Hydrogen Mobility Europe

Overarching progress beyond the current state of the art and gaps preventing full commercialisation (WP6, Task 6.3)

Deliverable 6.14	Overarching progress beyond the current state of the art and gaps preventing full commercialisation - Final
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Document Status	Final (October 2023)
Dissemination Level	Public

A project co-funded by
under the Grant Agreement n.671438

Clean Hydrogen Partnership

Co-funded by the European Union

Report produced by elementenergy an ERM Group company

Contents

1. Introduction

2. Progress under H2ME

3. Hydrogen Vehicle Developments

FCEV market summary in Europe

Light duty vehicle progress outside of Europe

Contrasting with BEVs

4. Hydrogen light duty vehicle policy in Europe

European wide political trends

National policy strategies

5. Refuelling Infrastructure Developments

Strategic developments

Technical developments

6. Understanding the customer proposition

7. Remaining barriers to light duty vehicle commercialisation

Economic barriers

Competition for funding

Technical barriers

8. Conclusions and recommendations

This report has been prepared as part of the CH2 JU-funded project H2ME 2 by Element Energy

This project has received funding from the **Fuel Cells and Hydrogen 2 Joint Undertaking** (now the Clean Hydrogen Partnership) under grant agreement No 671438 and No 700350. This Joint Undertaking receives support from the EU's Horizon 2020 research and innovation programme, **Hydrogen Europe Research** and **Hydrogen Europe**.

The report was prepared between January and November 2023 in consultation with by the H2ME 2 projects partners

Report's author:	List of projects partners:
This report has been prepared by Element Energy	Air Liquide Advanced Business. Air Liquide Advances Technologies SA. Air Liquide France Industrie. Alphabet Fuhrparkmanagement GMBH. Audi Aktiengesellschaft. B.Kerkhof & ZN BV. Bayerische motoren Werke Aktiengesellschaft (BMW). Brintbranchen. Centre of excellence for low carbon and fuel cell technologies (CENEX). Compagnie Nationale du Rhone SA. Danish Hydrogen Fuel AS. EIFER Europaisches Institut Fur Energieforschung EDF KIT EWIV. ERM France. GNVERT SAS. Elogen. H2 Mobility Deutschland GMBH & CO KG. Honda R&D Europe (Deutschland) GMBH. Hydrogene de France. HYPE. Hysetco. hySOLUTIONS GmbH. ISLENSKA VETNISFELAGID EHF. ITM Power (trading) LTD. Icelandic New Energy LTD. Islenska Vetnisfelagid EHF. Kobenhavns Kommune. Manufacture française des pneumatiques (Michelin). McPhy Energy. Mercedes-Benz AG. Ministerie Vann Infrastructuur en Waterstaat. Nel Hydrogen AS. Open Energi LTD. R-Hynoca. Renault SAS. Renault Trucks SAS. Réseau GDS. Société d'économie mixte des transports en commun de l'agglomeration Nantaise (SEMITAN). Stedin Netbeheer BV. Symbio SAS . The University of Manchester. Toyota Danmark AS. Toyota Norge AS. and Waterstofnet VZW.

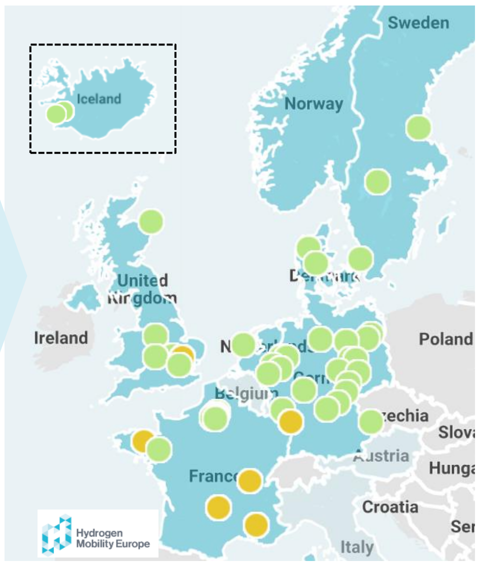
The H2ME initiative will deploy >1,400 FCEVs and >45 HRS across 10 countries by the mid-2020s

Hydrogen Mobility Europe

H2ME overview

Endorsers:

- Mobilité Hydrogène France
- H_2 Mobility
- UK H_2 Mobility
- Scandinavian Hydrogen Highway Partnership
- Hydrogen mobility grouping in Benelux
- Hydrogen mobility grouping in Austria
- Hydrogen mobility grouping in Italy



Concept:

- Joint initiative from the **most ambitious European hydrogen mobility initiatives**
- **One 'working framework'** linking these initiatives, which provide the opportunity to:
  1) identify **optimal commercialisation strategies** and **synergies between countries**
  2) develop **European strategies for commercialisation**

New hydrogen refuelling stations:

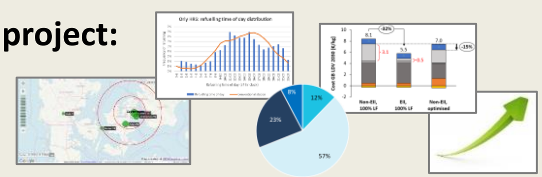
Germany	20
France	14
Iceland, Denmark, Norway, Sweden	11
United Kingdom	5
Netherlands	1

Fuel cell vehicles:

- **1,000** OEM cars
- **400** fuel cell RE-EV vans

Performance and market analysis conducted during the project:

- Data performance analysis
- Market readiness and customer value proposition
- Electrolyser in grid operation



Hydrogen Refuelling Stations under commissioning (yellow)
Hydrogen Refuelling Stations Commissioned (green)

HRS: Hydrogen Refuelling Station
FCEV: Fuel Cell Electric Vehicle
RE-EV : Range-Extended Electric Vehicle
OEM: Original Equipment Manufacturer

This document summarises the H2ME initiative learnings, and provides recommendations for projects looking to commercialise light duty hydrogen mobility technology

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Summary (1/3)

- The H2ME initiative, a **flagship European project**, has resulted in the deployment of hundreds of fuel cell hydrogen cars and vans and the associated refuelling infrastructure, across 8 countries in Europe. **It creates the basis for a first truly pan-European network, and contributes to building the world's largest network of H_2 refuelling stations.**

- The project is made up of two phases, H2ME -1, which started in 2015, and H2ME-2, which started in 2016. Over the course of these two phases, **as of May 2023 >1,100 vehicles and 45 hydrogen refuelling stations** have been deployed. The deployments are intended to jump start the drive towards fuel cell vehicles and establish the conditions in which fuel cell vehicles and the underlying refuelling stations can thrive.

- The project was supported by the European Union through the **Clean Hydrogen Partnership** (previously, FCH 2 JU) but was driven by the **continuous engagement of the industry.**

- This documents provides a **summary of the progress achieved by the industry on the key technical and commercial aspects needed to secure the commercialisation of hydrogen and fuel cell technology in Europe**, as a result of H2ME and other development projects since the H2ME project began in 2015.

- This report is the final report on the topic of *Overarching progress beyond the current state of the art and gaps preventing full commercialisation*. Three previous interim reports on the same topic are available, and this report summarises the interim reports and includes new learnings from the period January – October 2023.
- **All sections have been updated and the following new sections have been included:** Summary of the achievements of H2ME, extended learnings and recommendations for future deployments.

Executive summary (1/2)

Summary (2/3)

Report overview

The **progress and findings of five key areas** are summarised in this report:

- **H2ME background and achievements**
- **Vehicle deployment progress**
- **Hydrogen mobility policy progress**
- **Station deployment progress**
- **Customer validation**

These updates inform a **final section**, which summarises the key **remaining gaps to commercialising the technology**, and provides recommendations for overcoming these barriers in the near and medium term.

Progress under H2ME

- The H2ME project has been instrumental in Europe to begin to establish a publicly accessible hydrogen network, and prove the technical maturity of hydrogen vehicles.

Vehicle deployment

- Since the launch of H2ME, the variety of hydrogen vehicle products available in Europe has increased, with the first introduction of van products, including from Renault and Vauxhall, and HGV products from various manufacturers including a 27t VDL truck.

European hydrogen mobility policy

- The energy security crisis has heightened awareness of the need to shift away from fossil fuels. Green hydrogen is now strongly preferred and most refuelling stations use green H_2.
- Hydrogen prices have increased as a result of the crisis, although other fuels also have and there is strong political momentum to invest in hydrogen to bring down costs for the medium-long term.
- National strategies focus on high fuel usage applications and demand clustering.

Executive summary (2/2)

Hydrogen Mobility Europe

Summary (3/3)

Hydrogen station developments

- The economics for hydrogen refuelling are highly dependent on achieving large scale (several hundred kilograms per day) offtake for each station.
- There is a trend towards developing hydrogen stations for heavy duty vehicles, due the high fuel consumption of HDVs and the substantial portion of the fleet which will be difficult to electrify.
- Whilst there remain a handful of technical barriers to address in order to improve user experience, hydrogen stations have been proven to be technically viable. One remaining area to improve is the availability of the refuelling station.

Customer proposition

- Customers reported a broadly positive experience of using hydrogen fuelled vehicles.
- There were mixed responses related to the hydrogen refuelling infrastructure. The most important metrics to improve relate to the number of fuelling stations, followed by the station availability performance.

Remaining barriers to commercialisation

- There remains an economic barrier to commercialisation, due to the premium for hydrogen vehicles and price of hydrogen fuel. However, this economic barrier has been greatly reduced for light duty vehicles.
- The key barrier to address is the low deployment of hydrogen refuelling stations. These often require funding to be able to achieve viable hydrogen prices of below €10/kg, and the investment in station construction is a substantial risk for infrastructure providers based on current vehicle volumes.
- New business models are being investigated to accelerate the deployment of hydrogen fuelled vehicles and overcome the risks and economic challenges of H_2 vehicle deployment.

Public resources with preliminary results of the H2ME initiative

Hydrogen Mobility Europe

- This document provides an overarching summary of the activities undertaken in the project. However, more detailed reports are available on the H2ME project website: https://h2me.eu/publications/
- The key reports that contributed to forming the views in this report were prepared by the H2ME project partners. The publicly-available reports used are:
  - Summary of solutions adopted to resolve outstanding network and precommercial issues around hydrogen fuel retailing, H2ME (1) D2.6, Element Energy
  - Final yearly technical report reviewing the technical progress for FCEVs & HRS in the project, H2ME (1) D4.17, Cenex
  - Well to Wheels environmental impact assessment, H2ME (1) D4.19, Cenex
  - Status and advancements in the customer value proposition offered by the FC vehicle technology, H2ME (2) D6.3/D6.6, Element Energy
  - Summary and lessons learnt from the hydrogen mobility strategies tested in this project, H2ME (1) D5.13, Element Energy
  - Strategic recommendations for supporting the commercialization of fuel cell electric vehicles in Europe, H2ME (1) D5.16, Element Energy
  - Six Monthly Summary Technical Report Presenting Project Data to May 2022, H2ME (2) D5.12, Cenex
  - Annual H2ME Vehicle and Infrastructure Performance Reports (2015-2022), H2ME (2) D5.14-D5.17, Cenex
  - HRS Safety, Regulations, Codes and Standards. Lessons Learned: Interim Report 3, H2ME (2), D5.21, Cenex
  - Technical performance of HRS under high utilisation and recommendations, H2ME (2) D5.37, Element Energy
  - Overarching progress beyond the current state of the art and gaps preventing full commercialisation - Interim 2, D6.12, Element Energy
  - Commercial advancements in the hydrogen fuel retailing – final, H2ME (2) D6.10, Element Energy
  - Recommendations for harmonising the hydrogen refuelling business in Europe – final, H2ME (2) D6.18, Element Energy

Contents

1. Introduction

2. Progress under H2ME

3. Hydrogen Vehicle Developments

    FCEV market summary in Europe

    Light duty vehicle progress outside of Europe

    Contrasting with BEVs

4. Hydrogen light duty vehicle policy in Europe

    European wide political trends

    National policy strategies

5. Refuelling Infrastructure Developments

    Strategic developments

    Technical developments

6. Understanding the customer proposition

7. Remaining barriers to light duty vehicle commercialisation

    Economic barriers

    Competition for funding

    Technical barriers

8. Conclusions and recommendations

Contents overview

1. Introduction
- Background to the project
- Purpose of the report
- Summary of key findings

2. Progress under H2ME
- Key milestone achievements
- Trends and wider impacts from the project

3. Hydrogen vehicle developments
- Fuel cell vehicle models in Europe
- H2 and BEV progress
- International comparisons

4. European H2 vehicle policy
- European level policy drivers and the energy security crisis
- National, regional and local case studies

5. Hydrogen station developments
- Emerging trends in HRS business cases
- Technical developments for refuelling stations

6. Customer proposition
- Desirable end user characteristics for fuel cell vehicle deployment projects
- End user survey feedback summary

7. Barriers and recommendations
- Key limiting factors preventing full commercialisation (economic, technical and strategic)

8. Conclusions
- Summary of the most important project learnings
- Recommendations for future deployments

Activities under H2ME and H2ME2 are part of a much larger vehicle and HRS rollout in Europe

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H2ME (1) targets

29 stations
>300 cars and vans
€60m total cost
€32m funding
Started June 2015

Hydrogen Mobility Europe

- **>45 refuelling stations**
- **>1,400 cars, and vans**
- **€160m total cost**
- **€67m funding from EU**
- **~50 organisations**

A major European activity!

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Co-funded by the European Union

H2ME-2 targets

20 stations
>1,100 cars, vans and trucks
€100m total cost
€35m funding
Started May 2016

Achievements to date

A flagship project for Hydrogen Mobility **1/2**

Hydrogen Mobility Europe

Industry, SMEs and University collaboration

49 organisations

Advancements in commercialization strategies

Gather evidences for new deployment and business cases

-> Focus on co-location of demand and HRS usage for different vehicles type .

-> For vehicles, small and large fleet (>100)

Testing in real work conditions

Product ready for commercialisation

-> Up to 594 km of driving range – availability close to 100% – reached 100km/1kg H_2

-> max HRS load reaching 45% - Availability >95% - back to back refuelling for 6 vehicles

Building a rich dataset valuable for Europe

Achieved since 2016 (as of Q4 2022)

- > 29.3 million km driven

- > 484t of H_2 distributed (196 000 refuelling events)

Technical advancements

Deployment of new fuel cell electric vehicles models and hydrogen refueling stations technologies

Mercedes-Benz GLC, Hyundai Nexo new model of Renault Kangoo Z.E. Hydrogen (by Symbio) and Toyota Mirai

Development of new technologies and services

-> Maintenance strategies for HRS

-> payment by card and app increasingly common

-> Fleet uses validated for taxi and carsharing

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Achievements to date
A flagship project for Hydrogen Mobility **2/2**

Hydrogen Mobility Europe

Largest European deployment to date for hydrogen mobility

>45 HRS and >1,100 vehicles have been deployed in 9 countries (as of May 2023) incl. 20% of German national network

Largest fuel cell electric vehicles fleet in the world

~ 300 Fuel Cell taxis in Paris, 114 Fuel Cell Range Extender vans

High visibility first of a kind initiative

First deployment with European vehicles OEMs

First deployment for Daimler and Symbio

Fostering additional activities in existing regions and for partners

Most advanced coalitions in Germany, Scandinavia, France and the UK collaborating with observer coalitions becoming increasingly active (Benelux, Austria and Italy)

Dissemination of results to all relevant stakeholders

To date: > 90 articles and 7 newsletters published, social media presence, 3 conferences and 4 roundtables held in addition to 17 vehicles hand-over and 19 HRS openings and "ride and drives" events, 37 national events and presentations at conferences

Cross countries events

H2ME vehicles took a 6,000km road trip through Europe showing the advantages of the technology

Analysis and summary of key trends and best practices for the sector

To date: 94 reports produced

Knowledge development

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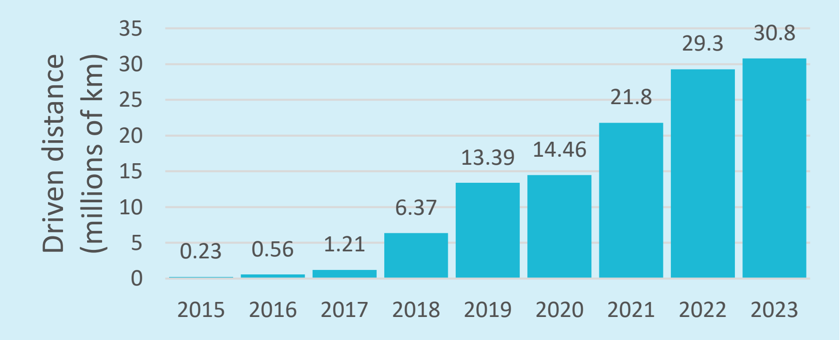
Key milestones have been achieved, including the driving of over 30 million km in hydrogen FCEVs

Hydrogen Mobility Europe

FCEV validation in fleets: performance

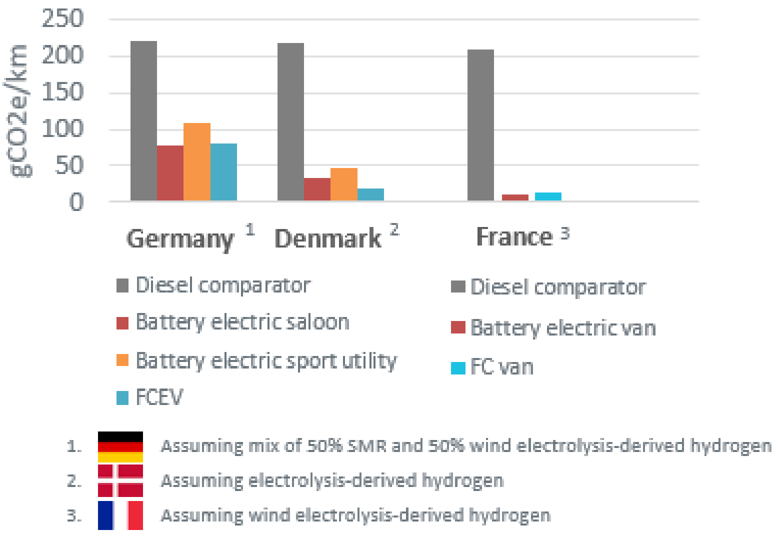
- Vehicles have reported a total of > **30.8 million km driven since the first vehicles were deployed.**
- **Average availability** is **effectively 99%+ for all FCEV.**
- **Daily distance** covered for **500-550 km** reported.
- **Up to 594 km of driving range.**
- **Reached 100+km/1kg hydrogen.**



Zero emission mobility: Wells to Wheels (WTW)*

- The vehicles emit no local pollutants.
- The project has shown that FCEV achieve significantly **lower WTW CO_2** emissions than diesel or gasoline vehicles even if using fossil (Steam Methane Reforming) -derived hydrogen.
- Emission savings compared to diesel or gasoline vehicles are increased even more significantly when using low carbon or green hydrogen.

Countries have different electricity generating mixes with ***CO2 emissions resulting from the amount of renewables/low carbon generation*** *employed*



Source: H2ME, D5.08 – D5.41 Performance reports, D4.19 Well to Wheels Report, Cenex

*Well-to-wheel emissions include all emissions related to fuel production, processing, distribution, and use.

The H2ME initiative has had a wider impact beyond the vehicles and infrastructure funded by the project

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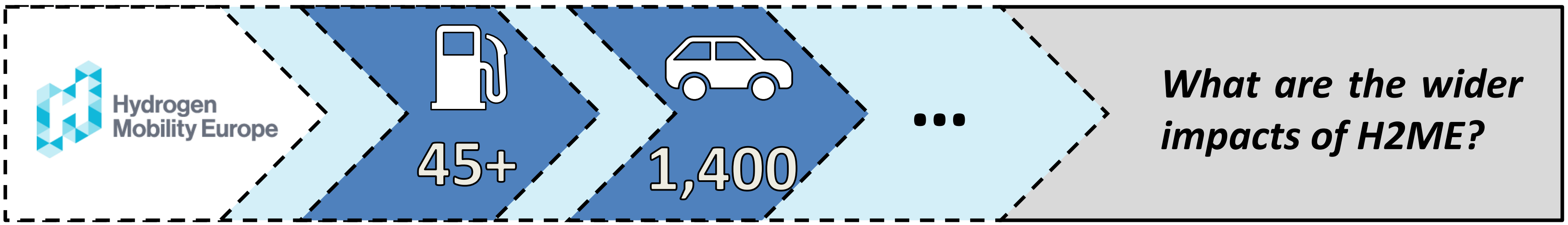


1. Technical validation & advancements

- Vehicles have been shown to perform highly reliably and safely
- Critical learnings about vehicles and infrastructure have been disseminated

2. Vehicle price reductions

- Measurable reduction in cost due to economies of scale in manufacturing
- Proven that cost reductions for future rollouts are possible

3. Pathway for future deployment

- An emerging station network has been set up which has attracted more OEMs to invest in the technology
- Increasing public focus and political interest

Commercialisation of the technology is closer to reality

Feedback from the H2ME initiative shows that vehicles can operate reliably for extended periods

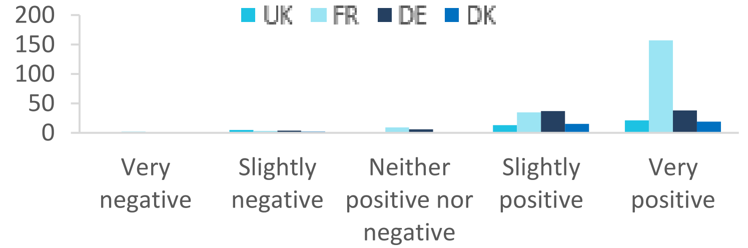
Hydrogen Mobility Europe

Technical validation and advancements

- The operation of over 1,400 vehicles to date has validated the technology, with strongly positive reviews regarding the vehicle performance and capability (see right).
- Hydrogen vehicle and HRS key areas of improvement have been identified, which can be built on in future projects e.g. compressors and dispensers are the least reliable aspects of HRS equipment and multiple spare parts are needed.

Overall, how would you describe your experience with FCEVs?

N = 368



The project has helped to validate hydrogen mobility technology

- Improvements achieved to date:
  - Increase of H_2 storage capacity (700 bar) as vehicles have matured – resulting in **increased driving range**.
  - **Safety** concerns have been addressed, with no significant H_2-related accidents for thousands of FCEVs (see next slide).
  - **Cold start** down to -25°C as the **heat management strategy** of the fuel cell engines has been optimised.
  - **Durability** improvements in fuel cell stacks and systems.
- The impact of these achievements has been significant:
  - Validation of the technology through the H2ME project has encouraged OEMs and infrastructure providers to further invest in hydrogen mobility solutions, e.g. launching of the next generation of Toyota Mirai 2021.
  - The demonstration also highlighted areas for future technical development, which will help to improve future design iterations. These are summarized in the later section '*Remaining barriers to commercialization'.* Key areas include: **improvements in fuel cell efficiency, improvements in station design and component reliability** and **reducing raw material requirements**.

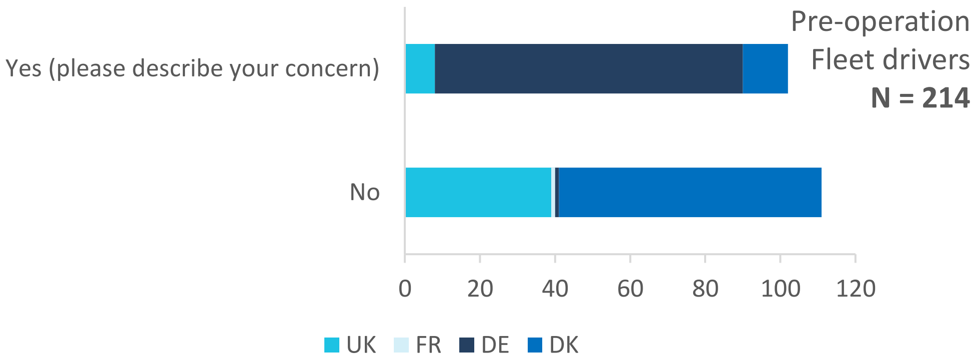
Source: Status and advancements in the customer value proposition offered by the FC vehicle technology, H2ME (2) D6.3/D6.6, Element Energy

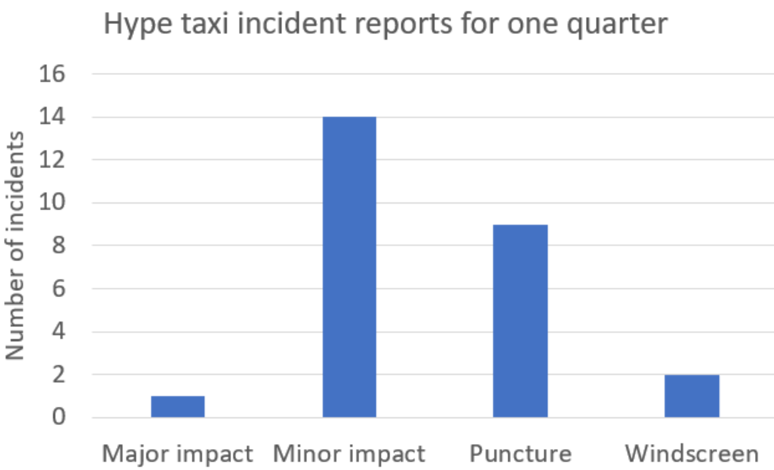
Case Study: Demonstration of FCEV safety

Before vehicle operation, some FCEV drivers expressed safety concerns

- Prior to operation commencement, a substantial number of fleet drivers (mainly German drivers) had concerns regarding the safety of FCEVs. These were mainly related to the high pressure tank systems.
- Despite a consistent daily usage resulting in occasional accidents, no incidents resulted in the release of hydrogen and hydrogen vehicles were not found to be more dangerous than petrol / diesel vehicles.
- By the end of the project, the number of vehicle drivers who indicated a concern about vehicle safety reduced to under 10%.

Do you have any concerns about the safety of the FCEV compared to a petrol / diesel vehicle?





Source: Yearly Vehicle and Infrastructure Performance Report 3 (2015-2019), Cenex, 2020

H2ME has formed a large part of the European effort to create a hydrogen refuelling network

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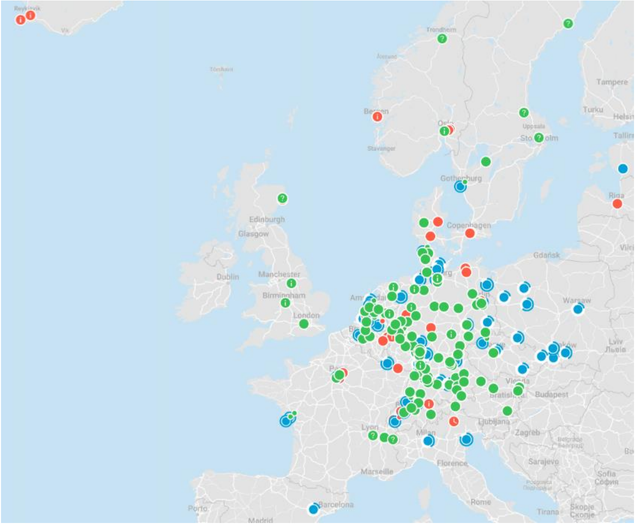
Pathways for future deployments

- Through the development of 49 stations in Europe, H2ME has largely contributed to the build out of a nascent station network.
- A reliable station network is essential to provide manufacturers with the confidence to invest in a region.
- There are now particular regions in Europe where manufacturers are taking steps to deploy products at a commercial scale e.g. Hyundai in Switzerland, European truck OEMs in the Netherlands and Germany.
  - H2ME has had a substantial impact in the German refuelling network build (20 HRS)
- Given this increased confidence, the number of manufacturers looking to invest in this sector has increased, with new OEM products available (see right).
  - This variety of options gives consumers more choice and helps to cover a wider portion of the whole vehicle market e.g. Wrightbus have now developed hydrogen fuel cell double decker buses.



H2Live map, October 2023
[H2.LIVE: Hydrogen Stations in Germany & Europe]

165 opened 41 implementation

Station network provides confidence to launch FCEV products

New OEM models announced

- Toyota Mirai Gen 2
- BMW iHydrogen
- Peugeot e-EXPERT
- Vauxhall Vivaro
- Wrightbus Hydroliner
- ADL Enviro400FCEV
- Hyundai XCIENT
- Renault Master
- Hyzon HyMax
- Trucks from European OEMs inc. Daimler, IVECO, and Volvo

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H2ME has identified several key areas of improvement to increase FCEV adoption

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Key areas of improvement identified by H2ME

- The key area of improvement identified by the H2ME project for increased hydrogen light duty vehicle adoption is in **increasing the number of hydrogen refuelling stations** to provide more places to refuel for vehicle customers, whilst also **improving the location of hydrogen refuelling stations** through for example, deploying more stations on major roads.
- To ensure that hydrogen mobility can be adopted by the mass-market, three key areas of improvement in station performance have been identified by H2ME.
  - **Improvements in station design,** involving designing stations to be multiply redundant (with multiple dispensers and compressors operating in parallel).
  - **Improvements in station component reliability to decrease periods of downtime.**
  - **Improvements in refuelling station interoperability .**
- H2ME has identified that further improvements are needed for FCEVs to improve the Total Cost of Ownership for the customer.
  - Improvements identified include vehicle driving range and range of FCEV models available for purchase, improvements in fuel efficiency.
- Furthermore, with the majority of hydrogen price at the pump related to hydrogen production costs, improvements in electrolyser technologies and increases in the scale of hydrogen production projects are needed to lower hydrogen costs at the pump and improve the business case for FCEVs.

Contents

1. Introduction

2. Progress under H2ME

3. Hydrogen Vehicle Developments

- FCEV market summary in Europe
- Light duty vehicle progress outside of Europe
- Contrasting with BEVs

4. Hydrogen light duty vehicle policy in Europe

- European wide political trends
- National policy strategies

5. Refuelling Infrastructure Developments

- Strategic developments
- Technical developments

6. Understanding the customer proposition

7. Remaining barriers to light duty vehicle commercialisation

- Economic barriers
- Competition for funding
- Technical barriers

8. Conclusions and recommendations

2. Hydrogen Vehicle Developments
Section overview

- This chapter is subdivided into three sections:

FCEV market summary in Europe

- Timelines for hydrogen product development.
- Highlights:
  - Launch of Stellantis and Renault van products in Europe.
  - Announcements from major European truck OEMs.

Contrasting with progress outside Europe

- Japan, South Korea and the US dominated the light duty fuel cell market, due to strong political will and subsidy plans.

Contrasting with BEV developments

- BEVs have been fully commercialised. FCEVs need to adopt strategies to bring down costs and build out the HRS network.

Contents

1. Introduction

2. Progress under H2ME

3. Hydrogen Vehicle Developments

- **FCEV market summary in Europe**
- Light duty vehicle progress outside of Europe
- Contrasting with BEVs

4. Hydrogen light duty vehicle policy in Europe

- European wide political trends
- National policy strategies

5. Refuelling Infrastructure Developments

- Strategic developments
- Technical developments

6. Understanding the customer proposition

7. Remaining barriers to light duty vehicle commercialisation

- Economic barriers
- Competition for funding
- Technical barriers

8. Conclusions and recommendations

New models and brands will enable a wider range of customers to be reached

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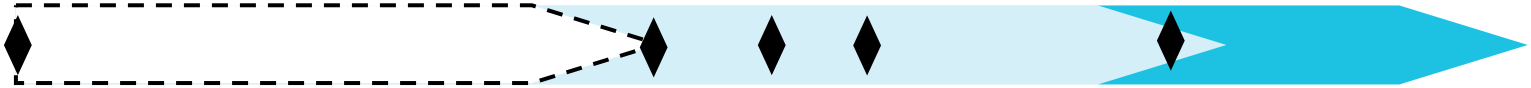
2019	2020	2021	2022	2023	2024	2025

Dual fuel ULEMCO vans in use in the UK

HV Systems H2Van deployment

Stellantis announce plans for a manufacturing plant for up to 5,000 FCEVs

Vans



Low 100s Symbio/Renault Kangoos operating across Europe

Stellantis launch Vauxhall Vivaro and Peugeot e-EXPERT in Europe by end 2021

Renault launch the Renault Master Van H2

Source: elementenergy an ERM Group company

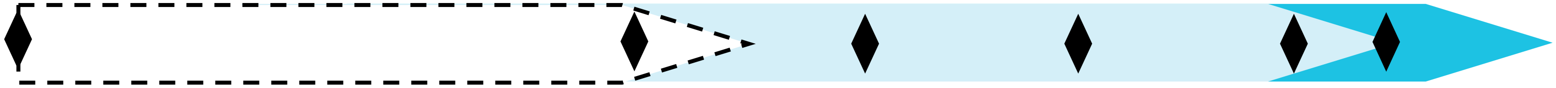
2 Coradia iLint trains are carrying passengers in Lower Saxony, Germany

12 more iLint trains deployed in Lower Saxony*

6 Coradia stream in Lombardy

12 Regiolis H2 trains in France

Trains



*Note: Lower Saxony decided in August 2023 to shut down its hydrogen train network in favour of developing electric trains

First Alstom Coradia Polyvalent trains to be developed in France

12 iLints deployed in Frankfurt (Note: fleet of 27 planned but delays have meant only 12 trains currently deployed)

Legend

- Demo projects / development
- Early commercial
- Mass market introduction

Based on public announcements from vehicle manufacturers and deployment projects

Advancement in hydrogen mobility is coming with a new range of FC vehicle types and brands

Hydrogen Mobility Europe

2019	2020	2021	2022	2023	2024	2025

Cars

100s of FCEV cars in Europe (mostly Toyota Mirai and Hyundai ix35)

2nd gen Toyota Mirai begins production of ~30,000 stacks per year

BMW starts small series production of the iX5 Hydrogen

Hyundai Nexo starts European deployment

The 2022 Mirai launches, marking a c.14% price reduction, starting at €64,000

Honda RC-V fuel cell model goes on sale in the US and Japan

Source: elementenergy an ERM Group company

Buses

Increasing number of OEMs developing FC buses for European markets

Major OEMs unveil hydrogen bus models

c.100 fuel cell buses (Wrightbus and Van Hool) are operating in Europe

The JIVE programme successfully deploys 300 buses across 14 European cities

Birmingham City Council to convert full depot of 124 buses to hydrogen

Legend: Demo projects / development | Early commercial | Mass market introduction

Based on public announcements from vehicle manufacturers and deployment projects

Clean Hydrogen Partnership

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Deployment of fuel cell trucks has started in Europe with 50 operational in Switzerland, bringing significant hydrogen demand

Hydrogen Mobility Europe

2019	2020	2021	2022	2023	2024	2025

Source: elementenergy an ERM Group company

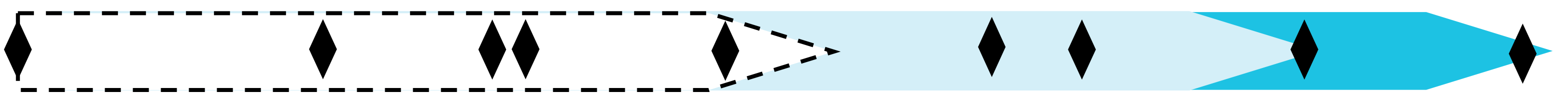
ULEMCO dual fuel street sweepers deployed (UK)

Hyzon opens dedicated FC trucks manufacturing facility in the Netherlands. Well over 100 orders received

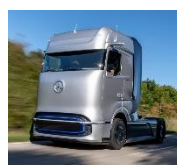
16 heavy duty trucks from VDL and Iveco will be deployed as part of the H2Haul project across Europe

Target date for 1,600 Trucks to be deployed in Switzerland

Trucks



Hyundai 1,600 Trucks project in begins in Switzerland, with a first deployment of 10 XCIENT trucks



Daimler and Volvo form a JV, cellcentric, to develop heavy duty fuel cells

VDL deploy a 27 tonne hydrogen truck for trials in Germany, the Netherlands, Belgium and France

IVECO enters European production

Scania and Cummins to deliver 20 fuel cell trucks to Rotterdam

H2A

H2Accelerate TRUCKS plans to deploy 150 FC trucks across Europe by mid-to-late 2020s

Legend Demo projects / development | Early commercial | Mass market introduction

Based on public announcements from vehicle manufacturers and deployment projects

Clean Hydrogen Partnership

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Commercialisation status today

Number of FCEVs and HRS operating in Europe

Hydrogen Mobility Europe

Over four thousand hydrogen vehicles and over 200 HRS have now been deployed in Europe

Vehicles/HRS in June 2023 Data includes but is not limited to H2ME	Germany	France	UK	Nordic	BeNeLux	EUROPE
Cars	2,326	635	372	562	771	>5,000
Vans (including range extended vans)	16	273	2	2	15	306
Buses	108	33	98	12	64	>200
Trucks	29 (IPHE)	1	2	6	28	55
Trains	12	-	-	-	-	12
Active HRS	101	50	9 (UK H_2Mobility)	18 (H2Stations)	18 (H2Stations)	255 (H2Stations)

Source: EAFO (excludes retirements) unless otherwise stated; IPHE country statements, UK H_2Mobility, H2Stations.org (LBST), European Hydrogen Observatory

- The FCEVs (>1,400) & HRS (>45) deployed in H2ME kick-started this growth and remain a large share of deployments.
- H2ME numbers are supplemented by private initiatives such as the HyTruck programme in Austria, the HyTrucks consortium in Northern Europe, Hyundai's plan to deploy 1,600 Xcient trucks in Switzerland, and the EU project ZEFER, which is deploying 180 light duty vehicles in Paris, London and Copenhagen.

Clean Hydrogen Partnership

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Contents

1. Introduction

2. Progress under H2ME

3. Hydrogen Vehicle Developments

- FCEV market summary in Europe
- **Light duty vehicle progress outside of Europe**
- Contrasting with BEVs

4. Hydrogen light duty vehicle policy in Europe

- European wide political trends
- National policy strategies

5. Refuelling Infrastructure Developments

- Strategic developments
- Technical developments

6. Understanding the customer proposition

7. Remaining barriers to light duty vehicle commercialisation

- Economic barriers
- Competition for funding
- Technical barriers

8. Conclusions and recommendations

Whilst the H2ME initiative has been instrumental in Europe, Asia and the US have achieved faster deployment rates

Hydrogen Mobility Europe

Hydrogen mobility deployment: Global learnings

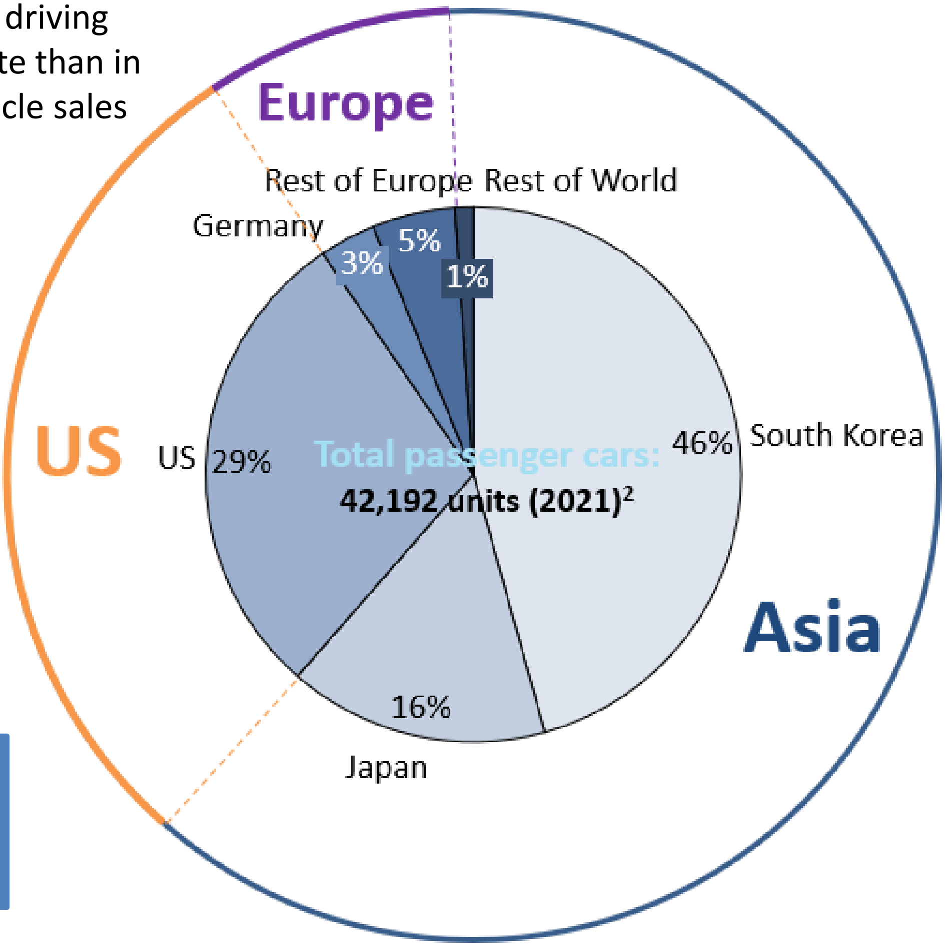
- This section analyses the key initiatives which are driving vehicle deployment in Asia & the US at a faster rate than in Europe. In 2021, c.7% of hydrogen passenger vehicle sales worldwide were in EU countries.[1]

8,500 hydrogen cars sold in South Korea in 2021

92% of South Korea vehicle sales were Hyundai Nexo models[1]

Japan and US were other major markets (>2,000 units)

Japan has the most hydrogen stations of any country



[1] [The Hydrogen Powered Car Is Alive: Sales Up By 84 Percent In 2021 (motor1.com)]

[2] [Deployment of Fuel Cell Vehicles and Hydrogen Refueling Station Infrastructure: A Global Overview and Perspectives (ieafuelcell.com)]

Learnings from the US: A critical hydrogen refuelling density is required to stimulate vehicle deployments

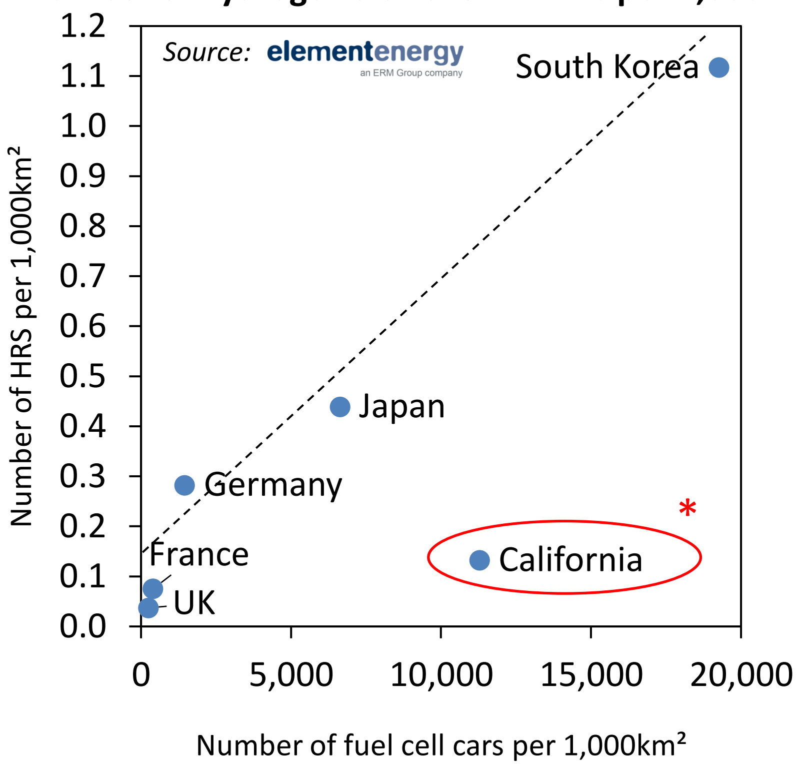
Hydrogen mobility deployment: learnings from the US

- The graph here provides an overview and comparison of fuel cell car and HRS deployments per 1,000km² for a number of countries where deployments have occurred. The graph aims to show how the density of HRS in a country impacts the level of fuel cell car deployments.
- The key observations are that:
  - The key barrier to passenger car deployment is the availability of fuel.
  - In countries with a high density of refuelling stations, hydrogen vehicles have been deployed in the 10,000s.
  - In California, station deployments are clustered, resulting in fewer stations required to support vehicle deployments in these regions.

*

California appears as an outlier to this trend as all stations are clustered in two regions (Los Angeles and San Francisco), causing higher regional density which has created a more robust HRS network to support a larger fleet of light-duty FCEVs. Furthermore,

Number of hydrogen stations & FCEVs per 1,000 km²



Learnings from the US: A critical hydrogen refuelling density is required to stimulate vehicle deployments

Hydrogen Mobility Europe

Hydrogen mobility deployment: learnings from the US

Key Learning 1	Key Learning 2
The trend for global station and vehicle deployment data shows that station density (number of HRS per 1,000 km^2) is a key metric to improve in Europe to facilitate more passenger car deployments	The outlier to the trend, California, highlights that strong policy support for zero emissions vehicles (e.g. super-credits which incentivise manufacturers to produce zero emissions vehicles), combined with a well-planned network of refuelling stations can lead to a significant uptake of light-duty vehicles.

Key Learning 3

Since 2021 sales of FCEVs have largely stagnated in California, with several factors negatively affecting the continued ramp up of light-duty FCEV deployments, these are exemplified by the following recent developments.

- California's largest hydrogen retailer raised its hydrogen price at the pump to $36/kg in Q3 2023 (~$13/kg in Q2 2021) across all its stations making it almost 14 times more expensive to drive a Toyota Mirai in California than a comparable BEV[1].
- Shell in Q3 2023 announced the scrapping of plans to build 48 new light-duty hydrogen filling stations in California, citing "political and economic uncertainty in the initial stages of market deployment present a significant risk in further investment"[2].

Although sales for FCEVs in California for 2023 have already surpassed 2022 numbers, with record sales in Q2, the increased cost of operating an FCEV compared to a comparable BEV presents challenges for the wider adoption of FCEV passenger technology in the state. These points highlight that even with strong political incentives and a well-planned network, the price of hydrogen at the pump is a key factor for light-duty FCEV success.

Clean Hydrogen Partnership

[1] ANALYSIS | It is now almost 14 times more expensive to drive a Toyota hydrogen car in California than a comparable Tesla EV | Hydrogen news and intelligence (hydrogeninsight.com) [2] Shell scraps plan to build 48 new hydrogen filling stations in California, for which it had been awarded $40.6m grant | Hydrogen news and intelligence (hydrogeninsight.com)

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Learnings from Asia: Funding and long-term policy support has been clearer in Asia, led by their manufacturing bases with positive results

Hydrogen Mobility Europe

Hydrogen mobility deployment: learnings from Asia

- Japan and South Korea have had long-term, ambitious strategies in place to accelerate hydrogen mobility deployment, and clear routes to funding.
  - Funding is at a scale which is orders of magnitude greater than European member states initiatives, e.g. South Korea $2.3Bn commitment to supporting the FCEV market.

Japan & South Korea: Key steps taken to stimulate FCEV deployment

1. Publish near & long term targets for FCEV and station deployment
2. Fund near term projects already at a high readiness level
3. Outline a medium-long term roadmap, with a large funding commitment

- Japan and South Korea have been incentivised to commit these funds, in part, as Toyota and Hyundai represent major manufacturing bases in their respective countries.
  - Investment in hydrogen is a growth & export opportunity.

Key Learning 3

European countries should look to use the opportunity of developing a hydrogen mobility network to stimulate homegrown manufacturing bases for vehicles and supply chain components

Hydrogen policy in South Korea & Japan

South Korea	Year	Japan
HyNET, initial $119M funding to expand the HRS network to 310 by 2022	2019	Targets set for 200,000 FCEVs and 320 HRS by 2025 in strategic roadmap
2040 FCEV target set to 3 million	2020	Green Growth Strategy highlights hydrogen as a key sector
$702M spending on hydrogen projects by South Korean Government	2021	$3.4Bn allocation from the Green Innovation fund for 2 hydrogen projects
$2.3Bn committed to establishing an FCEV market by end of 2022	2022	Focus on Hydrogen: Japan's energy strategy for hydrogen and ammonia announced

South Korea's Hydrogen Industrial Strategy | Center for Strategic and International Studies (csis.org)
A clean start: South Korea embraces its hydrogen future | Macquarie Group
Japan's Hydrogen Industrial Strategy | Center for Strategic and International Studies (csis.org)

Contents

1. Introduction

2. Progress under H2ME

3. Hydrogen Vehicle Developments

FCEV market summary in Europe

Light duty vehicle progress outside of Europe

Contrasting with BEVs

4. Hydrogen light duty vehicle policy in Europe

European wide political trends

National policy strategies

5. Refuelling Infrastructure Developments

Strategic developments

Technical developments

6. Understanding the customer proposition

7. Remaining barriers to light duty vehicle commercialisation

Economic barriers

Competition for funding

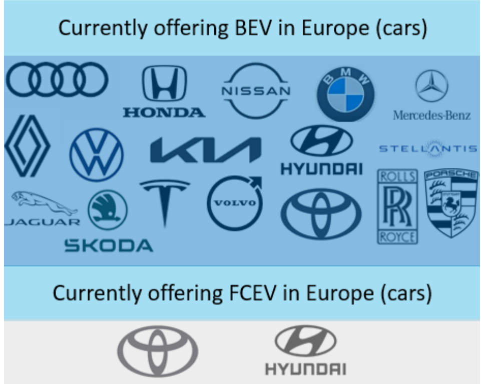
Technical barriers

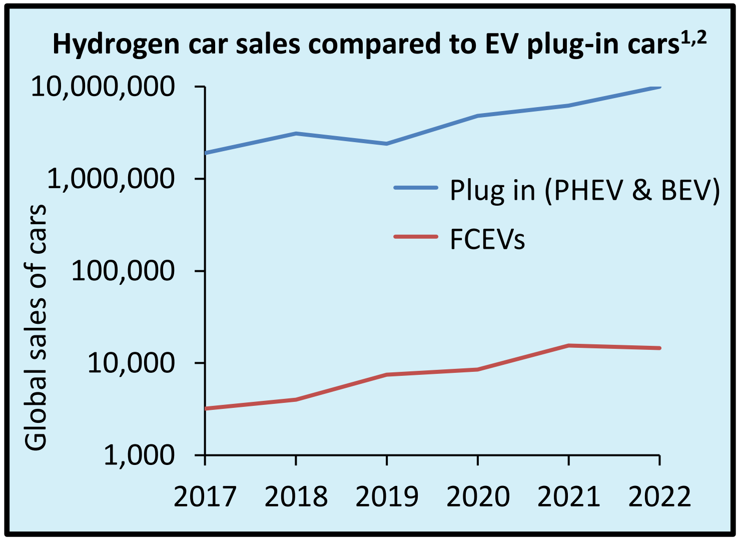
8. Conclusions and recommendations

Many OEMs have developed a range of BEV models over the past 7 years. In this time, FCEVs have not seen the same commercial success.

FCEV commercialisation: Comparison to BEVs

- **Battery electric cars have been commercialised in recent years**
  - Over the course of H2ME, battery electric vehicle (BEV) uptake has largely outpaced the rate of FCEV uptake. BEV car sales have remained c.500 times higher than FCEV sales since 2017.
- **There are a number of contributing factors:**
  - Passenger car OEMs have largely preferred developing BEV models
  - Battery technology has progressed to cover a greater number of duty cycles than expected in 2015
  - Good availability of recharging infrastructure
  - Lower ownership costs (fuel and vehicle costs)
- There are only two manufacturers selling hydrogen cars at scales >1,000 units per year (Toyota and Hyundai).
  - This could change as BMW has recently announced the launch of their hydrogen FCEV iHydrogen NEXT
- Product variety is important if we are to ensure a thriving hydrogen light duty vehicle market. To attract **more OEMs** to bring products to market, there needs to be evidence of a **market pull for hydrogen vehicles.**
  - Increasing sales of existing models
  - Education around the benefits of hydrogen
  - Reducing fuel prices and availability of fuel





[1] The Hydrogen Powered Car Is Alive: Sales Up By 84 Percent In 2021 (motor1.com) [2] Trends in electric light-duty vehicles – Global EV Outlook 2023 – Analysis - IEA

Hydrogen for HGVs is facing increasing competition from BEV models, with some major manufacturers stating preference for BEVs

Heavy duty vehicles: Increased competition from BEVs

- Battery electric technology has progressed over the past decade, and has now not only been proved to be a viable solution for light duty vehicles, but also is seeing increasing interest from OEMs looking to produce heavy duty products.
  - Major truck OEMs are looking to produce BEV products at scale (thousands) by the mid-2020s
  - Hyzon, a leading FCEV HGV manufacturer, has seen recent setbacks[2]
- A major factor in this increase in interest are the improvements in battery cost and energy density, with Traton group claiming improvements have outpaced industry forecasts[1]
  - To keep pace, continued improvements are required in fuel cell and electrolyser price and efficiency

Increasing interest in BEVs for the heavy duty sector…

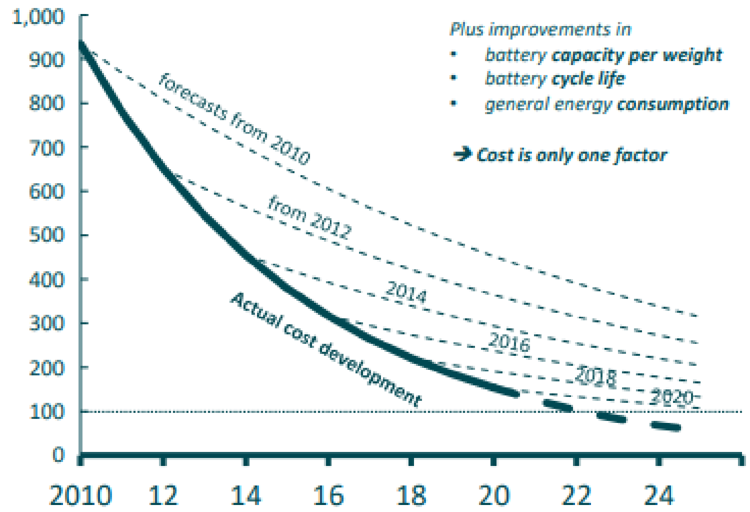
Scania launches BEV & PHEV truck series - electrive.com

Battery-electric trucks are our future (mantruckandbus.com)

Battery Electric Vehicles - DAF Trucks N.V.

Daimler Truck unveils battery-electric eActros LongHaul truck (fleetpoint.org)

Battery pack cost, illustrative[1] [EUR/kWh]



[1] 210510_TRATON_IR_Presentation_Deep_dive_e_mobility.pdf
[2] Hyzon fined $25m by the SEC over the misrepresentation of business dealings – Compliance Week

Several strategies are being developed by industrial and regional stakeholders to allow hydrogen to keep pace with BEV deployments

Hydrogen Mobility Europe

FCEV technologies: evolving strategies to ensure competitiveness

- Given the progress seen in battery technologies, it is important that hydrogen is deployed strategically to ensure that hydrogen projects are successful and investment into the hydrogen mobility sector continues.
  - Hydrogen FCEV projects are sometimes competing with BEV projects for the same funding.
  - End users are unsure which technology to adopt.
- The evolving strategies to ensure hydrogen projects are competitive are as follows:
- **Developing hydrogen transport hubs to achieve scale**
  - Aggregating demand around a single geographic region helps to build in redundancy into the refuelling network and attracts more local operators to participate. It also reduces transportation distance for hydrogen from a single centralised production facility, helping to reduce costs.
- **Linking to a heavy duty anchor demand**
  - Whilst BEVs have progressed substantially, there are still some duty cycles that BEVs will struggle to decarbonise e.g. long distance freight haulage, vehicles with power take-off requirements etc. Building stations for these vehicle types will have spillover effects into the light duty sector if the HRS are publicly accessible.
- **Linking to industrial clusters**
  - Green hydrogen will be essential for the decarbonisation of ports and industrial clusters. These are ideal locations for HRS as they will have access to low cost hydrogen and a strong anchor demand.
- **Taking a loss leader position**
  - In the near term, investors in hydrogen infrastructure may need to take a loss leader position or hedge against the price of electricity over the long term, due to the recent price spikes related to the energy security crisis.

Contents

1. Introduction

2. Progress under H2ME

3. Hydrogen Vehicle Developments

FCEV market summary in Europe

Light duty vehicle progress outside of Europe

Contrasting with BEVs

4. Hydrogen light duty vehicle policy in Europe

European wide political trends

National policy strategies

5. Refuelling Infrastructure Developments

Strategic developments

Technical developments

6. Understanding the customer proposition

7. Remaining barriers to light duty vehicle commercialisation

Economic barriers

Competition for funding

Technical barriers

8. Conclusions and recommendations

Hydrogen strategies for energy system decarbonisation are now emerging across Europe, and mobility is seen as a key aspect

National and regional strategies

In the past four years, numerous national hydrogen strategies have been released which have emphasised the role of hydrogen in delivering the transition to net-zero energy economy, and the potential benefits of deploying hydrogen technologies at scale for applications such as industrial energy, transport applications (including marine and aviation as well as road transport) and heating.

The development of hydrogen for mobility is seen as an important early market to develop in order to compliment the decarbonisation of the energy system using hydrogen, due to the high technology readiness and relatively high-cost counterfactual in taxed petrol / diesel. To support this national strategies set out ambitions and funding commitments to support the development of green hydrogen production and the refuelling infrastructure needed to enable vehicle uptake. Often these strategies assume hydrogen transport will begin with heavier duty bus, truck and rail transport.

- **France:** National Hydrogen Plan (French Government, 2018) - link
- **Germany:** National Hydrogen Strategy (German Government, 2020) – link (An updated strategy was released in July 2023) - link
- **Norway:** Norwegian Government's Hydrogen Strategy (Norwegian Government, 2020) - link
- **Netherlands:** Government Strategy on Hydrogen (The Netherlands Government, 2020) - link
- **Iceland:** 2030 vision for H_2 in Iceland (Icelandic New Energy Ltd., 2020) - link

Strategy and funding at European level

The European Commission released *A hydrogen strategy for a climate-neutral Europe* in July 2020, as part of the European Green Deal (a policy package intended to deliver net-zero by 2050). The strategy objectives are consistent with the national strategies, setting out the investments required to deliver the hydrogen economy, as part of a sustainable economic recovery from Covid-19 impacts.

- Where previously, European funding for hydrogen activities had been largely contained within The Clean Hydrogen Partnership, support for hydrogen technologies will now be integrated within all packages in the Green Deal, with funding to be made available across transport, industry, heat and wider energy system applications. Targets for renewable hydrogen in specific end-use sectors will also be considered as part of future European policy measures.

Source: Summary and lessons learnt from the hydrogen mobility strategies tested in this project, 2020, H2ME (1) Deliverable 5.13, Element Energy

3. Hydrogen mobility strategies
Section overview

- This section is subdivided into two sections, with the first focusing on overall European trends, e.g. concerns due to the war in Ukraine and energy security considerations. The second relates to national schemes being implemented to support hydrogen.

European political trends

- Alternative Fuels Infrastructure Regulation Updates
- Political context, energy security and price volatility

National level hydrogen

- Overview H2 Mobility Strategies
- Vehicle and station deployment under H2ME
- Trends in funding and future outlook

- For further detail on the national level hydrogen strategies, including case studies, please see H2ME Emerging Conclusions report, Element Energy.

Contents

1. Introduction

2. Progress under H2ME

3. Hydrogen Vehicle Developments

    FCEV market summary in Europe

    Light duty vehicle progress outside of Europe

    Contrasting with BEVs

4. Hydrogen light duty vehicle policy in Europe

    European wide political trends

    National policy strategies

5. Refuelling Infrastructure Developments

    Strategic developments

    Technical developments

6. Understanding the customer proposition

7. Remaining barriers to light duty vehicle commercialisation

    Economic barriers

    Competition for funding

    Technical barriers

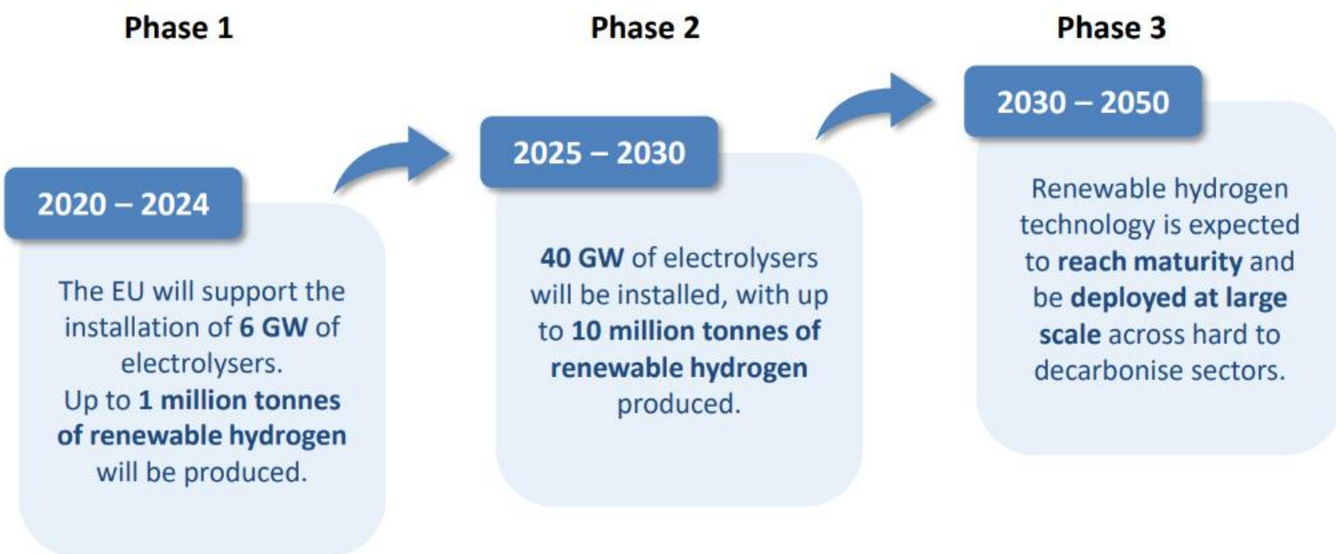
8. Conclusions and recommendations

The EU Hydrogen Strategy did not identify light-duty mobility as a key sector for uptake

Hydrogen Mobility Europe

EU Hydrogen Strategy

- On the 8th July 2020 the European Commission published its “powering a climate-neutral economy” vision. This included publication of:
  - EU Hydrogen Strategy – addresses how to transform this potential into reality, through investments, regulation, market creation and research and innovation
- The strategy provides a roadmap for renewable hydrogen production as well as for key sectors for the uptake of hydrogen



Key sectors identified for hydrogen

- Existing H2 production (e.g. chemicals)
- Industrial processes
- Heavy-duty transport Steel manufacture
- Trucks, rail, some maritime, other transport
- Daily / seasonal storage of renewable energy
- All “hard to decarbonise” sectors

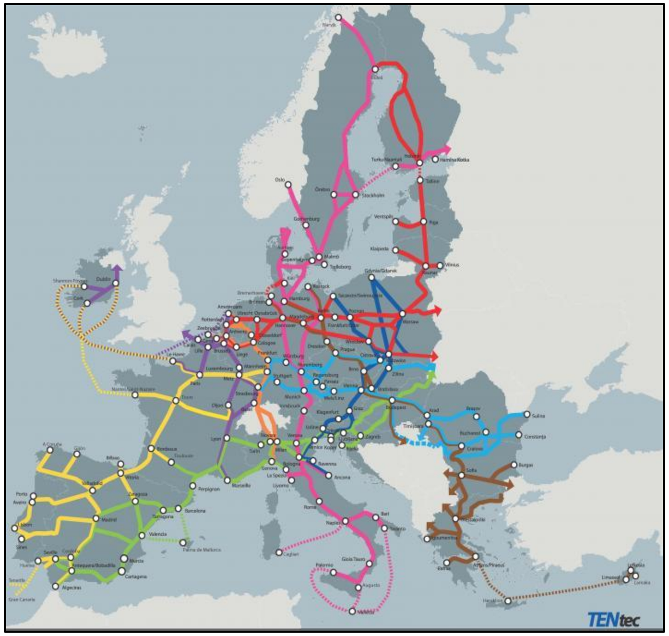
- Heavy duty road transport was identified as a key sector for hydrogen uptake in the strategy, with light duty road transport not identified as a key sector for hydrogen uptake

The European AFIR regulations show ambition to establish a European network of HRS

Hydrogen Mobility Europe

European regulations: AFIR

- As part of the European 'Fit for 55' package, in July 2021 the European Commission proposed a revision to the 2014 Alternative Fuels Infrastructure Directive to turn it into a regulation, the Alternative Fuels Infrastructure Regulation (AFIR)
- In July 2023 the European Council adopted a position on AFIR which outlined that hydrogen refuelling stations must be[1] deployed by **December 31st 2030** to satisfy the following:
  - Hydrogen refuelling stations deployed **at all urban nodes**
  - Hydrogen refuelling stations deployed every **200km along the TEN-T core network**
  - Hydrogen refuelling stations should at least dispense hydrogen at **700bar** and must be equipped to serve **both heavy and light duty vehicles**
  - Minimum cumulative capacity of **1tpd hydrogen**
  - HRS must be equipped with **at least one 700 bar dispenser for liquid hydrogen**



EU TEN-T Network, [Trans-European Transport Network (TEN-T) (europa.eu)]

- These legislations will now need to be implemented into a national level for each member state (c.2024).
- The announcement could be a substantial boost for hydrogen, in particular for light duty transport which requires a good network coverage of public stations to encourage uptake.
  - It is now important that these stations are supported by subsidy schemes on a national level for vehicles, to ensure that stations are well-utilised and have sustainable business cases.

[1] European Commission

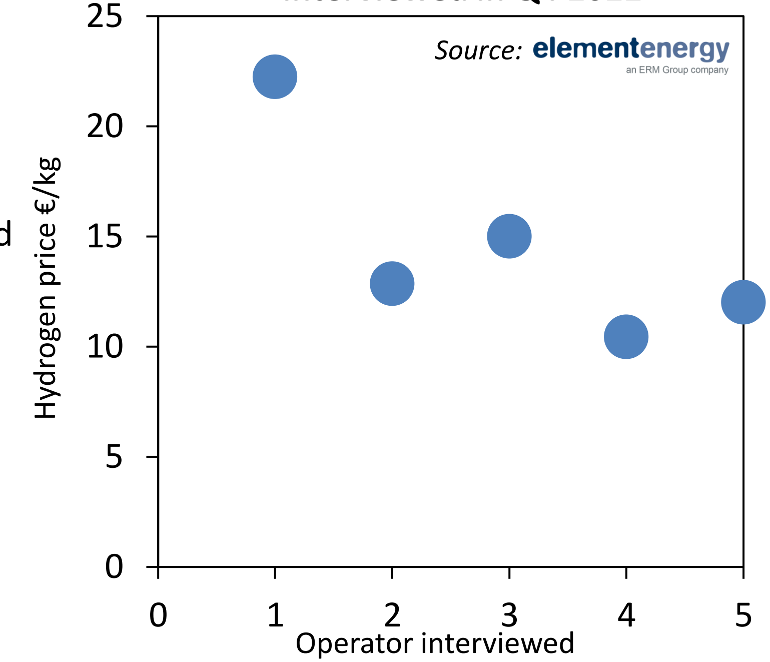
The high cost of energy in Europe has led to high hydrogen prices

Hydrogen Mobility Europe

European policy: effects of the energy security crisis (1/2)

- The price of hydrogen at the pump is extremely important for the customer.
- High hydrogen costs at the pump put a large financial strain on customers and could lead to such customers looking for alternatively powered vehicles.
- Operators have indicated that customers have been dissatisfied in some cases when prices at the pump have increased.
- There was a large spread seen in the current pump price that operators within H2ME2 were offering for hydrogen.
  - The highest price seen was **€22.24/kg** of hydrogen, with the lowest price seen at **€10.44/kg**.
  - The mean price seen was **€14.506/kg**
- These changes represent a **25-60%** increase in hydrogen price compared to 2021 prices.
- However, note that the energy security crisis also resulted in a **diesel price** increase of **50-70%** between the peak in July 2022 and the price one year prior, and also greatly increased **electricity prices**.
- Prices look to remain high for the foreseeable future, causing hydrogen producers to investigate new investment options.

Graph showing the average hydrogen price at pump for operators interviewed in Q4 2022



Operator price increases for hydrogen at the pump (€/kg)

€13.89	€22.24
€9.50	€12.85
€12.00	€15.00

Clean Hydrogen Partnership

Source: Commercial advancements in the hydrogen fuel retailing – final, D6.10. Recommendations for harmonising the hydrogen refuelling business in Europe – final, D6.18. H2ME (2), Element Energy

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The overall reaction to the energy security crisis has been positive for hydrogen, despite the fuel price increases

European policy: effects of the energy security crisis (2/2)

- Despite the increases in hydrogen prices, hydrogen has largely been seen as an effective medium and long-term solution to the energy security crisis.
- Hydrogen has a number of advantages which position it well to address both the climate and energy security crises:
- **Green hydrogen can be produced from renewables**
  - European countries have invested substantially in renewable generation capability over the past decade, meaning that there is a viable route to generating hydrogen from renewables in the near term. It is worth noting that the support for hydrogen resulting from the energy security crisis is largely focused on green hydrogen, not blue or grey due to concerns over gas supplies.
- **Low resource intensity**
  - Hydrogen fuel cells can be produced largely from readily available materials and do not have a high resource intensity. Fuel cell and hydrogen vehicle manufacturing, however, does require high-skilled engineering jobs. This combination of low resource intensity and skilled jobs is well-suited to the European workforce, and hence hydrogen mobility offers a solution which helps improve technology security in addition to energy security. This is particularly relevant given the reliance on China for battery manufacturing.
- **Diversification of the supply chain**
  - Developing a hydrogen mobility ecosystem helps to reduce dependency on a single supply chain for technology components or fuel, hence presents a hedging option compared to investing only in one zero emission solution. For instance, the H2Global scheme seeks to incentivise the development of ammonia production and shipping to Europe from a variety of countries.

Green hydrogen: a key to unlocking energy security in Europe

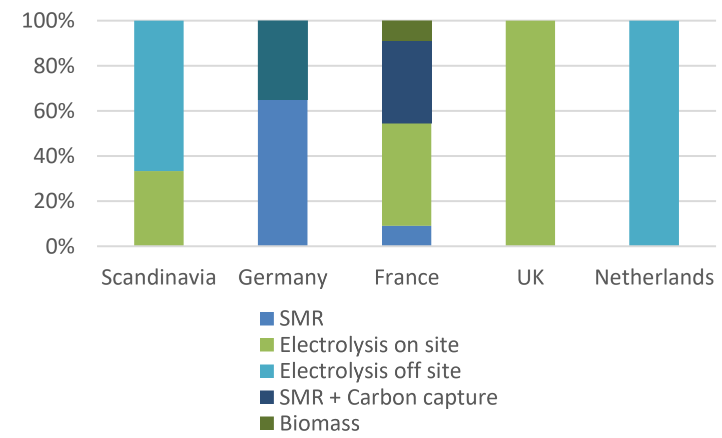
Green hydrogen: a key to unlocking energy security in Europe (siemensgamesa.com)

Also linked to the energy security crisis, there has been an increasing focus on green hydrogen

European policy: green hydrogen focus

- Government policies are now emphasising *green* hydrogen production with an increasing focus.
  - The energy security crisis has somewhat damaged the perception of grey and blue hydrogen, due to the links to (Russian) natural gas.
- Policies such as RED (EU) and the RTFO (UK) support the uptake of green hydrogen in the transport sector, whilst national funding mechanisms e.g. Ademe in France and the Zero Emission Road Freight Demonstrator in the UK fund vehicles and stations that dispense green hydrogen.
- The H2ME project has deployed a number of green hydrogen stations, with 60% of the 43 stations deployed stations having robust plans to use green hydrogen at project inception.
- In most cases, green hydrogen is produced via electrolysis on site in the H2ME project. Other options for green or low carbon hydrogen include off-site production with decentralised electrolyzers, production via biomass, reforming of biomethane and production by SMR with capture of carbon.
  - The proportion of green H_2 dispensed at H2ME HRS has grown over the project execution, demonstrating a motivation and an ability to move towards greener production methods.

Source of hydrogen at the H2ME stations – per coalition



Source: Technical performance of HRS under high utilisation and recommendations, H2ME (2) D5.37, Element Energy

Contents

1. Introduction

2. Progress under H2ME

3. Hydrogen Vehicle Developments

    FCEV market summary in Europe

    Light duty vehicle progress outside of Europe

    Contrasting with BEVs

4. Hydrogen light duty vehicle policy in Europe

    European wide political trends

    National policy strategies

5. Refuelling Infrastructure Developments

    Strategic developments

    Technical developments

6. Understanding the customer proposition

7. Remaining barriers to light duty vehicle commercialisation

    Economic barriers

    Competition for funding

    Technical barriers

8. Conclusions and recommendations

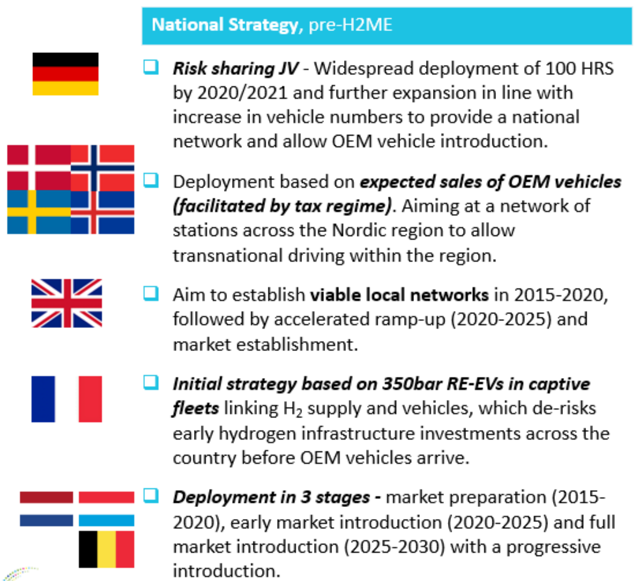
Deployment & national refuelling infrastructure introduction strategies: pre-H2ME

National Strategy, pre-H2ME	**HRS in H2ME[1]**	**Vehicles in H2ME[1]**
Risk sharing JV - Widespread deployment of 100 HRS by 2020/2021 and further expansion in line with increase in vehicle numbers to provide a national network and allow OEM vehicle introduction.	20 x 700 bar HRS in Germany	>900 FCEVs across Scandinavia, Germany, France, the UK and the Netherlands
Deployment based on ***expected sales of OEM vehicles (facilitated by tax regime)***. Aiming at a network of stations across the Nordic region to allow transnational driving within the region.	8 x 700 bar HRS in Scandinavia	
Aim to establish **viable local networks** in 2015-2020, followed by accelerated ramp-up (2020-2025) and market establishment.	6 x 350/700 bar HRS in the UK	>500 RE-EV vans and trucks initially in France and Germany then across Europe
Initial strategy based on 350bar RE-EVs in captive fleets linking H_2 supply and vehicles, which de-risks early hydrogen infrastructure investments across the country before OEM vehicles arrive.	13 x 350/700 bar HRS in France	
Deployment in 3 stages - market preparation (2015-2020), early market introduction (2020-2025) and full market introduction (2025-2030) with a progressive introduction.	1 x 700 bar HRS in the Netherlands	

[1] Planned deployments throughout lifetime of the H2ME project

Large subsidy schemes have emerged in Europe, signifying a shift from testing to deployment

Pre-2018:
Early-stage strategies and demonstration projects


National Strategy, pre-H2ME

- ***Risk sharing JV*** - Widespread deployment of 100 HRS by 2020/2021 and further expansion in line with increase in vehicle numbers to provide a national network and allow OEM vehicle introduction.
- Deployment based on ***expected sales of OEM vehicles (facilitated by tax regime)***. Aiming at a network of stations across the Nordic region to allow transnational driving within the region.
- Aim to establish **viable local networks** in 2015-2020, followed by accelerated ramp-up (2020-2025) and market establishment.
- ***Initial strategy based on 350bar RE-EVs in captive fleets*** linking H_2 supply and vehicles, which de-risks early hydrogen infrastructure investments across the country before OEM vehicles arrive.
- ***Deployment in 3 stages*** - market preparation (2015-2020), early market introduction (2020-2025) and full market introduction (2025-2030) with a progressive introduction.

(Learnings facilitated by projects such as H2ME and ZEFER)

- *Proof of concept*
- *Testing of national strategies*

Post-2023:
Dedicated policy mechanisms and long-term support schemes

- National policies have been tested and adapted.
  - Efforts to create nationwide hydrogen refuelling infrastructure in Europe have seen mixed results.
  - Germany is the only EU country with a network resembling national coverage.
  - Captive fleets and demand hubs appear to be preferred by current schemes.
- A number of European nations have implemented long-term, larger subsidy schemes:
  - Ademe (France)
  - Commercial fleet support (6.6Bn Euro pledged) (Germany)
  - ZERFD / ZEBRA (UK)

Case Study: French policy statements have led to the development of regional H_2 hub plans

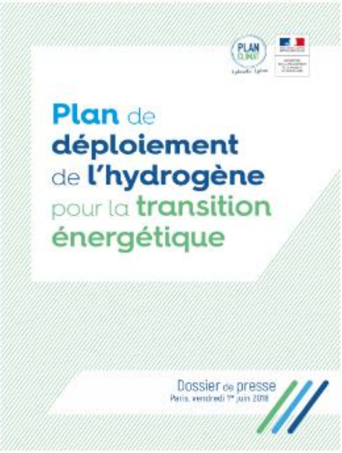
elementenergy
an ERM Group company

Hydrogen Mobility Europe

France subsidy scheme

- Policy and funding have been major drivers to increase support and demand for H_2 mobility:
- The **Loi de Transition Energétique (2015)** set out aims to renew >50% of public transport fleets with low emission vehicles by 2020 and 100% by January 2025.
- The **Plan National Hydrogène (2018)** set targets to transition French transport to hydrogen, with supporting funding of ~€100 million through public tenders. Specific targets include:
  - 5,000 light commercial vehicles and 200 heavy vehicles in operation by 2023
  - 100 new HRS using H_2 produced locally by 2023, increasing to 400-1,000 HRS by 2028
  - 20,000-50,000 light commercial vehicles and 800-2,000 heavy vehicles by 2028
- Following the Plan National Hydrogène, ADEME published calls for hydrogen mobility projects, aiming to support projects with a total budget of over 1 billion euros. **The COVID recovery plan of September 2020 allocated a total of 7.2 billion euros to deliver on the Plan**.
- In November 2021, President Macron confirmed **€1.9 billion will be dedicated to the objective of "making France the leader in green hydrogen"** as part of the France 2030 investment plan, in addition to the €7.2 billion of the National Hydrogen Strategy.
- **Numerous regions of France have now developed (and allocated funding for) their own H_2 mobility deployment plans.** Many of the plans include heavy duty transport applications alongside the deployment of cars and vans, with strategies following **an integrated approach to activation of regional demand,** pioneered by the Zero Emission Valley initiative.
- Alongside the development of regional government plans, the high level of national ambition and support has stimulated the development of **numerous hydrogen transport initiatives being led by the private sector**. Some key examples are set out on the following pages.

LA LOI de TRANSITION ÉNERGÉTIQUE



Clean Hydrogen Partnership

Source: Summary and lessons learnt from the hydrogen mobility strategies tested in this project interim 2020, H2ME (1) Deliverable 5.12, Element Energy

As hydrogen FCEV technology has developed, the funding needs are now focused on deployment rather than R&D

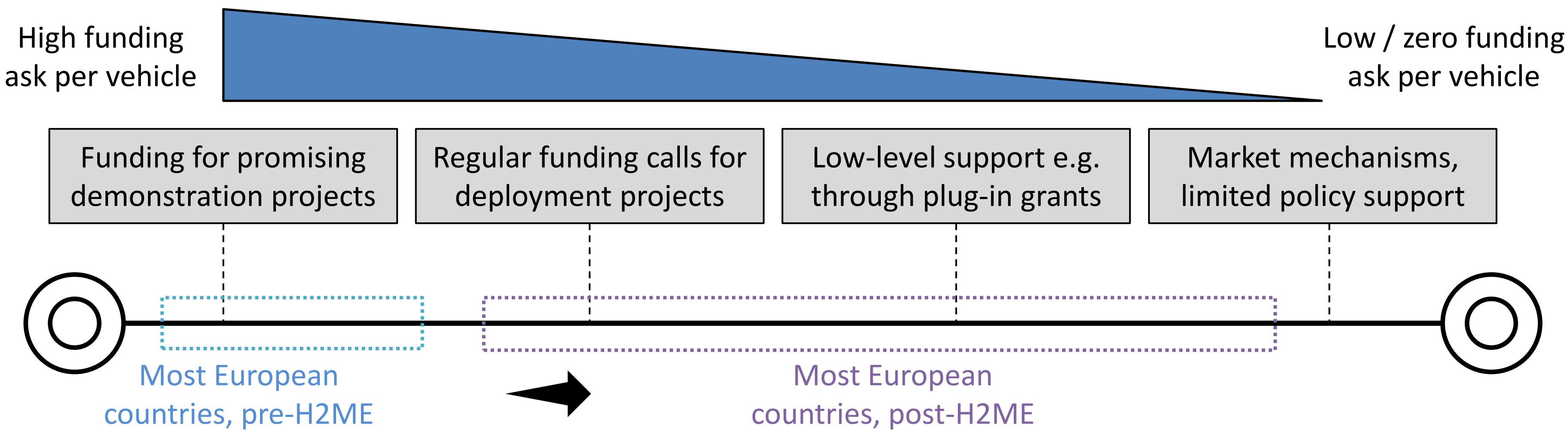
elementenergy
an ERM Group company

Hydrogen Mobility Europe

National subsidy schemes: future outlook

- The announcement of large European funding schemes is to be expected, based on the increased maturity and commercial realisation of hydrogen mobility technologies. As maturity increases, more frequent support (with a lower subsidy per vehicle), could be expected until the market *willingness to pay* value is reached.
- Moving forwards, one could expect that European countries could phase out funding for hydrogen cars and focus on technologies at a lower technology readiness level e.g. trucks.
- Policy is also moving from subsidies to incentivise uptake of ZEVs towards regulations / mandates that will ban the sale / use of ICEVs. Under such regimes FCEVs will have to compete with BEVs

Evolution of preferred funding mechanisms for hydrogen mobility in Europe



Further details on HRS rollout policies and support mechanisms for selected European nations is summarised in *Refuelling Infrastructure Developments*

Clean Hydrogen Partnership

Contents

1. Introduction

2. Progress under H2ME

3. Hydrogen Vehicle Developments

    FCEV market summary in Europe

    Light duty vehicle progress outside of Europe

    Contrasting with BEVs

4. Hydrogen light duty vehicle policy in Europe

    European wide political trends

    National policy strategies

5. Refuelling Infrastructure Developments

    Strategic developments

    Technical developments

6. Understanding the customer proposition

7. Remaining barriers to light duty vehicle commercialisation

    Economic barriers

    Competition for funding

    Technical barriers

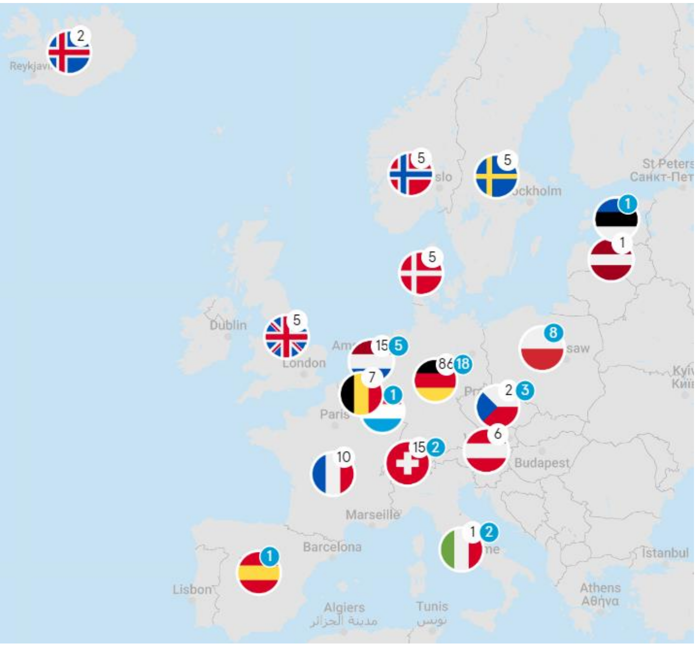
8. Conclusions and recommendations

The hydrogen refuelling network in Europe is growing steadily, with over 200 stations installed

European HRS network: Required further development

- Hydrogen Europe's Technology Roadmap sets a target of **1,000 public hydrogen refuelling stations (HRS) across Europe by 2025**.
- Significant acceleration in the deployment of new HRS over the next 5 years will be required to achieve this: as of June 2023, there are c.250 public operational HRS in Europe, most of which are installed in Germany, France the Netherlands, and Switzerland.[1]
- While this represents the start of a pan-European refuelling network, **many of the existing stations currently only have the capacity to refuel relatively small numbers of light duty vehicles** (i.e. cars and vans), with only a few stations having the capacity to serve fleets of taxis, buses or other high-demand vehicles.
- **Significant further investment is required** to provide a sufficient network of refuelling stations to meet the potential needs of the hydrogen mobility market, especially when considering the adoption of heavy duty hydrogen vehicles such as trucks, which will also require national networks of high capacity refuelling stations. The network development should focus on offering refuelling for both the light duty and heavy duty segment.

Operational public HRS in Europe (October 2023)



Map of operational 700-bar hydrogen refuelling stations as of October 2023. Source: H2Live

[1]*Source: H2Stations*

H2ME has explored possible advancements and best practices for a range of hydrogen refuelling aspects

Hydrogen Mobility Europe

European HRS network: Barriers to growth of the network

- Ensuring that customers' experiences match, if not exceed, that of the incumbent technology is important for the success of new technologies. Despite significant improvements across a number of areas in HRS networks and hydrogen fuel retailing, **various challenges still remain before the convenience of petrol/diesel refuelling is matched from the customer perspective**.
- Throughout the H2ME projects, **commercial issues relating to hydrogen refuelling stations (HRS) and the sale of hydrogen as a fuel have been explored** via workshop discussions and bilateral interviews with vehicle manufacturers and refuelling stations.
- The following section summarises the progress made under the H2ME project and current state of the art for both the **strategic** and **technical** barriers which have limited the growth of hydrogen refuelling infrastructure. For the technical barriers, H2ME partners have mainly focused on the following aspects:
  - **Permitting processes: reducing the time required for HRS installation;**
  - **Availability: station back-up solutions and provision of reliable network;**
  - **Provision of real-time availability updates to vehicle users;**
  - **State of charge (i.e. the ability of stations to refuel vehicles to design capacity).**

Contents

1. Introduction

2. Progress under H2ME

3. Hydrogen Vehicle Developments

    FCEV market summary in Europe

    Light duty vehicle progress outside of Europe

    Contrasting with BEVs

4. Hydrogen light duty vehicle policy in Europe

    European wide political trends

    National policy strategies

5. Refuelling Infrastructure Developments

    Strategic developments

    Technical developments

6. Understanding the customer proposition

7. Remaining barriers to light duty vehicle commercialisation

    Economic barriers

    Competition for funding

    Technical barriers

8. Conclusions and recommendations

As the focus shifts to heavy-duty applications, hydrogen stakeholders must continue to push for policy support and learn from best practices for different vehicle types

Hydrogen Mobility Europe

Summary

Business cases

The **next phase of European HRS deployment** is shifting to the development of fewer, higher capacity **refuelling stations targeting heavy-duty vehicles** as the main users. Larger stations can offer economies of scale and therefore can provide a stronger business case to HRS operators. However, **gathering sufficient demand for such stations is critical**.

Projects are shifting their focus to:

- Larger stations which service multiple transport modes
- Depot based stations which service high demand HGV fleets

The role of policy

Future HRS business cases will rely on the **accelerated scale-up of fuel cell vehicle fleets**, especially in heavy-duty applications. This will **require national subsidies and incentives** for all vehicle types alongside incentives for low carbon hydrogen and disincentives for fossil fuel vehicles.

Policies such as the AFIR should ensure HRS deployments accelerate in Europe.

Emerging trends

Some of the refuelling requirements of heavy-duty fleets will reflect the aims of the public HRS deployed to date, but there are some differences (e.g. refuelling schedules, user groups, use cases) that will impact the specifications and design for HRS focusing on these fleets. Comparisons of light vehicles with bus fleets can provide examples of some key similarities and differences. As such, HRS suppliers and operators for future stations can draw from experiences of hydrogen bus projects such as NewBusFuel, and JIVE, combined with the solutions adopted in H2ME, to **ensure that the most relevant best practices and insights are applied to future HRS.**

To create sustainable hydrogen refuelling networks, network growth and performance criteria must be balanced with the need to operate cost-effectively

Overview of HRS business case considerations

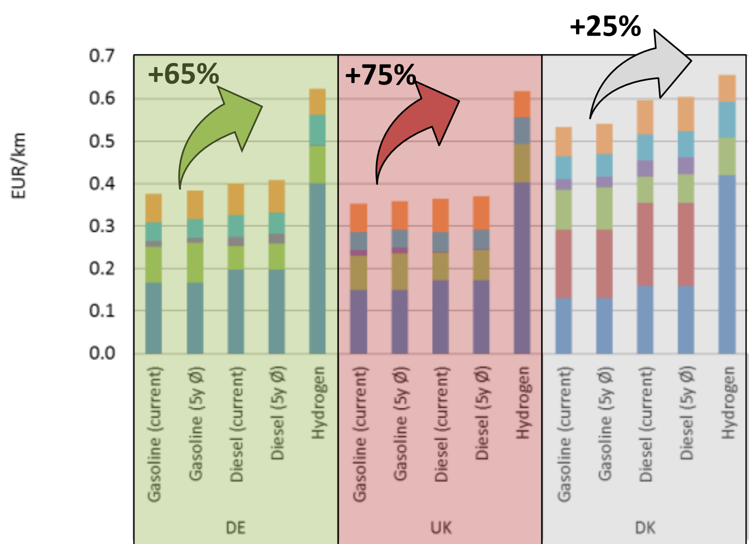
- To support the continued commercialization of hydrogen mobility in Europe, HRS operators need to balance key objectives:
  - Installing enough HRS to provide sufficient coverage of the operating area for their target market;
  - Providing a high quality service to customers: crucially, this means providing high HRS availability to ensure that customers have access to hydrogen when required, and communicating HRS availability to customers;
  - Ensuring that fixed and variable operating costs are not prohibitive to the long-term business case.
- The business case for public HRS operators can be challenging for several reasons:
  - In the absence of demand commitments from customers, investment in new HRS or continued operation is risky due to the uncertainty of future demand growth and the high costs of current HRS capex and opex.
  - Overall utilisation of public refuelling networks is low compared to installed capacity during the early years of deployment: even in areas of relatively high FCEV deployment (e.g. Paris, London, Hamburg) average levels of HRS utilisation only recently exceeded ~30% of capacity.
  - Access to low cost, low carbon, fuel-cell quality hydrogen is currently limited. There is a focus on the provision of electrolytic hydrogen from renewable electricity, supply of which is scarce and the cost of which is strongly influenced by the currently high energy prices.
- These considerations have contributed to the following emerging trends in hydrogen mobility:
  1. Focus on large capacity stations serviced by high utilisation fleets
  2. Focus on heavy duty applications (buses and HGVs)

Introducing the role of policy in hydrogen vehicle projects

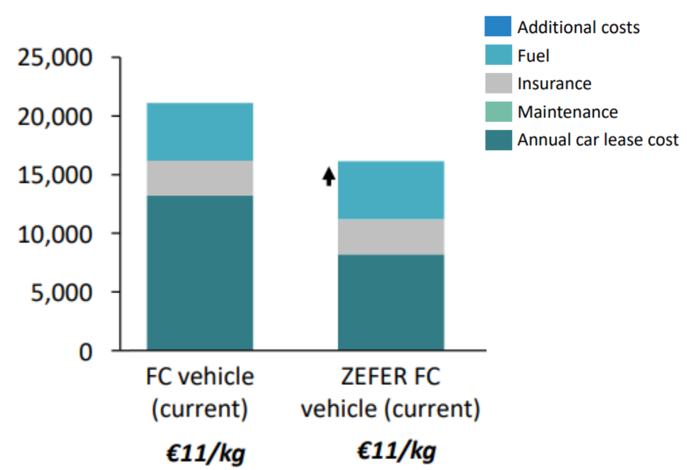
Business case considerations: effect on TCO

- The business case considerations outlined on the previous slide mean that most hydrogen fuel cell vehicles deployed would have an increased total cost of ownership (TCO), in part due to high hydrogen prices. Early on in the H2ME project, this cost differential was c. 65% between hydrogen and gasoline vehicle TCOs (see HyFIVE data below).
- To mitigate against this, and encourage uptake, Governmental financial intervention is therefore required. This can come in various forms, e.g. project based funding, plug-in vehicle grants/HRS subsidies, tax incentives and soft financing. The effect of subsidy in the ZEFER taxi deployments decreased the ownership cost by c.25%.
- Government approaches to funding HRS vary, and have evolved over the course of H2ME (see next slides).

HyFIVE total cost of ownership, 2018[1]



ZEFER taxi TCO with and without funding[2]



[1] HyFIVE project, Call for information for IR2 and alike (europa.eu) [2] ZEFER Deliverable 4.1 Results from vehicle driver surveys

The UK strategy focuses on the development of local clusters with the Scandinavian strategy placing more emphasis on regional coverage

Evolution of network development strategies (1/2)

- Shifting to a heavy-duty, green hydrogen focused business model for hydrogen refuelling stations requires policy support, due to the TCO differential to diesel heavy duty vehicles.
- These emerging trends have therefore been mirrored in the recent policy developments for HRS rollout.
  - Increasing support for clustered, large scale stations targeting HGVs (vs full network coverage of small stations).
  - Funding focused increasingly on large scale (100s MW - GW) production projects, enabling economic off-site production and delivery to HRS.

Network Development Strategies: UK and Scandinavia

Region	Initial strategy	Recent developments
UK	• Initial deployment focusing on achieving good station coverage around London and other urban clusters. • Mix of passenger cars, vans and buses through the Hydrogen Transport Program.	• Launch of the ZERFT scheme and recent ZEBRA funds has focused station development around infrastructure for HGVs and buses. • Testing the 'ecosystem' model with the Tees Valley Hydrogen Hub fund.
Scandinavia	• HRS network to allow long distance mobility across Scandinavia. • Continued investment in HRS deployment in advance of significant vehicle numbers. • Mix of passenger cars, vans and buses.	• Initial "network coverage" already achieved in Denmark, with the rest of Scandinavia looking to follow. • Large scale deployment of hydrogen buses coming over the next 5 years.

Germany's initial focus on network coverage is moving towards demand-driven HRS placement, whilst France continues its captive fleet approach

Hydrogen Mobility Europe

Evolution of network development strategies (2/2)

Hydrogen Mobility Strategies: Germany and France

Region	Initial strategy	Recent developments
Germany	• 100 'unconditional' stations to be deployed independently of FCEV roll-out • Strong focus on achieving national coverage as well as networks in major cities • Increasing linkage of HRS and vehicle demand	• Move towards 'demand driven' HRS placement, with funding for commercial vehicles through the NIP 2 scheme • Upgrading of existing stations to be 350 bar compatible (ca. 30 HRS) for HGVs • Target for HRS increased to 300 by 2030
France	• Captive Fleet approach: letters of intent from end users received prior to HRS investment decisions • Early focus was on applications for range extended vehicles (low hydrogen demand)	• Funding competitions focus on ecosystem bids (Ademe), including hydrogen production (from electrolysis), dispensing & linked vehicle offtake. • Demonstrations have to show a path to high HRS utilisation (>50%)

- Despite different initial strategies in Europe, the following trends have emerged in several countries:
  - Co-location of vehicles and HRS (e.g. adoption of **demand-led approach**) when siting new stations.
  - Developing **clusters** of stations in key locations (e.g. Paris, Hamburg) where the **redundancy and convenience of multiple stations** increases the attractiveness of fuel cell vehicles to fleet operators.
  - Interest in **heavy duty vehicle fleets** and **high demand applications** (e.g. taxis) to help sustain the business case for the early hydrogen supply & distribution network, which in turn will **support the development of infrastructure needed for private user passenger car roll-out**.
  - Countries are investigating the viability of mixed-vehicle stations.

Copenhagen case study: experiences following the temporary shutdown of Prags Boulevard

Copenhagen – Prags Boulevard case study

Reasons for temporary HRS shutdown

- Due to issues with hydrogen trailers that were supplying the Prags Boulevard station in Copenhagen, the HRS has been closed since June 2023. With no other refuelling option, the FCEVs operated by DRIVR also had to cease operations.
- The trailers supplying the station with hydrogen are operated by Everfuel. Following an initial investigation of a malfunction and leak on one of its hydrogen trailers, Everfuel stopped and inspected all trailers. At the end of August, Everfuel communicated about its decision to restructure the hydrogen station network and to focus on heavy duty vehicles for future hydrogen station network. Some stations might reopen, but at the same time the price of hydrogen could increase. The Copenhagen HRS stays paused until further notice.

Lessons learned

- The impact of the HRS closure on the taxi fleet DRIVR illustrates the need to build an infrastructure that the end users, but also the supplier of hydrogen can depend on. It is essential to be able to switch to another station in case of closure.
- Copenhagen demonstrates that stakeholders of the hydrogen sector need to collaborate in order to be able to create a reliable infrastructure. Demand and supply must arise simultaneously. In the case of Copenhagen, demand could not develop fast enough to maintain an economically viable supply. This also had an impact on the technical functioning of the station.
- This shows that the business case for a public HRS can be challenging, as mentioned on a previous slide:
  - The overall utilisation of the HRS was low compared to the installed capacity.
  - The low carbon hydrogen is not available or at too high cost.

More information about Everfuel's realignment strategy: [Update - Everfuel.com]

Increasing the supply of renewable hydrogen and capacity of HRS to dispense hydrogen is being targeted to achieve economies of scale

Hydrogen Mobility Europe

Emerging Trends

- Shift towards higher capacity refuelling stations serving heavy-duty vehicles
  - The Hydrogen Mobility Europe partners have refined their business cases for refuelling station deployment based on the lessons learned over the course of the project, and on the development of the FCEV market in Europe.
  - For many of the national hydrogen mobility initiatives, the focus in the past decade has been on installing as many individual public HRS as possible. However, the current phase of European HRS deployment in the early 2020s is shifting to the development of fewer, higher capacity refuelling stations (as opposed to a greater number of smaller stations), targeting heavy-duty vehicles as the main users of these stations. Larger stations can offer economies of scale compared to smaller stations and therefore can provide a stronger business case to the HRS operators. However, gathering sufficient demand for such stations is critical.
  - Although a trend is emerging towards serving heavy-duty vehicles, AFIR mandates require HRS to be equipped with at least one 700 bar dispenser and be capable of serving both light and heavy-duty vehicles
- Increased ambitions for supply of renewable hydrogen
  - National governments in Europe see a key role for hydrogen technologies as part of a net-zero future. Many have published hydrogen strategies emphasising their ambitions to increase the capacity of renewable hydrogen production, and its use for transport. Currently, hydrogen from low-carbon production routes (including renewable hydrogen) is more costly than fossil hydrogen.
  - To maximise the potential benefits of hydrogen mobility there is therefore a need for a stronger business case for refuelling stations to supply renewable hydrogen. Policy support will be critical in this area.

Further details can be found in: H2ME deliverable 5.13 – Summary and lessons learnt from the hydrogen mobility strategies tested in this project, 2020. Available at: https://cordis.europa.eu/project/id/671438/results and https://h2me.eu/reports/

H2ME project deployments have mirrored the global trends in hydrogen mobility deployment strategy: larger, HGV focused stations

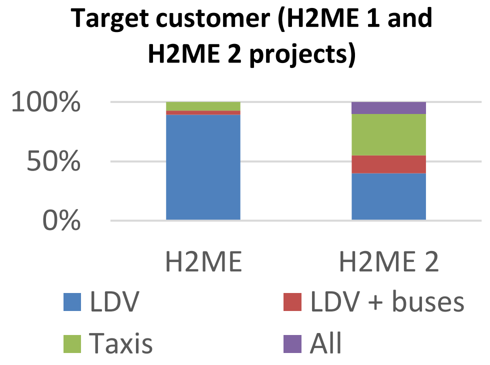
Emerging Trends in H2ME (1/2)

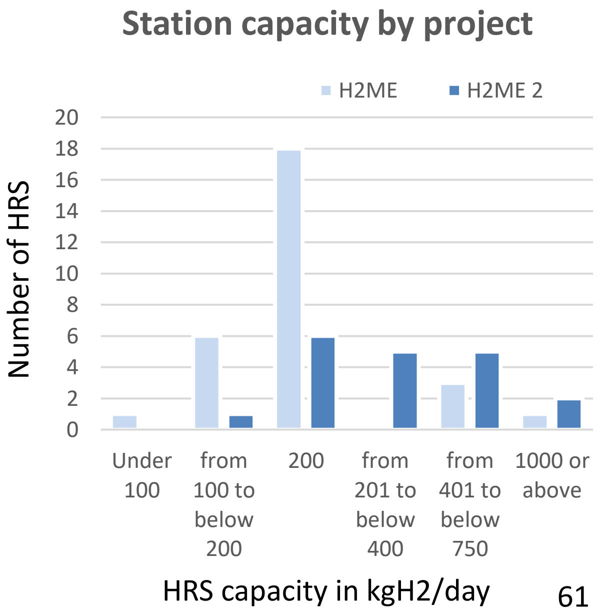
Captive fleet model

- The majority of H2ME 1 stations targeted light duty vehicle users as the primary offtake, including private customers using their personal vehicles.
- Later, in H2ME 2, the majority of projects included either buses or taxis in their business case plans.
  - Industry has learned that a reliable demand source is essential to secure at the project initiation phase, and that demand is unlikely to materialise through market mechanisms alone.

Station capacity

- The stations in H2ME 2 were of larger rated capacity that H2ME 1 stations:
  - There were fewer ‘demonstrator’ stations, and stations are seen as a commercial undertaking.
  - It has been found that larger stations are more reliable (see infrastructure technical developments).
  - The increase in vehicle options and modes available has encouraged the development of multi- use stations with dual pressure options.





Project data, H2ME 1 and H2ME 2, Element Energy

H2ME 2 stations have been fuelled by predominantly green hydrogen

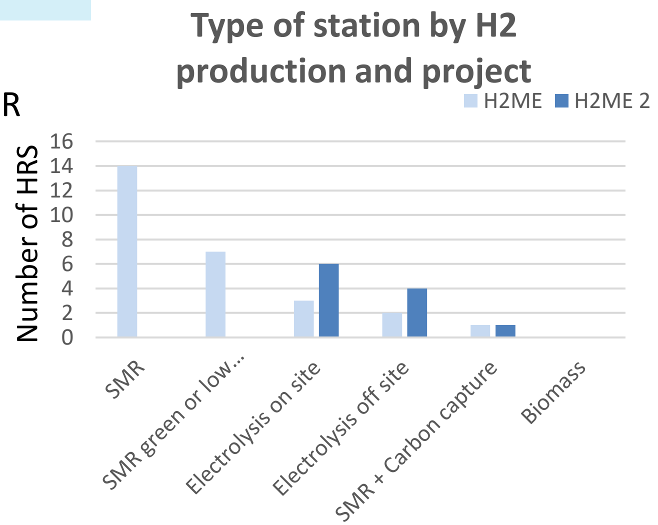
Emerging Trends in H2ME (2/2)

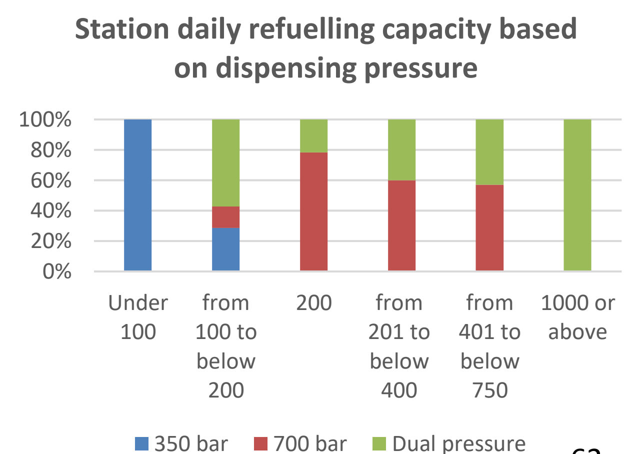
Green hydrogen

- The most common hydrogen production method for H2ME 1 was SMR (produced from fossil fuels). All H2ME 2 projects planned to procure hydrogen from low or zero carbon sources.
- Global pressure to decarbonise has ensured that most hydrogen mobility projects are now planning to use green or low-carbon hydrogen. Analysis conducted under the H2ME project has shown that Well-to-Wheel carbon emissions from hydrogen vehicles can be comparable to or lower than battery electric vehicles, depending on hydrogen production mechanism and electricity supply strategy.[1]

Dual pressure solutions

- Several stations deployed early in the H2ME project serviced only 350 or 700 bar. An increasing number of large scale stations are able to service both pressures.
    - Larger scale stations may have an improved business case and hence are able to justify the capital investment of equipment for fuelling at two refuelling pressures.
    - Large scale stations may in the coming years service the HGV market, which is emerging. There remains debate over the preferred refuelling pressure for HGVs, with major OEMs developing a variety of solutions (350 bar, 700 bar and liquid hydrogen)





[1] H2ME: Emerging conclusions, Nov 2022

Contents

1. Introduction

2. Progress under H2ME

3. Hydrogen Vehicle Developments

FCEV market summary in Europe

Light duty vehicle progress outside of Europe

Contrasting with BEVs

4. Hydrogen light duty vehicle policy in Europe

European wide political trends

National policy strategies

5. Refuelling Infrastructure Developments

Strategic developments

Technical developments

6. Understanding the customer proposition

7. Remaining barriers to light duty vehicle commercialisation

Economic barriers

Competition for funding

Technical barriers

8. Conclusions and recommendations

Whilst the H2ME programme has helped to progress the technical development of HRS, there remain barriers to full commercialisation

Hydrogen Mobility Europe

- The H2ME project partners have contributed to the deployment of 180 public HRS and over 3,100 cars and vans in Europe to date.
- **While progress has been made on HRS commercialisation, there is a clear need for further development of the supply chain and harmonisation across the network.**
- This section summarises the state of the art for key performance areas to optimise for hydrogen station development and operation.

Siting and permitting	Continued efforts are needed to identify sites and gain planning approvals. Future HRS may require more space, to enable higher capacities, meaning that partnerships with existing fuel providers will have increasing strategic importance.
Communication with customers	Widespread provision of data to consistent maps and apps will be the key to providing network visibility; alongside this, harmonisation of access, billing and services such as 24/7 helplines at HRS help to optimise the customer experience.
Technical performance and station design improvements	Following significant efforts by HRS operators to optimise maintenance and functionality, further work is needed to ensure wider adoption of best practices and to ensure that components are reliable, user-friendly and cost-effective. Whilst the percentage of successful refuelling events (where the tank is filled to >92% of capacity) is increasing over time, continued work is needed to understand fully the causes and potential solutions of station downtime and incomplete refuelling events.
Safety	Best practices on HRS safety (including quality assurance processes and contingency measures) must be widely disseminated and adopted to minimise the risks associated with hydrogen as a transport technology.

Close engagement with planning authorities can reduce times for HRS permitting

Siting and permitting (1/2)

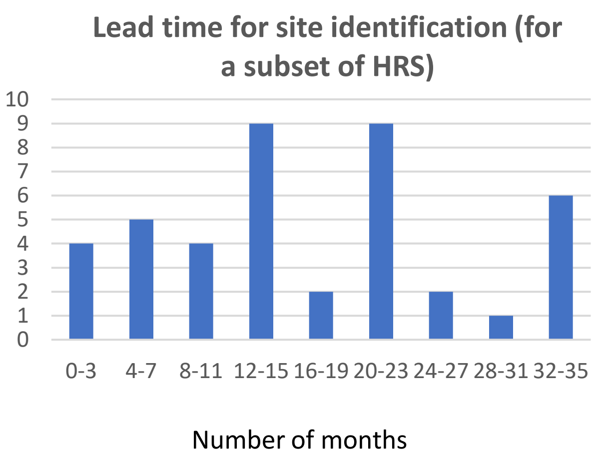
- While progress has been made, challenges associated with **siting and permitting can lead to significant delays for new HRS deployment**, particularly when the planning authorities do not have prior experience of the technology (permitting can take several months).
- Addressing this issue will help alleviate the most commonly cited barrier to adoption of FCEVs: the low number of available refuelling stations.
- Significant variability exists between regions and countries, ranging from a few weeks to 24 months for approval being granted. **Countries where regulations relating to permitting exist at the national level have been able to reduce approval times to a much greater extent than those with regulation and processes that differ at the regional level**.
- Based on experiences of different permitting processes for HRS in Europe, the ideal governance models for short planning approval timescales appear to be **those that enable local authorities to make decisions based on precedents established in other local authorities**. This allows experience gained through HRS installation to be applied to future proposed installations. Such a system was demonstrated in Denmark, where station permitting times have now fallen from around six months (in HyTEC) in 2012 to four days in 2016 (H2ME). However, evolutions to the local context can present new hurdles even in regions were progresses have been achieved previously.

Identify licensing authority → Initial discussions with authorities, detailed concept design review → Building approval from local building authority → Granting of the permit for construction and operation → *Build Phase* → Official inspections & ongoing post commissioning inspections

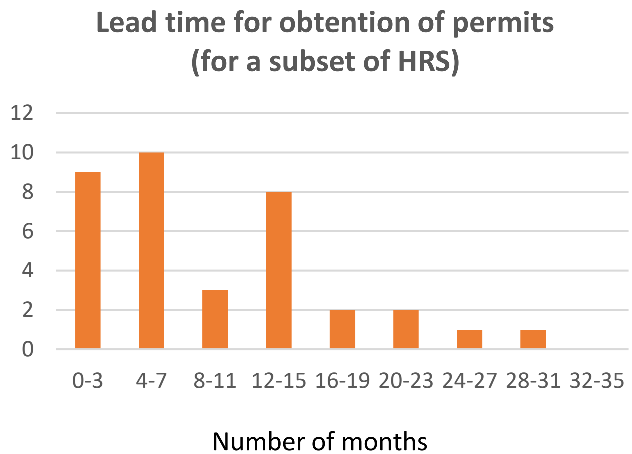
Typical permitting time: 12 months

Siting, permitting and building
Analysis of H2ME stations deployment

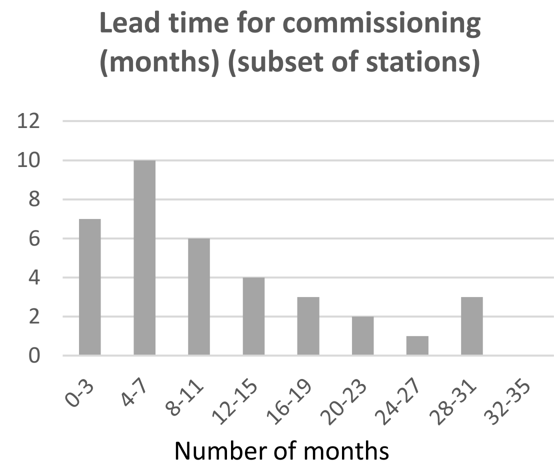
Siting and permitting (2/2)



Finding a suitable site can be complex. The main cited reasons for long lead time for confirming sites are: contractual discussions for land usage, discussion with DNO for grid connection upgrade (electrolyzer), additional studies required due to surroundings, change of sites after initial selection due to unforeseen complications (e.g. change of plan for land usage, issues with permits etc.)



- Lead time for permits can vary significantly. On average, permits are obtained after 8 months in most locations with the exception of France with an average time of 12 months for obtaining permits.
- While it is expected lead time for permitting might decrease as the technology is more widely understood by authorities providing the permits, sites might require increasingly complex applications as options for easier sites are reduced and while the footprint of stations is increasing to support mixed usage.



Building and commissioning of the HRS is generally the fastest phase of the installation process. On site electrolyzer HRS typically require 25 to 50% more time to be built compared to HRS with hydrogen supplied by trucks. This is due to more complex equipment and civil works.

Source: data H2ME projects, Element Energy, 2022

Case study: Experiences and lessons learnt from a national HRS network implementation in Germany (H_2 Mobility Deutschland)

Hydrogen Mobility Europe

Hydrogen refuelling station installation process

- Since its inception in 2015, H_2 Mobility Deutschland has decreased the total time to deliver an HRS from 24 down to 16 months, with an end target of 12 months

H_2 MOBILITY WASSERSTOFF TANKEN

- A number of challenges makes reducing lead time difficult:
  - **Location**: various criteria for network planning ; the number of different stakeholders involved; constructional constraints (space, noise, etc.)
  - **Permitting**: lack of standardised permitting process with authorities - regional differences in Germany lead to unpredictable lead times
  - **Delivery time of HRS**: immaturity in the supply chain results in delivery time of 9-10 months from HRS suppliers as well as limited capacities
  - **Resource bottlenecks**: Requirement for OEM approval and vehicle testing at each station can delay commissioning process

Lessons learnt have been recorded and guidance documents (DE)| (EN)| (FR) developed to help new-comers to the HRS installation process. Work is on-going in addressing the challenges identified.

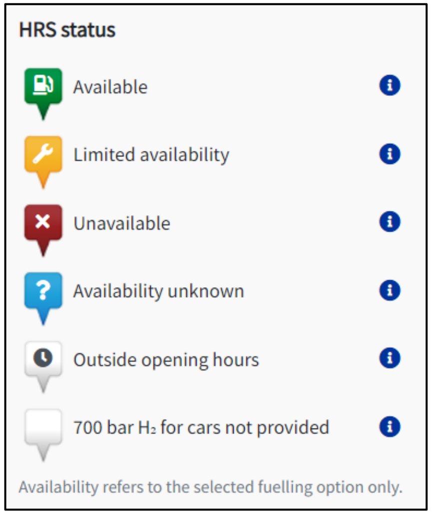
Sources: H_2 Mobility Deutschland, Element Energy, France Hydrogène

Source: Summary and lessons learnt from the hydrogen mobility strategies tested in this project interim 2020, H2ME (1) Deliverable 5.12, CONFIDENTIAL, Element Energy

Communication with customers: provision of live availability information is improving rapidly

Live availability data

- Relative to the existing petrol/diesel station network, Europe's HRS network will remain relatively sparse in the coming years. Providing **reliable information** on the real-time availability of HRS will therefore be critical to increase confidence and **avoid the inconvenience** of users travelling to an HRS to find that it is not open, and to allow users to **plan their routes.**
- Feedback from early customers suggests that customers are **more accepting of station downtime (and the technology overall) if they are informed of this in advance**, and are provided with an **expected date and time for station re-opening**.
- **Direct communication methods such as WhatsApp and email have worked well** as a means of informing users of station downtime in places with less developed networks. These methods are however not sustainable longer term as the sector moves towards mass commercialisation.
- There is an increasing focus on the development of more automated, instant, and integrated methodologies that can be used by a large user base e.g. the development of live availability apps including "H2.LIVE" which covers stations in Germany and across Europe, "FillnDrive" in France, "H2 Station Finder" from Air Liquide in France, "MySymbioRech2rge" from Symbio covering Normandy, and a CH2 JU -funded map (h2-map.eu) which shows live availability data from all participating stations.



[HRS Availability Map (h2-map.eu)](h2-map.eu)

Updated

HRS availability is improving as best practice continues to emerge

Hydrogen Mobility Europe

Refuelling Infrastructure development: Availability (1/3)

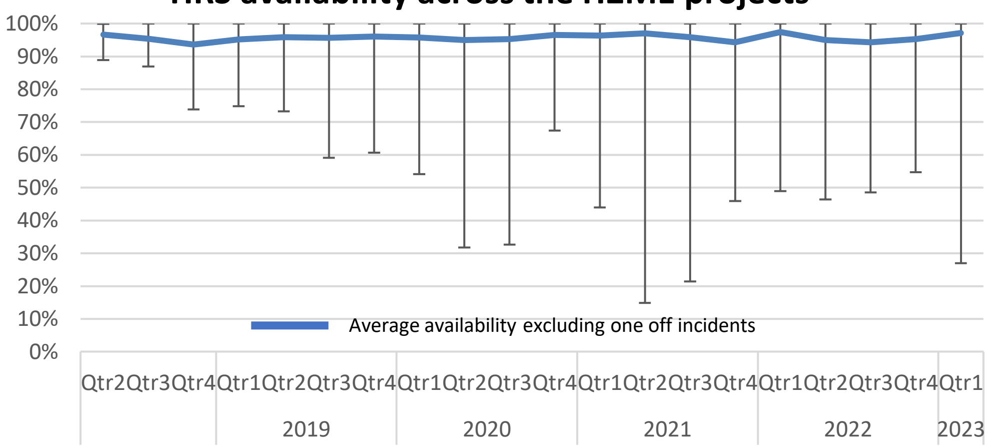
- In the HyFIVE project (2015-2018) and in the first phase of the H2ME projects, vehicle manufacturers and end users identified **improvements in station availability (i.e. the % of time in which the station can be used by customers) as the highest priority for improvement of HRS,** critical to the commercialisation of the technology as a whole. High availability is particularly important in early stages of infrastructure roll-out, when users typically rely on one or two stations in their local area for refuelling.
- Availability figures are rising as utilisation increases; the average availability for HRS monitored in this project as of Q1 2023 was **>95%.** Larger, well-utilised stations have also been shown to have a higher availability.
- Stations still tend to require more maintenance during the first few months of operation, **leading to lower availability during this time**.
- **The following "best practices" for HRS operators have resulted in improved availability:**
  - Rigorous testing of stations onsite and off-site
  - Maintenance procedures and contracts (including approach to availability targets)
  - Providing 24/7 assistance via customer helplines
  - Increased monitoring and remote maintenance
  - Provision of maintenance staff at the site or nearby with clear responsibility for maintaining high availability
- **The supply chain is maturing** as a result of scale-up in recent years, and further development of **codes and standards for stations and components** is ongoing. These developments are anticipated to improve component lifetimes and reduce timescales for station repairs.

Data from the selection of HRS monitored in the project shows that while many HRS are performing well, some still have relatively low availability

Refuelling Infrastructure development: Availability (2/3)

- As of March 2023, 26 HRS were reporting availability data to the H2ME projects. Quarterly availability is defined here by the percentage of time that the HRS can dispense hydrogen, excluding planned maintenance.
- Range bars on the graph (bellow) also highlight the **variable performance of HRS across the project,** with some stations only achieving **~20% availability in Q2 and Q3 2021.** This can be explained mainly by the **'teething phase' experienced by newer stations and some consequences from the Covid-19 crisis.** This has improved and stabilised between Q4 2021 and Q4 2022, with lowest value at 45-50%. However**, in Q1 2023,** the range of availability stretched again, with some stations only achieving **levels slightly above 25%.**

HRS availability across the H2ME projects [1]



Average availability across HRS is shown by the blue line. This average excludes stations with lower than 80% availability in the quarter, as this is generally due to one-off issues.

From Q2 2020 onwards, the availability of some stations was affected by the impacts COVID-19 (e.g., from restrictions to maintenance activities), with availability still lower than that seen in 2018.

[1] *Source – Internal project data, Cenex (data up to Q1 2023).*

Source: Technical performance of HRS under high utilization and recommendations, 2023, H2ME (2) Deliverable 5.37, Element Energy

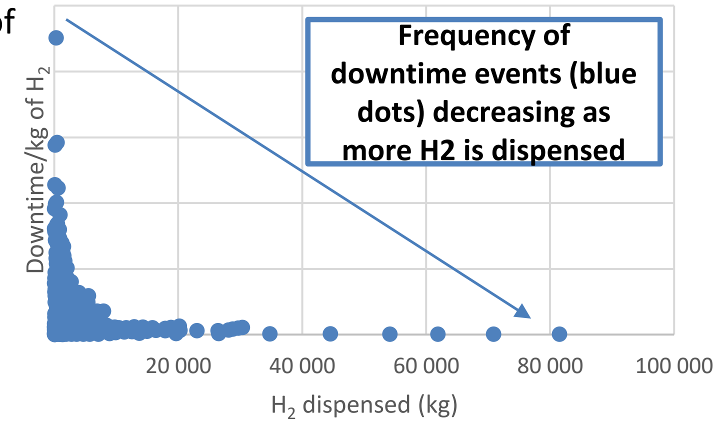
HRS with low utilisation after opening are prone to lower availability than HRS with high utilisation

Refuelling Infrastructure development: Availability (3/3)

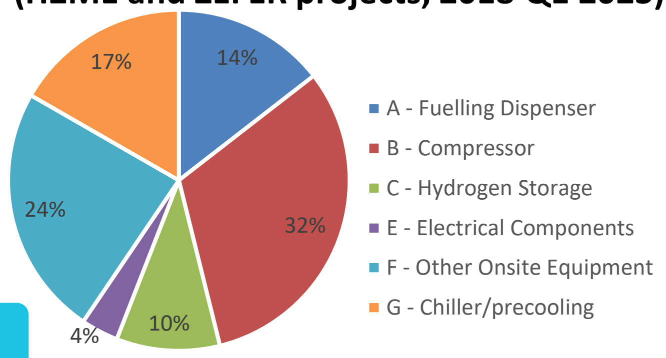
- Many of the HRS providing data to the project have seen relatively low levels of utilisation, which can lead to lower availability. The reduced frequency of problems as utilisation of equipment increases is a well-established effect, known as the ***bathtub curve***.
- Smaller, less well utilised stations have low availability due to three primary reasons:
  - Large stations have **multiple units** deployed on site, e.g. compressors and dispensers are deployed in parallel, improving redundancy.
  - Low levels of utilisation can be detrimental to some HRS components which **function best when used consistently**.
  - Smaller stations are lower priority for **supply chain components** and maintenance resource.
- Data from HRS providers identify **compressors, chiller/precooling and fuelling dispensers** as the largest cause of HRS downtime, accounting for 63% of total HRS downtime in the project. Deploying multiple units on site would improve availability.

For further details on station availability progress, please see H2ME2 D5.37: Technical performance of HRS under high utilisation

Downtime per kg of hydrogen dispensed for H2ME2 HRS[1]



HRS downtime hours by reported category (H2ME and ZEFER projects, 2018-Q1 2023)[1]



[1] Cenex analysis of data reported by refuelling stations across H2ME, H2ME2, and ZEFER projects

Source: H2ME, D6.10/D6.18, Commercial advancements in the hydrogen fuel retailing – final / Recommendations for harmonising the hydrogen refuelling business in Europe – final, Element Energy

HRS suppliers and operators need to minimise the frequency of refuelling events where the maximum state of charge that can be achieved is below 95%

Refuelling Infrastructure Development: State of charge issues (1/3)

- A major selling point of FCEVs is the ability to provide **long distance zero-emission driving.** When state of charge (SOC, i.e. how full the tank is as a percentage of its design capacity or pressure) at the end of refuelling is significantly less than 100%, the **maximum range of the vehicle is reduced.** This reduces the long distance benefits offered by FCEVs, particularly in the early stages of HRS network development when the number of nearby alternative HRS will be limited.

- At present, OEMs have identified that there are **too many partial fills by stations**, and customer feedback has highlighted that as a result of this **users often feel vehicles are not meeting their advertised range.** As such, achieving a consistently high SOC is a priority for HRS operators and suppliers.

- In some cases the HRS detects that vehicles have not been fully refuelled. In others, there are discrepancies between HRS and FCEV readings. A number of OEMs and station suppliers and operators are working together, and **within H2ME a dedicated taskforce was established, to create a methodical monitoring of SOCs to inform further understanding and improvement**.

- H2ME Deliverable D6.17[1] provides an in depth analysis of the causes of partial fills. This section of the report provides a brief summary of the findings.

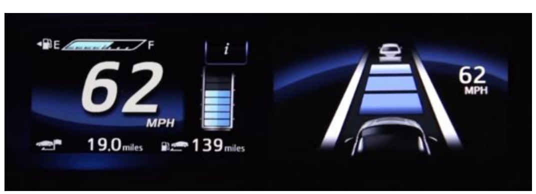
[1] H2ME D2.6_H2 fuel retailing_DRAFT

Stations do not currently display information on the SOC achieved, which increases the need for a reliably high SOC

Hydrogen Mobility Europe

Refuelling Infrastructure Development: State of charge issues (2/3)

- At present, **customers must switch on their vehicle to determine SOC** as this is not displayed by the HRS**;** however the accuracy provided by the vehicle electronic display may not differentiate between e.g. 95% and 100% SOC (see examples of vehicle display panels below).
- Vehicle manufacturers have suggested that it would be beneficial for HRS to display information to customers on the SOC achieved after refuelling, and (if below 100%) further information briefly stating the cause and recommended actions (if appropriate). For example, in some cases, a more complete SOC could be achieved by waiting a few minutes for the quantity of high pressure hydrogen available to increase.
- This could:
  - allow customers to gauge the **volume of H2 refuelled** without having to turn on their vehicles (thus aligning with the current customer experience with regards to petrol and diesel refuelling);
  - enable customers to choose to **take measures to achieve a more complete refuel**, where this is applicable (e.g. wait or contact the HRS operator);
  - ensure that **range expectations** following refuelling are appropriately aligned with the SOC achieved.
- Efforts should be made to ensure that **different HRS operators across Europe follow a consistent approach** to providing this information.



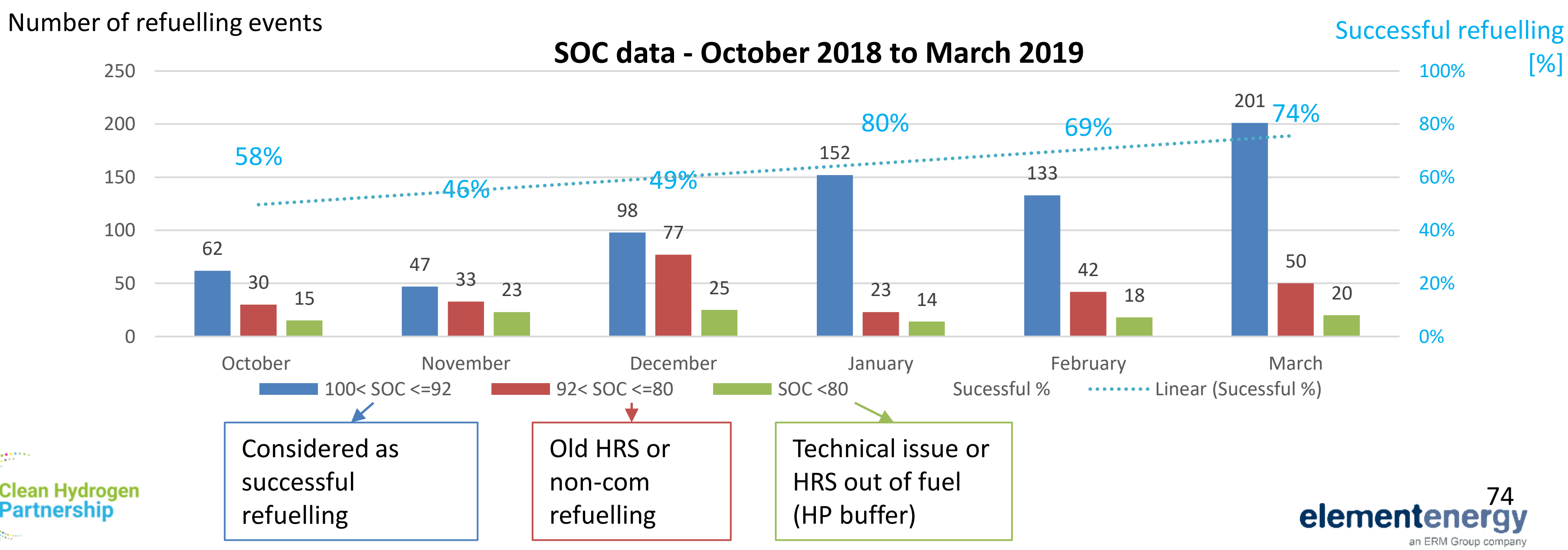
Examples of FCEV display panels showing SOC and estimated range

H2ME project partners are working collaboratively to monitor the causes of low SOC refuelling events; results show that the frequency of low SOC events is decreasing

Hydrogen Mobility Europe

Refuelling Infrastructure Development: State of charge issues (3/3)

- **Within H2ME, a taskforce was established between October 2018 and March 2019 to carry out systematic testing** logging instances of low SOC refuelling events and creating a database of technical issues and user errors that lead to zero and <95% fills.
- Overall, the percentage of successful refuelling events (>92% SOC) has increased over time.
- This is increasing under new SAE J2601 regulations and with communicative filling protocols.
  - Non-communicative fills typically result in SOC between 80-90%.
- Remaining areas to address include increasing pressure ratings for system components, training to reduce user error and improving the availability of hydrogen to reduce failed refuelling events due to lack of supply.



Clean Hydrogen Partnership

elementenergy
an ERM Group company

Minimising the frequency and impact of safety incidents at HRS is vital for the successful commercialisation of hydrogen mobility

Hydrogen Mobility Europe

Overview of HRS safety

- The successful commercialisation of hydrogen mobility will rely on achieving a certain level of **public confidence** in the technology, including safety aspects.
- As such, the **frequency of incidents should be minimised**, and when they do occur (however rare), it is important that HRS operators and suppliers are prepared, both in terms of taking all necessary steps to contain and address issues, and also in terms of how incidents (and the measures taken) are **communicated externally**.
- Currently, at the European regulatory level, only sites with over 5 tonnes of hydrogen are required to report safety incidents. Incidents (including 'near misses' and cases where no hydrogen is released) can also be reported to the Hydrogen Incidents and Accidents Database (HIAD) on a voluntary basis.
  - According to the European Hydrogen Safety Panel (EHSP), the total number of events reported in HIAD in 2018 was 272 (155 of which were in Europe). Of these, 7 incidents related to HRS.
- The EHSP extracted the following findings based on incidents reported to HIAD:
  - Overall, the overarching lesson learnt is that accidents might consist of several causal events that, if occurring separately, might have little consequences; but if these minor events occurred simultaneously, they could still result in extremely serious consequences. Fault analysis allows for safe designs.
  - Accidents are often initiated under special conditions, like maintenance, revision or restart after changing the system. Most cases are attributed to the human factor (wrong design, wrong operation). By recording and conveying lessons learned, the industry can adapt its processes.

Source: Summary of solutions adopted to resolve outstanding network and precommercial issues around hydrogen fuel retailing, 2020, H2ME (1) Deliverable 2.6, Element Energy

Nordic region case study: experiences following the incident at Kjörbo emphasise the importance of safety processes and redundancy

Nordic case study

Reasons for HRS shutdown in Nordic regions

- The majority of Scandinavian HRS have been operated by two companies: Uno-X (whose stations are supplied by NEL) and previously HYOP.
- In September 2018 HYOP closed its network of refuelling stations in Norway (following their bankruptcy), meaning that all the open HRS were supplied by NEL.
- In June 2019 a NEL station in Kjörbo, Norway experienced a hydrogen leak which led to a fire. NEL responded rapidly to ensure that all appropriate measures were taken to avoid escalation or further safety incidents. Following the incident, all HRS with the same design were closed so that inspections and verifications could be carried out. This included the only three stations in Iceland, leaving the island with no way to refuel its FCEVs.

Lessons learned

- The impact of the HRS closure on the overall networks in Nordic regions shows the importance of redundancy in station design in HRS networks. This will minimise the impact of financial or technical issues on network availability, and the resulting damage to the reputation of H_2 in these regions. By having different HRS suppliers, systemic errors are less likely.
- In addition, this emphasises the need for vigorous training and safety processes that encompass the design, assembly, and operation of HRS, as well as well-established procedures for responding in the event of a safety incident.

Uno X nel

Uno-X and NEL station in Norway
Source: adressa.no

HYOP station in Norway
Source: hyop.no

Source: Summary and lessons learnt from the hydrogen mobility strategies tested in this project, 2020, H2ME (1) Deliverable 5.13, Element Energy

Implementation of rigorous safety processes and checks is an essential part of HRS installation and operation

Summary of recommended best practices on HRS safety

HRS and component design

- Equipment should be designed so that any **failures can be detected at the testing stage**.
- One cause of leakages in Japan and the USA is **poorly planned fatigue**. Considering the incidents in EU, Japan and the USA, it is very important to adequately consider operational conditions in the design; compressor-induced vibrations are a key example that should be taken into account.
- Some leakage events are caused by **screw joints and inappropriate sealings**. If welded joints are to be used instead, do careful statistical checks of weldings and control certificates and capabilities of suppliers. Obtain data on the strength of welded parts and develop technology and techniques for improving quality of welding of hydrogen compatible material and reducing the pipe thickness.
- Be aware of differences between specifications and standards between different markets (e.g. North America / Europe) – this can cause issues if not identified early.

HRS installation and operation

- Insist on fully documented quality control, appropriate checks and prompt documentation of installation (and upgrade) procedures.
- Develop and implement thorough quality control processes and checks (e.g. regular leak tests). Training procedures should include appropriate testing to ensure capability.
- Implement a Safety Alarm Plan in response to sensor conditions and ensure that this is kept up to date following any changes.
- Carry out Emergency Response training for first responders (both internally and with local Emergency Services).
- Ensure that contingency plans are in place setting out clear actions in the event of an incident.

Source: Summary of solutions adopted to resolve outstanding network and precommercial issues around hydrogen fuel retailing, 2020, H2ME (1) Deliverable 2.6, Element Energy

Contents

1. Introduction

2. Progress under H2ME

3. Hydrogen Vehicle Developments

    FCEV market summary in Europe

    Light duty vehicle progress outside of Europe

    Contrasting with BEVs

4. Hydrogen light duty vehicle policy in Europe

    European wide political trends

    National policy strategies

5. Refuelling Infrastructure Developments

    Strategic developments

    Technical developments

6. Understanding the customer proposition

7. Remaining barriers to light duty vehicle commercialisation

    Economic barriers

    Competition for funding

    Technical barriers

8. Conclusions and recommendations

Key drivers for the adoption of hydrogen vehicles are air quality improvements and carbon reductions

Hydrogen Mobility Europe

Why are fleets interested in trialling hydrogen vehicles, despite the economic barriers?

1.	Fleets realise that a transition will be needed over the next 20 years to zero emission vehicles only. Early stage trials therefore provide a learning opportunity to familiarise with the technology and gain data to inform investment decisions.
2.	Fleets are eager to decrease their transport emissions to meet corporate targets, and it provides an advertising opportunity for the company.
3.	Vehicles offer operational benefits over other zero emission options (and potentially fossil vehicles), e.g. fast fuelling, fast acceleration, long driving ranges.

For hydrogen vehicles to meet expectations, it is therefore important that the experience closely matches conventional vehicle performance, whilst delivering carbon reductions >80%

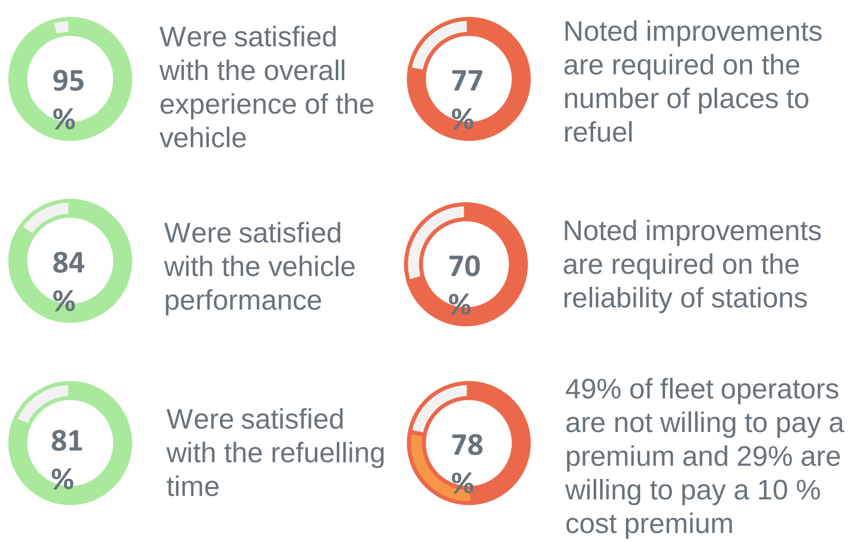
The following section outlines how user perception of these metrics has changed over the project

FCEVs can meet operational needs of users, but the business cases requires support

Technology readiness, business case and customer

- **Drivers and operators have a high opinion of the vehicles' performance.**
- **Viability and practicality of FCEVs** in meeting the needs of a range of existing vehicle users **has been demonstrated.**
- Several countries now have hundreds of FCEVs in operation, with 100-300 vehicles in fleets in high mileage applications.
- This demonstrates that the vehicles can meet these applications needs and **can offer an attractive customer proposition** when compared with other zero emission options.
- The main drawback was the **purchase or lease price of the vehicle** and **H_2 price** as well as the **availability of HRS.**
- This will improve with increase scale, but commercialisation **support is needed near term.**

Driver and operator views on FCEVs



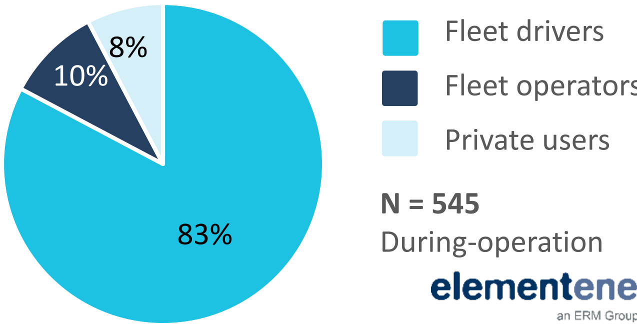
Source: Hydrogen Mobility Europe, Deliverable 6.22 – Report on vehicle user attitudes, driving behaviours and HRS network access trend (interim 2)

A note on private customers and hydrogen vehicles

FCEVs: private owner perspective

- The deployment of hydrogen FCEVs has to date been focused on commercial fleets, with **limited uptake from private vehicle owners**.
- Learnings from initiating deployment schemes have shown hydrogen FCEVs are better suited to commercial fleet deployment in the early years, for a number of reasons:
  - Private vehicle owners are driven in their purchasing decisions primarily by:

  1. *Vehicle capital cost and fuel cost*
  2. *Availability of a nationwide refuelling network*
- Hydrogen currently performs poorly on both of these metrics, and **private customers are less driven by areas where hydrogen performs well** (vehicle utilisation and environmental benefits):
  - Private customers are typically able to **charge overnight**, hence are less concerned about refuelling time (important for commercial fleets to maximise fleet utilisation).
  - Private customers cannot **monetise the environmental benefits** from zero emission technology in the same way as commercial fleets (e.g. through advertising and meeting carbon reduction targets).
- Private users also require **greater levels of resource and engagement** from fuel suppliers and OEMs i.e. training and sales support is required for each vehicle compared to a single point of contact for fleets.
- Due to these considerations, only a small portion of the responses in the following section from the H2ME analysis are from private users.
- To increase the uptake in the private customers in the future:
  - **Improve advertising of the fuel cell cars**
  - **Improve station coverage nationally**
  - **Provide grants for vehicle purchase and/or fuel usage**



N = 545
During-operation

Source: Hydrogen Mobility Europe, Deliverable 6.3 - Status and Advancements in the Customer Value Proposition

Fleet customers have seen most success in deploying hydrogen fuel cell vehicles

Hydrogen Mobility Europe

FCEVs: fleet owner perspectives

- In H2ME, light duty hydrogen vehicles have been used in multiple proof of capability demonstrations, leading to refinements of business models:
  - **HYPE: ~300 fuel cell taxis in Paris**, with plans for over 1600 taxis to be in operation by the end of 2024
  - **Green Tomato Cars: 50+ fuel cell taxis in London** (Concluded in 2022)
  - **CleverShuttle: 45 FCEVs in ride-sharing fleets in Germany:**
    >4.4 million km covered until 2020 (when the fleet was disbanded)
  - **Delivery & utility vans**: Plans for demonstrations by DHL, La Poste, City Logistics, water & energy companies: >150 Kangoo ZE H_2 vans in France
  - **Last Mile delivery**: HYPE/Akuo Energy facilitating Galeries Lafayette in the wholesale delivery to its stores in the Paris Area, HYPE/Ecolotrans (now part of the ADEME H24byHype project)
  - **HysetCo: >100 fuel cell taxis in Paris driven by independent taxi drivers** with plans for 400 by the end of 2023.

hype greentomatocars HYSETCO LA POSTE CleverShuttle DHL

- Currently, specific market conditions (which apply in the cases above) make fuel cell vehicles particularly attractive for these applications:
  - Fleets have high daily mileages and/or a need for fast refueling to enable flexible operations
  - Strong regional incentives for zero emission vehicles make the purchase or lease price more attractive and/or increase the financial burden associated with operating fossil fuel vehicles
    - Operational area aligns with locations of refueling infrastructure

Analysis of H2ME customer questionnaires: Customer Groups

Hydrogen Mobility Europe

FCEVs: questionnaire analysis

- Cars and vans have been deployed in a diverse range of applications, with a mixture of public and private organisations. Based on driver responses (including vehicles deployed in the ZEFER project), **the largest markets are currently taxi and ride-sharing applications**. Fleet driver responses from **Hype, CleverShuttle** and **Green Tomato Cars** account for the majority of this data.
- Overall, **29% of fleet operators expected each FCEV to be driven over 100km per day prior to trial commencement. The average expected distance was 80km per day**. For comparison, in the HyFIVE project, only 14% of respondents reported daily distances of over 100 km per day. The greater share of fleet deployments in recent years, and the fact that fleet applications tend to have higher mileages than private customer use, means that the average mileage per vehicle are increasing for FCEVs. This is important for increasing station utilisation.
  - In real operation, nearly 50% of fleet operators stated that their FCEVs were driven either 51 to 100 km, or over 100 km each day, indicating that the **cars are able to meet range expectations**.
- The **majority of car fleet customers use their vehicles mainly on urban roads** (with very few customers operating mainly on motorways). This is likely due to intra-city taxi services dominating the data set.
  - Van fleet customers used more of a mixture of journey types, ranging from urban and country roads to motorways / inland highways.
  - Vans were used by emergency service fleets or municipal fleets, where driving services are more unpredictable.
- The main reasons for purchasing / leasing an FCEV were: 1) to try out new technology and 2) to reduce CO_2 emissions.

Source: Hydrogen Mobility Europe, Deliverable 6.3 - Status and Advancements in the Customer Value Proposition

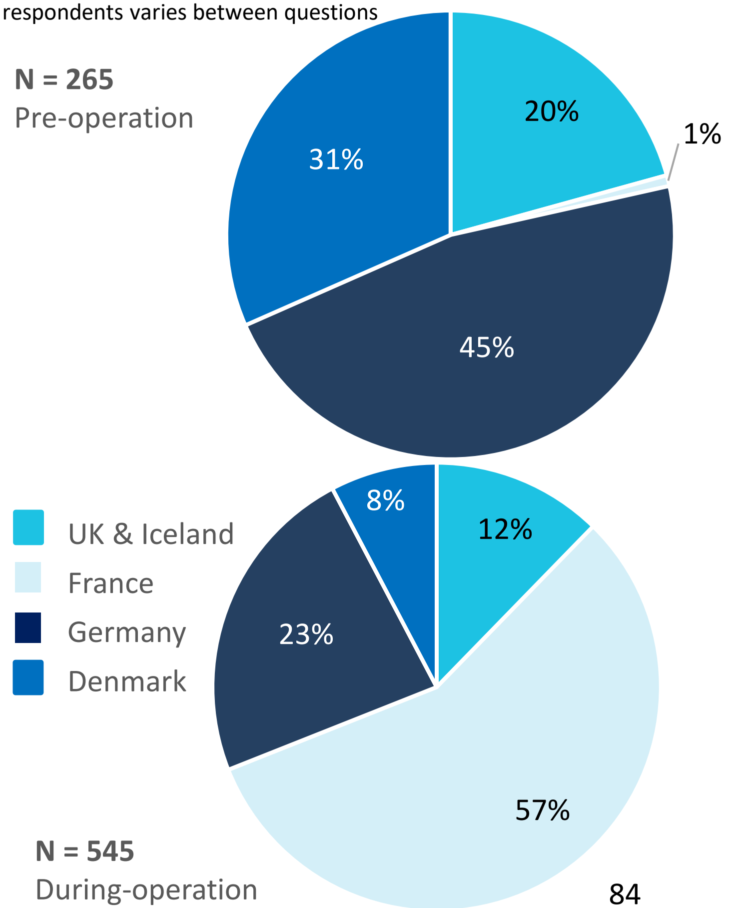
Overview of H2ME customer questionnaires responses: Breakdown by country

FCEVs: customer questionnaires

- The FCEV customers and end users in the H2ME projects have completed questionnaires which captured their expectations, requirements and experiences of hydrogen mobility. Questionnaires were completed both before using the vehicles and while using the vehicles.
- The questionnaires have been completed by a mix of by **fleet operators, fleet drivers, and private drivers of cars and vans** deployed in H2ME. The same questionnaires have been completed by fleet operators and drivers under the **ZEFER project**, which focuses on deployment in fleet applications, and responses from these users have also been included.
- The response rate as of January 2023 reflects **around 24%** for the pre operation survey and **50%** for during operation (of the ~1,100 cars and vans deployed as part of the H2ME and ZEFER projects to date).
- Findings from this questionnaire are presented in the following pages, providing insights into the customer value proposition:
  - **Customer characteristics and requirements**
  - **Expectations and experiences of FCEVs**
  - **Expectations and experiences of refuelling**

Respondents split by chosen questionnaire language

Note that some surveys were incomplete and hence the number of respondents varies between questions

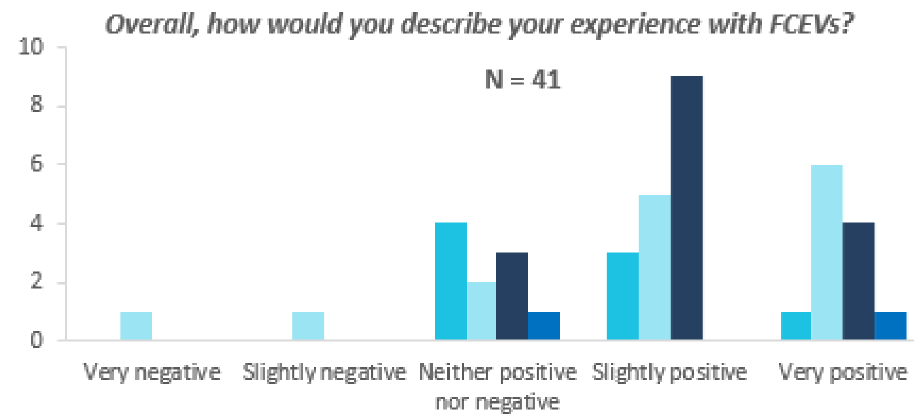


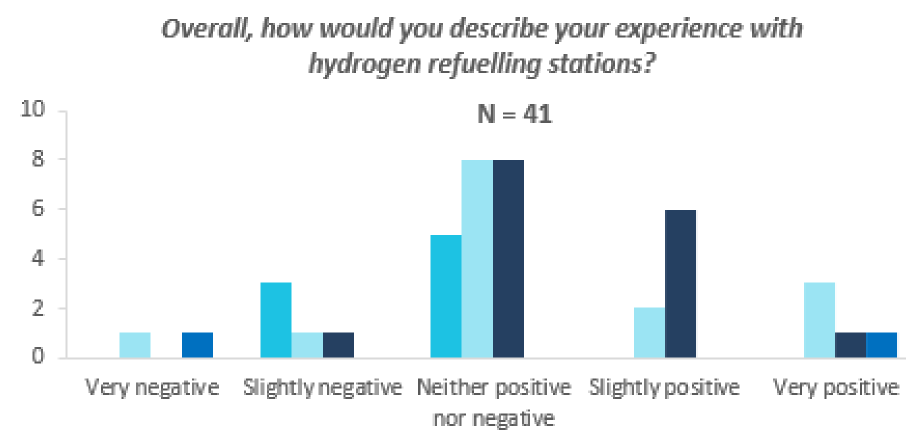
Source: Hydrogen Mobility Europe, Deliverable 6.3 - Status and Advancements in the Customer Value Proposition

Overall experience with HRS and FCEVs: Fleet operators

Experiences with FCEVs have been broadly positive amongst fleet operators, with mixed views on HRS

- While fleet operators identified areas for improvement with FCEVs, the majority of operators said that their **overall experience was positive**. Only 5% of operators considered their experience to be negative to some degree.
- Operator **experiences of HRS were mixed;** individual experiences varied from very negative to very positive, with more than half of responses saying that the overall experience had been neither positive nor negative.
- The less positive experiences of HRS compared to FCEVs reflects the feeling among FCEV users that the **current number of HRS is insufficient**, and, to a lesser extent, that **improvements to reliability are needed.**
- Operators in the different countries seem to have a similar profile of experiences of FCEVs and HRS.

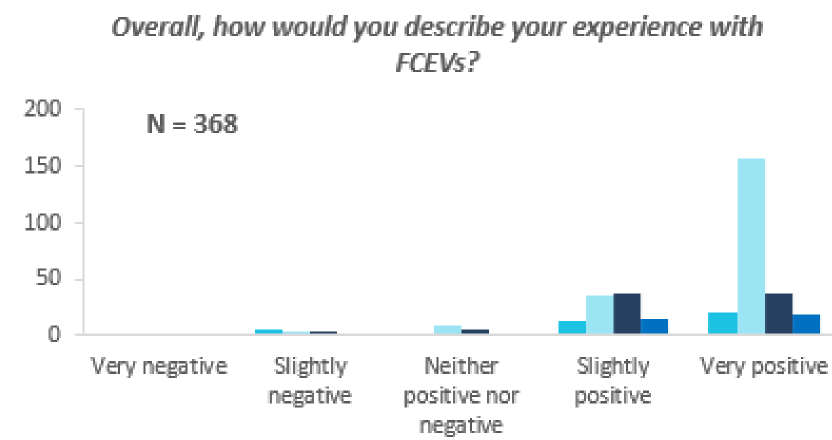


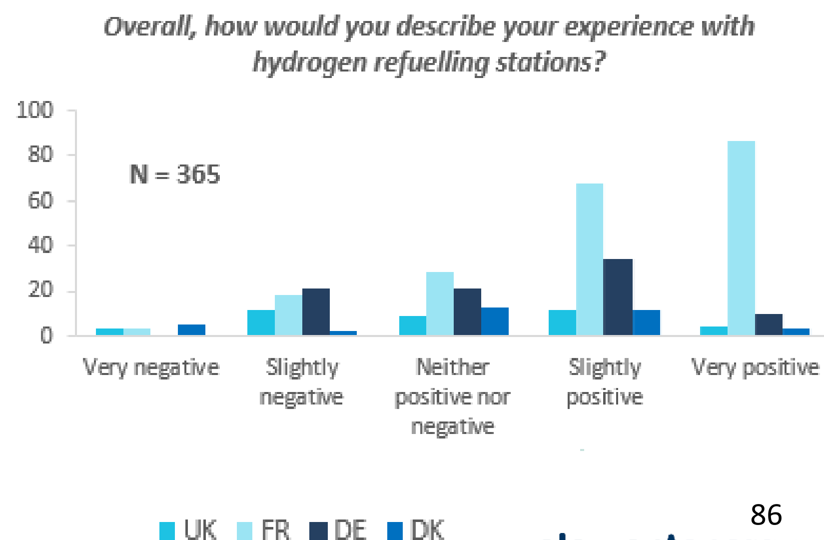


Overall experience with HRS and FCEVs: Fleet drivers

Experiences with FCEVs and the associated infrastructure have been broadly positive amongst fleet drivers

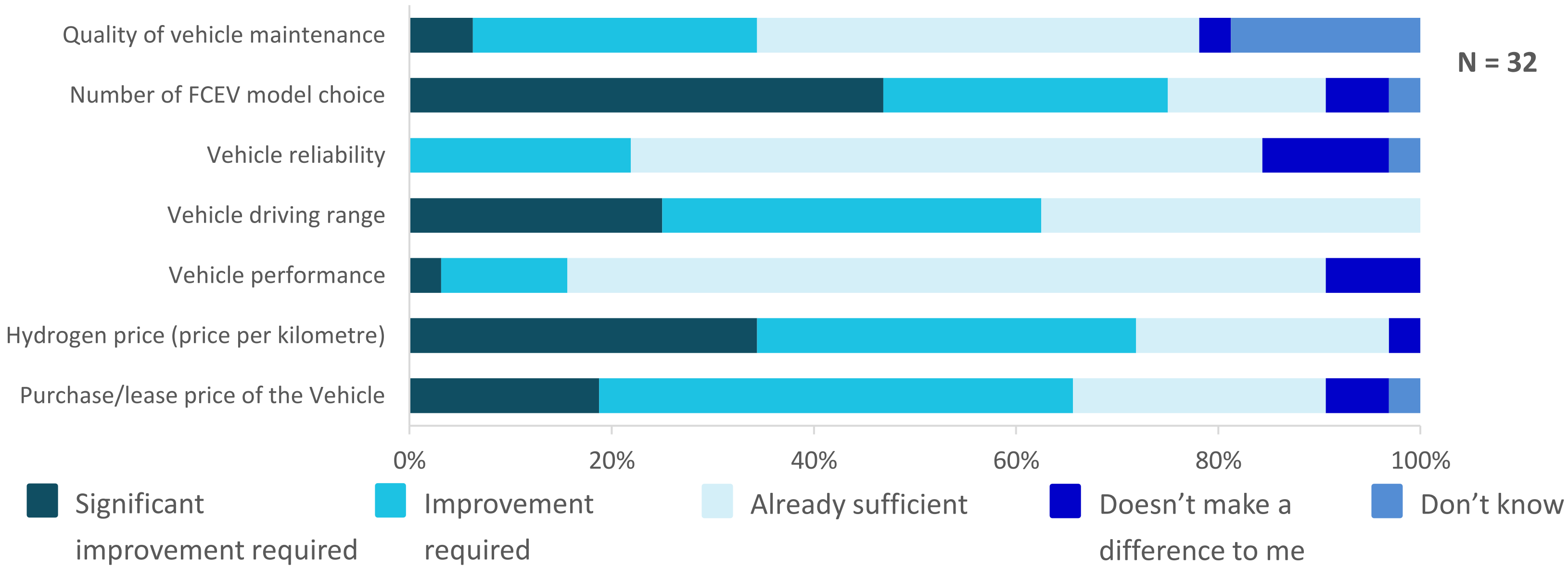
- The majority of fleet drivers, despite identifying areas for improvement, felt that they had a positive experience with both FCEVs and HRS.
- **91% of drivers noted a positive experience with FCEV technologies**, with 64% actually describing a 'very positive' experience. This supports anecdotal feedback and performance data which highlights that vehicles have been 'bullet-proof' with >99% availability across the project.
- Similarly to fleet operators, fleet drivers rated their experience of vehicles more highly than that with HRS. Of all the countries surveyed, French drivers had the most positive outlook, with the largest percentage of drivers reporting their experiences as slightly positive and very positive. This reflects the trends noted for other questions, and could be due to the large share of Hype taxi drivers (who are specifically recruited to drive FCEVs) in the data, as well as the approach to HRS deployment in France (which includes basing siting choices on fleet demand locations).





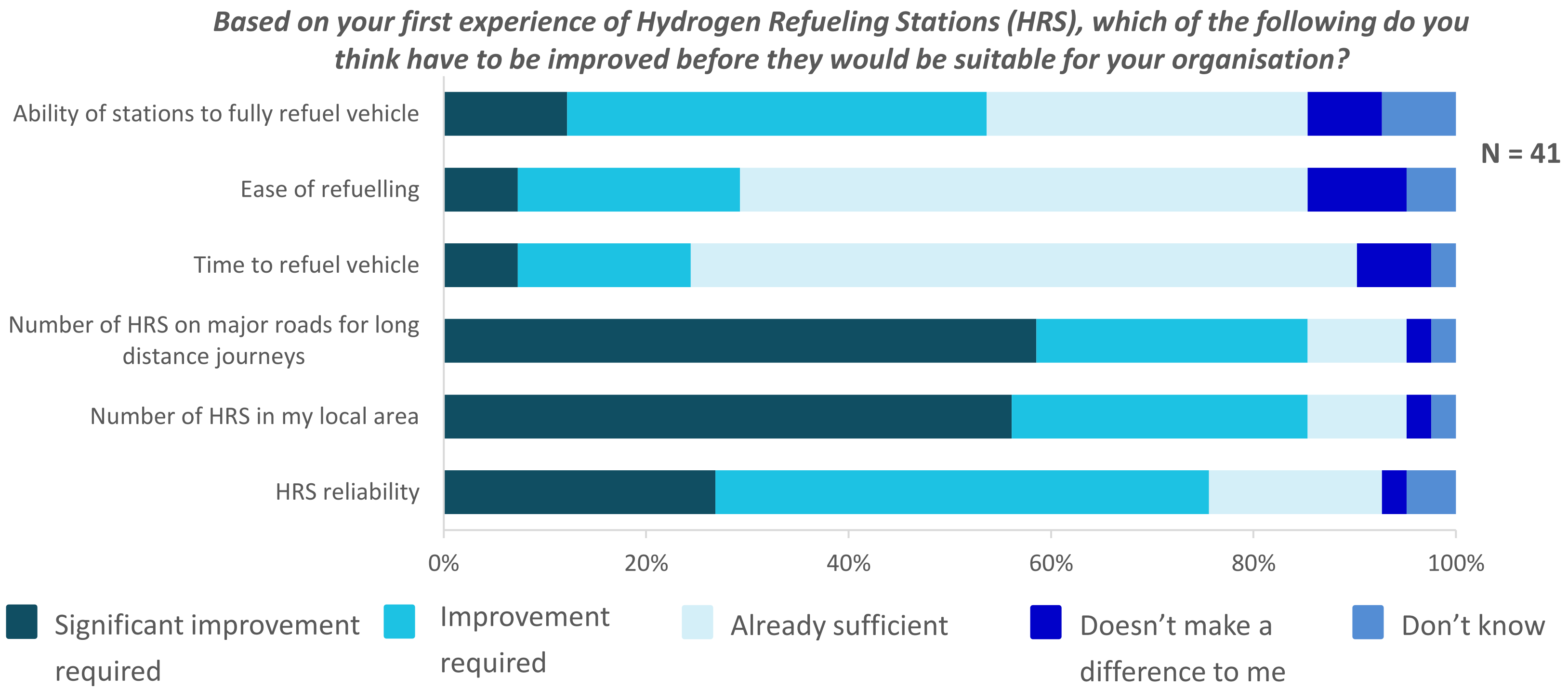
Improvements to FCEVs required for future use: Fleet operators

Based on your experience with a FCEV, which of the following do you think have to be improved?



- The FCEV aspect requiring improvement for the highest number of private users was the **number of FCEV model choice**, with 80% requesting some improvement.
- The second aspect requiring improvement was the **hydrogen price**; more than 70% of private users asked for (significant) improvement.
- Most private users (>50%) also felt that improvements would be needed to purchase/lease price of the vehicle and the driving range.
- Most private users think that the vehicle performance (75%) and the vehicle reliability (63%) are already sufficient.
- In previous reports, private users were not considered as there were not enough responses available. Therefore, no conclusion can be drawn on the evolution of the experience of private users regarding FCEVS and required improvements.

Improvements to HRS required for future use: Fleet operators



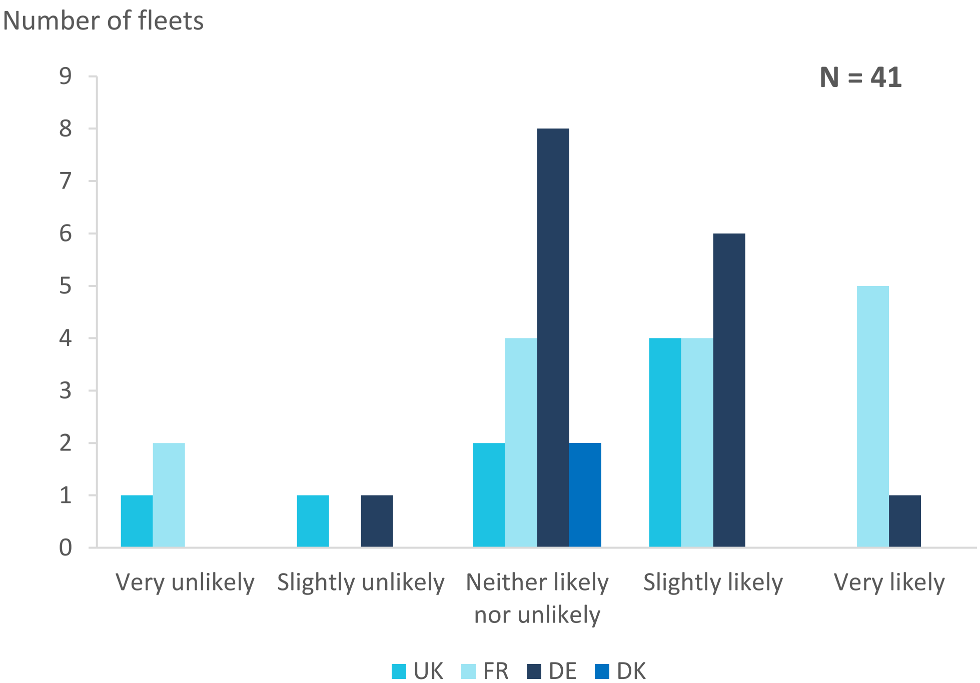
- **Numbers of stations in local areas and along major roads** were identified as the two areas **requiring most improvement** amongst fleet operators, with over 85% of operators stating that these aspects need to improve. It is notable that van operators disproportionately felt that significant improvements to numbers of HRS were required; this suggests that, due to the fact that the operating area is typically more dispersed, a more comprehensive level of HRS coverage is needed for van fleet operators, compared to e.g. taxi operations in city centres.
- There is no difference between geographies: fleet operators in all countries think that improvement is needed (7 out of 8 in the UK; 15 out of 16 in Germany; 11 out of 15 in France; 2 out of 2 in Denmark).
- **HRS reliability** was also frequently considered to be an area where improvement is needed, although to a lesser extent compared to number of HRS.

Likelihood of adopting more FCEVs in future: Fleet operators

Operators currently have mixed opinions on whether they would buy FCEVs in future

- Operator responses regarding the likelihood of adopting further FCEVs in their fleet were **varied. The most common answer was 'neither likely nor unlikely'**.
- It is possible that fleet operators are currently undecided about the role of the technology within their organization due to the current **early stage of infrastructure roll out**.
- There are no discernable differences between the intentions of operators from different countries, or the intentions of operators with different models of vehicles in their fleets.
- Based on these finding, the most important aspects to address to improve uptake are:
    1. Improving station coverage
    2. HRS reliability
    3. Vehicle and fuel prices

How likely are you to purchase/lease other FCEVs for your fleet in the next 5 years?



Fleet operators were typically willing to pay up to 0-10% cost premium relative to diesel/petrol vehicles TCO

Contents

1. Introduction

2. Progress under H2ME

3. Hydrogen Vehicle Developments

    FCEV market summary in Europe

    Light duty vehicle progress outside of Europe

    Contrasting with BEVs

4. Hydrogen light duty vehicle policy in Europe

    European wide political trends

    National policy strategies

5. Refuelling Infrastructure Developments

    Strategic developments

    Technical developments

6. Understanding the customer proposition

7. Remaining barriers to light duty vehicle commercialisation

    Economic barriers

    Competition for funding

    Technical barriers

8. Conclusions and recommendations

Although significant progress has been made, the roll-out of vehicles and refuelling stations in Europe has been slower than anticipated

Hydrogen Mobility Europe

Current outlook on deployment progress

- In comparison to the targets set by technology roadmaps developed at the European level, and by the regional hydrogen initiatives, **the initial rollout of HRS and vehicles has been slower than anticipated**. Nevertheless, **the first networks of public HRS are beginning to emerge** and are set to continue to grow.
- In several countries, the creation of an initial public HRS network has involved providing a minimum level of regional or national coverage, to enable FCEVs to be a feasible powertrain choice for early users. **The number of stations required to create these initial networks, and the relatively low numbers of vehicles currently using these networks, make for a challenging business case for HRS operators.**
- In several countries, hydrogen industry stakeholders are collaborating to form innovative business models such as public-private partnerships and joint ventures, in order to reduce the overall risk to each company and demonstrate the commitment of the sector to the continued growth of the hydrogen refuelling networks.
- For commercialisation to be achieved, strategies for the regional development of hydrogen mobility will ultimately need to identify how to deploy and operate refuelling networks that provide sufficient utility for customers, while also supporting a sustainable business case for HRS operators without long-term support from public funding.

Commercialisation Barriers: Section Overview

- There are three main barriers identified in this section, which are preventing the commercialisation of light duty FCEVs, despite the progress under H2ME as outlined in the previous chapters.

Economic barriers

- Hydrogen price premium
- Vehicle capex premium
- Cost of detour time & lack of station coverage

Zero emission competition for funding & investment

- Further development for BEVs
- Reduced appetite for funding zero emission light duty vehicles

Technical barriers

- Low availability of vehicle products
- Availability & state of charge
- Regulatory barriers
- Future concerns about efficiency and raw material scarcity

Contents

Hydrogen Mobility Europe

1. Introduction

2. Progress under H2ME

3. Hydrogen Vehicle Developments

FCEV market summary in Europe

Light duty vehicle progress outside of Europe

Contrasting with BEVs

4. Hydrogen light duty vehicle policy in Europe

European wide political trends

National policy strategies

5. Refuelling Infrastructure Developments

Strategic developments

Technical developments

6. Understanding the customer proposition

7. Remaining barriers to light duty vehicle commercialisation

Economic barriers

Competition for funding

Technical barriers

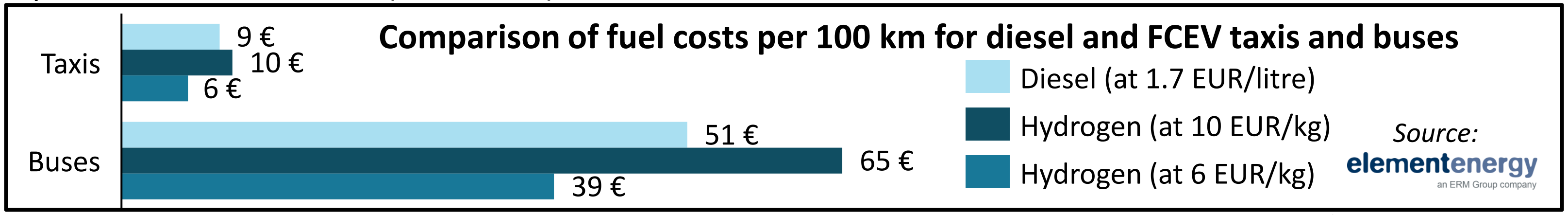
8. Conclusions and recommendations

At current levels of demand, the per kg cost of hydrogen at the dispenser can be a barrier; public funding could help to reduce the risks of scaling up

Hydrogen Mobility Europe

Hydrogen mobility: hydrogen cost at the dispenser as a barrier

- Many of the potential transport applications of hydrogen have high annual mileages. This means that **fuel costs are a major factor in the total cost of operation**.
- Numerous studies have shown that the price of hydrogen could be competitive with current fuels when produced at sufficient scale[1]. However, at current levels of hydrogen demand (i.e. below 200 kg/day/station), the **total cost per kg of hydrogen** (including the cost of production, storage and/or distribution, and operating the refuelling station) tends to be in excess of 10 €/kg. When hydrogen is sold at this price, the resulting **fuel cost per km for FCEVs compared to diesel vehicles** mean that FCEVs have a significant operating cost premium compared to diesel vehicles (see below).



- Successful initial deployments to date have been made possible through financial incentives/tax exemptions for zero emission vehicles, and/or restrictions placed on diesel vehicles such restricting access to city centres for polluting vehicles. However, **restrictions alone do not remove the additional cost for end users**, and while the cost of hydrogen is still high, this can present a significant barrier to adoption, especially in fleet use where fuel costs are a major factor. This presents a challenge for achieving the levels of demand required to enable suppliers to unlock hydrogen supply at lower costs per kg.
- **Public sector funding to subsidise short-term hydrogen supply** and **joint ventures/partnerships between HRS operators and end users** (to reduce risk to both parties) are both options which could help to achieve scale-up.

[1]References: 1) IEA, 2019, The Future of Hydrogen: Seizing today's opportunities. 2) Strategic Analysis for DoE, 2016. Hydrogen Production Pathways Cost Analysis (2013-2016). 3) Progressive Energy Ltd for Cadent, 2019. HyMotion: Network-supplied hydrogen unlocks low carbon transport opportunities.

Routes to low cost hydrogen (1/2)

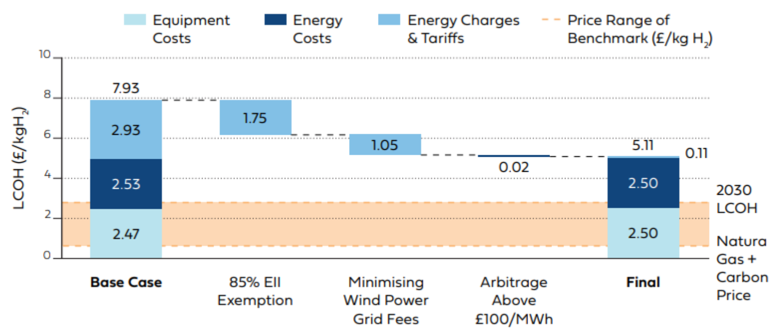
Hydrogen Mobility Europe

Routes to low cost hydrogen: production and distribution

- In order to achieve diesel parity or better than diesel parity hydrogen prices, there are four key factors which need to align:

Lower hydrogen production costs

- Hydrogen production costs are currently around €8/kg for large scale green hydrogen production, linked primarily to the capital cost of the electrolyser and the cost of electricity.
- In order to reduce these costs, the following needs to occur:
  - Electricity prices need to decrease from their current peak and remain low through long term offtake arrangements with renewable assets. In a fully decarbonised world, as the levelized cost of electricity production from renewables continues to fall, so should the input price for hydrogen production.
  - The cost for producing and installing an electrolyser needs to decrease, and the efficiency of electrolysers needs to increase.
  - Regulatory barriers need to be addressed: energy charges & tariffs need to be removed for renewable assets which power electrolysers



Contributions to the LCOH, Gigastack[1]

More efficient hydrogen distribution

- Centralised production with distribution to HRS is a promising, scalable model for supplying hydrogen to the transport sector. To minimise hydrogen distribution costs distances between production sites and HRS should be limited (maximum of low hundreds of km) and opportunities to maximise the use of assets should be taken.
  - Industrial clusters and regions with access to offshore renewables are ideal locations to start to build out the hydrogen refuelling station network.

[1] Gigastack | Phase 2 Public Report

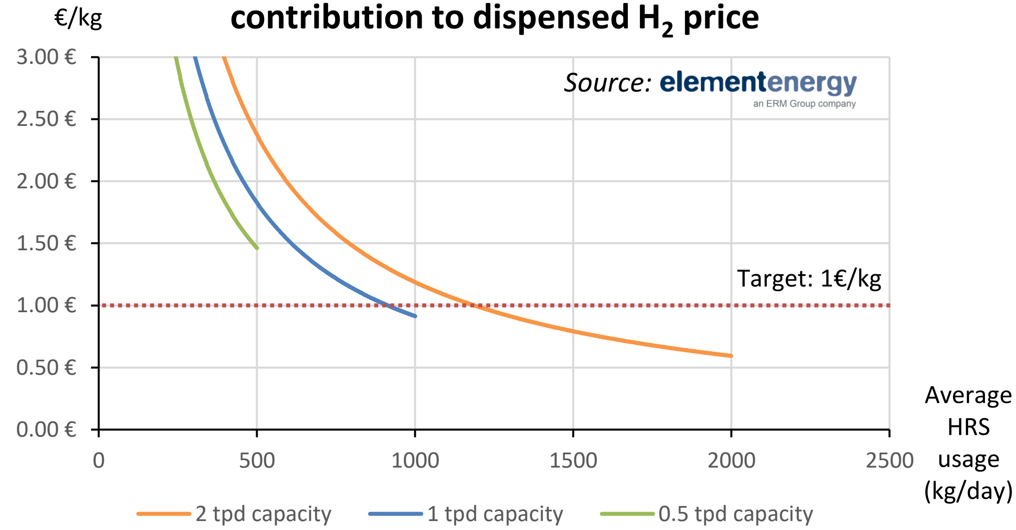
Routes to low cost hydrogen (2/2)

Routes to low cost hydrogen: demand and subsidy support

Aggregated offtake demand

- Achieving large hydrogen refuelling station demand is critical to achieving low hydrogen prices. This is because the economics of installing the capital equipment for a permanent hydrogen station do not scale down well.
- A scale of below 1 tonne per day station capacity allows for station amortisation costs below €1/kg if it is fully utilised. A 500 kg/day capacity station cannot achieve these prices, see right.
- €1/kg HRS contribution is a good figure to aim for in future deployment projects.

Hydrogen refuelling station capex contribution to dispensed H_2 price



- To achieve this cost, a refuelling station needs to serve an average of 50 heavy duty vehicles per day. Given these economics, refuelling station providers are looking to develop projects in tandem with large scale potential offtakers (bus & truck operators), with contracts to secure demand over the long term. Furthermore, stations should be located not too far from the hydrogen production source.

Continued subsidy support

- There is subsidy support available for green hydrogen that is used in transport, as outlined by the Renewable Energy Directive (RED 2). This support is essential to encourage green hydrogen's use in transport, and the business case for green hydrogen in transport would currently not work without the support.
  - Other countries also have policy support schemes, e.g. the RTFO (UK, up to £7.33/kg current value) and through the inflation reduction act (US, up to $3/kg).

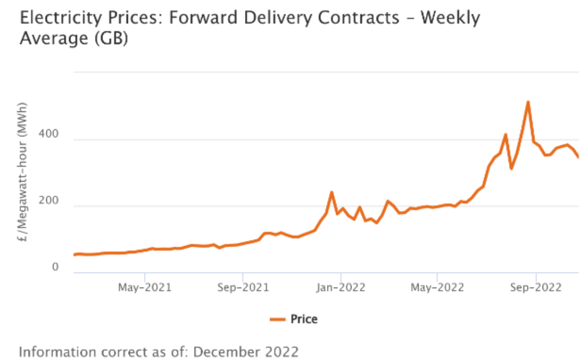
Effects of the current energy security crisis on the business case for hydrogen mobility

Hydrogen Mobility Europe

Hydrogen mobility business case: impacts of the energy crisis

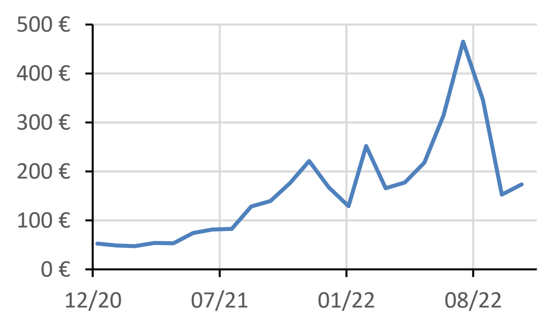
- Wholesale electricity prices have increased as a result of the war in Ukraine and energy security crisis. Since mid-2021, wholesale electricity prices have increased by around 400% across Europe.
  - Prices have largely levelled out or began to fall throughout the second half of 2022, however, we can expect prices to remain above their 2021 level in the immediate future.
- Due to the lower efficiency of the hydrogen supply chain compared to the BEV round trip efficiency, hydrogen is more exposed to electricity price fluctuations (as more electricity input is required).

UK wholesale electricity price (£/MWh), 2021-2022[1]

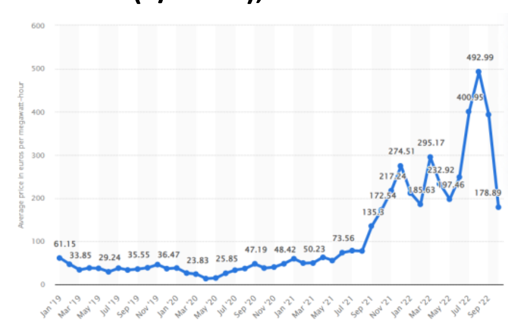


- Therefore, electricity price fluctuations needs to be planned for and mitigated against. Potential mitigations include:
  - Contracting for long term power purchase agreements at a fixed price.
  - Developing projects to supply hydrogen from large scale renewable assets in a system which can be isolated from the electricity grid.
  - Diversifying hydrogen supply options e.g. investigating bio-H2 projects alongside electrolysis projects.
  - Hedging the price of electricity over the long term.

German wholesale electricity price (€/MWh), 2020-2022[2]



France wholesale electricity price (€/MWh), 2019-2022[3]



[1] Wholesale market indicators | Ofgem [2] Market data | Nord Pool (nordpoolgroup.com)
[3] France: monthly electricity prices 2022 | Statista

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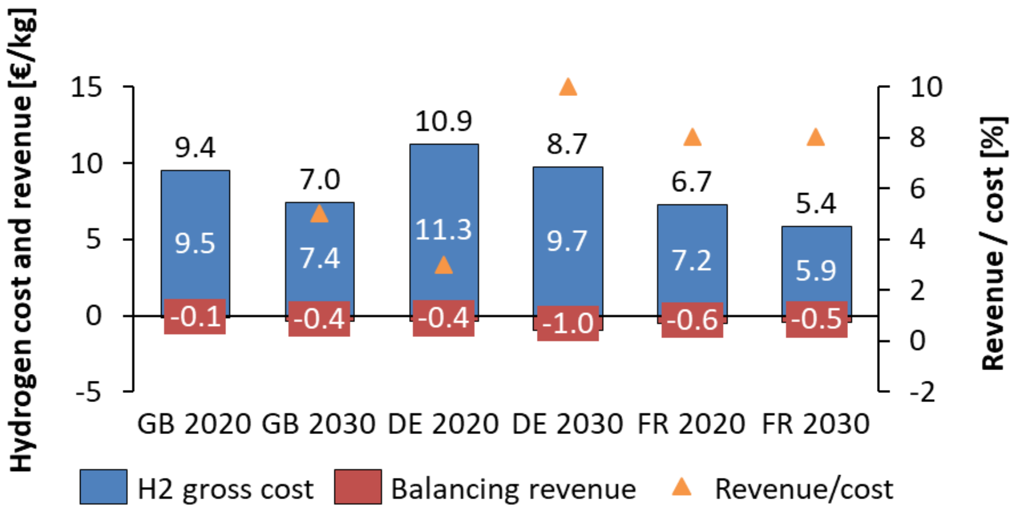
Hydrogen's use as an energy storage vector could help to address economic barriers

Hydrogen as a storage vector: balancing services provided by hydrogen

- The energy security crisis, and Europe's reliance on Russian natural gas for daily and seasonal matching of electricity grid supply and demand, has increased the attention on hydrogen's potential to act as an energy storage vector. This could also be a potential new revenue source for hydrogen production projects.
- Production of H_2 by electrolysis can **help the transition to Variable Renewable Energy (VRE)** such as wind and solar power by balancing the grid in hours of low electricity demand and high VRE production.



- Analysis undertaken as part of the H2ME2 project suggests that balancing revenues **reduce** the **cost** of hydrogen by **1-10%** across countries. Revenues increase if a lower load factor is used, which offers more capacity for balancing services. This is likely to be the case **in Great Britain and Germany** in 2030, as marginal electricity costs will become more volatile.

- The Balancing Services market by electrolysis is in strong competition with other storage technologies (mainly batteries). They can help to **improve the business case** but they should not be a main pillar of it.

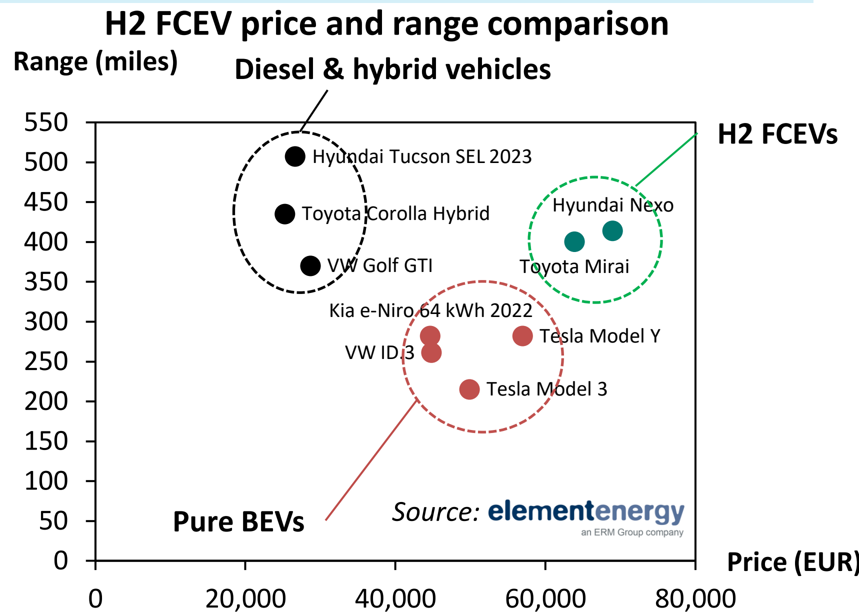
Source: Desirable design changes and operating regimes for electrolyser-HRS for 2020-2030, 2020, H2ME 2 Deliverable 4.17, Element Energy

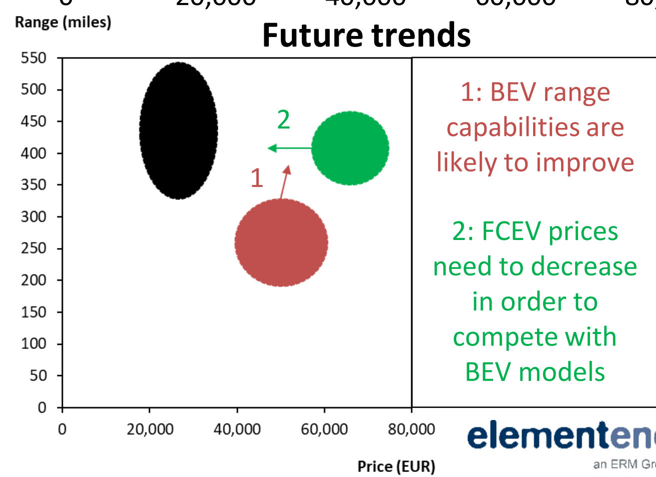
Hydrogen vehicles need to see reductions in capital cost in order to achieve mass market penetration

Hydrogen Mobility Europe

FCEVs: cost improvements to improve market penetration

- Hydrogen vehicles currently fulfil a niche in the zero emission vehicle market, for end users which require a solution with a comparable user experience to diesel who are able and motivated to pay the cost premium.
- We expect that BEVs will continue to improve in terms of range capabilities and charging times, which could narrow the market for FCEVs at their current prices.
- It is therefore important that FCEVs continue to decrease in price over the next 5 years. Achieving a price of c. €40,000 - €50,000 for the cheapest FCEV models should help to improve market penetration.
- The main drivers for cost reduction are likely to be:
  - Fuel cell cost reductions
  - Production capability upscaling
  - Increased competition from new models & new market entrants
- Current costs for hydrogen and FCEV purchase result in a TCO differential of c.27% for FCEVs compared to petrol vehicles (see next slide).





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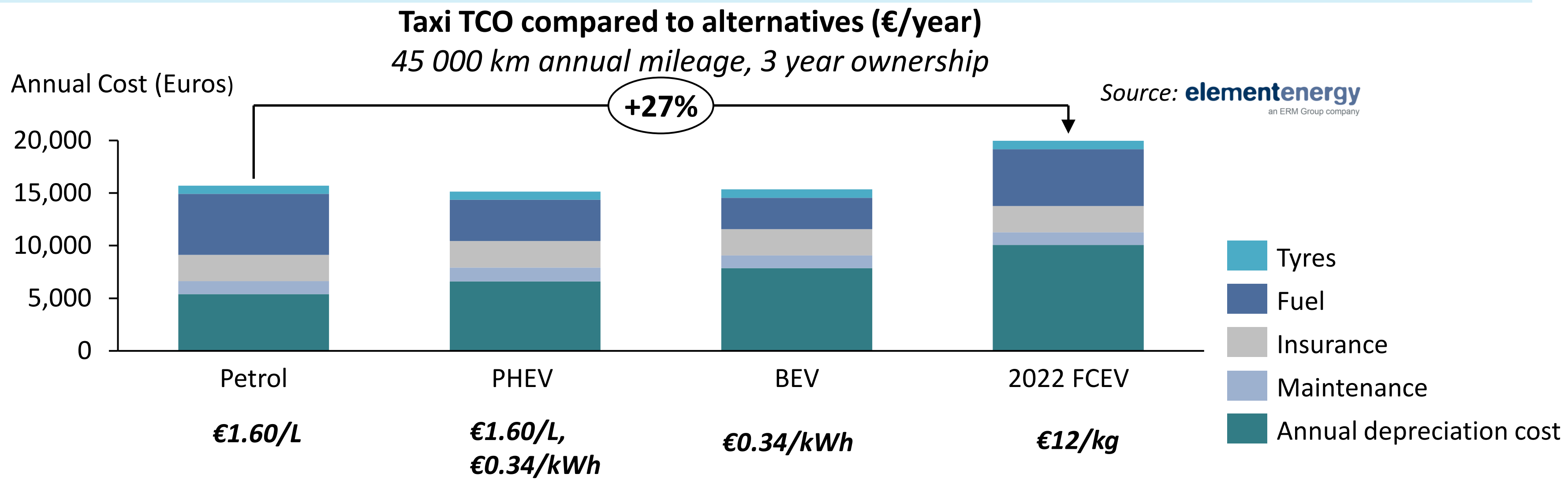
FCEVs are the most expensive drivetrain for fleet operators but the cost differential has decreased significantly since the start of H2ME

Hydrogen Mobility Europe

FCEVs: improvements in TCO



- Using updated figures (post energy security crisis), **FCEVs come at a ~27% premium to current petrol hybrids and ~plug-in hybrid vehicles without subsidy**. This is greatly improved compared to before large scale deployment (c.95% premium[1]). This is because:
  - FCEVs are expected to have a **strong residual value after** their first 3 years of operation. This represents a significant development in the sector, with OEMs increasingly standing behind their FCEV products. A clear appetite for a second-hand market has also been identified for the vehicles.
  - **Capital costs of FCEVs have decreased** with the new generation technology. This accounts for a 'basic' specification of vehicle although 'executive' versions are available at a higher price.
  - **Higher fuel or electricity costs are accounted for in the model.** Principally, petrol prices have risen by over 50% since the beginning of the ZEFER project.

[1] For further detail on the TCO for FCEVs, see ZEFER Deliverable 3.7

Barriers to commercialisation largely relate to the business case and the limited HRS network

Hydrogen Mobility Europe

Summary of economic barriers

- At current small scales of deployment the **business case for FCEVs and their supporting infrastructure is challenging:**
  - With limited hydrogen demand relative to the cost of installing and operating infrastructure, **HRS operators struggle to make a business case for operation** and are required to sell hydrogen at high prices to cover costs.
  - In addition, current **cost premiums for FCEVs are prohibitively high (relative to petrol/diesel vehicles)**, resulting in a TCO which performs worse than BEV and conventional fuel options.
- For hydrogen to move beyond a niche application, the cost gap between FCEVs and BEVs must be closed. Today, this factor makes industry investment in scale up activities difficult meaning that **costs remain high** and end users are faced with an **infrastructure network which is sparse.**
- In order to facilitate large scale hydrogen projects, **Government involvement** is typically required to offset some of the cost differential and encourage the private sector to take the risk on building HRS.
  - Competition for such funds is high, as discussed in the following section.
- There is significant potential for FCEV economics to improve, under the following conditions:
  - Careful planning of projects to ensure a commercially viable business case for hydrogen at a competitive price with diesel (e.g. aggregation of demand, colocation of supply and demand, linking to heavy duty offtake demand).
  - Deploying vehicles at scale to ensure cost reductions for fuel cells and savings from series manufacturing.

Contents

1. Introduction

2. Progress under H2ME

3. Hydrogen Vehicle Developments

- FCEV market summary in Europe
- Light duty vehicle progress outside of Europe
- Contrasting with BEVs

4. Hydrogen light duty vehicle policy in Europe

- European wide political trends
- National policy strategies

5. Refuelling Infrastructure Developments

- Strategic developments
- Technical developments

6. Understanding the customer proposition

7. Remaining barriers to light duty vehicle commercialisation

- Economic barriers
- **Competition for funding**
- Technical barriers

8. Conclusions and recommendations

Hydrogen projects require funding to achieve a critical demand level

Hydrogen Mobility Europe

Funding requirements

- New hydrogen stations need to be **well-utilised** and **large scale** to justify the capital investment, preferably >1 tonne per day offtake.
  - This necessitates an offtake of c.1,000 passenger car FCEVs per station, or c.50 HGVs.
- This scale of deployment requires substantial funding for vehicles, given the current TCO premium for hydrogen vehicles.
- The level of funding will vary by vehicle type based on the technology maturity.
  - There is a large capital premium between H2 HGVs and diesel HGVs given the small production volumes, and there remains a small capital premium for light duty vehicles.
- A **key metric** to analyse when planning hydrogen projects is the **value for money** of the vehicles in terms of demand generation, i.e. the funding requirement for a given vehicle compared to the demand it will generate at the station (€/kgH2/day).
  - E.g. a taxi operator might require a subsidy of c. €10,000 to incentivise them to buy hydrogen taxis, which require 1.5 kg/day for each vehicle, whilst a truck operator might require a subsidy of c. €300,000 to buy a H2 vehicle which would use 15 kg/day. In this example, value for money for the taxi is 3 times better than the HGV (€6,667/kg/day compared to €20,000/kg/day).
- Value for money for hydrogen FCEVs will typically vary between €5,000/kg/day and €30,000/kg/day. This means that, to justify a large scale hydrogen station there is a **funding requirement of between €5M to €30M for vehicles alone**.
- Whilst this requirement will decrease as technologies mature, **in the near term it is important to secure funding for the majority of hydrogen mobility projects.**

There is strong competition for funding from BEVs

Hydrogen Mobility Europe

Competition for funding

- There are a number of funds which aim to help commercialise zero emission transport in European countries.
- Some of these are hydrogen specific, however, the majority are open to **both BEV and FCEV solutions**. E.g.:
  - ZERFD (£140M) and ZEBRA 2 (£129M) schemes in the UK[1, 2]
  - German funding to support the purchase of climate-friendly commercial vehicles (€1.3Bn) and for the construction or expansion of refuelling and charging infrastructure for cars and trucks (€6.3Bn) [3]
- Given that the TCO differential between BEV and conventional fuel vehicles is lower than between FCEV and conventional fuel vehicles, as discussed in *Economic barriers*, there is typically a greater funding requirement for a given carbon saving for FCEVs compared to BEVs. Thus, within a given funding envelope, more battery electric vehicles can be deployed and hence **these projects may be preferred for funding**.
  - **This limits the uptake of hydrogen**, and results in battery electric solutions commercialising at a faster rate than FCEVs.
  - Given the improvements in battery technology seen over the past decade, BEVs are now also starting to penetrate into the HGV market, further narrowing the potential funding opportunities and hence number of hydrogen projects.
- This effect may lead to **fewer hydrogen stations being built** in the near term, hence diminishing opportunities for deployments of FCEV passenger vehicles given the strong link between station density and vehicle volumes.

[1] Apply for zero emission bus funding (ZEBRA 2) - GOV.UK (www.gov.uk)
[2] Zero Emission Road Freight Demonstrations: battery electric and hydrogen fuel cell trucks - Innovate UK KTN (ktn-uk.org)
[3] German Federal Ministry of Digital Affairs and Transport awards subsidy funding worth €24.6 million for all-electric Volta Zeros - Volta Trucks (SE)

Coupled with the strong competition for funding, funding for some vehicle types is being reduced

Hydrogen Mobility Europe

Decrease in available funding

- In addition to **strong competition** currently for funding for HGVs and buses, the historic funding for zero emission passenger car vehicles has largely been capitalised on by BEVs.
  - There are c.400 times more BEVs deployed globally than FCEVs.
- Electric car registrations now make up c. 18% of the European passenger car market sales, and are being commercialised largely with only minimal funding from plug-in car grants. As the market share of EVs increases, the need for funding for light duty zero emission vehicles becomes redundant.
- We expect this to happen in the near term for light duty vehicles, however, this trend will continue to heavier weight classes as **the majority of vehicles become decarbonised**. Caps have also been placed on the total cost of the vehicle which often **exclude hydrogen models**.
  - The plug-in car grant has been phased out in the UK.
  - The ecological grant in France has been extended for another year, however, there is a continuous review process and the vehicle capex cap of €60,000 excludes hydrogen models.[2]
- This prevents hydrogen vehicles from accessing the same commercialisation support that BEVs have received over the past 10 years.
  - UK Government estimates that **£1.4Bn** has been provided through the plug-in grant scheme since its inception in 2011.
  - Assuming all of France's eligible 500,000 all-electric passenger cars have applied for the ecological scheme at a funding of €6,000 per vehicle, **c. €3Bn** has been provided through the scheme.
- It is unlikely that H2 light duty vehicles will receive this level of Government support over the next decade.

[1] New registrations of electric vehicles in Europe (europa.eu) [2] Grants for Electric Vehicles in France | French-Property.com

Despite the difficulty of obtaining funding for hydrogen mobility projects, it is important to continue to build out the hydrogen ecosystem

Hydrogen Mobility Europe

Support for hydrogen

- There remain strong driving factors to encourage the uptake of hydrogen for transport, for instance:
  - Hydrogen vehicles help to accelerate **decarbonisation**, whilst actively helping to reduce **air pollution** in cities.
  - Hydrogen vehicles have a **low resource intensity**. Fuel cells are largely made from readily available carbon supports, polymers and metals, the rarest of which is platinum. Platinum content in fuel cells has been decreasing over time, and the platinum requirement is now approximately in line with that of a diesel catalyst. The fuel cell is also highly recyclable.
  - Hydrogen mobility presents a good opportunity for **jobs and skills** for countries which do not have access the metals required for battery manufacturing. Fuel cell vehicle manufacture is linked to high-skilled engineering jobs, and therefore is well-suited to the European workforce.
  - Hydrogen's use in transport helps to improve **energy and technology security** for a number of countries. Hydrogen can be produced from local renewable power, and the hydrogen vehicle and refuelling station supply chain can largely be concentrated in European countries.
- Given these factors, there remains **strong political will** to deploy hydrogen vehicles in Europe.
  - Whilst funding for vehicle purchase may be difficult to access, **multimodal hubs** are being set up across Europe, noting the importance of developing a hydrogen mobility ecosystem in Europe.
  - Examples of this concept include the Hydrogen Valley projects (Clean Hydrogen Partnership), the Hype and DRIVR projects (France, Denmark) and the Tees Valley H2 Hub (UK).
  - By funding station development and a mix of vehicles through these hubs (e.g. buses, trucks), there are trickle-down effects for cars (better station availability and cheaper fuel).

Contents

Hydrogen Mobility Europe

1. Introduction

2. Progress under H2ME

3. Hydrogen Vehicle Developments

    FCEV market summary in Europe

    Light duty vehicle progress outside of Europe

    Contrasting with BEVs

4. Hydrogen light duty vehicle policy in Europe

    European wide political trends

    National policy strategies

5. Refuelling Infrastructure Developments

    Strategic developments

    Technical developments

6. Understanding the customer proposition

7. Remaining barriers to light duty vehicle commercialisation

    Economic barriers

    Competition for funding

    Technical barriers

8. Conclusions and recommendations

In order to achieve full commercialisation, further vehicle related R&D is required in some areas, in particular for heavy duty vehicles

Hydrogen Mobility Europe

Vehicle research and development

- Whilst hydrogen passenger cars have performed well throughout H2ME and other deployment projects globally, there are still technical advancements which, if achieved, could help accelerate the commercialisation of the technology (see below).
- Recent end user feedback has been that series-produced products from OEMs in the passenger car and bus markets have delivered a satisfactory standard of performance and reliability over the last 3 years.
  - This has not always been the case, with early bus deployments demonstrated e.g. through the CHIC project achieving an availability of below 70% (compared to >90% for diesel)[1].
- Due to the nascent nature of the hydrogen HGV market, specifications and standards are yet to be fully developed by a number of OEMs, and hence there remain a number of technical barriers to address.
- Advancements for HGVs are also included in this section, as these developments will be critical to allow the build out of a hydrogen network, given that HGVs may be HRS anchor customers due to the high demand.
- The following slides provide an overview of the expected advancements in vehicle performance which are expected over the next decade, and how these will impact the commercialisation of H2 mobility:
  - Improvements in fuel cell efficiency
  - Improvements in drivetrain optimisation
  - Collaborations to develop hydrogen HGV fuel cells
  - Development of 700 bar and LH2 storage solutions
- In addition to the above points, it is important that *more OEMs* develop hydrogen vehicle solutions, to provide more product offerings and variety for customers.

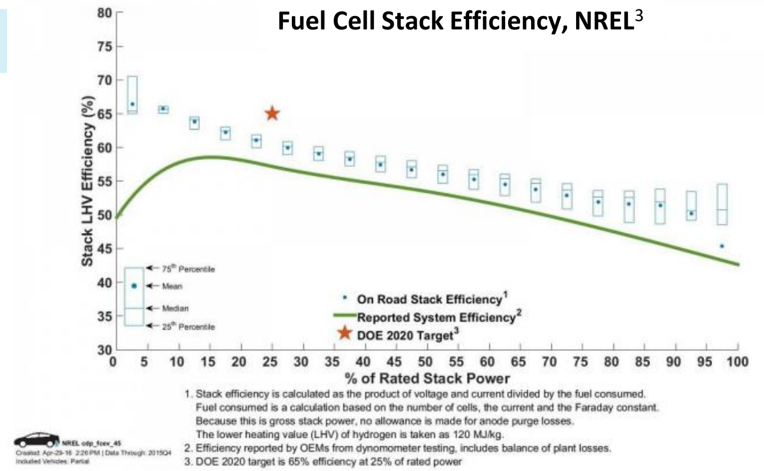
[1] Final Report_CHIC_28022017_Final_Public (fuelcellbuses.eu)

It is important to continue to improve the efficiency of hydrogen vehicles, as this improves the economics and diesel parity price for H2 sale

Hydrogen Mobility Europe

Improvements in fuel cell efficiency

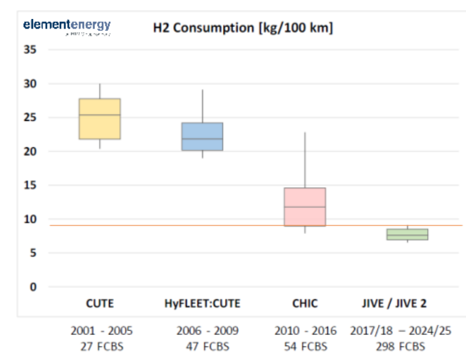
- Typical fuel cell efficiency varies by vehicle type and duty cycle, as fuel cells are most efficient when used at output powers substantially below their maximum (see right).
  - Efficiency is maximised at speeds of around 40 km/hour.
- Fuel cell efficiency for passenger car technology is around 50%. The theoretical maximum efficiency is 85-90%, although it is limited by resistances to electron flow and mass transfer.



- As fuel cell designs continue to be optimised and losses reduced, the efficiency could improve to be closer to 60-65%, with the US Department of Energy in 2020 announcing a target of 65% efficiency at 25% power.[2]

Improvements in drivetrain optimisation

- In addition to improvements in fuel cell efficiency, there are continued improvements which will be possible through the optimisation of the FCEV drivetrain.
  - Improvements are in particular possible for new vehicle classes / demonstrators, which are often built on a BEV base vehicle.
  - More commercialised products e.g. buses have seen efficiency increases of over 300% since early prototypes.
- Smart use of the battery and fuel cell system can ensure that the fuel cell operates as close as possible to the power output which gives highest efficiency.



Bus fuel efficiency for various deployment projects, Element Energy

Clean Hydrogen Partnership

[1] Final Report_CHIC_28022017_Final_Public (fuelcellbuses.eu)
[2] DOE Technical Targets for Fuel Cell Systems and Stacks for Transportation Applications | Department of Energy
[3] Fuel Cell Electric Vehicle Durability and Fuel Cell Performance (nrel.gov)

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Further reducing the raw material burden for FCEV production will help to improve the long term sustainability credentials for hydrogen

Hydrogen Mobility Europe

Raw material requirement for FCEVs

- Hydrogen fuel cell vehicles have a relatively low resource intensity, see right: modelling from the Hydrogen Council and World Bank estimate that to achieve a scale up for hydrogen to account for 10% of total energy consumption by 2050, only platinum and iridium annual consumption would increase by a significant portion.
- The amount of platinum required for fuel cells is an area where it will be desirable to see continued improvements, both to decrease the cost of fuel cells and to improve the sustainability of the technology.
    - Substantial progress has already been made on reducing this (see bottom right), and the platinum requirement for passenger cars is now comparable to the platinum requirement for diesel catalysis.
- In PEM electrolysers, Iridium is used as a catalyst on the anode. Iridium is commercially produced typically as a by-product of platinum production, in small quantities (total annual production of c.7 tonnes/year).
    - The iridium requirement is projected to reduce by 80% by 2050[1]. Further R&D is required to reduce the catalyst loading of iridium in PEM electrolysers.

Annual consumption of selected raw materials in the 2050 scale up scenario relative to their annual production volumes in 2021[1]

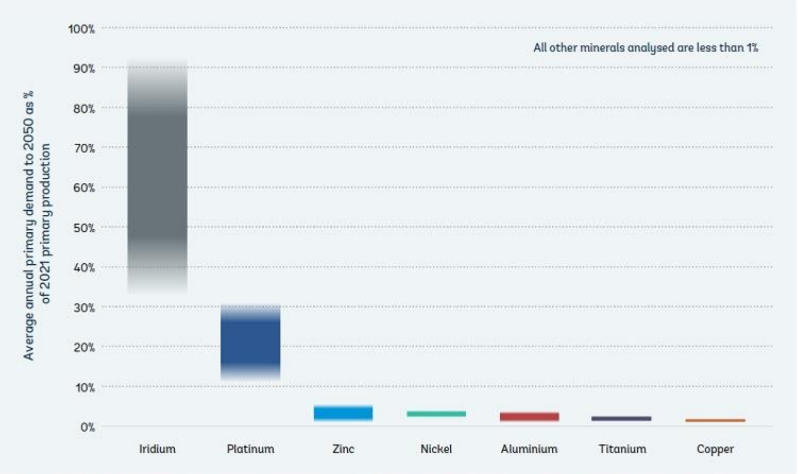
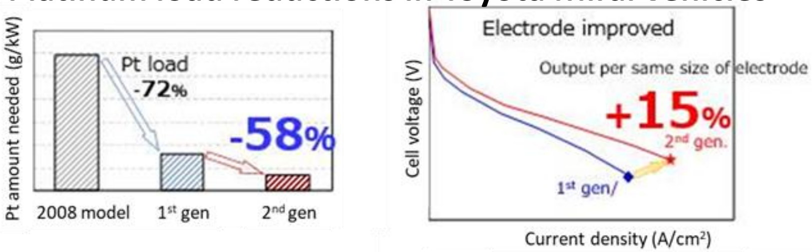


Figure ES1: Modelled average annual primary demand from clean hydrogen production and consumption to 2050 as a percentage of current primary production

Platinum load reductions in Toyota Mirai vehicles[2]



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[1] Sufficiency, Sustainability, and Circularity of Critical Materials for Clean Hydrogen | Hydrogen Council
[2] News & Media | UK H2Mobility

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There are several ongoing areas of R&D for HGVs, which are highlighted below given the importance of deploying HGVs to build out the HRS network

Hydrogen Mobility Europe

Developments in fuel cells for HGVs

- Global truck OEMS are increasingly looking at investing in the hydrogen heavy duty market.
  - Daimler and Volvo have formed a joint venture to develop fuel cells for heavy duty vehicle applications.
- Whilst most fuel cells used in HGV applications today scale up passenger car technology to the required performance level, Daimler and Volvo aim to develop a bespoke solution for HGV applications.
- The aim is to optimise the efficiency of fuel cells for HGV applications, and to align the geometry with the usual installation spaces of diesel engines to maximise storage space on the tractor unit (e.g. for H2 storage tanks).

Daimler Truck AG and Volvo Group fully committed to hydrogen-based fuel-cells - TruckingJobs.co.uk

700 bar and liquid H2

- In order to increase the range of commercial vehicles to be comparable to diesel, European OEMs are developing solutions that use hydrogen stored at 700 bar or in liquid form.
  - Iveco are developing HGVs to use 700 bar hydrogen, whilst Daimler plan to use liquid hydrogen tanks in their vehicles from the late 2020s.
- Developing vehicles that can store >50kg H_2 will be a novel development for commercial vehicle operation, and this presents a number of challenges that need to be addressed through R&D, e.g. safety implications, fuelling protocols to achieve adequate fill speeds, and how the fuel tanks are integrated into the limited space on the vehicle.

Hydrogen stations are beginning to move from a demonstration phase to commercialisation

Hydrogen Mobility Europe

Technical barriers to station performance

- Hydrogen stations have to date had mixed performance, with a number of different station designs being developed and trialled by different hydrogen refuelling companies.
- The following improvements are needed to ensure that hydrogen for mobility can be adopted by the mass-market.
- **Improvements in station design**
  - Stations should be designed to be multiply redundant (with multiple dispensers and compressors operating in parallel). This should help improve reliability from c.96% to >99%.
- **Improvements in component reliability**
  - The main causes of downtime at stations are the dispenser and compressor units. Investment into developing more reliable products for hydrogen refuelling stations should be considered.
- **Improvements in refuelling station interoperability**
  - Increased standardisation of stations will help to improve the user experience.
  - Currently, all new vehicle products typically require safe fuelling testing at each station design within the network. This could become unmanageable as the station network is built out, in particular as a variety of start ups and traditional companies look to invest in the sector.
  - In addition, stations often require individual drivers to complete safety training prior to granting access to sites. This again presents a barrier to uptake for FCEVs and could be unmanageable or frustrating for drivers.

Removing regulatory barriers will help to speed up the deployment of hydrogen stations and vehicles

Hydrogen Mobility Europe

Regulatory barriers

- There are a number of regulatory barriers to be addressed for H2 mobility to achieve mass commercialisation:

Planning & permitting for hydrogen stations

- Hydrogen refuelling stations have a lead time of c. 24 months from investment decision. Within this process, obtaining planning approvals typically takes between 3 months and 18 months.
- There is a large variation due to varying degrees of standardisation. In order to speed up station build, and reduce the costs associated with gaining planning permission, standardised process steps should be published by governing countries, and local authorities should be engaged with at an early stage.

Tunnel regulations

- Currently, hydrogen vehicles are prevented from entering a number of selected tunnels across Europe due to safety concerns related to the release of hydrogen in confined spaces.
- Safety risks for hydrogen vehicles are inherently mitigated when in the open air, due to the buoyancy of hydrogen in air meaning that hydrogen quickly escapes upwards in a loss of containment.
- There are safety studies currently underway to assess the risk of hydrogen-fuelled vehicles in tunnels, including the HyTunnel-CS project, which provides recommendations for optimising tunnel safety.

Training and safety standards

- Given that FCEVs are currently a niche market, safety protocols are often not implemented in local emergency departments, and there is a lack of standardised training programmes for drivers, technicians and safety staff. As a result, these often need to be developed on a case-by-case basis for projects.
- Hydrogen specific training programmes will gradually be implemented as the prevalence of vehicles increases.

Several technical barriers need to be overcome related to hydrogen production, such as the successful demonstration of CCUS at scale

Hydrogen Mobility Europe

Hydrogen production R&D

- The majority of hydrogen price at the pump is associated with hydrogen production costs, hence continued research is needed in this sector to minimise costs and increase the volume of low carbon hydrogen supply for the mobility sector.
- Examples of important research activities related to hydrogen production include:

Improving the efficiency of electrolysers

- Maximising electrolyser efficiency is important to reduce production costs associated with electricity consumption. Incumbent alkaline and PEM technologies have already seen efficiency improvements from scale-up, to around 70% system efficiency.
- As solid oxide electrolyser technology continues to mature, a switch to SOECs could improve efficiency to c.80%[1], and novel research into high performance electrolysis cells have demonstrated that efficiencies above 95% are possible.[2]

Developing CCUS technologies

- Large-scale CCUS for hydrogen production is largely yet to be demonstrated, however, a number of initiatives are investigating using blue hydrogen given the potential to decarbonise in a cost effective manner, depending on the relative price of electricity and natural gas.
- It is important that first-of-a-kind projects for blue hydrogen are implemented to demonstrate carbon capture rates of over 90%, as targeted by some blue hydrogen project developers.[3]

Clean Hydrogen Partnership

[1] Solid Oxide Based Electrolysis and Stack Technology with Ultra-High Electrolysis Current Density and Efficiency (energy.gov) [2] A high-performance capillary-fed electrolysis cell promises more cost-competitive renewable hydrogen | Nature Communications [3] 'Yes, our blue hydrogen project will increase electricity costs and fossil gas use, but society will benefit' | Recharge (rechargenews.com)

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Contents

1. Introduction

2. Progress under H2ME

3. Hydrogen Vehicle Developments

    FCEV market summary in Europe

    Light duty vehicle progress outside of Europe

    Contrasting with BEVs

4. Hydrogen light duty vehicle policy in Europe

    European wide political trends

    National policy strategies

5. Refuelling Infrastructure Developments

    Strategic developments

    Technical developments

6. Understanding the customer proposition

7. Remaining barriers to light duty vehicle commercialisation

    Economic barriers

    Competition for funding

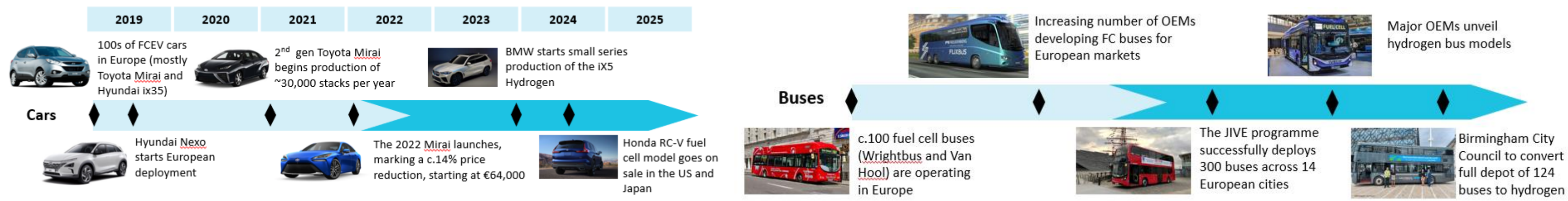
    Technical barriers

8. Conclusions and recommendations

Conclusions: Availability, price and performance of FCEV products are improving, and there are strong drivers to accelerate uptake

Hydrogen Mobility Europe

- There are a number of **new hydrogen vehicle models** being launched, in particular in the commercial vehicle sector, and the **deployment volume** for existing products has increased (e.g. order for 124 buses from West Midlands (UK)).
  - This will help achieve economies of scale for vehicle and fuel cell manufacture.

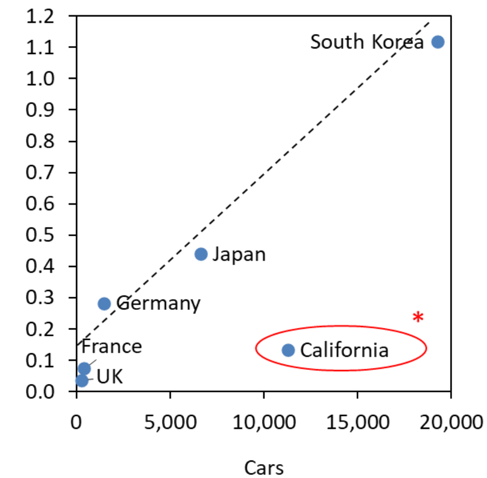


- There are strong drivers that are resulting in this increased interest in the sector, including:
- **Climate crisis**
  - Many countries and the EU as a whole remain committed to transitioning to decarbonised energy systems, and it is widely acknowledged that hydrogen produced from renewables will be required to achieve net zero.
- **Customer demand**
  - Customer feedback related to the OEM products deployed in H2ME project is overwhelmingly positive, and the vehicles provide a comparable driving experience to fossil vehicles.
- **Energy security**
  - The energy security crisis has heightened the political awareness in Europe of the importance of investing in technologies which provide energy independence and diversification. The hydrogen molecule and hydrogen vehicle components can be made in European countries, from European renewable sources.

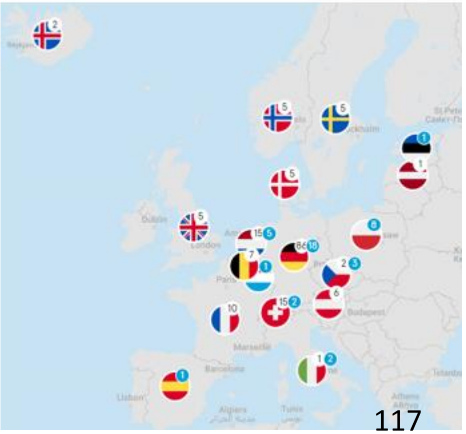
Conclusions: Provision of reliable hydrogen refuelling infrastructure at sufficient density is needed for further uptake of FCEVs

- The number of hydrogen light duty vehicles deployed is strongly linked to the number of hydrogen stations in a region.
- The European nation with most hydrogen stations and light duty vehicles is Germany, although these numbers are still substantially below the volumes in Japan, South Korea and California.
- Hydrogen stations are substantial infrastructure investments, costing several million euros, depending on specification.
  - In order to justify this investment and ensure the sale of cost competitive hydrogen, minimum demands of c.500-1,000 kg/day are required.
- Hydrogen light duty vehicles are not currently deployed in sufficient volumes to achieve this required critical mass, and hence stations are likely to be built around heavy duty demand (trucks and buses) in the near future.
  - Whilst buses are becoming increasingly commercially viable, HGVs are in small scale production and hence costs are high. Deployment projects will therefore require funding in the near term.
- Numerous European countries have announced ambitious targets for the number of hydrogen fuelling stations by 2030. For these to be achieved, private-public partnerships and deployment focused funding will be required in the near term.

Number of hydrogen stations & FCEVS per 1000 km²



Operational public HRS in Europe (October 2023)



Conclusions: There is strong competition for zero emission vehicle products, although there remain compelling reasons to invest in hydrogen

- Fully battery electric vehicle solutions are being commercialised by most of the automotive industry, and the deployment volumes for BEVs are nearly 1,000 times higher than for FCEVs.
  - BEVs are beginning to compete at even the heaviest weight classes (articulated trucks).
- However, hydrogen continues to be of interest for Governments, OEMs and transport operators for a number of reasons:
- **Refuelling time**, short refuelling times can increase fleet operability.
- **Payload and range performance**, hydrogen is more energy dense than batteries, hence H2 vehicles can travel further and reduce the payload for commercial vehicles less.
- **Energy system benefits**, hydrogen is a versatile energy vector. Hydrogen is likely to be deployed across the energy system, and the economics for hydrogen refuelling and production improve at scale.
- In the future, we expect that there will be a mix of hydrogen and battery technologies deployed, with increasing portions of hydrogen used for heavier weight classes.

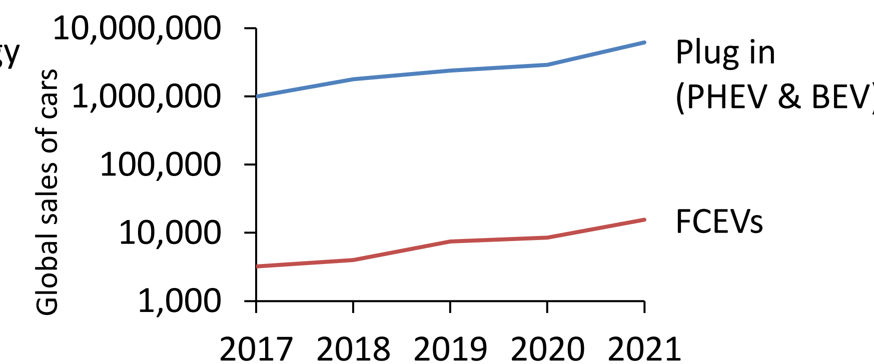
Scania launches BEV & PHEV truck series - electrive.com

Battery-electric trucks are our future (mantruckandbus.com)

Battery Electric Vehicles - DAF Trucks N.V.

Daimler Truck unveils battery-electric eActros LongHaul truck (fleetpoint.org)

Hydrogen car sales compared to plug-in cars



Recommendations: The most important recommendation for developing future hydrogen projects is to ensure stations are well-utilised

- **Ten key learnings** for future H2 mobility projects, based on H2ME findings, are summarised below:
  1. Build **large scale** hydrogen stations to ensure viable economics in the long term.
  2. Ensure that stations are **well utilised**, potentially through a variety of end users and vehicle models.
  3. Developing **multiple stations** in a confined geographic region is the best way to improve light duty vehicle uptake prospects.
  4. Early hydrogen deployments should be targeted at end users who will buy in to the technology, who need the performance benefits it offers and who may be willing to pay a premium.
  5. Baseload demand for hydrogen refuelling stations typically requires **public funding** and/or **novel business models** to overcome the upfront capital cost barrier.
  6. The key technical barrier to address is the **availability** of refuelling stations. This improves with large, well-utilised stations due to inbuilt redundancy and the continuous operation of components.
  7. Continued R&D to improve the **efficiency** of hydrogen vehicles will help to alleviate the cost premium for hydrogen fuel.
  8. Hydrogen vehicles have reduced in **price** substantially in price over the past decade. Further reductions to c.€40-50k could help to accelerate uptake, once a viable refuelling network emerges.
  9. Hydrogen station **build time** could be reduced in order to align better the lead time for vehicles and stations. This could help to mitigate the investment risk by closer aligning the investment decision for vehicles and stations. One key area that could be streamlined is the time for **site permitting**.
  10. Increased availability of **low cost green hydrogen** is needed to fuel the pipeline of mobility projects. A number of barriers should be removed for production projects, including but not limited to: reducing grid fees, improving availability of support through the Renewable Energy Directive and research into reducing the capex and improving the efficiency of electrolysers.

Acknowledgements

This project has received funding from the ***Fuel Cells and Hydrogen 2 Joint Undertaking*** *(now* ***Clean Hydrogen Partnership****) under Grant Agreement No 671438 and No 700350. This Joint Undertaking receives support from the European Union's Horizon 2020 Research and Innovation programme,* ***Hydrogen Europe*** *and* ***Hydrogen Europe Research****.*