)

No.	**Parameter**	**Unit**	**State of the art**		**Clean Hydrogen JU target**		
			2012	**2017**	**2020**	**2024**	**2030**
1	Fuel cell system durability	h	10000	16000	20000	24000	28000
2	Hydrogen consumption	kg/100	9	8.5	8.0	7.5	7.1
3	Availability	%	85	90	90	93	93
4	Yearly operation cost (including labour)	EUR/year	n/a	n/a	16000	14000	11000
5	Fuel cell system cost	EUR/kW	3500	1500	900 (250 units)	750 (500 units)	600 (900 units)
6	Bus cost	Thousand EUR	1300	650	625 (150 units)	600 (250 units)	500 (300 units)

Source: Addendum to the Multi-annual Work Plan of the FCH 2 JU (Fuel Cells and Hydrogen 2 Joint Undertaking (FCH JU), 2018)

Notes:

1) Durability of the fuel cell system subject to EoL criterion, fuel cell stack life 10% degradation in power or H2 leak rate as per SAE2578.

2) Hydrogen consumption for 100 km driven under operations using exclusively hydrogen feed according to SORT 1 and 2 drive cycle.

3) Percent amount of time that the bus is able to operate versus the overall time that it is intended to operate for a fleet availability same as diesel buses.

4) Costs for spare parts and man-hours of labour for the drivetrain maintenance.

5) Actual cost of the fuel cell system - excluding overheads and profits subject to yearly overall fuel cell bus module volume as stated.

6) Cost of manufacturing the vehicle. In case of buses for which a replacement of the fuel cell stack is foreseen, the cost of stack replacement is included in the calculation. Subject to yearly volumes per OEM as assumed in Roland Berger FC bus commercialisation study.

Additionally, the following parameters related to the deployment of fuel cell buses have also been studied to assess the progress of FCH 2 JU projects:

1. *Number of buses deployed in operation (units)*. Number of buses deployed in operation during the reference period in the reference location by the end date of the present reporting exercise.
2. *Number of buses deployed, cumulative (units)*. Cumulative number of buses deployed during the reference period in the reference location by the end date of the present reporting exercise.
3. *Distance driven (km).* Yearly distance driven by the buses over the timeframe of the data collection exercise.
4. *Distance driven, cumulative (km).* Total distance driven by the buses within the project, until the end date of this data reporting exercise.

3.2.6 Performance evaluation of FCEB projects in Europe

In this section, the performance of the reviewed projects versus a series of specific KPIs is assessed. The KPI values from each project were extracted from final reports, the TRUST database and other sources of information.

The information obtained from this study has then been used to review how the programme is progressing against its overall targets, and to suggest future modifications to the research programme and associated targets. This will be put into context regarding the scale of the project and the conditions under which the particular performance was achieved. The data presented is obtained from the following demonstration projects: ECTOS, CUTE, HY:FLEET CUTE, CHIC, HIGH V.LO-CITY, HYTRANSIT, 3EMOTION, JIVE, JIVE2.

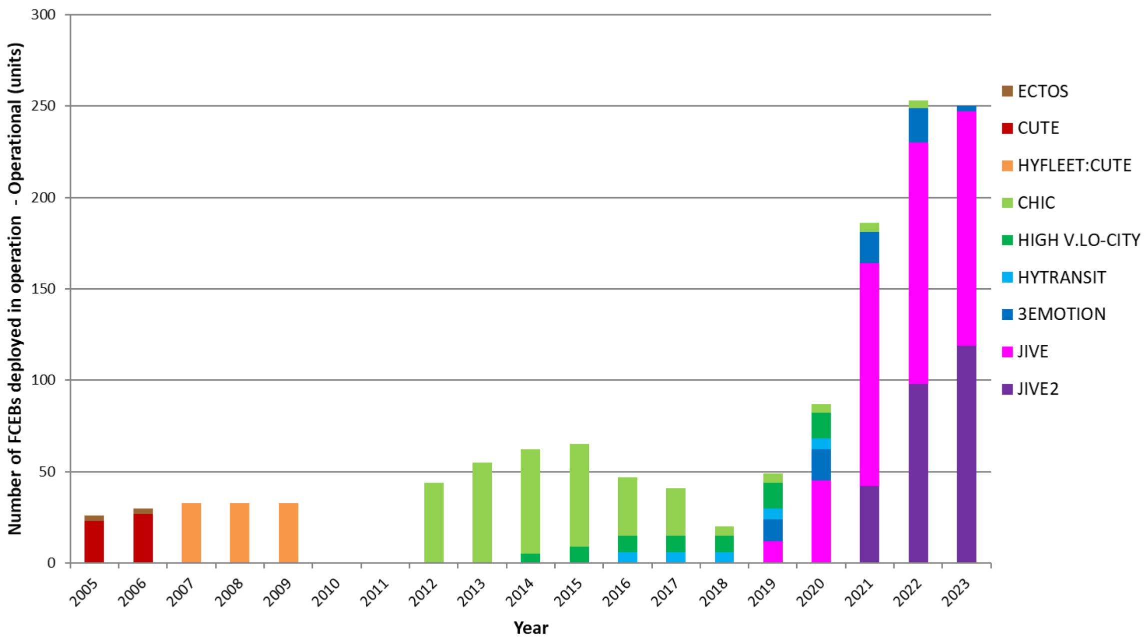
It should be noted that the values obtained from these projects should be provided under standard boundary conditions applying to all system KPIs (as defined in Table 11). In general, it has not been possible to establish whether all data has been given under these standard conditions.

3.2.6.1 Number of buses deployed in operation (units)

Figure 41 shows the number of FCEBs deployed and in operation over the years by the early European FCEBs initiatives and the Clean Hydrogen JU FCEBs projects. A gap regarding deployment can be observed between the early European projects (ECTOS, CUTE, HYFLEET:CUTE) and the FCH JU projects kicking off (starting with CHIC).

It is noticeable that compared to the early deployments that started with the ECTOS, CUTE and HYFLEET:CUTE projects, deployment numbers have seen a significant growth with the FCH JU projects, especially with JIVE and JIVE2 projects. In 2023 (data collected from May 2022 to May 2023), 250 FCEBs were in operation and reporting data from 3EMOTION, JIVE and JIVE2 projects in Europe. These FCEBs are distributed in cities from seven European countries.

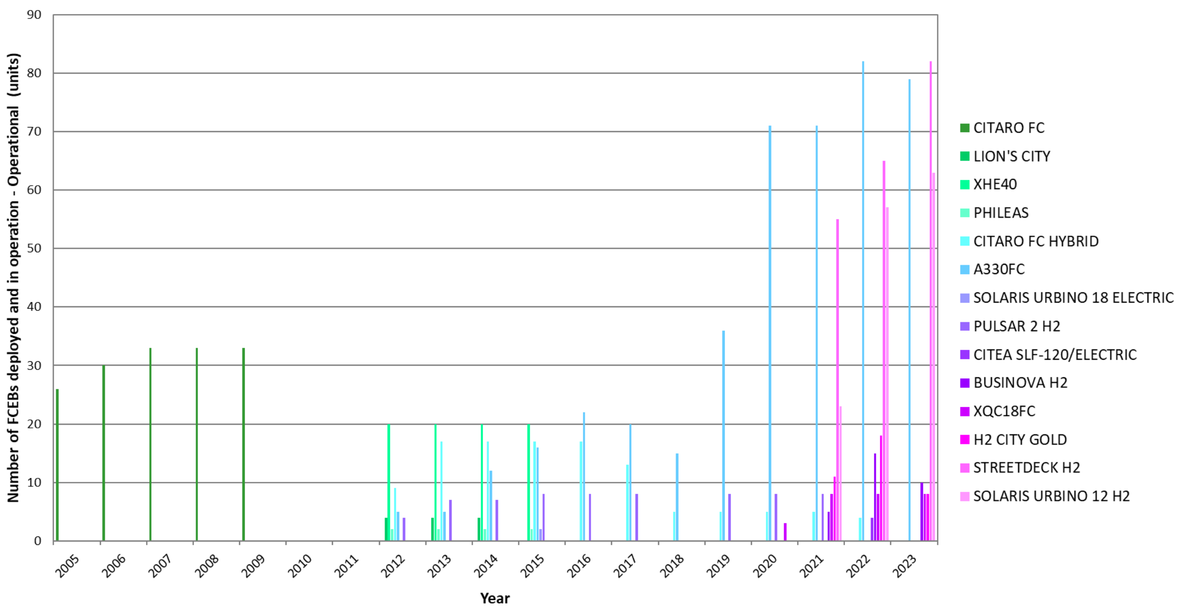
Figure 41. Number of FCEBs deployed and in operation per project versus year



Source: JRC based on data from Clean Hydrogen JU, 2023.

Figure 42 and Figure 43 show a detail of the FCEB models deployed and in operation over the years and the models deployed within each project over the years, respectively.

Figure 42. Number of buses deployed and in operation from each model versus year for FCEB projects

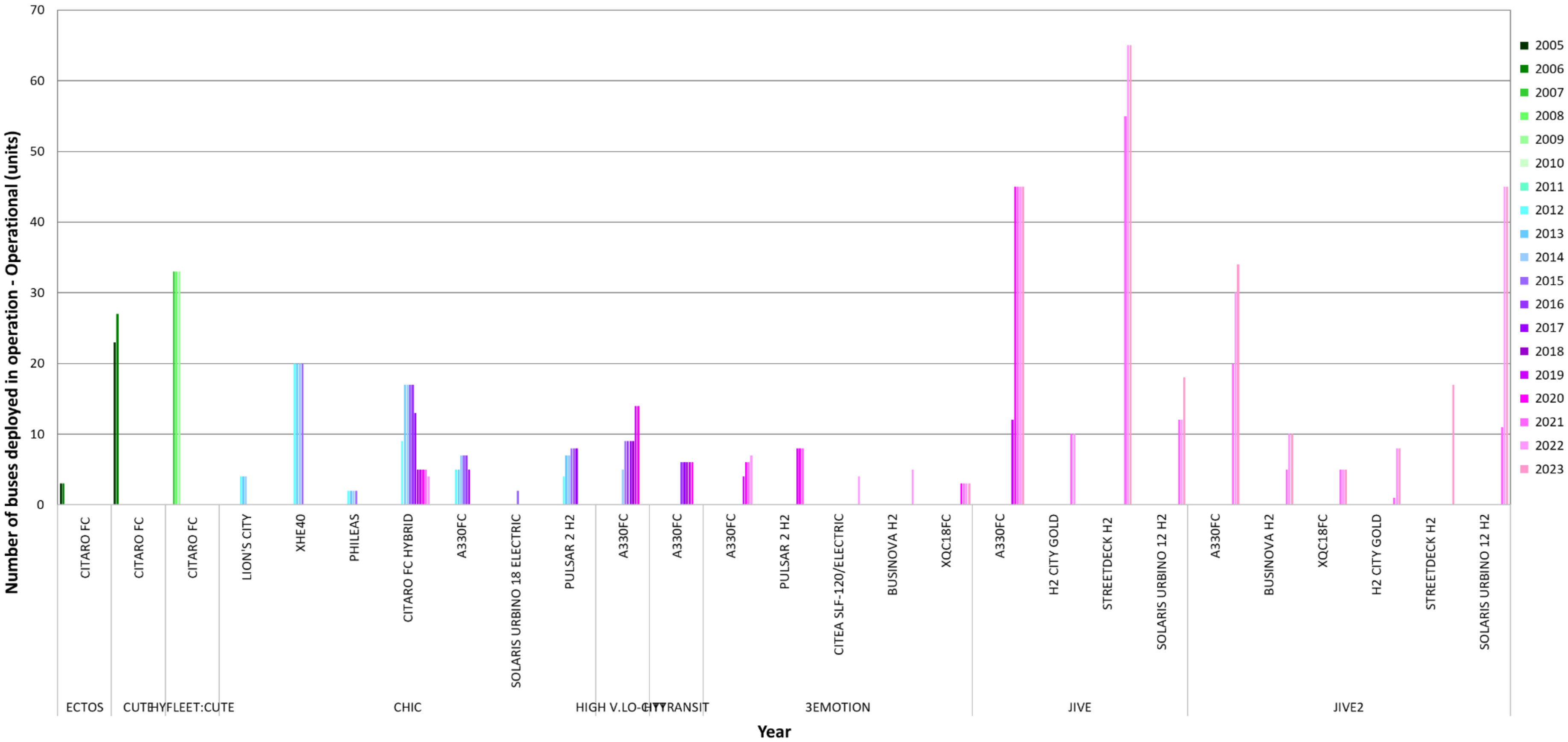


Source: JRC based on data from Clean Hydrogen JU, 2023.

The models deployed came from a wide variety of manufacturers: Mercedes-Benz group (CITARO FC and FC Hybrid), MAN Truck & Bus (LION'S CITY), APTS (PHILEAS), Van Hool (A330FC and XQC18FC), New Flyer (XHE40), Safra Bus (BUSINOVA H2), VDL (CITEA SFL-120 ELECTRIC), Wright Bus (PULSAR 2 H2 and STREETDECK H2), Caetano (H2 CITY GOLD) and Solaris (URBINO 12 H2). A total of 13 different FCEB models were deployed over the years in the different projects. The deployment followed the international state of art with the latest models launched to the market being deployed in the FCH JU projects. In some cases, prototype/concept buses were also deployed and tested within the projects timeframe.

Figure 43 details the FCEB models deployed within each project. We can observe that the models most deployed for each project were: 1) CITARO FC for ECTOS, CUTE and HYFLEET:CUTE with 3, 27 and 33 units respectively, 2) XHE40 for CHIC with 20 units, 3) A330FC for HIGH V.LO-CITY, HYTRANSIT and JIVE with 14, 6 and 45 units respectively, 4) PULSAR 2 H2 for 3EMOTION with 8 units and 5) SOLARIS URBINO 12 H2 for JIVE2 with 45 units.

Figure 43. Number of buses deployed in operation from each model per year over the different FCEB projects

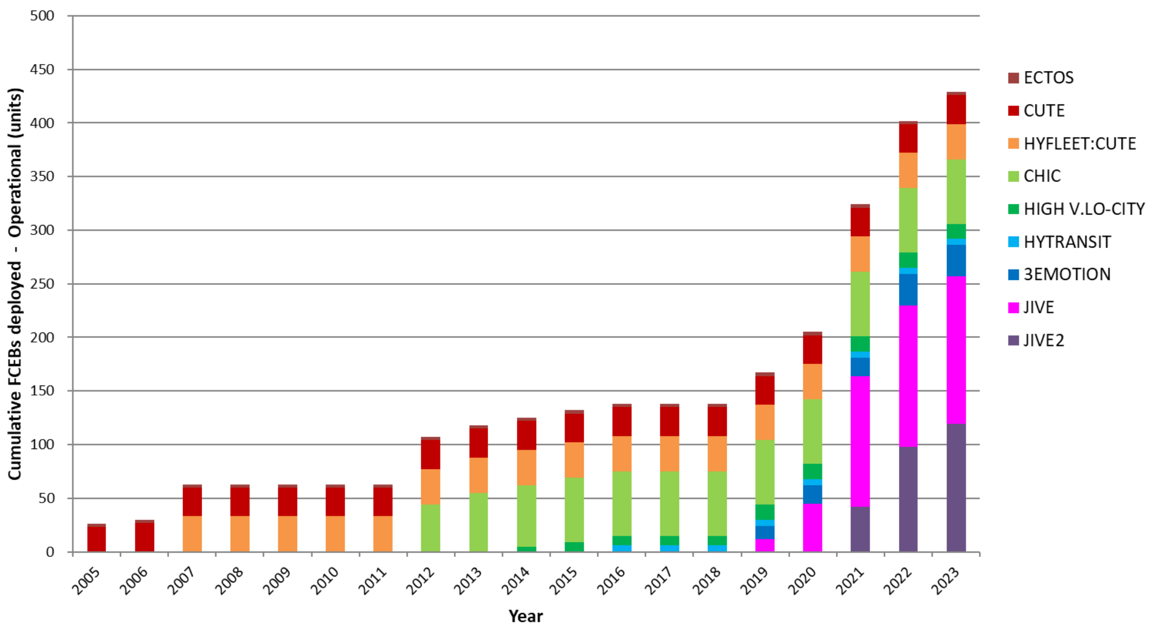


Source: JRC based on data from Clean Hydrogen JU, 2023.

3.2.6.2 *Number of buses deployed, cumulative (units)*

Figure 44 illustrates the cumulative FCEBs deployed over the years by the different projects. The three deployment periods described in Section 3.2.3 are easy to distinguish in Figure 44: 1) the early FCEBs initiatives in the 2005-2010 period with the first FCEBs demonstration (ECTOS, CUTE, HYFLEET:CUTE projects); 2) the early Clean Hydrogen JU projects in the 2011-2019 period, focusing on the wider demonstration, progress and validation of FCEB technology (CHIC, HIGH V.LO-CITY, HYTRANSIT and 3EMOTION projects); and 3) the recent Clean Hydrogen JU projects in the 2020-2023 period, focusing on demonstrating market readiness and identifying business cases (JIVE and JIVE2 projects). It is also noticeable the significant growth of FCEBs deployment with the Clean Hydrogen JU projects, especially with JIVE and JIVE2 projects in 2022 and 2023. The total FCEB fleet deployed over the 2005-2023 period surpasses the 400-unit milestone.

Figure 44. Cumulative FCEBs deployed per project versus year

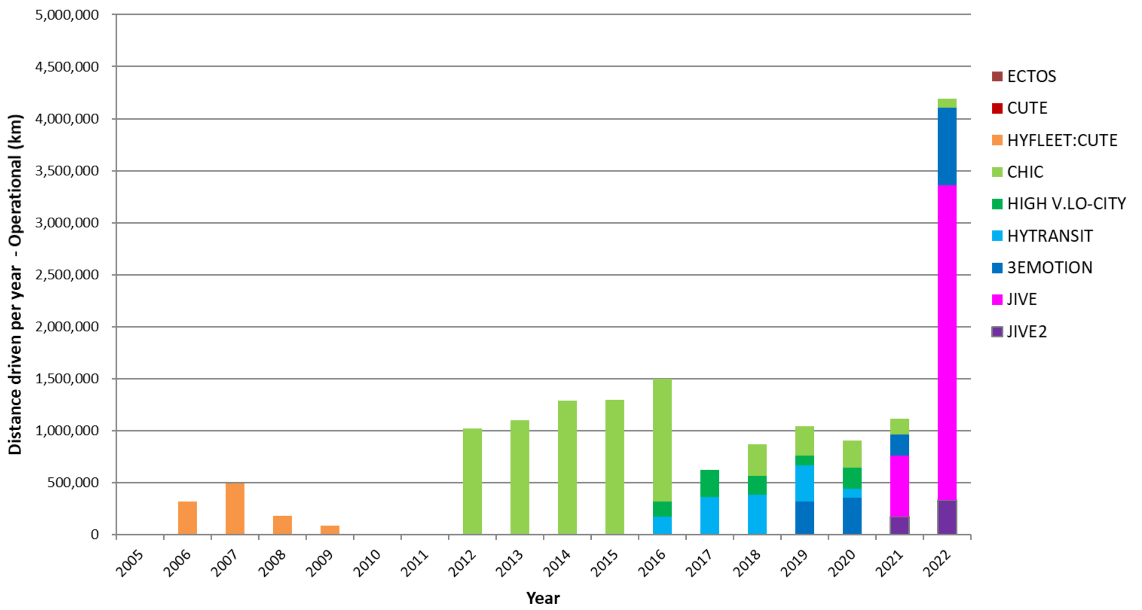


Source: JRC based on data from Clean Hydrogen JU, 2023.

3.2.6.3 *Distance driven (km)*

Figure 45 shows the distance driven by the buses deployed in each project per year. There is a lack of data reporting on yearly distance driven for the early European projects (ECTOS and CUTE). They cannot be considered in this analysis for that reason. Clean Hydrogen JU projects have reported the yearly distance driven by the FCEBs since 2012. It is observed that the distance driven by the FCEBs per year was growing until the end of CHIC project where it stagnated for several years. However, the year 2022 showed great distance driven figures from 3EMOTION, JIVE and JIVE2 projects. This was partly caused by the lock-downs from the COVID-19 pandemic, with fleets not operating for long periods of time and the FCEB deployments being postponed due to bottlenecks in supply chains. The recovery in distance driven is significant for 2022.

Figure 45. Yearly distance driven by the buses deployed versus year of data collection

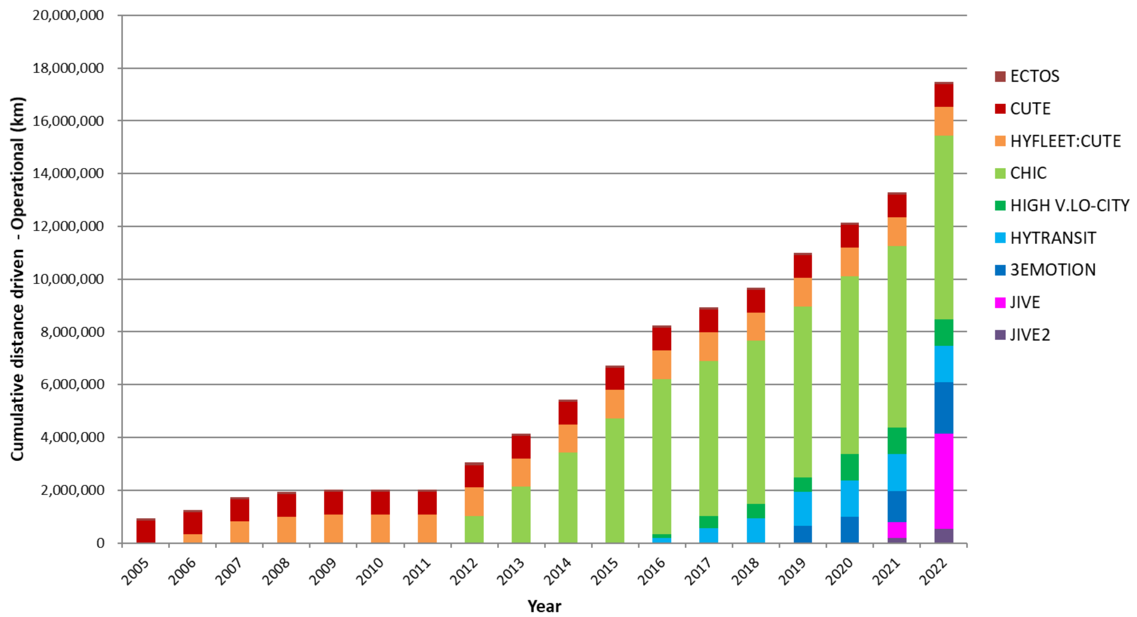


Source: JRC based on data from Clean Hydrogen JU, 2022.

3.2.6.4 Distance driven, cumulative (km)

Figure 46 illustrates the cumulative distance driven by the FCEBs for all the projects. It can be concluded that the FCEBs deployed over the 17 year period (2005-2022) accumulated a mileage of more than 17 million km, demonstrating the readiness of the FCEB technology.

Figure 46. Cumulative distance driven by the FCEBs per project versus year



Source: JRC based on data from Clean Hydrogen JU, 2022.

3.2.6.5 Fuel Cell System Durability (h)

Similarly to FCEV (Section 3.1.6.5), three different parameters have been analysed to assess the fuel cell system durability of the FCEBs in the reviewed projects from the TRUST database.

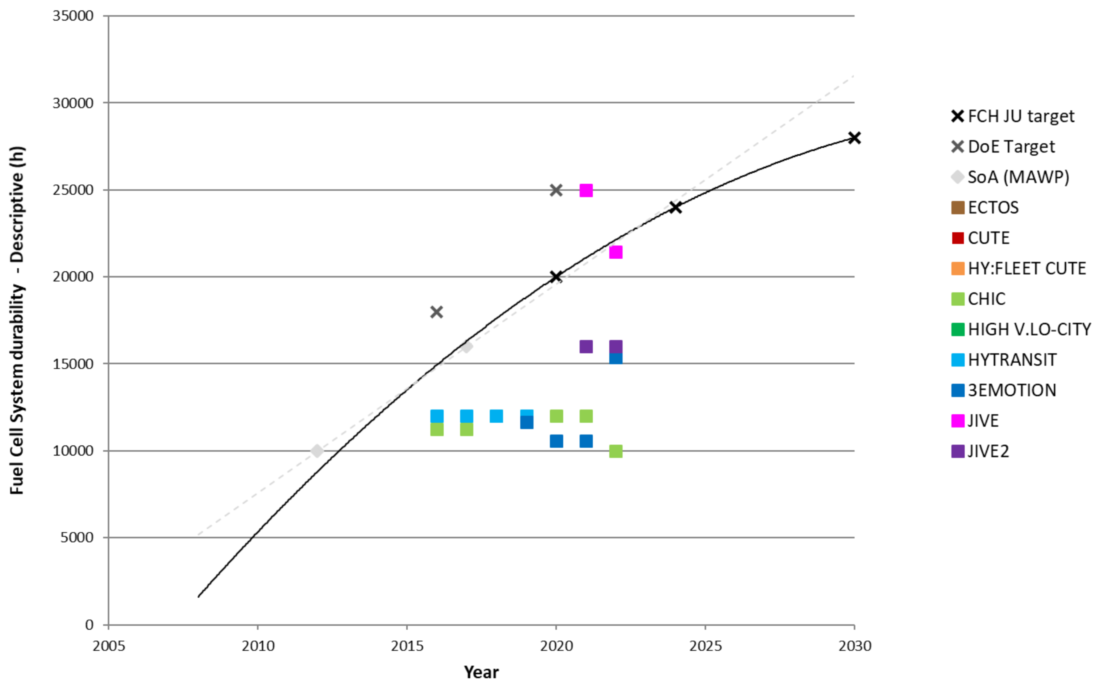
- Fuel Cell System Durability - Descriptive: Durability of the fuel cell system as rated by the manufacturer - Indicative End of Life criterion: 10% stack power degradation or H_2 leak rate as per SAE2578.
- Fuel Cell System Durability - Operational: Only if at least one of the stacks reached their EoL (10% power degradation)[20] during the timeframe of this exercise: Total hours of operation (since they were first put in operation) at the time they are taken out of service.
- Hours of operation – Operational: Total hours of operation without considering the EoL criterion of 10% power degradation.

Figure 47 shows the descriptive fuel cell system durability versus the year of the data collection. The target values from the MAWP of the Clean Hydrogen JU and the US Department of Energy are shown for comparison as FCH JU target and DoE target, respectively. Two sets of targets, defined in the 2015 and 2017 updates of the MAWP, are included. It is worth mentioning that the US Department of Energy targets allow for 20% power degradation whereas the FCH JU and MAWP targets are set with the constraint of 10% power degradation, which is more limiting. The projects are ordered in the legend according to start date, with the earliest first. This format will be used for all subsequent figures regarding KPIs. In the figures of this section, targets are denoted by exes, state-of-the-art values are denoted by diamonds and the average KPI values for each project are denoted by coloured squares. The colour on the squares is used to identify the corresponding project.

Unfortunately, there is not much data reported by the projects on the rated fuel cell system durability. The only data reported for this parameter was from some of the models deployed in the CHIC, HYTRANSIT, 3EMOTION, JIVE and JIVE2 projects. A weighted average of the values for the models deployed in each project provided by the FCEB manufacturers is plotted. The data set is not complete as for some specific models the values were not provided. The rated fuel cell system durability observed ranges between 8000 and 15000 h in the earlier projects whereas the models deployed in the most recent projects offer a durability ranging from 15000 to 25000 h. This is an indication of the advancement of the fuel cell technology. Despite the fact that some of the latest models offer 25000 h of fuel cell system durability (e.g. Van Hool A330 FC), the weighted average value of JIVE2 is not reaching the targets trend line set by the Clean Hydrogen JU with 20000 h in 2020. This is partly due to the lower figures provided for the 18 m buses deployed under JIVE2 in 2021 and 2022 with 16000 h. The manufacturers are following a conservative approach for these new 18 m buses providing lower descriptive fuel cell durability values.

[20] Average for all stacks

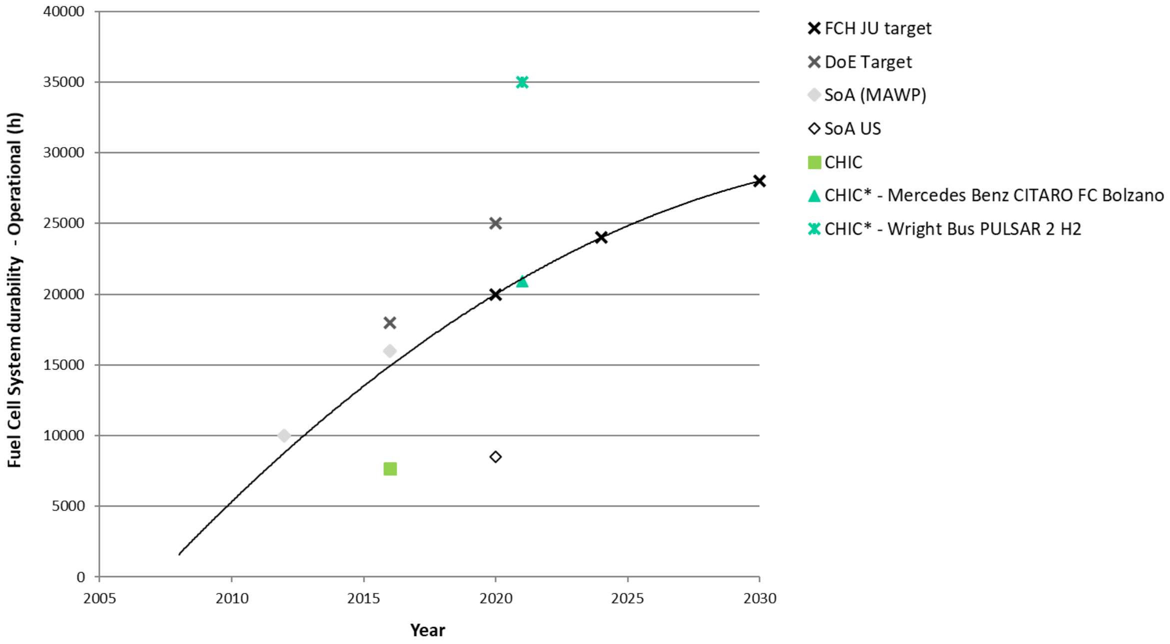
Figure 47. Descriptive fuel cell system durability (h) versus year for FCEB projects



Source: JRC based on data from Clean Hydrogen JU, 2022.

Figure 48 shows the operational fuel cell system durability versus the year of the data collection for specific models. The value for the US state of the art is included (US Department of Energy, 2021), along with the FCH JU and DoE target trend lines for comparison. The two sets of targets, defined in the 2015 and 2017 updates of the MAWP, are also included in the figure. In Figure 48, targets are denoted by exes, state-of-the-art values are denoted by diamonds and the values for each model is denoted by a marker other than a square (squares refer to average value of the project). The colour of the markers is used to identify the corresponding project. It can be observed that there is little data available on operational fuel system durability from the Clean Hydrogen JU projects, the reason being that most of the FCEB deployed are still in operation. Nevertheless, the average operational hours for the older FCEB models recorded (CHIC) have not reached the targeted 20000 hours with less than 10% degradation before 2020. The main reason for this is the short timeframe of the project. However, some of the buses deployed under CHIC project continued operation under other newer projects, recording higher operational fuel cell durabilities. If we do not considered the 10% degradation constraint (no information on fuel cell stack degradation was reported), the Wrigh bus PULSAR 2 H2 deployed in London and the Mercedes Benz CITARO FC deployed in Bolzano accumulated more than 35.000 h and 20.000 h, respectively. These data points have been included in the Figure 48 with an asterisk as the power degradation for these buses has not been reported. The US department of Energy reported the achievement of 8500 h durability with less than 10% degradation and 17000 h with less than 20%, also lagging behind its targets (DOE/DOT interim FCEB durability target of 18000 h with less than 20% degradation in 2015 and 20000 h in 2020).

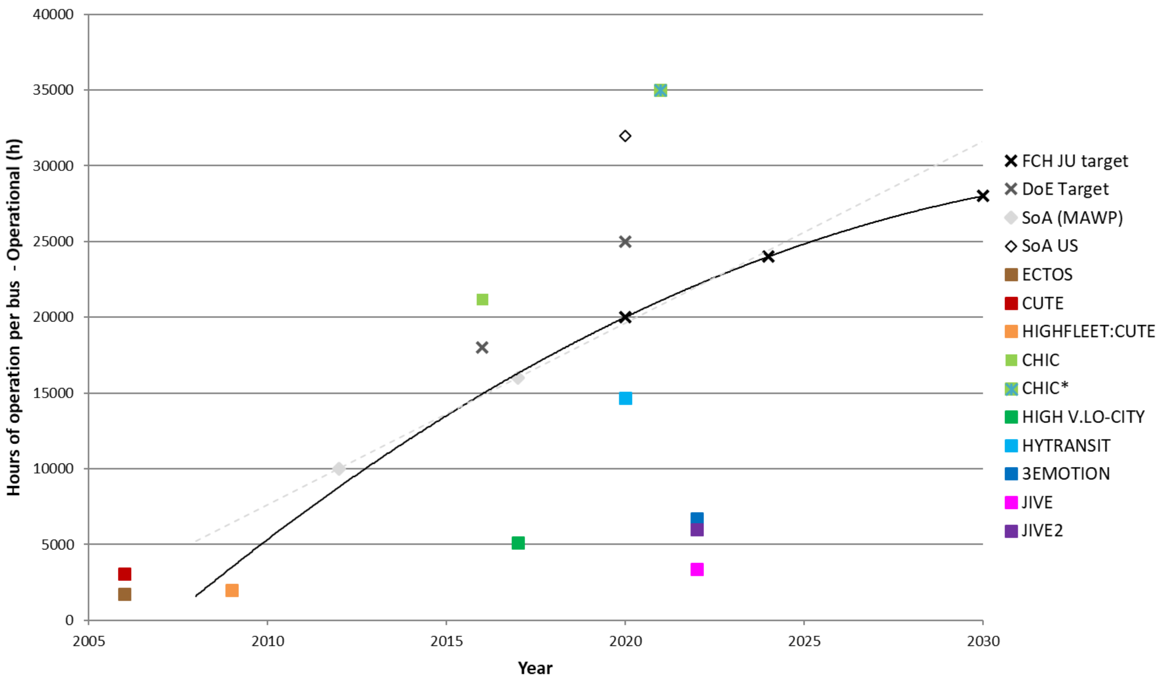
Figure 48. Operational Fuel Cell System Durability (h) versus year of the end of data collection for FCEB projects



Source: JRC based on data from Clean Hydrogen JU and NREL, 2022.

Figure 49 shows the cumulative hours of operation of the best performing FCEB of each project (the bus that operated the most hours in the timeframe of the project) versus the year of the end of the project or end of the FCEB operation. Additionally, the operational data point of the best performing US fleet has also been added, provided that fuel cell system degradation was not limited to 10% (US Department of Energy, 2021). This fleet, already retired from service because it could no longer provide the power necessary to meet service requirements, operated for over 32000 h. The figure shows that the early FCH JU projects which have already finished (HYTRANSIT) accumulated around 15000 h of operation, getting close to the FCH JU target trend line and surpassing greatly the hours accumulated by former European projects (ECTOS, CUTE and HYFLEET:CUTE). CHIC, also finished, accumulated over 20000 h before concluding, surpassing the FCH JU target trend line. Some of the buses from CHIC continued operation after the project finalised and managed to accumulate the staggering 35.000 h of operation. This was the case of the Wrigh PULSAR 2 H2 buses deployed in London, depicted in the graph as CHIC*. HIGH V.LO-CITY, another FCEB project already finished, did not reach that amount of operation hours because of the short duration of the project (the bus operation was only recorded for 2 years). These FCEBs were only operating during a short timeframe and therefore not accumulating enough operation hours to demonstrate the durability. That does not mean that the durability of these buses was limited to the operation hours recorded in the project timeframe. As the data recording stops when the projects finishes it is not possible to assess further the operation of these buses or draw conclusions on bus durability. Most recent projects (3EMOTION, JIVE and JIVE2) show less hours of operation, the reason being that these projects deployed their FCEBs very recently (many of them in 2021 and 2022) and the projects are still active. These FCEBs are still running, accumulating hours of operation. As these projects have been running for less time, they have not yet accumulated the sufficient amount of hours to be compared with the best performing FCEB from CHIC or HYTRANSIT. It is also worth mentioning that the lock-downs during the COVID-19 pandemic have had a significant effect on the total hours of operation recorded. This effect can be observed specially for 3EMOTION and JIVE projects. JIVE2 bus fleet started operation in 2021.

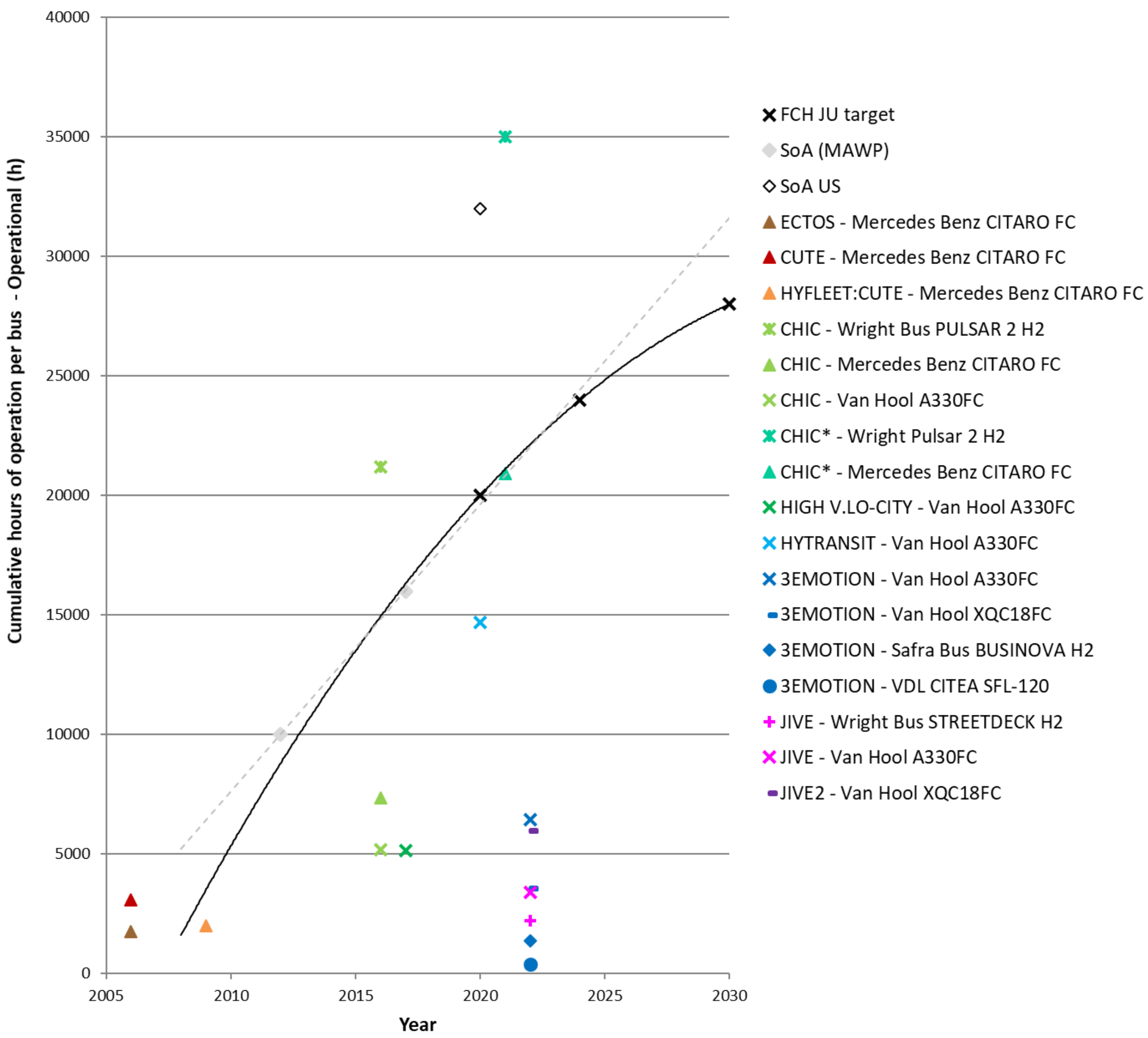
Figure 49. Total hours of operation of the best performing bus (h) versus final year of the project or final year of the data collection if the project is still active.



Source: JRC based on data from Clean Hydrogen JU and NREL, 2022.

Figure 50 shows the cumulative hours of operation of the best performing FCEB for each model and for each project (the bus that operated the most hours in the timeframe of the project) versus the final year of the data collection. The different markers displayed in the figure refer to different models while the colour of the marker is selected according to the corresponding project. It is important to note that the data points collected for 2022 are misleading because the projects are not yet finished. The improvement on hours of operation recorded over the years is noticeable, for example for the Mercedes Benz CITARO FC and the Van Hool A330FC, (from 1700 h in ECTOS to 21200 h in CHIC and from 3500 h in CHIC to close to 15000 h in HYTRANSIT, respectively). The FCEB model that recorded the greatest number of operation hours was the CHIC FCEB Wright Bus PULSAR 2 H2 with over 15000 h, close to the FCH JU and MAWP target trend lines. This bus model continued operation after the project CHIC finished and managed to accumulate over 35000 of operation (denoted as CHIC*). This bus has greatly surpassed the FCH JU target trend line. However, it is not known if the fuel cell degradation has surpassed the threshold stated in the MAWP. FCEB models operating under 3EMOTION, JIVE and JIVE2 have accumulated less hours due to the fact that these projects have started operation very recently and are still active. Recent models like the Safra BUSINOVA H2 and the VDL CITEA SLF-120 in 3EMOTION project, the Wright Bus STREETDECK H2 in JIVE project and the Van Hool XQC18FC in JIVE2 project have been operating only for a year. Additionally, the effect of the lock-downs during the COVID-19 pandemic have had a significant effect in these projects (recording less hours than in normal years and delaying FCEBs deployment).

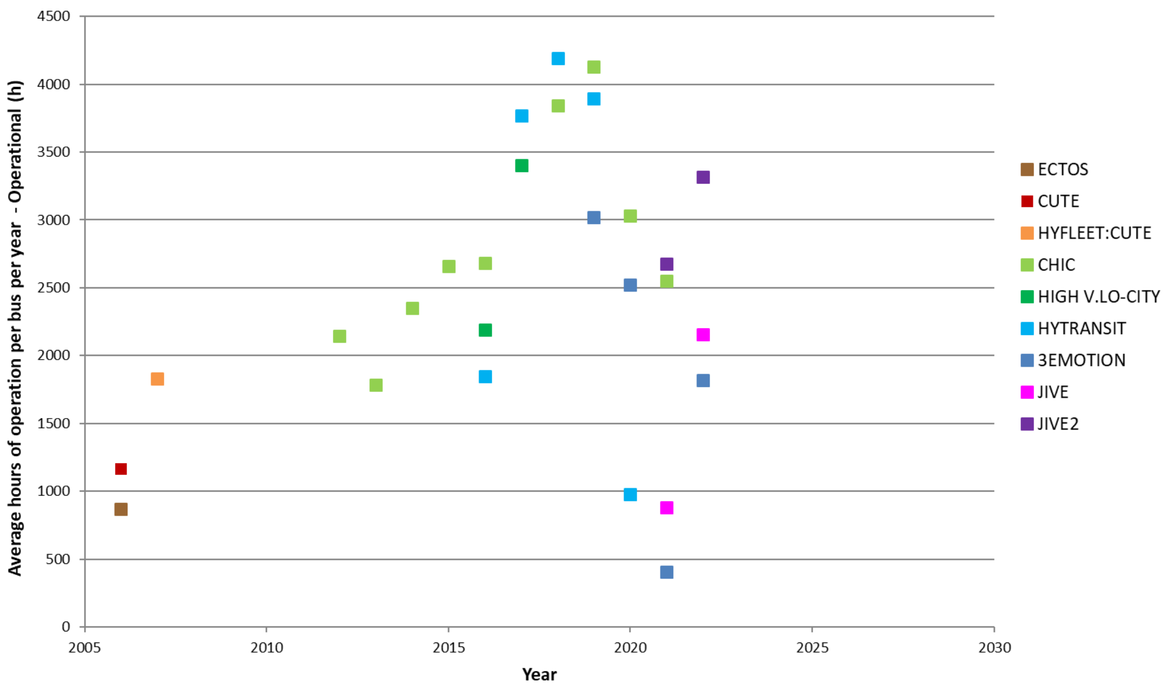
Figure 50. Total hours of operation of the best performing bus from each model (h) versus final year of the project or final year of the data collection if the project is still active



Source: JRC based on data from Clean Hydrogen JU and NREL, 2022.

Figure 51 shows the average operation hours per bus recorded per project per year. This figure gives an insight on the evolution of the use of FCEBs in the Clean Hydrogen JU projects over the years. It can be observed that the amount of operation hours per year has increased significantly from 2015 up to 2019 included, with values ranging the 870 h of operation in 2006 to values of 4200 h in 2019. In 2020 however, the significant effect of the COVID-19 lock-downs is noticeable with a sudden decrease in operation hours for HYTRANSIT, 3EMOTION and JIVE projects. This effect continued over 2021. Operation hours have slightly increased in 2022 with the end of the restrictions.

Figure 51. Average hours of operation per bus per year versus year for FCEB projects



Source: JRC based on data from Clean Hydrogen JU and NREL, 2022.

3.2.6.6 Hydrogen consumption (kgH$_2$/100km)

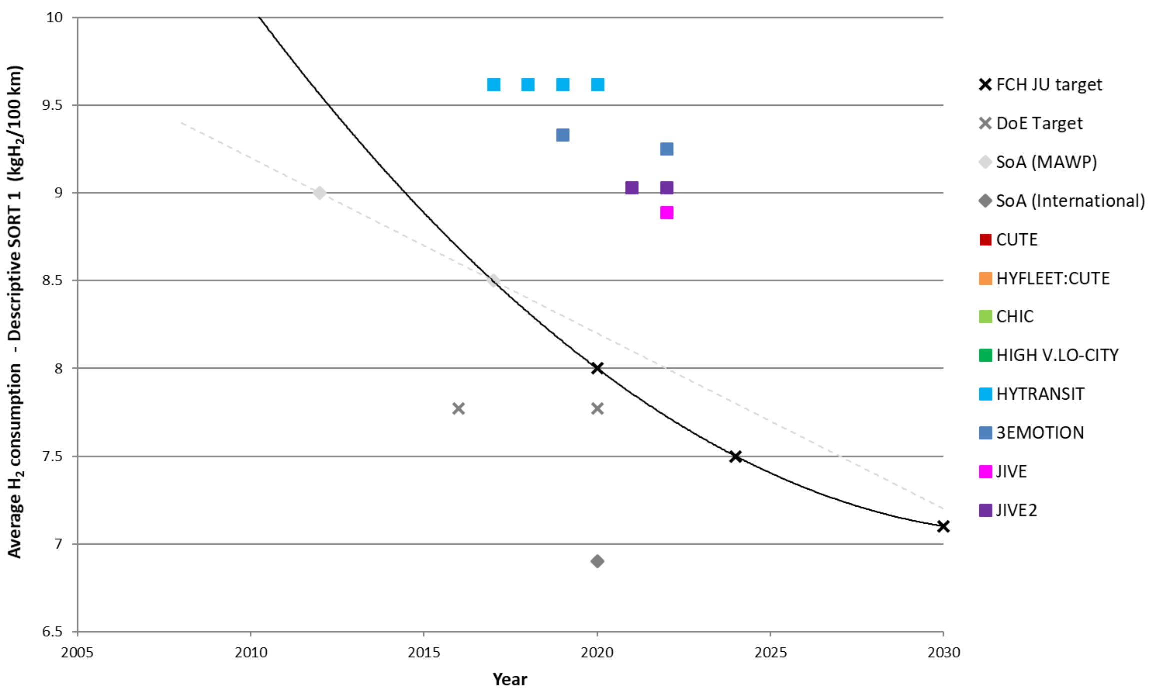
It is important to make the distinction between the two different parameters that have been analysed to assess the hydrogen consumption of the FCEBs in the reviewed projects from the TRUST database.

- Hydrogen Consumption - Descriptive: Hydrogen tank to wheel (TTW) consumption for 100 km driven according to SORT 1 and SORT 2 drive cycles rated by the manufacturers.
- Hydrogen Consumption - Operational: Hydrogen consumption for 100 km driven under real operation conditions, measured in the projects.

An additional remark to the "Hydrogen Consumption – Descriptive" is that it can be provided according to different drive cycles. The descriptive hydrogen consumption of the FCEBs deployed has been provided according to "Standardised On-Road Test" (SORT) cycles developed by the UITP Bus Committee specifically for comparing energy consumption between different buses (International Association of Public Transport). Descriptive hydrogen consumption has been provided according to SORT 1 and SORT 2 cycles that represent heavy urban and urban, respectively.

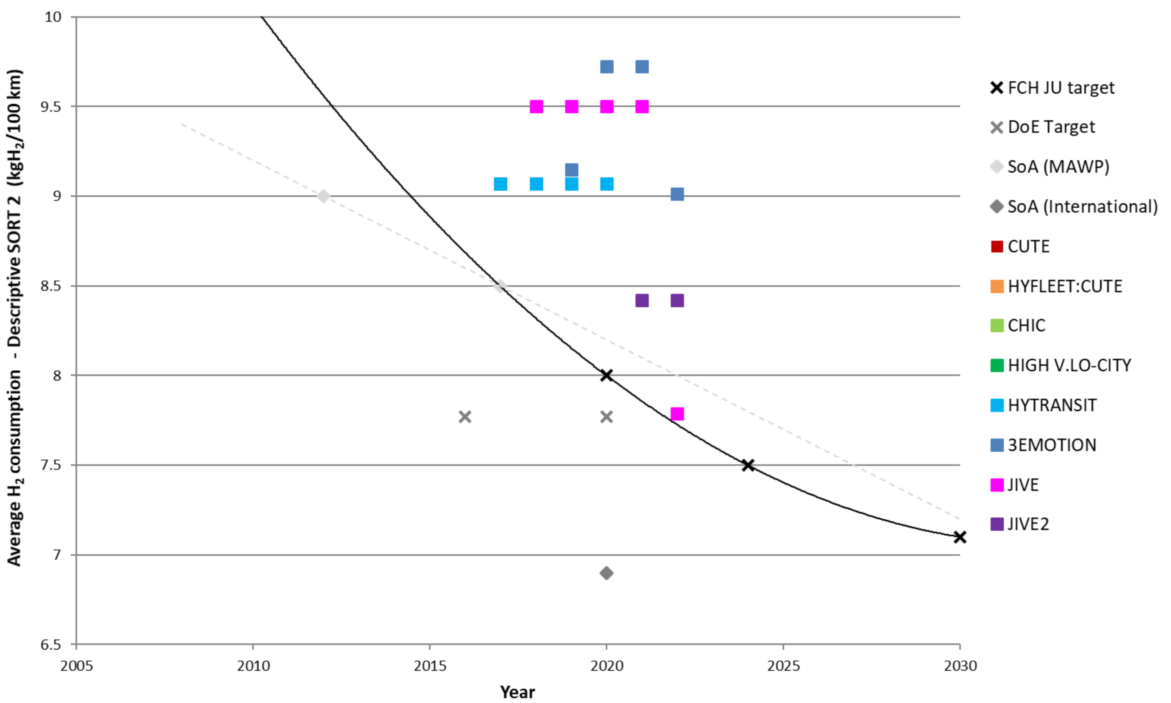
Figure 52 shows the average descriptive hydrogen consumption of the FCEBs deployed per project according to SORT 1, while Figure 53 shows the average descriptive hydrogen consumption according to SORT 2. It is observed that most projects show a potential hydrogen consumption slightly above the FCH JU targets. The figures also show that the FCEBs deployed over the last years (JIVE and JIVE2) have a rated consumption lower than the buses deployed in previous projects, confirming the improvement in the consumption efficiency over the years. The value assigned to the international SoA is given by the rated consumption of Hyundai Elec City Fuel Cell and the New Flyer XHE40, both rated at 6.9 Kg H_2/100 km. However, it must be noted that these models are battery dominant and that is why their hydrogen rated consumption is lower.

Figure 52. Descriptive average hydrogen consumption for 100 km driven (SORT 1) versus year for FCEB projects



Source: JRC based on data from Clean Hydrogen JU, 2022.

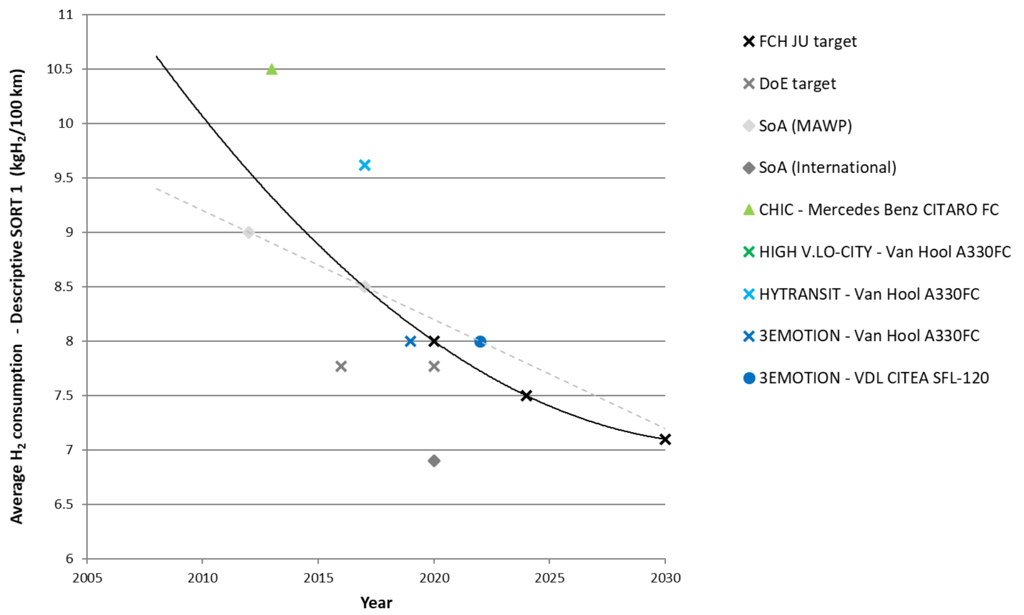
Figure 53. Descriptive average hydrogen consumption for 100 km driven (SORT 2) versus year for FCEB projects



Source: JRC based on data from Clean Hydrogen JU, 2022.

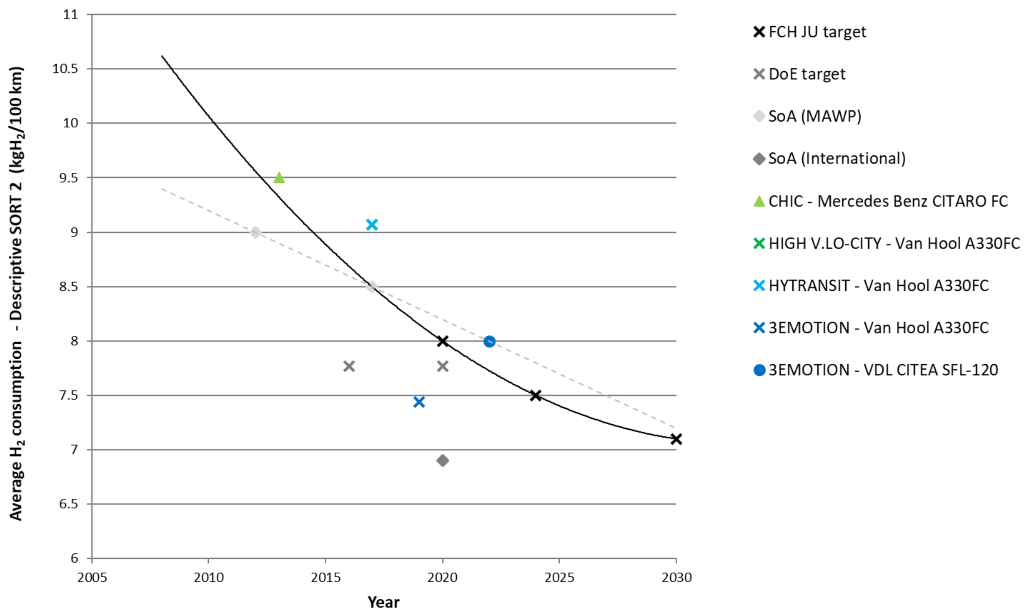
Figure 54 displays the descriptive hydrogen consumption of FCEBs deployed per model according to SORT 1 (where available), while Figure 55 shows the descriptive hydrogen consumption per model according to SORT 2

Figure 54. Descriptive hydrogen consumption for 100 km driven per model (SORT 1) versus year for FCEB projects



Source: JRC based on data from Clean Hydrogen JU, 2022.

Figure 55. Descriptive hydrogen consumption for 100 km driven per model (SORT 2) versus year for FCEB projects

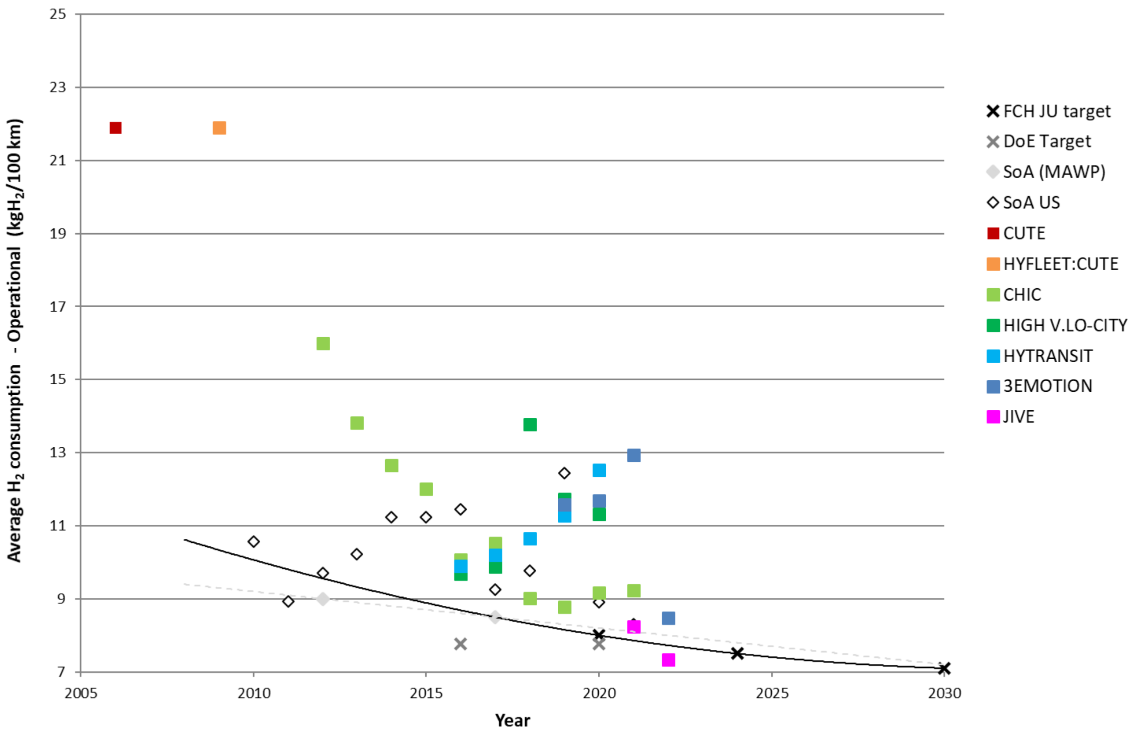


Source: JRC based on data from Clean Hydrogen JU, 2022.

It is noticeable in both figures (Figure 54 and Figure 55) that the newer FCEB models deployed over the last years (project 3EMOTION) have a rated consumption lower than the bus models deployed in previous projects (CHIC and HYTRANSIT), reassuring the improvement of the consumption efficiency over the years.

Figure 56 shows the average hydrogen consumption of the FCEBs deployed per project over the years (operational). We can observe a major shift on fuel efficiency from the projects preceding the FCH JU (CUTE, HYFLEET:CUTE) to the FCH JU projects (e.g. CHIC). The fuel cell technology evolved significantly over these years.

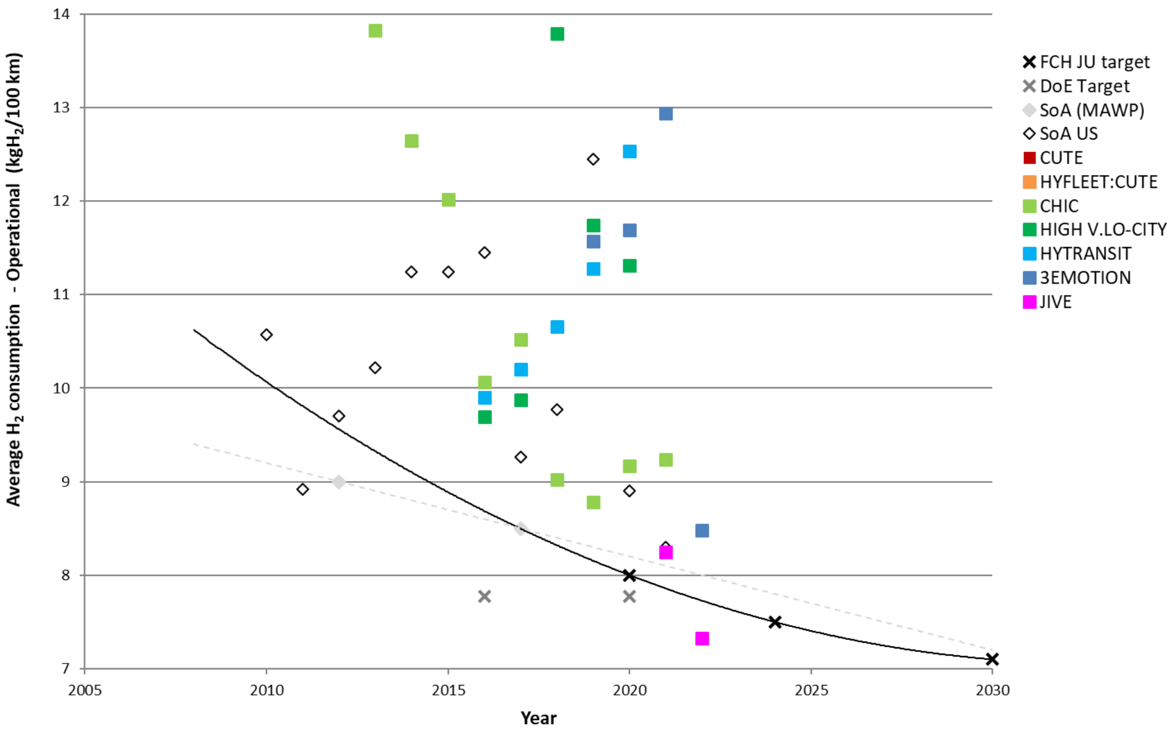
Figure 56. Operational average hydrogen consumption for 100 km driven versus year for FCEB projects



Source: JRC based on data from Clean Hydrogen JU and NREL, 2022.

Figure 57 focuses only on the evolution of the hydrogen consumption of the FCEBs deployed through FCH JU projects. It is observed that despite the significant improvement on fuel efficiency of the FCEBs over the years, the hydrogen consumption is still slightly higher than the FCH JU targets with the exception of JIVE buses in 2021. If we compare the FCHJU data with the data from NREL reflecting the US SoA, we can observe that the hydrogen consumption is very much in line with the reported by the FCH JU projects. It is worth noting that the geographical conditions of each deployment site will also differ, these have an influence on the fuel consumption reported.

Figure 57. Operational average hydrogen consumption for 100 km driven versus year for FCH JU FCEB projects

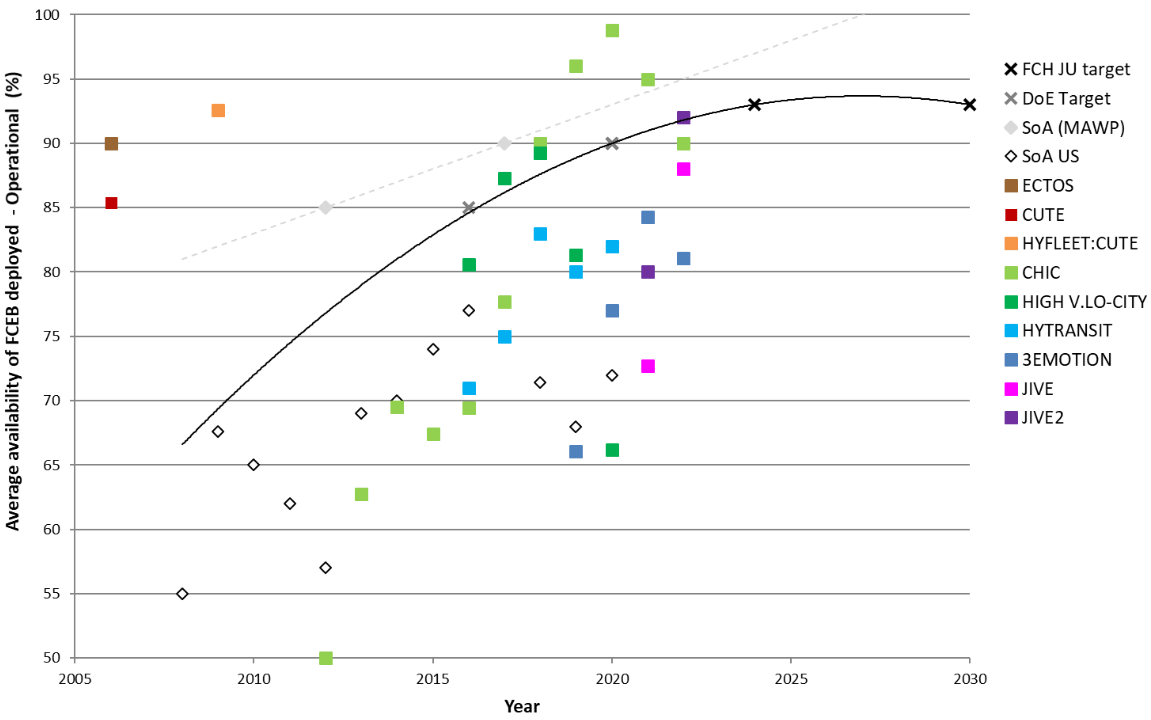


Source: JRC based on data from Clean Hydrogen JU and NREL, 2022.

3.2.6.7 Availability (%)

Figure 58 shows the average availability of the FCEBs deployed per project over the years. The availability is defined in the TRUST database as the percentage of time that the bus was able to operate versus the overall time that it is intended to operate for a fleet availability same as diesel buses. From the data analysis we can observe that the availability has significantly increased over the years for FCH JU projects. Most of the projects have met or surpassed the trend line of the FCH JU target over the years. The exceptions are projects HYTRANSIT and 3EMOTION which reported lower average availabilities. This is mainly due to data points of lower availability in some specific sites which impacted the average value while most of the sites reported availabilities close to the FCHJU targets. Recent projects such as JIVE and JIVE2 have surpassed or closely met the FCH JU targets over the years with the exception of the year 2021. The cause for a lower average availability that year could be related to the impact of lock-down periods in specific sites. It must be noticed that the European fleets deployed under the FCH JU projects have outperformed US fleets in terms of availability (data from NREL reports).

Figure 58. Average availability of the buses deployed per project versus year for FCEB projects

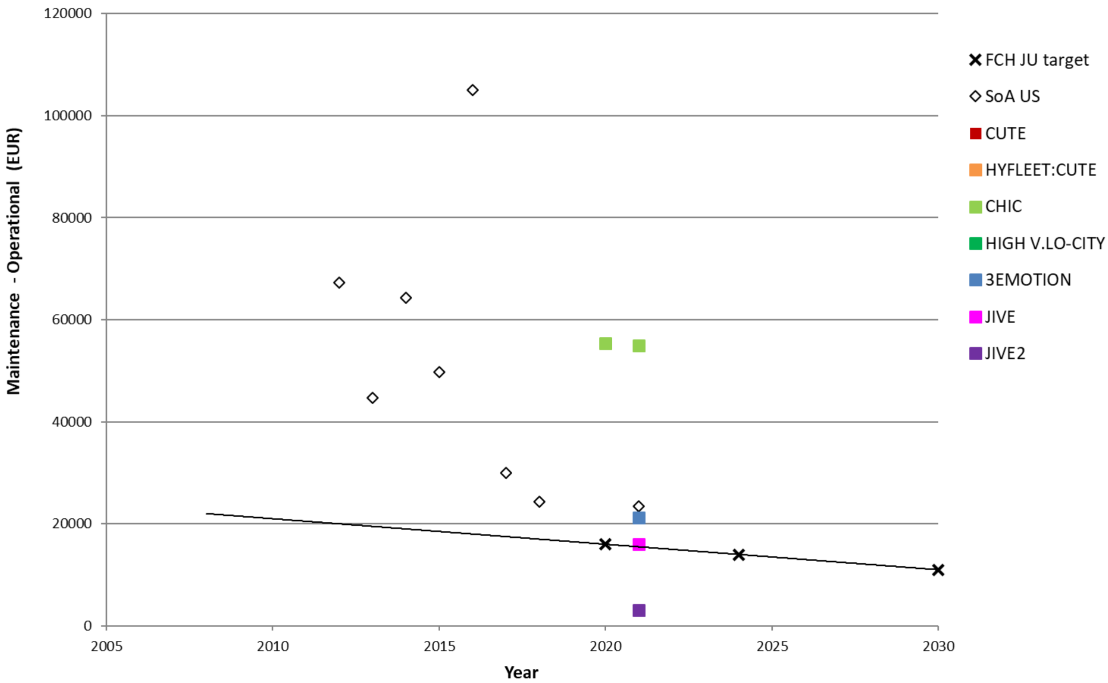


Source: JRC based on data from Clean Hydrogen JU and NREL, 2022.

3.2.6.8 Maintenance (EUR)

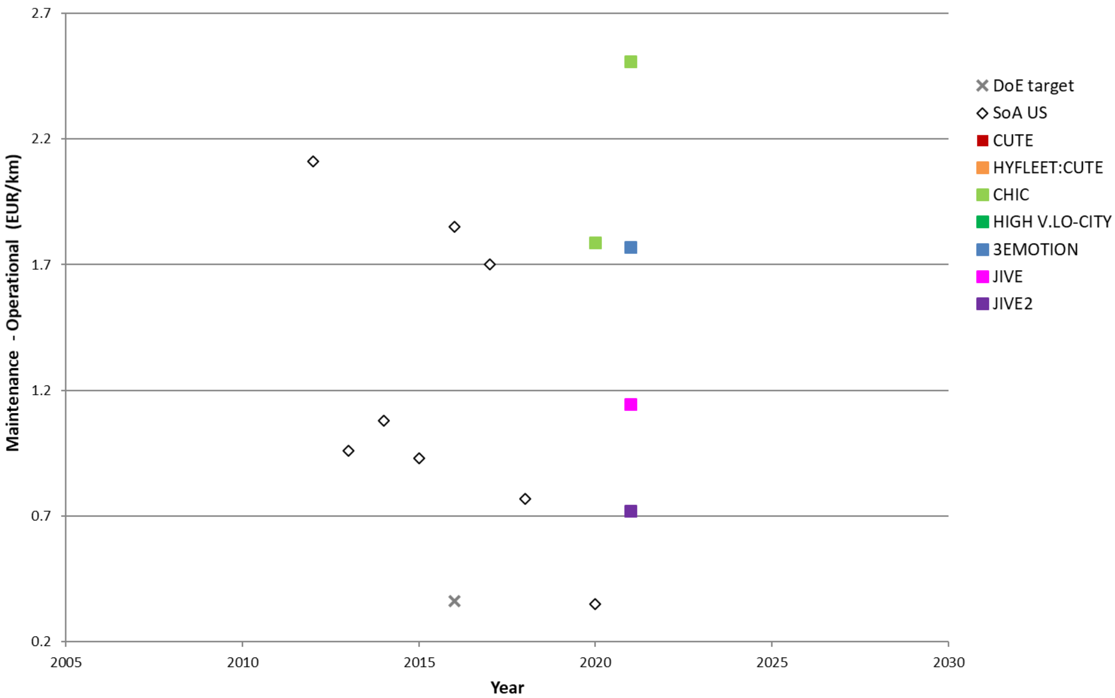
Final project reports and the TRUST database were consulted to gather yearly maintenance costs (spare parts and labour for the drivetrain maintenance in EUR). Few projects reported information on maintenance costs, only CHIC, 3EMOTION, JIVE and JIVE2. Figure 59 shows the average yearly maintenance costs for these projects. It can be seen that the maintenance costs have decreased over the years, a good example of this is the data collected by NREL fleets reflecting the US SoA. This effect is also noticed in the FCH JU projects when comparing earlier projects with recent ones. While project CHIC exceeded significantly the FCHJU target trend line, recent projects like JIVE and JIVE2 achieved the FCHJU targets in maintenance costs. The exception is 3EMOTION project which in 2021 exceeded slightly the FCHJU targets. If the data is expressed in EUR/km units (see Figure 60) it can be observed the maintenance costs have decreased significantly in recent projects compared to early ones. The lessons learned from the early projects include changes to the maintenance strategy. For example, allocating a dedicated person full-time on-site for preventive and corrective maintenance on a 10-bus fleet has proven to be worthwhile. Additionally, building a spare parts shop at the depot, providing spare components has been shown to reduce maintenance time and, consequently, minimize downtime. It is worth mentioning that project participants pointed out that an additional factor of variability in the maintenance costs is the difference in labour costs among countries.

Figure 59. Average maintenance costs (spare parts and labour) of each project versus year



Source: JRC based on data from Clean Hydrogen JU and NREL, 2022.

Figure 60. Average maintenance costs (spare parts and labour) per km of each project versus year



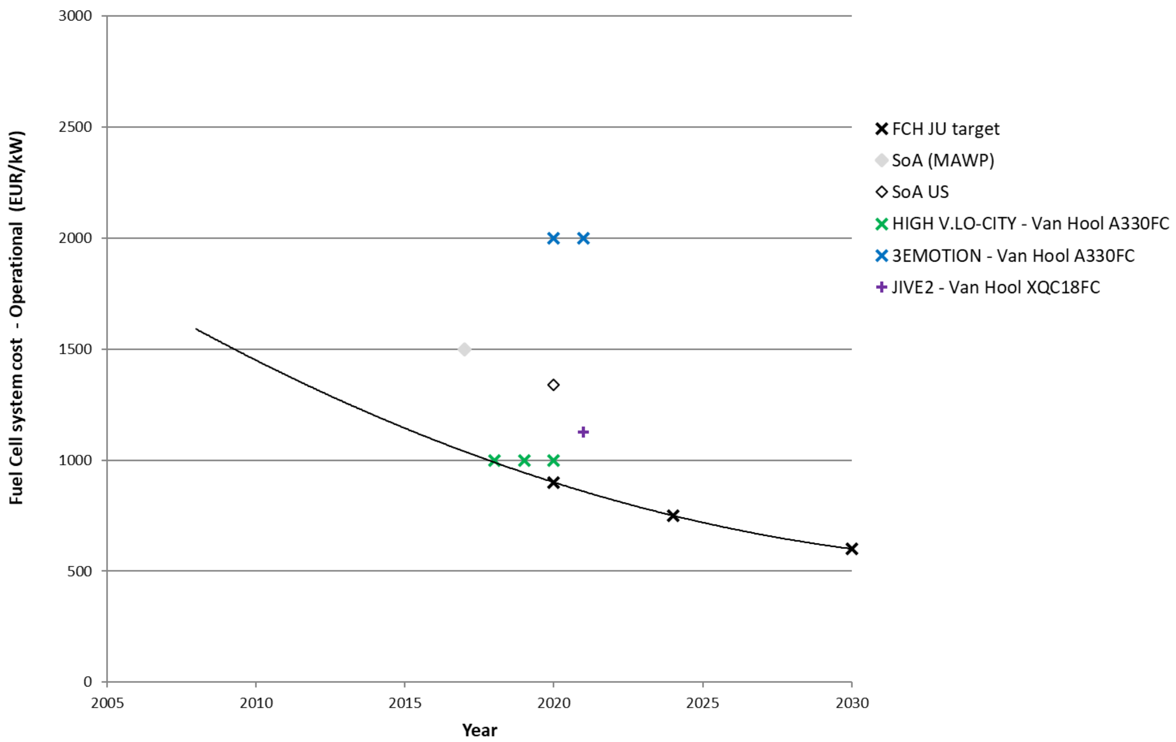
Source: JRC based on data from Clean Hydrogen JU and NREL, 2022.

3.2.6.9 *Fuel cell system cost (EUR/kW)*

There is not enough data reported on fuel cell system costs in the final project reports or TRUST database to conduct an in-depth analysis. The US targets for fuel cell system cost are not given per kW but as overall costs (US Department of Energy, 2012) and therefore excluded from the analysis. The FCH JU target was 900 EUR/KW for 2020. The data found in TRUST is really scarce, available only from some FCEB models of the projects HIGH V.LO-CITY, 3EMOTION and JIVE2. The costs reported by those projects surpassed the FCH JU target for 2020.

The TRUST database recorded two parameters related to the fuel cell system cost analysis: “fuel cell system costs” and “estimated fuel cell system costs”. Figure 61 shows the fuel cell system costs reported for HIGH V.LO-CITY Van Hool A330FC, 3EMOTION Van Hool A330FC, and JIVE2 Van Hool XQC18FC. From the data analysed it can be concluded that the fuel cell system varies among projects and models. The common trend is that in all cases the costs have surpassed the FCHJU targets, even if slightly in the case of the HIGH V.LO-CITY Van Hool A330FC.

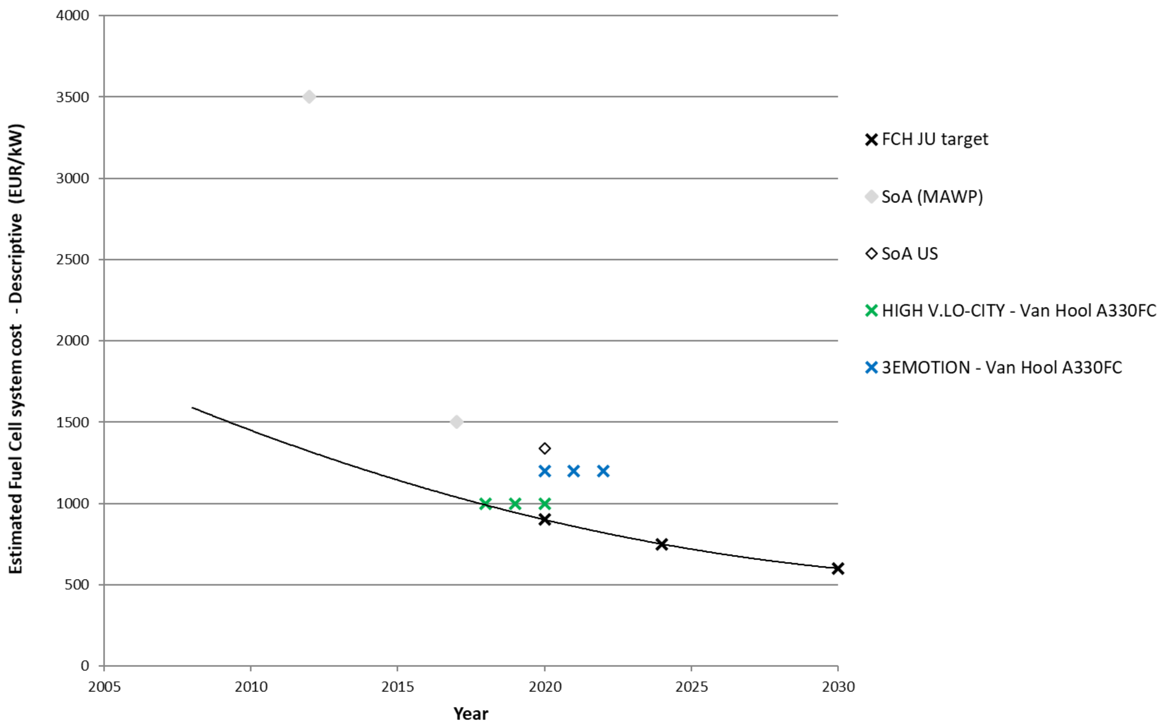
Figure 61. Operational fuel system costs (EUR/kW) versus year for FCEB projects



Source: JRC based on data from Clean Hydrogen JU, 2022.

In terms of the parameter “estimated fuel cell cost in EUR/kW” (estimated cost of the fuel cell system at an assumed mass production) the models reported values that surpassed slightly the FCHJU targets, see Figure 62. Further efforts are required to lower the fuel cell system costs.

Figure 62. Estimated fuel cell system costs at mass production (EUR/kW) versus year

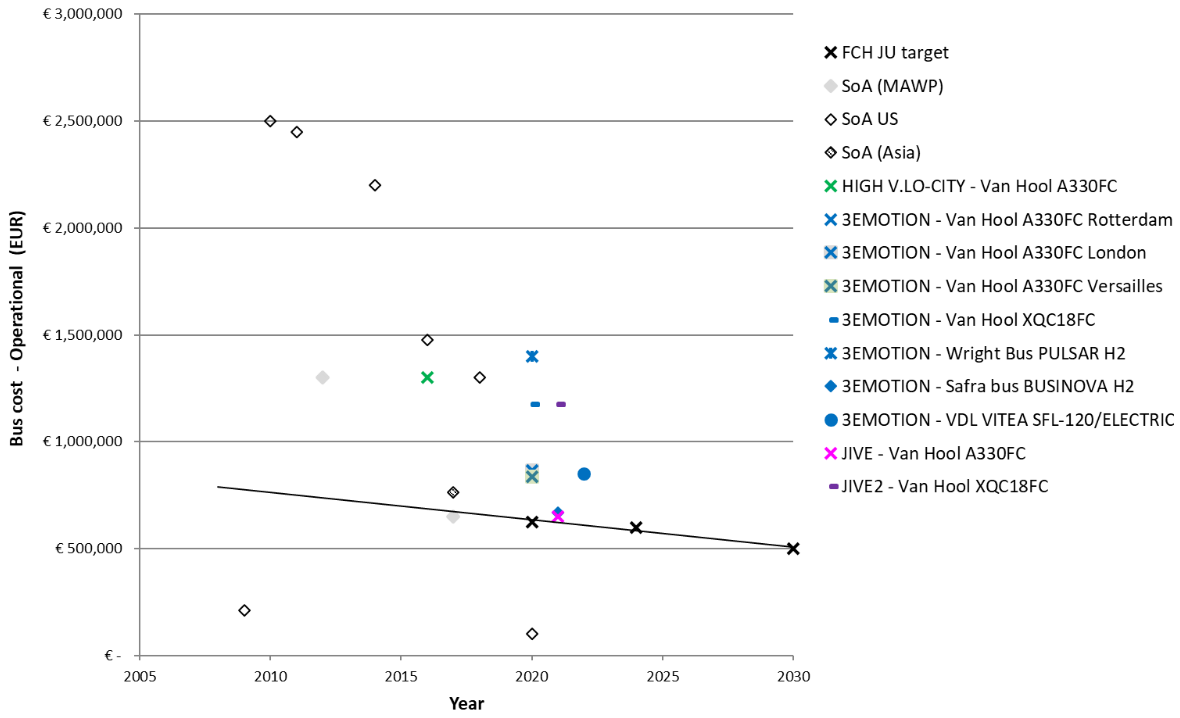


Source: JRC based on data from Clean Hydrogen JU and PwC, 2022.

3.2.6.10 Bus cost (thousand EUR)

Final project reports and the TRUST database were consulted to gather bus cost per model and year. Only recent projects reported information on capital costs for specific models (HIGH V.LO-CITY, HYTRANSIT, 3EMOTION, JIVE and JIVE2). Figure 63 shows the capital cost for specific models from these projects compared against the SoA of US and Asia. It is observed that the costs have decreased over the years, a good example of this is the data collected by NREL fleets reflecting the US SoA on bus costs. This effect is also noticed in the FCH JU projects when comparing the same model over different projects. This can be observed for the Van Hool A330FC, the price has halved from the HYTRANSIT project to the JIVE project. Some variability was reported for this model in the 3EMOTION project, depending on the location the bus was deployed. These differences for the same model (Van Hool A330FC) can be explained by the customisation of the buses depending on the requirements of the local fleets. JIVE 2 project also shows higher bus cost because it is an 18 m bus, more costly than the 14 m ones. The US SoA data is in line with the data from the FCHJU projects but the region most competitive on bus price is Asia (Toyota Sora).

Figure 63. Bus costs (thousand EUR) versus year



Source: JRC based on data from Clean Hydrogen JU and NREL, 2022.

3.2.7 Summary

This section provides a summary and conclusions for Section 3.2. A complete list of recommendations is provided in Chapter 4.

- FCEB projects primarily deploy commercial or near-commercial bus models.
- FCEBs deployment in Europe has seen a significant growth with the Clean Hydrogen JU projects, especially with JIVE and JIVE2 projects in 2022 and 2023. The total FCEB fleet deployed over the 2005-2023 period surpasses the 400-unit milestone.
- The FCEBs deployed in Europe over the 17 year period (2005-2022) accumulated a mileage of more than 17 million km, demonstrating the readiness of the FCEB technology.
- Not all relevant information is being submitted to the TRUST database due to data unavailability and commercial sensitivity.
- Fuel cell system durability, fuel cell system costs, and maintenance costs are often not reported.
- The fuel cell system durability of FCEBs has been analysed using three parameters (descriptive durability, operational durability and total hours of operation). The best performing buses from early FCH JU projects have accumulated around 35000 hours of operation. However, the fuel cell power degradation of these buses was not reported. Fuel cell degradation is not being measured in the projects and should be reported for better assessment. The average hours of operation have significantly increased over the years. FCH JU projects following CHIC and HYTRANSIT were too short to assess durability.

- Hydrogen consumption is slightly higher than the FCH JU target but has consistently improved.
- Bus availability has notably increased over the years, with European fleets outperforming US fleets.
- Limited information has been reported on maintenance costs, but the available data aligns with the FCH JU target.
- The data on fuel cell system cost is scarce and mostly exceeds the FCH JU target.
- Bus capital cost has decreased remarkably over the years and recent projects have achieved the FCH JU target. Asian countries are the most competitive in terms of bus cost.
- Despite falling short on some KPIs, overall improvement has been seen in many areas, with many KPIs achieving the FCH JU target values.

4 Conclusions and Recommendations

4.1 Conclusions

The Clean Hydrogen Joint Undertaking (JU) has played a pivotal role in the advancement of hydrogen mobility in Europe, as evidenced by the deployment of over 1300 Fuel Cell Electric Vehicles (FCEVs) and more than 400 Fuel Cell Electric Buses (FCEBs) from 2005 to 2023. These initiatives have not only demonstrated the operational advantages and technological readiness of hydrogen-powered transport but have also established a foundation for the first pan-European hydrogen refuelling network.

The FCEV projects have shown promise in high mileage applications, such as taxi fleets, and have spurred interest from various partners in scaling up their fleets. Similarly, the success of FCEB deployment has been marked by the growing involvement of regions and an increase in private contributions, highlighting the technology's viability for public transport systems.

Both FCEV and FCEB projects have provided a wealth of data for improving performance benchmarks, such as Key Performance Indicators (KPIs), Well-to-Wheel (WTW) analysis, and Total Cost of Ownership (TCO) models. Collaborations between manufacturers and hydrogen providers have promoted the rapid development and integration of hydrogen solutions in the mobility sector.

Despite these successes, challenges persist. Both FCEVs and FCEBs face competition from battery electric alternatives, which benefit from lower operational costs and advancements in technology. The energy crisis of 2022 has further impacted the financial viability of hydrogen-powered transport by increasing hydrogen fuel costs. The supply chain for components remains fragile, with limited flexibility to ramp up production or expand spare parts inventory. Specific challenges for FCEBs include long manufacturing times and the slow development of 'package solutions' for hydrogen refuelling infrastructure.

4.2 Recommendations

To address these challenges and to continue fostering the growth of hydrogen mobility in Europe, the following recommendations are suggested:

- Enhanced Financial Support: Implement long term financial mechanisms, such as subsidies or tax incentives specific to hydrogen mobility, to offset the higher operational costs and make FCEVs and FCEBs more competitive.
- Supply Chain Development: Strengthen the European supply chain for hydrogen mobility components by incentivising investments and encouraging manufacturers to increase production flexibility and spare parts availability.
- Standardisation and Data Transparency: Develop standardised methodologies for measuring and reporting fuel cell degradation and operational metrics. Encourage comprehensive data sharing to refine performance assessments and inform technology improvements.
- Research and Innovation: Continue investments in research and development to reduce costs and enhance the efficiency of fuel cell systems, as well as hydrogen production and refuelling infrastructure.
- Infrastructure Expansion: Continue expanding the hydrogen refuelling network for FCEVs and develop integrated 'package solutions' for FCEBs and Fuel Cell Electric Trucks (FCET) that combine hydrogen production, storage, dispensing, and maintenance.
- Public Education and Market Creation: Launch campaigns to raise public awareness of the benefits of hydrogen mobility and skills development related to hydrogen mobility applications. It is also instrumental to continue supporting initial markets, such as public transport fleets and corporate usage, as well as hydrogen valleys to foster broader hydrogen adoption.

- Collaboration and Best Practices: Continue international collaboration to learn and exchange global best practices, particularly in regions with competitive cost structures, to drive down capital costs and accelerate market readiness. It is pivotal to reinforce European leadership in such collaborations.
- Policy Alignment: Align policies in East Europe to support the expansion of FCEVs, FCEBs, and hydrogen refuelling infrastructure, as participation in Clean Hydrogen JU projects and other pioneering initiatives has been primarily from west European countries.
- Monitoring and Evaluation: Continue to uphold the robust established frameworks for ongoing monitoring and evaluation to measure the impact of hydrogen mobility projects and adapt strategies as needed.

By implementing these recommendations, the EU can continue to lead in the transition to a sustainable transportation system, leveraging the full potential of hydrogen mobility to achieve its ambitious decarbonisation targets. The progress made by the Clean Hydrogen JU projects provides a strong foundation upon which to build a resilient, efficient, and low-carbon future for European transport.

References

Ajanovic, A., and R. Haas, 'Economic and Environmental Prospects for Battery Electric- and Fuel Cell Vehicles A Review', *Fuel Cells*, Vol. 19, No. 5, 2019, pp. 515–529.

Belfast Telegraph, 'Wrightbus to Supply German City of Cologne with 60 Hydrogen Buses', 2022. https://www.belfasttelegraph.co.uk/business/northern-ireland/wrightbus-to-supply-german-city-of-cologne-with-60-hydrogen-buses/41696266.html.

BMW, 'BMW IX5 Hydrogen Defies the Extreme Cold', 2022. https://www.bmwgroup.com/en/news/general/2022/bmw-ix5-hydrogen.html.

BMW, 'Launch of the BMW IX5 Hydrogen Pilot Fleet', 2023. https://www.bmwgroup.com/en/news/general/2023/BMWiX5Hydrogen.html.

Bus World Europe, 'Exhibitor List 2023', 2023. https://busworldeurope.org/exhibitor-list-2023.

Can, R., and M. Rex, 'Deployment of Fuel Cell Vehicles in Road Transport and the Expansion of the Hydrogen Refueling Station Network: 2023 Update', *Energy and Environment*, Vol. 611, 2023, p. 15.

Clean Hydrogen JU, *Strategic Research and Innovation Agenda 2021-2027*, 2021.

Element Energy, *Hydrogen Mobility Europe: Emerging Conclusions*, 2022.

Energy News, 'Changan Dreams of Being the Tesla of Hydrogen', 2022. https://energynews.biz/changan-dreams-of-being-the-tesla-of-hydrogen/.

European Commission, '2030 Climate & Energy Framework', 2021. https://ec.europa.eu/clima/policies/strategies/2030_en.

European Commission, 'A Hydrogen Strategy for a Climate-Neutral Europe, COM(2020) 301', 2020. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0301.

European Commission, 'Clean Energy for All Europeans Package', 2019. https://energy.ec.europa.eu/topics/energy-strategy/clean-energy-all-europeans-package_en.

European Commission, 'Hydrogen and Decarbonised Gas Market Package', 2021. https://energy.ec.europa.eu/topics/markets-and-consumers/market-legislation/hydrogen-and-decarbonised-gas-market-package_en.

European Commission, 'Implementing the Repower EU Action Plan: Investment Needs, Hydrogen Accelerator and Achieving Bio-Methane Targets, SWD(2022) 230', 2022. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52022SC0230&from=EN.

European Commission, 'REPowerEU Plan, COM(2022) 230', 2022. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52022DC0230&from=EN.

European Commission, 'The European Green Deal', 2019. https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en.

European Union, 'Regulation (EU) 2023/1804 of the European Parliament and of the Council of 13 September 2023 on the Deployment of Alternative Fuels Infrastructure, and Repealing Directive 2014/94/EU', 2023. https://eur-lex.europa.eu/eli/reg/2023/1804/oj.

European Union, 'Regulation (EU) 2023/956 of the European Parliament and of the Council of 10 May 2023 Establishing a Carbon Border Adjustment Mechanism', 2023. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=OJ:L:2023:130:FULL.

European Union, 'Regulation (EU) 2023/957 of the European Parliament and of the Council of 10 May 2023 Amending Regulation (EU) 2015/757 in Order to Provide for the Inclusion of Maritime Transport Activities in the EU Emissions Trading System and for the Monitoring, Repor', 2023. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=OJ:L:2023:130:FULL.

Express & Star, 'West Midlands to Launch UK's Largest Hydrogen Bus Fleet after Securing £30m Government Funding', 2022. https://www.expressandstar.com/news/local-hubs/birmingham/2022/03/28/west-midlands-to-launch-uks-largest-hydrogen-bus-fleet-after-securing-30m-government-funding/.

Fuel Cell Works, 'Deutsche Bahn Approves Purchase of 60 Hydrogen Buses', 2023. https://fuelcellsworks.com/news/deutsche-bahn-approves-purchase-of-60-hydrogen-buses/?mc_cid=bcc521eb55&mc_eid=da4624d261.

Fuel Cell Works, 'Great Wall Motors to Launch Independent Brand for Fuel Cell Passenger Vehicles', 2022. https://fuelcellsworks.com/news/great-wall-motors-to-launch-independent-brand-for-fuel-cell-passenger-vehicles/.

Fuel Cell Works, 'Higer Will Have an Articulated Electric Bus Running in Brazil and Uruguay by July', 2023. https://fuelcellsworks.com/news/higer-will-have-an-articulated-electric-bus-running-in-brazil-and-uruguay-by-july/?mc_cid=762126b762&mc_eid=da4624d261.

Fuel Cell Works, 'In 2023, Korea Will Provide 16920 Hydrogen Vehicles With Subsidies of 30M Won ($24.4M)', 2023. https://fuelcellsworks.com/news/in-2023-korea-will-provide-16920-hydrogen-vehicles-with-subsidies-of-30m-won-24-4m/?mc_cid=49fd008c93&mc_eid=da4624d261.

Fuel Cell Works, 'Weimar Becomes First City With Hydrogen Buses in Thuringia', 2023. https://fuelcellsworks.com/news/weimar-becomes-first-city-with-hydrogen-buses-in-thuringia/?mc_cid=850deae301&mc_eid=da4624d261.

Fuel Cells and Hydrogen 2 Joint Undertaking (FCH JU), *Addendum to the Multi-Annual Work Plan 2014-2020*, 2018.

H2-view, 'Hydrogen Buses Enter Passenger Service in Liverpool', 2023. https://www.h2-view.com/story/hydrogen-buses-enter-passenger-service-in-liverpool/.

Hino, 'Isuzu, Toyota, Hino, and CJPT to Promote Planning and Development of Mass-Market Light-Duty Fuel Cell Electric Trucks', 2022. https://www.hino-global.com/corp/news/2022/20220719-003291.html.

Hydrogen Central, 'Korea – 700 Hydrogen-Powered Buses In Incheon By End Of 2024', 2023. https://hydrogen-central.com/korea-700-hydrogen-powered-buses-incheon-2024/.

Hydrogen Fuel News, 'Frankfurt to Boost Presence of Hydrogen Buses in Its City', 2023. https://www.hydrogenfuelnews.com/hydrogen-buses-icb-solaris/8558799/#:~:text=The German metropolis has ordered,ICB fleet in Q1 2024.

Hydrogeninsight, 'South Korean Capital City Signs Deal for 1,300 New Hydrogen Buses by 2026, Says Hyundai', 2023. https://www.hydrogeninsight.com/transport/south-korean-capital-city-signs-deal-for-1-300-new-hydrogen-buses-by-2026-says-hyundai/2-1-1463347.

International Association of Public Transport, 'UITP SORT & E-SORT Brochures', n.d. https://www.uitp.org/publications/uitp-sort-e-sort-brochures/.

International Energy Agency, 'Global Hydrogen Review 2023', 2023. https://iea.blob.core.windows.net/assets/8d434960-a85c-4c02-ad96-77794aaa175d/GlobalHydrogenReview2023.pdf.

International Energy Agency, *Hydrogen Fuel Cell Electric Buses: Comparative Analysis of Six National Projects*, 2019.

International Energy Agency, *Hydrogen Patents for a Clean Energy Future*, 2023.

Jaguar Land Rover, 'Jaguar Land Rover to Develop Hydrogen-Powered Defender Fuel Cell Prototype', 2021. https://media.jaguarlandrover.com/news/2021/06/jaguar-land-rover-develop-hydrogen-powered-defender-fuel-cell-prototype.

Kurtz, J., S. Sprik, C. Ainscough, G. Saur, and S. Onorato, *NREL Fuel Cell Electric Vehicle Performance Composite Data Products : Spring 2018*, 2018.

Luo, Y., Y. Wu, B. Li, T. Mo, Y. Li, S.P. Feng, J. Qu, and P.K. Chu, 'Development and Application of Fuel Cells in the Automobile Industry', *Journal of Energy Storage*, Vol. 42, No. August, 2021.

Renault, 'Renault Niagara Concept', 2023. https://www.renault.co.uk/concept-cars.html.

Renault Press, *Renault Runs on Hydrogen with Master ZE Hydrogen and Kangoo ZE Hydrogen*, 2019.

Riversimple, 'Riversimple Rasa Is Unveiled', 2022. https://www.riversimple.com/riversimple-rasa-is-unveiled-2/.

Solaris, 'Cologne to Operate the Biggest Fleet of Hydrogen Solaris Buses', 2022. https://www.solarisbus.com/en/press/cologne-to-operate-the-biggest-fleet-of-hydrogen-solaris-buses-1787.

Solaris, 'Online Launch of the Solaris Urbino 18 Hydrogen Bus on 14 September', 2022. https://www.solarisbus.com/en/press/online-launch-of-the-solaris-urbino-18-hydrogen-bus-on-14-september-1816.

Stellantis, 'Hydrogen Fuel Cell Technology', 2023. https://www.stellantis.com/en/technology/hydrogen-fuel-cell-technology?adobe_mc_ref=.

TopElectricSUV, '12 Upcoming Hydrogen FCEVs with up to 500 Miles of Range', 2023. https://topelectricsuv.com/featured/upcoming-hydrogen-fcev-cars/.

Toyota Motor Corporation, 'CaetanoBus Receives Large Order for Hydrogen Buses', 2023. https://www.toyota-europe.com/news/2023/caetanobus-receives-large-order-for-hydrogen-buses.

US Department of Energy, *2019 Fuel Cell Technologies Market Report*, n.d.

US Department of Energy, *DOE Hydrogen and Fuel Cells Program Record: Automotive Fuel Cell Targets and Status 2020*, 2020.

US Department of Energy, 'DOE Hydrogen and Fuel Cells Program Record: Fuel Cell System Cost - 2016', 2016.

US Department of Energy, *DOE Hydrogen Program Record: Durability-Adjusted Fuel Cell System Cost*, 2021.

US Department of Energy, *Fuel Cell Bus Targets*, Vol. i, Vol. i, 2012.

US Department of Energy, 'On-Road Transit Bus Fuel Cell Stack Durability', 2021. https://www.hydrogen.energy.gov/pdfs/20008-fuel-cell-bus-durability.pdf.

VINCI Airports, 'Kansai Airport Launches a Hydrogen Shuttle Bus Service', 2022. https://www.vinci.com/vinci.nsf/en/news-update/pages/kansai_airport_launches_a_hydrogen_shuttle_bus_service_japan_052022.htm.

List of abbreviations and definitions

AFID	Alternative Fuels Infrastructure Directive
AFIR	Alternative Fuels Infrastructure Regulation
BEB	Battery Electric Bus
BEV	Battery Electric Vehicle
CBAM	Carbon Border Adjustment Mechanism
CHP	Combined Heat and Power
CTP	Common Transport Policy
DoE	US Department of Energy
EC	European Commission
EU-ETS	EU Emissions Trading System
FC	Fuel Cell
FCEB	Fuel Cell Electric Buses
FCEV	Fuel Cell Electric Vehicles
FCET	Fuel Cell Electric Trucks
FCH JU	Fuel Cells and Hydrogen Joint Undertaking
FCH 2 JU	Fuel Cells and Hydrogen 2 Joint Undertaking
FC REEV	Fuel Cell Range Extender Electric Vehicles
FP	Framework Programme
GHG	Green House Gas Emissions
HD	Heavy Duty
HRS	Hydrogen Refuelling Stations
HPF	High Performance Fuels
KPI	Key Performance Indicators
LHP	Lighthouse Project
MS	Member States
MAIP	Multi-Annual Implementation Plan
MAWP	Multi-Annual Work Plan
MD	Medium Duty
NEDC	New European Driving Cycle
OEMs	Original Equipment Manufacturer
PGM	Platinum Group Metals
PV	Photovoltaic Installation
PWC	PriceWaterhouseCoopers
SoA	State-of-the-art
TCO	Total Cost of Ownership

TIM	Tools for Innovation Monitoring
TRL	Technology Readiness Levels
TTW	Tank to Wheel
UITP	International Association of Public Transport
WTW	Well to Wheel

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