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Fuel Cell Technology in the European Union

2024

STATUS REPORT ON TECHNOLOGY DEVELOPMENT, TRENDS, VALUE CHAINS & MARKETS

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Abstract

This report is an output of the Clean Energy Technology Observatory (CETO). CETO's objective is to provide an evidence-based analysis feeding the policy making process and hence increasing the effectiveness of R&I policies for clean energy technologies and solutions. It monitors EU research and innovation activities on clean energy technologies needed for the delivery of the European Green Deal; and assesses the competitiveness of the EU clean energy sector and its positioning in the global energy market.

CETO is being implemented by the Joint Research Centre for DG Research and Innovation, in coordination with DG Energy.

Foreword on the Clean Energy Technology Observatory

The European Commission set up the Clean Energy Technology Observatory (CETO) in 2022 to help address the complexity and multi-faceted character of the transition to a climate-neutral society in Europe. The EU's ambitious energy and climate policies create a necessity to tackle the related challenges in a comprehensive manner, recognizing the important role for advanced technologies and innovation in the process.

CETO is a joint initiative of the European Commission Joint Research Centre (JRC), who run the observatory, and Directorate Generals Research and Innovation (R&I) and Energy (ENER) on the policy side. Its overall objectives are to:

- monitor the EU research and innovation activities on clean energy technologies needed for the delivery of the European Green Deal
- assess the competitiveness of the EU clean energy sector and its positioning in the global energy market
- build on existing Commission studies, relevant information & knowledge in Commission services and agencies, and the Low Carbon Energy Observatory (2015-2020)
- publish reports on the Strategic Energy Technology Plan (SET-Plan) SETIS online platform

CETO provides a repository of techno- and socio-economic data on the most relevant technologies and their integration in the energy system. It targets in particular the status and outlook for innovative solutions as well as the sustainable market uptake of both mature and inventive technologies. The project serves as primary source of data for the Commission's annual progress reports on competitiveness of clean energy technologies. It also supports the implementation of and development of EU research and innovation policy.

The observatory produces a series of annual reports addressing the following themes:

- Clean Energy Technology Status, Value Chains and Market: covering advanced biofuels, batteries, bioenergy, carbon capture utilisation and storage, concentrated solar power and heat, geothermal heat and power, heat pumps, hydropower & pumped hydropower storage, novel electricity and heat storage technologies, ocean energy, photovoltaics, renewable fuels of non-biological origin (other), renewable hydrogen, solar fuels (direct) and wind (offshore and onshore).
- Clean Energy Technology System Integration: building-related technologies, digital infrastructure for smart energy system, industrial and district heat & cold management, standalone systems, transmission and distribution technologies, smart cities and innovative energy carriers and supply for transport.
- Foresight Analysis for Future Clean Energy Technologies using Weak Signal Analysis
- Clean Energy Outlooks: Analysis and Critical Review
- System Modelling for Clean Energy Technology Scenarios
- Overall Strategic Analysis of Clean Energy Technology Sector

More details are available on the CETO web pages

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Executive Summary

Hydrogen serves as an *energy carrier* that can generate alternative fuels and downstream products like e-ammonia. It can also be *a decarbonised gas produced through renewable electricity*[1]. With the capability to decarbonise hard to abate sectors that are not easily electrified, hydrogen is pivotal in reaching the 2050 net zero emissions goal.

The European Commission has defined the policy framework and essential steps for the advancement and deployment of renewable hydrogen[2] within the 2030 timeframe through the Hydrogen Strategy for a Climate Neutral Europe Communication[3] (the Hydrogen Strategy). The REPowerEU Communication[4] reinforces the goal of producing up to 10 million tonnes annually and anticipates importing the same amount by 2030. The Green Deal Industrial Plan designates water electrolysers and fuel cell technologies as key decarbonisation tools capable of supporting Europe's climate objectives. Additionally, the associated Net Zero Industry Act[5] advocates for streamlined permitting processes and improved access to funding, while also reducing the EU's reliance on Critical Raw Materials (CRM) through the Critical Raw Materials Act[6].

European financing mechanisms are currently in place at both EU and Member State levels. The approval of the 3rd and 4th Important Projects of Common European Interest (IPCEI) in 2024 has resulted in a total of EUR 18.9 billion of public funding, mobilising an expected EUR 15.7 billion in private investment to support the development of the hydrogen market. In particular, the 4th IPCEI "Hy2Move" focuses on the development of mobility and transport applications, high-performance fuel cell technologies, next-generation on-board hydrogen storage solutions, and technologies to produce hydrogen for mobility and transport applications. The first auction of European Hydrogen Bank successfully awarded 7 projects in 2024, matching long-term offtake agreements between producers and buyers with a first auction of EUR 720 million for the production of 1.58 million tonnes over 10 years. A second auction of EUR 1.2 billion is planned for the end of 2024. Furthermore, the EU has allocated over EUR 528 million between 2008 and 2023 through the Clean Hydrogen Joint Undertaking for advancing the penetration of hydrogen and fuel cell technologies in the transport sector, channelling additional EUR 630 million from partners. Lastly, from all national Recovery and Resilience Plans (RRPs), EUR 42 billion are earmarked to support hydrogen technologies, with an additional EUR 12 billion exclusively dedicated to hydrogen technologies among other categories.

With regard to technology aspects, fuel cells remain innovative energy conversion devices to provide efficient and clean power generation using hydrogen as a fuel. Six main fuel cell technologies are identified: Polymer Exchange Membrane Fuel Cells (PEMFC), Solid Oxide Fuel Cells (SOFC), Alkaline Fuel Cells (AFC), Molten Carbonate Fuel Cells (MCFC), Phosphoric Acid Fuel Cells (PAFC), and Proton Conducting Fuel Cells (PCFC). PEMFC for mobility applications, and PEMFC and SOFC for stationary applications are the most mature and well-established technologies, with MCFC, PAFC and AFC seeing declining market shares and PCFC at a much earlier development stage. SOFC, MCFC and PCFC work at higher temperature, can recover high grade waste heat from other industrial processes and intrinsically operate at higher electrical efficiencies.

In the last decade, global fuel cell installed capacity (GW) has experienced steady growth, primarily driven by Asia, followed by North America and Europe. Estimates indicate that in 2021, the total worldwide fuel cell installed capacity ranged between 6.9 – 7.3 GW, with European installed capacity (EU + UK, NO, CH) ranging between 0.5 – 0.6 GW, representing 8.1 – 8.3 % of the total capacity worldwide. Although the overall installed capacity has grown, recent data shows a stagnation in worldwide installed capacity, with a slowing growth rate. By 2023, the fuel cell installed capacity in Europe (EU + UK, NO, CH) was estimated to be around 0.6 GW, accounting for 7.7 % of the total installed capacity worldwide. The Asian region continues to lead the fuel cell deployments, with transport applications (PEMFC) dominating the market share, followed by stationary fuel cells used in residential, commercial, and industrial sectors. Portable fuel cells, on the other hand, represent only a small fraction of the total fuel cell market.

[1] Renewable hydrogen can also be derived from low carbon biomass sources meeting a 70% CO_2 reduction target as defined by the European Taxonomy. This is however not relevant for the current report on electrolysis and in the following report 'renewable hydrogen' will refer to hydrogen produced by electrolysis powered by renewable electricity.

[2] Renewable hydrogen, as defined in the Hydrogen Strategy, is hydrogen produced through the electrolysis of water (in an electrolyser, powered by electricity), and with the electricity stemming from renewable sources.

[3] A hydrogen strategy for a climate-neutral Europe, COM(2020) 301 final.

[4] REPOWEREU Plan - COM(2022) 230 final.

[5] Proposal for a Regulation of the European Parliament and of the Council on establishing a framework of measures for strengthening Europe's net-zero technology products manufacturing ecosystem (Net Zero Industry Act) (COM(2023) 161 final)

[6] Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL establishing a framework for ensuring a secure and sustainable supply of critical raw materials and amending Regulations (EU) 168/2013, (EU) 2018/858, 2018/1724 and (EU) 2019/1020 (2023/0079(COD))

In terms of mobility applications, the global fleet of fuel cell electric vehicles (FCEVs) is approaching 80 000, with Rep. Korea and China leading the market for cars, buses, and trucks. The expansion and diversification of fuel cell applications is expected as sustainable transportation gains traction, particularly in heavy-duty road transport. In terms of stationary applications, Asia has taken the lead with 0.9 - 1.2 GW installed capacity for stationary fuel cells, while the US has experienced stalled installation volumes. In Europe, the total installed capacity is approximately 10 % of the global capacity, with a focus on decarbonisation efforts and a lower priority for stationary fuel cell deployment. Europe aims to use renewable hydrogen to decarbonise hard-to-abate sectors, such as heavy-duty mobility, while renewable hydrogen is considered too valuable for typical stationary fuel cell applications, despite offering higher efficiency. Most stationary fuel cells deployed globally are running on natural gas, limiting their decarbonisation benefits.

Efforts are being made to expand manufacturing capacity in Europe. The projected increase in manufacturing capacity for fuel cells may outpace market demand, particularly in Europe where manufacturers are concentrating on producing stacks and systems for the heavy-duty sector despite the current low deployment numbers in mobility applications. As for electrolysers, public support for hydrogen end-use technologies will be crucial in the coming years.

Analysis of fuel cell system costs for mobility applications, such as FCEVs and fuel cell electric buses (FCEBs), reveals a lack of comprehensive data from manufacturers. The data available shows that the costs reported by the FCEV and FCEB demonstration projects have surpassed the costs targeted set by organisations such as the Clean Hydrogen Partnership and the US Department of Energy. The estimated costs for fuel cell systems assuming production of 100 000 systems/year significantly surpasses the 100 EUR/kW figure for FCEV projects. The cost of fuel cell systems for FCEBs has varied among projects and models, and while the costs observed are for small fleets in demonstration projects and not at mass production level, they have generally surpassed the targets with values of 1 000 EUR/kW. The analysis also indicates that further efforts are necessary to lower fuel cell system costs for mobility applications. On the other hand, for stationary applications, the cost of manufacturing micro, mid-size, and large-scale combined heat and power (CHP) fuel cell units has been targeted for reduction by organisations such as the Clean Hydrogen Partnership. The targets set for 2030 aim for a significant reduction in costs, and as of 2024, some manufacturers have achieved the 2024 targets for micro (5 000 - 6 000 EUR/kW), mid-size (1 800 – 5 000 EUR/kW) and large-scale CHP installations (1 200 – 5 000 EUR/kW)[7], while the exact CAPEX values remain confidential. Similar to mobility applications, further efforts are required to achieve the cost reduction targets for stationary applications. It is also noteworthy that the production of hydrogen fuel itself, through electrolysis, is a costly endeavour as analysed in the CETO water electrolysis report.

The EU and Japan collectively accounted for 65 % of total global public investments in fuel cells from 2013 to 2023, with the EU's contribution of 48 % being particularly significant. Private investments in the EU and globally outweigh public investments, with the EU showing a substantial increase in private investment from 2010 to 2020, led by Germany. Japan represents the highest percentage of cumulative private investments globally. Although global venture capital investments in fuel cell companies have fluctuated, there was a notable increase in 2022, primarily driven by Chinese firms. However, early-stage and later-stage investments in EU VC companies have decreased, indicating a competitive position stagnation in the global investment race. Despite a weak internal market, Europe plays a prominent role as an international patenting actor and is involved in research and development activities, demonstrating a strong global scientific presence alongside China and the US.

Only 3 % of raw materials, 18 % of processed materials, and 25 % of components used in fuel cell manufacturing are generated in Europe. Additionally, Europe heavily relies on foreign sources, particularly China, for critical raw materials needed for fuel cell production. The situation is compounded by competing demands from various industries and poor social governance in these source countries, which is likely to keep prices high for these materials. While Asian companies dominate the supply chain steps, Europe holds the highest share in components and processed materials production.

The following SWOT table summarises the factors relating to the EU's competitiveness in the hydrogen fuel cell sector.

[7] The targets refer to SOFC and PEMFC respectively.

Table 1. CETO SWOT analysis for the competitiveness of fuel cells in the EU.

Strengths	Weaknesses
– Established European regulatory framework supporting the deployment of fuel cell manufacturing capacity, where fuel cell manufacturing facilities would enjoy a faster permitting and access to funding (Net Zero Industry Act). – Approval of 4 Important Project of Common European Interest (IPCEIs: Hy2Tech, Hy2Use, Hy2Infra, Hy2Move) for a total of EUR 18.9 billion of state aid exemption, supporting research, innovation and infrastructure development across the whole hydrogen value chain and catalysing coordination between European industrial stakeholders. – Established binding targets for the decarbonisation of transport (Regulation EU 2019/1242 on CO_2 emissions standards for heavy-duty vehicles, FuelEU maritime, ReFuelEU aviation). – Growing manufacturing capacity in Europe. Europe has the highest number of PEMFC and SOFC manufacturers and the highest number of fuel cell production lines. – European companies have a strong presence as international patent holders.	– Europe presents a low fuel cell installed capacity and a weak market for fuel cells compared to other regions. Asia is leading in fuel cell vehicle deployments. – European manufacturers rely heavily on public funding (EU's contribution of 48 % of total global public investments in fuel cells from 2013 to 2023). – Europe presents high manufacturing costs of fuel cell systems. – Despite having the highest number of production lines of fuel cells, European manufacturing capacity is relatively small (many small to medium size companies with limited manufacturing capacity). – Lack of a recycling infrastructure for fuel cell stacks. – Very high European reliance on imports of critical raw materials, which is partly addressed through the proposal on the Critical Raw Materials Act. – Additional emerging challenges for Research and Innovation, such as related to the replacement or substitution of materials in the membranes of fuel cells, some of which contain Per- and polyfluoroalkyl substances (PFAS).
Opportunities	**Threats**
– The implementation of the IPCEIs with effects on creating economies of scale and manufacturing capacities in Europe. Increasing coordination between industrial stakeholders could foster innovation and accelerate the uptake of fuel cells and the development of a coordinate infrastructure framework at European level. – Rich European system of manufacturers which could increase through funding schemes (such as IPCEI). – Europe holds an outstanding global share of public funding that could further improve technical competitive advantages (e.g. patents). – Europe involvement in international standardisation committees. – Research and Innovation initiatives should pursue opportunities to substitute PFAS, CRMs and define recycling solutions.	– Other competing technologies for decarbonisation offering lower total cost of ownership (TCO) and technical advantages. – High fuel costs relevant for TCO analysis. – Costs of production and assembly of stacks against other economies seem not competitive. – The US and China maintain or accelerate their public efforts in advancing the deployment manufacturing capacities of hydrogen technologies. – Lack of political mandate for deploying fuel cells.

Source: JRC analysis

1 Introduction

1.1 Scope and context

This report on fuel cells, produced by the Clean Energy Technology Observatory (CETO), is part of an annual series that examines technology maturity, development trends, value chain analysis, and global market positioning. It is the first report on this technology but builds on previous work by the JRC such as the historical analysis on fuel cell electric vehicles, buses and refuelling stations [1]. There are links between fuel cell technology and electrolysis, of which the latter is covered in a separate CETO report. Given the dominance of fuel cells in transport applications, most of the insights discussed in this report will primarily concentrate on PEMFC in transportation applications. Fuel cells for stationary applications will also be discussed based on data availability.

Renewable and low-carbon hydrogen can serve as an industrial feedstock or energy carrier, offering a significant potential for decarbonising hard-to-abate sectors that are difficult to electrify directly, including industrial processes like steel and cement production, ammonia, and fertilisers. Additionally, hydrogen can be used as fuel for fuel cells in heavy-duty transportation and long-distance transport, as well as a support for energy storage systems, particularly for seasonal applications. Stationary fuel cells can be deployed in residential and commercial sectors to provide heat and power.

The EU has made significant progress in climate action through various legislative frameworks, such as the 2030 Climate & Energy Framework, the Clean Energy for all Europeans package, and the European Green Deal. The EU's commitment to reducing greenhouse gas emissions is reinforced by the Fit-for-55 package, which was followed by the Alternative Fuels Infrastructure Regulation and the Hydrogen and Gas Markets Decarbonisation package. The REPowerEU Plan sets even more ambitious goals for renewable energy production and hydrogen integration in response to geopolitical shifts and the need for energy security. The NextGenerationEU and the European Hydrogen Strategy highlight the EU's dedication to establishing a robust hydrogen economy for sector decarbonisation.

Hydrogen's potential in the decarbonisation of the EU's energy system is significant, with its applications ranging from the chemical industry to integration of renewable energy sources. The EU's strategies and policies focus on scaling up hydrogen production and usage, particularly in hard-to-decarbonise sectors like heavy transport. The Fit-for-55 package and the REPowerEU Plan outline the role of hydrogen, setting specific targets for its production and use. The REPowerEU Plan strengthens previous hydrogen-related policies by increasing deployment targets through its Hydrogen Accelerator Pillar.

The Fit-for-55 package aims to align EU climate, energy, land use, transport, and taxation policies with the European Green Deal targets. The Alternative Fuels Infrastructure Regulation (AFIR) sets deployment targets for 2025 and 2030, mandating hydrogen refueling stations for cars and trucks from 2030 onwards in all urban nodes and along the Trans-European Transport (TEN-T) core network. The EU Emissions Trading System (EU-ETS) package extends to buildings, road transport, and maritime sectors, while introducing a Social Climate Fund to address the social impacts of the new system on vulnerable groups. The Carbon Border Adjustment Mechanism (CBAM) is part of this package, aiming to level the price of carbon between domestic products and imports.

According to the Renewable Energy Directive (RED) III, by 2030, hydrogen and e-fuels must account for at least 1 % of all transportation fuels, with double-counting for Renewable Fuels of Non-Biological Origin (RFNBOs) in the target. A multiplier allows for RFNBO use in aviation and shipping to count with a factor of 1.5. The recently adopted update of the EU Regulation on CO_2 emission standards for new heavy-duty vehicles has the revised targets including a 45 % reduction in emissions from 2030 (up from 30 %), a 65 % reduction from 2035 and a 90 % reduction from 2040. These targets apply to medium lorries, heavy trucks over 7.5 tons, and coaches, as well as their related vocational vehicles from 2035 onwards. Additionally, a 100 % zero-emission target for new urban buses is established by 2035, with an intermediate target of 90 % for this category. FuelEU Maritime focuses on reducing GHG emissions in the shipping sector by boosting demand for renewable and low-carbon fuels. However, it may encourage Liquified Natural Gas (LNG) more than RFNBOs in the first 10 years. ReFuelEU Aviation aims to increase Sustainable Aviation Fuels (SAF) demand and supply, including renewable hydrogen in aviation.

Four Important Projects of Common European Interest (IPCEIs) have been launched in the hydrogen value chain, featuring 99 companies in 16 Member States and Norway. These IPCEIs are expected to unlock over €27.1 billion in additional private investment, supported by up to €18.9 billion in national funding.

The first hydrogen IPCEI, IPCEI Hy2Tech, focuses on hydrogen technology and includes 35 companies from 15 member states. The project covers various aspects of the hydrogen technology value chain, including hydrogen generation, fuel cells, storage, transportation, distribution, and end-user applications, particularly in the mobility sector. This IPCEI is expected to create approximately 20 000 direct jobs and contribute to technological breakthroughs such as new electrode materials and more performant fuel cells. The workstream on fuel cells technology has 17 companies participating, among them Bosch, Alstom, Daimler Truck and Plastic Omnium. On 28 May 2024, the European Commission approved IPCEI Hy2Move as the fourth hydrogen IPCEI, with 11 companies from seven member states participating in 13 projects. IPCEI Hy2Move also covers a wide range of the hydrogen technology value chain, including the development of mobility and transport applications, high-performance fuel cell technologies, next-generation on-board hydrogen storage solutions, and technologies to produce hydrogen for mobility and transport applications. The projects aim to integrate hydrogen technologies in road, maritime, and aviation sectors, such as fuel cell vehicle platforms for buses and trucks, high-performance fuel cell technologies for ships and locomotives, and lightweight, robust hydrogen tanks for aircraft. The seven member states will provide up to EUR 1.4 billion in public funding, which is expected to unlock additional private investments of EUR 3.3 billion, resulting in a total of over EUR 4.7 billion. The workstream fuel cell technology has the participants Airbus, BMW, Hydrogene de France, Michelin and UFI.

As to the international context, China, the USA, Japan, and Rep. Korea are making significant strides in the hydrogen economy, driven by the need to reduce carbon emissions and improve air quality. China has set a target of 50 000 fuel cell electric vehicles (FCEVs) on the road by 2025, with a longer-term goal of 1 million by 2030, and plans to build over 1 000 hydrogen refueling stations by 2025. The Chinese regulatory framework is still evolving, with the National Development and Reform Commission issuing guidelines for hydrogen industry development and the Ministry of Science and Technology launching a hydrogen fuel cell technology innovation program.

The Inflation Reduction Act (IRA) in the USA provides a framework for hydrogen production tax credits, with four tiers of credits ranging from USD 3.0/kg to USD 0.6/kg, depending on the carbon intensity of the production process. The IRA also funds hydrogen infrastructure development and research.

Japan's Hydrogen Basic Strategy aims to create a hydrogen-based society by 2050, focusing on transportation, power generation, and industrial applications. The country has set targets of 200 000 FCEVs by 2025 and 800 000 by 2030. Japan's Ministry of Economy, Trade and Industry has established a hydrogen roadmap for supply chain and infrastructure development.

Rep. Korea has also set ambitious targets, aiming to produce 6.2 million tons of hydrogen by 2040 and have 6 200 hydrogen refueling stations by 2040. The government has launched a hydrogen economy roadmap, which includes support for hydrogen production, distribution, and consumption.

1.2 Methodology and Data Sources

The report has been written following the CETO methodology that addresses three principal aspects:

a) Technology maturity status, development and trends

b) Value chain analysis

c) Global markets and EU positioning

Each of these principal aspects uses a series of specific topics or indicators common to all the CETO technology reports. There are addressed to the extent that data is currently available. Annex 1 provides a summary of the indicators for each aspect, together with the main data sources.

The report uses the following information sources:

- Existing studies and reviews published by the European Commission;
- Information from EU-funded research projects;
- EU trade data, trade association reports, market research provider reports and others as appropriate;
- JRC own review and data compilation.

Details of specific sources are given in the corresponding sections.

2 Technology status and development trends

2.1 Technology readiness level

Fuel cells (FC) are energy conversion devices that have gained significant attention due to their potential to provide efficient and clean power generation. They are deployed in a diverse range of applications, from stationary power generation to mobile applications, such as transportation. The technology behind fuel cells encompasses various types, each tailored to specific applications and operating conditions, including proton exchange membrane fuel cells (PEMFC), solid oxide fuel cells (SOFC), and molten carbonate fuel cells (MCFC), among others. This section will provide an overview of fuel cells, their applications, the different technology types, and the different technology readiness levels, shedding light on the advancements and potential of this sustainable energy technology.

A fuel cell consists of three main active components: a fuel electrode (anode), an oxidant electrode (cathode), and an electrolyte in between. They can be implemented at various scales, from small capacity portable power sources in the mW range to multi-MW power generation.

Stationary FC provide electricity and sometimes heat, and are designed not to be moved. These applications include Combined Heat and Power (CHP), primary power units and back-up power units (e.g. uninterruptible power systems (UPS)). More commonly FC are used to provide power for mobility applications, such as cars and buses. Portable power is another application of fuel cells, almost negligible in terms of deployment however. Fuel cells stacks for stationary applications are typically installed in systems with external or internal reformers and run on natural gas or biogas. For mobility the fuel is commonly hydrogen. The requirements for the purity of hydrogen vary between the fuel cell types, with low temperature PEMFC having the most stringent specifications for fuel quality. High temperature fuel cells, which often have internal reforming capabilities, can run on a variety of (gaseous) fuels and are less susceptible to contaminants.

The different FC technologies are detailed below with their main characteristics and Technology Readiness Levels (TRL) summarised in Table 2 and Table 3, respectively.

Polymer electrolyte membrane fuel cells (PEMFCs) feature a proton-conducting polymeric membrane, such as Nafion or Fumapem, that separates porous electrodes and performs the functions of proton conduction, electronic insulation, and gas separation. The electrodes comprise a gas diffusion layer with a catalyst coating and a microporous layer. A Membrane Electrode Assembly (MEA) includes the membrane, bipolar flow plates, and electrodes. Hydrogen oxidation and oxygen reduction reactions occur at the anode and cathode, respectively, catalysed by platinum, driving up costs. To mitigate catalyst poisoning, high-purity hydrogen is necessary. PEMFCs typically operate within a temperature range of 60-80°C. The Balance of Plant (BoP) of a PEM fuel cell is composed of the peripheral equipment: water and thermal management, air blowers, humidifiers, control and operating systems and power conditioning.

The TRL of this technology is 9, except for specific applications, such as maritime or aviation.

High Temperature PEM fuel cells (HT-PEMFC), operating at 120-180°C can better tolerate impurities, such as carbon monoxide, and also have the advantages of improved performance, simplified water management and possible use of produced heat. HT-PEM are at a low TRL, with few commercial products on the market. The main challenges are durability and cost. PBI based membranes are used, and although these are less costly than Nafion, a much higher amount of catalyst loading is necessary, on the order of 2.5 times [2].

Solid oxide fuel cells (SOFCs) operate at elevated temperatures, typically above 600°C, for ions to be able to pass through solid electrolytes. The electrolyte material is often yttria-stabilised zirconia (YSZ), and the operation temperature depends on the electrolyte type. The cathode is usually a perovskite material, such as strontium-doped lanthanum manganite, while the anode is a nickel and YSZ cermet. The high temperature enhances reaction kinetics, allowing for non-precious metal catalysts like nickel and the usage of fuels other than hydrogen, such as CO. This high-temperature operation also generates high-quality heat for cogeneration or tri-generation applications. SOFC are most commonly deployed as micro-CHP for residential applications. SOFC have a high TRL, but are not fully commercialised yet. Issues such as cost, durability and maintenance are still hindering further deployment.

Alkaline fuel cells (AFC) employ an aqueous, highly conductive potassium hydroxide (KOH) solution as an electrolyte, operating within a temperature range of 70-250°C based on KOH concentration. Reactions occur at a triple-phase boundary where gas, liquid, and solid catalyst meet. Electrodes must withstand a corrosive alkaline environment and varying oxidizing and reducing conditions. The alkaline setting enhances oxygen reduction reaction kinetics at the cathode without requiring noble metal catalysts. With hydrogen supply, electrical efficiency can surpass 60%. Although this type of FC has been deployed for back-up power and off-grid solutions, there does not seem to be a strong market. Degradation of the electrodes still seems to be a challenge.

In a Molten Carbonate Fuel Cell (MCFC), the electrolyte is composed of a molten mix of alkali carbonates, either lithium-potassium or lithium-sodium based, with carbonate ions serving as charge carriers. MCFCs operate at temperatures ranging from 600 to 700°C. The cathode material is primarily nickel oxide, which faces a highly corrosive environment that may lead to material degradation. The anode consists of nickel alloys. The electrical efficiency of an MCFC is approximately 50%, with an overall energy efficiency of over 80%. Carbon dioxide recycling is essential in this system, as it needs to be transferred from the anode to the cathode. This process allows for easy CO_2 separation from the gas stream. Additionally, it is possible to generate extra hydrogen through a "tri-generation" method if there is local demand for it. MCFC systems, commercially available in the MW range (TRL 9), are widely used for heat and power production in Rep. Korea and the US.

Phosphoric Acid Fuel Cell (PAFC), are a type of fuel cell that utilises liquid phosphoric acid as the electrolyte. They were the first commercialized fuel cells (TRL 9), developed in the mid-1960s and tested since the 1970s, with notable improvements in stability, performance, and cost. The electrolyte consists of highly concentrated or pure liquid phosphoric acid saturated in a silicon carbide matrix, operating at a temperature range of 150 to 210 °C. Carbon paper with a finely dispersed platinum catalyst coating forms the electrodes. When stationary fuel cells for power generation started emerging around 50 years ago in the US, it was initially with PAFC systems for distributed power and co-generation. Global installations of PAFC had reached around 200 MW in 2017 [3]. The US saw significant growth in PAFC deployment for several years, with more recent installations mainly occurring in South Korea. Their low efficiency seems to hinder further development and deployment.

Proton Conducting Fuel Cells (PCFC), also known as Proton Ceramic Fuel Cells are a type of fuel cell that utilises proton ceramic conductors. While solid oxide fuel cells (SOFC) must function at temperatures above 700°C, as they employ oxygen-conducting electrolytes, ceramic proton conductors can operate in a temperature range of 400-600°C due to the lower activation energy of protons compared to oxide ions. This intermediate temperature benefits from numerous advantages of high-temperature operation while avoiding drawbacks such as material and sealing challenges. PCFC do not require precious metal catalysts, and their stacks could be more cost-effective to produce than SOFC, as they involve fewer high-temperature firing steps. In general, the lower overall operating temperature allows for the use of more affordable materials. This technology is at low TRL.

Table 2. Characteristics of the five main fuel cell technologies.

Fuel Cell Type	Operating Temperature	Typical Electrical Efficiency (Lower Heating Value)	Typical power range (kW)	Applications	Advantages	Challenges
Polymer Electrolyte Membrane or Proton Exchange Membrane (PEMFC) or Solid Polymer (SPFC)	<80°C	60% direct H_2; 40% reformed fuel	1 – 100	Back-up power Portable power Distributed generation Residential CHP Transportation	Solid electrolyte reduces corrosion & electrolyte management problems Low temperature Quick start-up and load following	Expensive catalysts Sensitive to fuel impurities
High temperature Polymer Electrolyte Membrane (HT-PEM)	120-180°C	50-60%	0.3 – 5	Auxiliary power Back-up power Residential CHP	Higher tolerance to impurities such as CO Easier water management No humidification needed Possible use of produced heat	High Pt loading Lower power density than LT PEM Degradation
Solid Oxide (SOFC)	500 - 1000°C	60%	1 – 2000	Auxiliary power Electric utility Distributed generation Residential CHP	High efficiency Fuel flexibility Solid electrolyte Suitable for CHP Potential for reversible operation Suitable for Hybrid/gas turbine cycle	High temperature corrosion and breakdown of cell components Long start-up time Limited number of shutdowns
Alkaline (AFC)	<100°C	60%	1 – 100	Military Space Back-up power Off-grid power	Wider range of stable materials allows lower cost components Low temperature Quick start-up	Sensitive to CO_2 in fuel and air (carbonate precipitation) Electrolyte management
Molten Carbonate (MCFC)	600 - 700°C	50%	300 – 3000	Electric utility Distributed generation Auxiliary power	High efficiency Fuel flexibility Suitable for CHP Suitable for hybrid/gas turbine cycle Suitable for Carbon Capture	High temperature corrosion and breakdown of cell components Long start-up time Low power density

Fuel Cell Type	Operating Temperature	Typical Electrical Efficiency (Lower Heating Value)	Typical power range (kW)	Applications	Advantages	Challenges
Phosphoric Acid (PAFC)	150 - 200°C	40%	5 – 400	Distributed generation	Suitable for CHP Increased tolerance to fuel impurities	Low efficiency Low power density Expensive catalysts Long start-up time Sulfur sensitivity
Proton Ceramic (PCFC)	400-600°C	Under development		Auxiliary power Distributed generation CHP	Lower temperature than SOFC	Materials issues Sensitive to CO_2

Source: Adapted from European Commission DG JRC, 2021, [4]

Table 3. TRL of the different fuel cell technologies.

	TRL (Technology Readiness Level)								
Sub-Technology	1	2	3	4	5	6	7	8	9
PEM[8]									
SOFC									
AFC									
MCFC									
PAFC									
PCFC									

Source: JRC estimate

There are several European R&D roadmaps for the development and implementation of the different fuel cell technologies which are detailed below:

SET-Plan (category Clean Transport). The European Commission's Strategic Energy Technology (SET) Plan includes a roadmap for the development and deployment of hydrogen and fuel cells as part of its overall strategy for decarbonising the energy system.

European Clean Hydrogen Alliance: This is a new initiative launched in 2020 as part of the EU's Hydrogen Strategy. The alliance aims to develop a clean hydrogen industry in Europe by 2030, with a focus on scaling up production, infrastructure, and demand. The alliance works closely with SET-Plan and other European R&D initiatives to coordinate research efforts and promote innovation in the hydrogen sector.

Clean Hydrogen Partnership: This is a public-private partnership between the European Commission and the hydrogen and fuel cell industry. The Clean Hydrogen Partnership, former FCH JU and FCH2 JU, funds research and demonstration projects in the areas of hydrogen production, storage, and distribution, as well as fuel cell technologies for transport, buildings, and industry. It has developed a research and innovation roadmap for hydrogen and fuel cells, outlining the key priorities and actions needed to advance the technology in Europe. Their Strategic Research and Innovation Agenda (SRIA) outlines the key performance indicators of hydrogen technologies, including fuel cell and electrolyser technologies, hydrogen production and storage, and integration with energy systems.

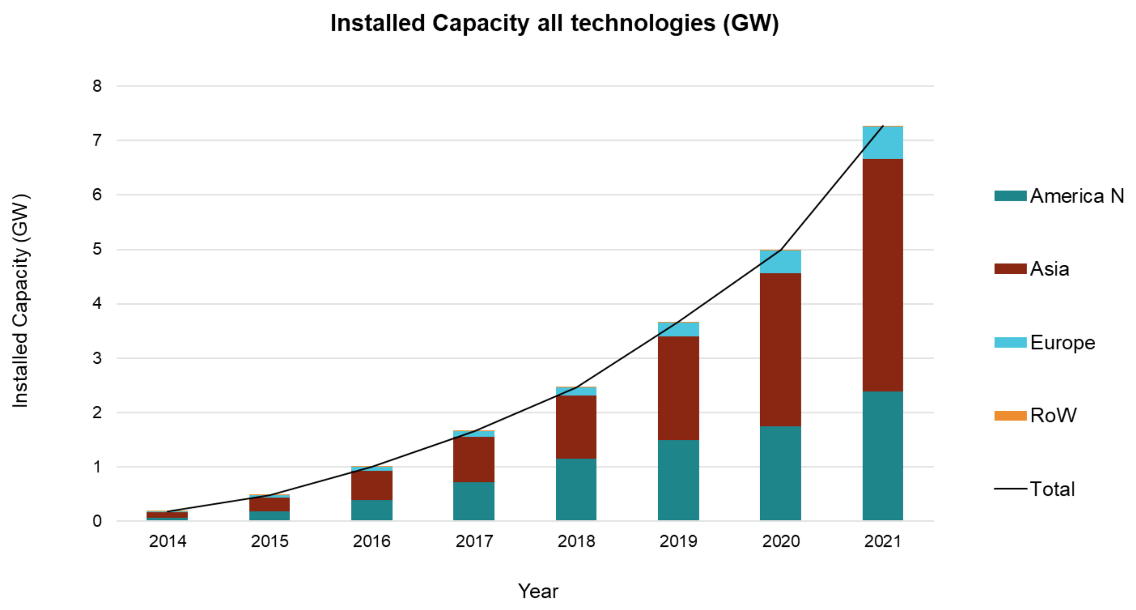
8 There are still R&D needs for specific applications, for example high power density (HT) PEMFC for aviation.

2.2 Installed Capacity and Production

2.2.1 Current situation and short-term forecasts

The fuel cell installed capacity (GW) worldwide has seen an steady growth over the last decade as it can be observed in Figure 1 [5]. Asia has been leading this growth, followed by North America and Europe. Estimates from different sources showed that the total fuel cell installed capacity in 2021 ranged between 6.9 – 7.3 GW worldwide. European installed capacity (EU + UK, NO, CH) ranged between 0.5 – 0.6 GW which represented 8.1 – 8.3 % of the total capacity worldwide.

Figure 1. Past evolution of total installed capacity (GW) per region for all fuel cell technologies (cumulative)

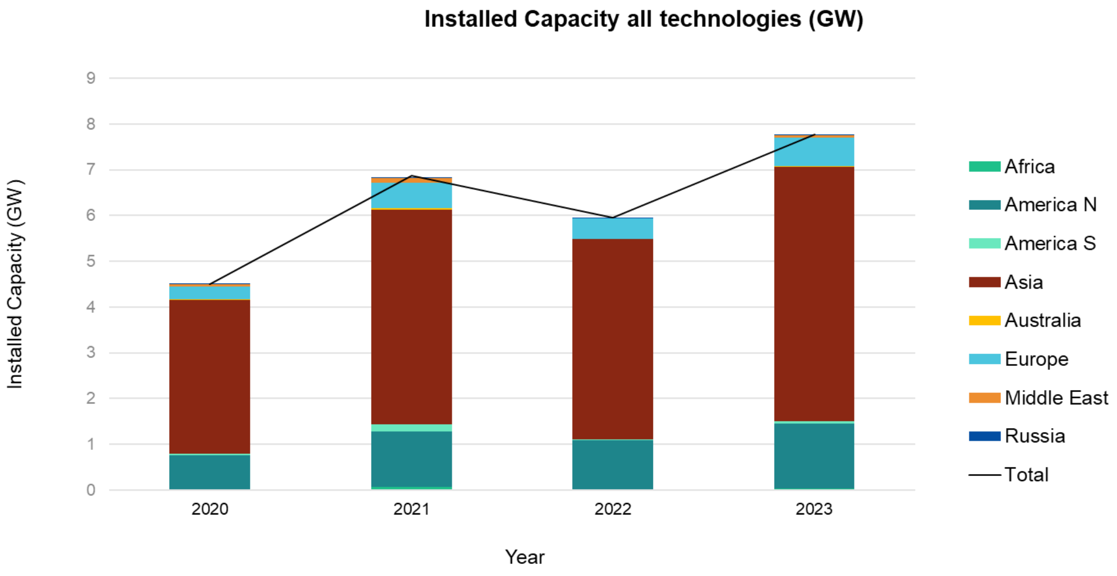


Source: European Hydrogen Observatory, 2021, [5]

Figure 2 shows the evolution of the fuel cell installed capacity in recent years, based on modelling estimations from the Rystad Energy database (years 2020-2023) [6]. It is evident that the worldwide installed capacity is stagnating recently as despite the overall increase, the growth rate is slowing down. In 2023, the fuel cell installed capacity in Europe (EU + UK, NO, CH) could be estimated around 0.6 GW, against a global installed capacity of around 7.8 GW. This represents 7.7 % of the total installed capacity worldwide. The Asian region (mainly Rep. Korea, Japan and China) continues to lead the fuel cell deployments with of 5.6 GW (71.6 %) installed capacity, followed by North America with 1.4 GW (18.3 %).

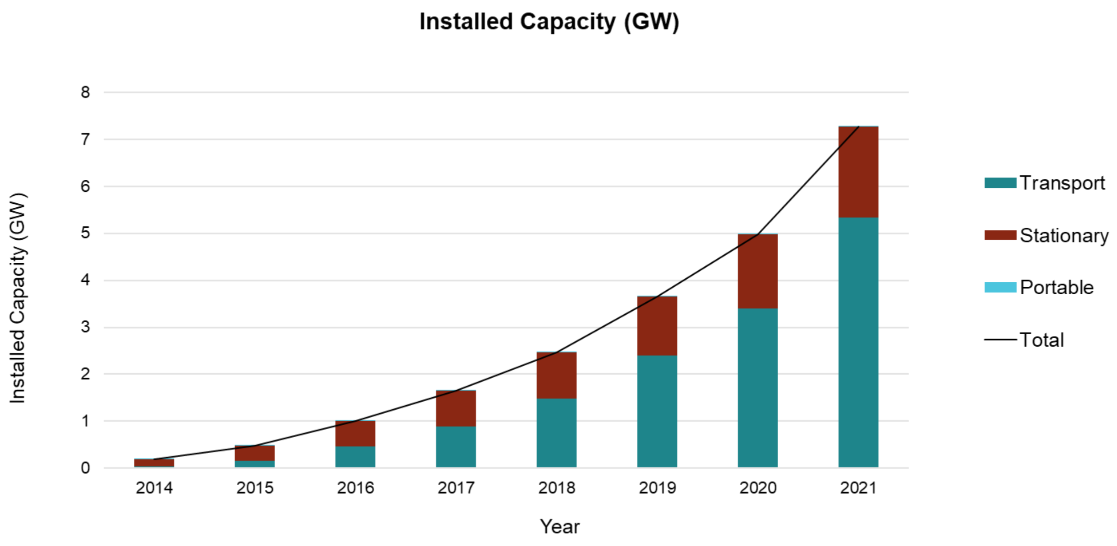
The evaluation of fuel cell installed capacity across different application types, including portable, stationary, and transport, reveals the dominance of transport applications in the fuel cell market, see Figure 3.

Figure 2. Recent evolution of total installed capacity (GW) per region for all fuel cell technologies (cumulative)



Source: Rystad Energy, 2024, [6]

Figure 3. Evolution of total installed capacity (GW) per application over the years (cumulative)



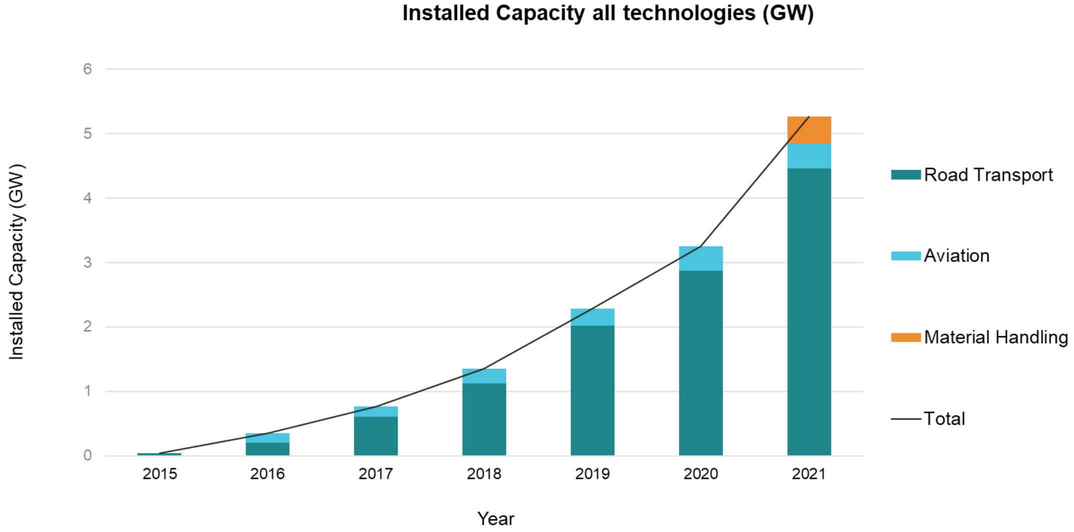
Source: European Hydrogen Observatory, 2021, [5]

Transport applications (PEMFC) accounted for approximately 73.4 – 76.7 % of the total fuel cell market share in 2021 [5], [6]. This substantial market share is primarily due to the growing interest in zero-emission vehicles and the need for efficient, clean energy solutions in the transport sector. In comparison, stationary fuel cells hold the second-largest market share with an installed capacity in the range of 23.3 – 26.5 % in 2021. These fuel cells are utilized in residential, commercial, and industrial sectors for power generation and combined heat and power (CHP) systems, offering advantages such as high efficiency, fuel flexibility, and low emissions. Lastly, portable fuel cells account for only a negligible portion (0.05 – 0.06 %) of the total fuel cell market, as their usage is limited to small-scale applications like electronic devices, consumer products, and portable power generation.

2.2.1.1 *Fuel cells for mobility applications*

In the transport sector, the deployment of fuel cells primarily focuses on road transport applications, accounting for a dominant 84.7 % share in 2021, see Figure 4. Material handling applications, such as forklifts, follow closely with a 8 % share in the same year. The presence of fuel cells in aviation applications completes the distribution with 7.3 %, according to Rystad Energy.[9]

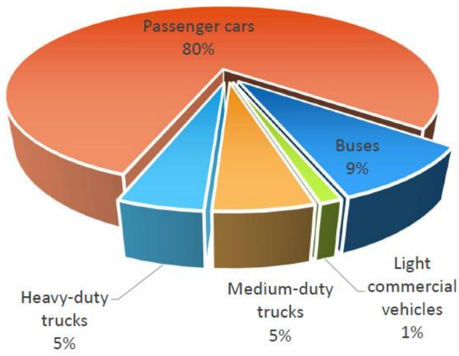
Figure 4. Evolution of the total installed capacity in the transport sector per transport group



Source: Rystad Energy, 2024, [6]

Regarding road transport, passenger cars dominate the global fleet of fuel cell vehicles, amounting to 80 %, see Figure 5. Buses make up the second highest share, with 9%. In total, both truck categories, namely heavy- and medium-duty, even have a higher share of 10% in total with 5% in each truck category [7].

Figure 5. Shares of different vehicle categories as of the end of 2022

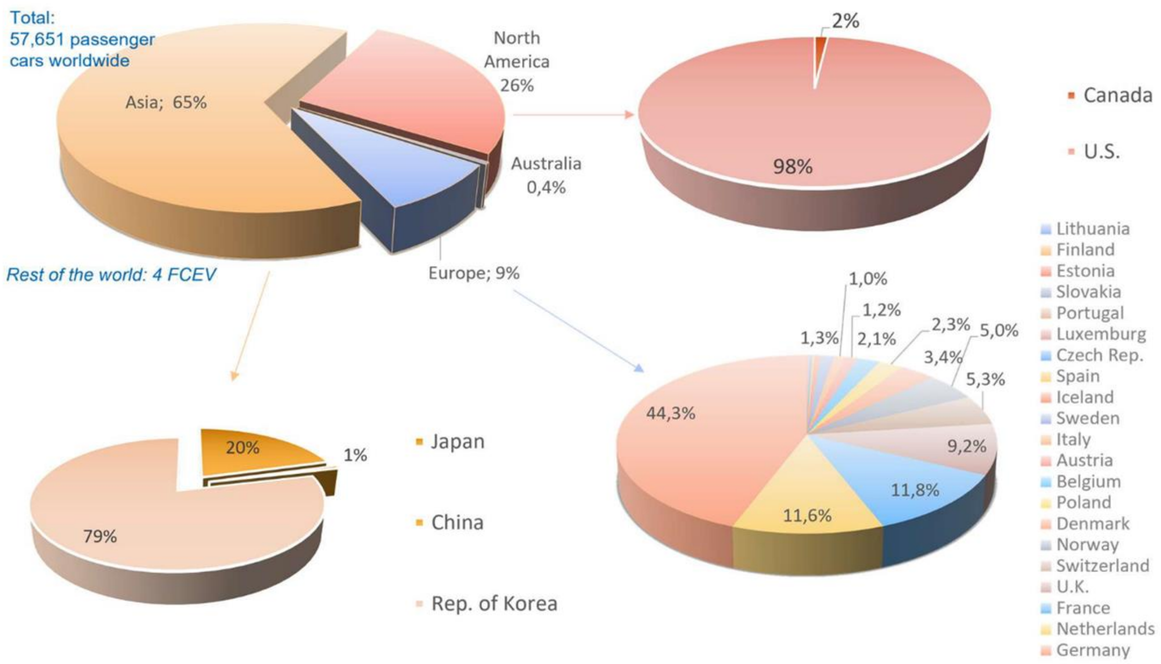


Source: Jülich Reihe Energie & Umwelt / Energy & Environment Band, 2023 [7]

The Asian region is dominating the global fuel cell electric vehicle (FCEV) market, with a 65% share in the deployment of FCEVs (passenger cars), followed by North America at 26 % and Europe at 9 %. Rep. Korea is the leading country in the FCEV market, accounting for 51% of the global fleet as is depicted in Figure 6. In Europe, Germany leads with 44.3% of the FCEV European fleet, followed by France (11.8 %) and the Netherlands (11.6 %) [7].

[9] Aviation applications refer to aerospace applications, unmanned air vehicles and drones, according to Rystad Energy. However, this data could not be contrasted with other sources.

Figure 6. Shares of FCEV (passenger cars) over continents, detailing the contributions within Asia, America and Europe.



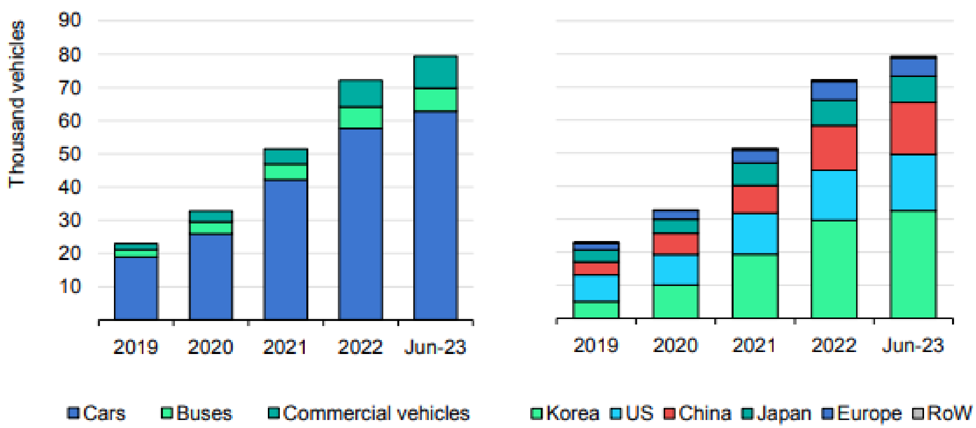
Source: Jülich Reihe Energie & Umwelt / Energy & Environment Band, 2023 [7]

Similarly, the Asian region leads the Fuel Cell Electric Buses (FCEBs) market with a 91 % share, followed by Europe at 5.6 % and North America at 3.4 %. China is the leading country in the FCEB market, accounting for 84 % of the global fleet. In Europe, the United Kingdom (1.5 %), Germany (1 %), and the Netherlands (0.8 %) are the top three countries in terms of FCEB deployment [7].

China also dominates the Medium-Duty Fuel Cell Electric Trucks (MD-FCET) market with a staggering 98 % share, while the Netherlands (1 %) and Germany (0.72 %) follow [7]. In the case of Heavy-Duty Fuel Cell Electric Trucks (HD-FCET), Asia once again leads, driven by China's 98 % deployment. Europe comes in second with 1.7 %, while North America has a 0.3 % share. Switzerland leads the European HD-FCET market with a 1.4 % share.

Overall, the Asian region's influence in the fuel cell vehicle market remains prominent, with China and Rep. Korea being the key drivers of this growth, see Figure 7. The global fleet of FCEVs, including passenger cars, buses and commercial vehicles (trucks) is closing in on 80 000, with Rep. Korea remaining the major market for cars and China for buses and trucks [8].

Figure 7. Fuel cell electric vehicle stock by segment and region



Source: International Energy Agency, 2023, [8] In terms of fuel cell production, estimates from the International Energy Agency (IEA) and the Hydrogen Council reveal that the overall manufacturing capacity for PEMFC worldwide in 2022 ranged between 12 to 23 GW. Among these estimates, China is leading in PEMFC manufacturing, closely followed by the Asia Pacific region, particularly countries such as Japan and Rep. Korea. The reported discrepancies between the sources can be attributed to a lack of comprehensive data availability on the manufacturing capacities of various countries. Nevertheless, recent announcements from industry leaders like Hyundai, Ballard Power Systems, etc., indicate a continuous growth trend in fuel cell manufacturing capacities [6], [8]. The IEA's figures showcase a 23 GW capacity in 2022, with China as the top contributor [8], while the Hydrogen Council reports a more conservative 12 GW capacity, highlighting Japan and Rep. Korea as the leading nations in this field [9]. Despite the inconsistencies, it is evident that the fuel cell industry is experiencing expansion, reflecting the growing global interest in clean and sustainable energy solutions. Particularly in Europe, companies such as Symbio FC and Elcogen have announced plans to expand their production capacities.

2.2.1.2 Fuel cells for stationary applications

In the realm of stationary fuel cells, the Asian region has taken a clear lead in deployment with 0.9 - 1.2 GW installed capacity out of the total 1.6 GW in 2021 [10] [6], followed by North America with around 0.5 GW and Europe with 0.09 -0.15 GW [6] [10]. For the US, which had the highest installed capacity globally up until 2018 with over 0.5 GW [11], seems to have either decommissioned many units, or installations have stalled. One source reports 0.25 GW installed in 2020 [10], another 0.55 GW in 2022 [12]. Europe has primarily been concentrating on decarbonisation efforts, resulting in a somewhat lower priority for stationary fuel cell deployment. As these fuel cells are predominantly powered by methane and other non-hydrogen fuels, they seem to be making a lesser impact in decarbonisation compared to the renewable hydrogen-based systems.

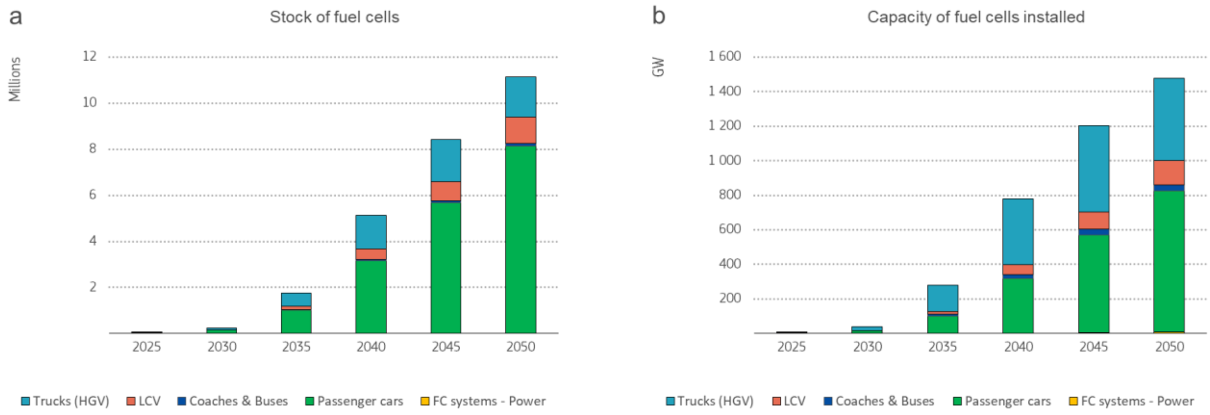
2.2.2 Long-term perspectives

Despite the overall increase of fuel cell deployment in road transportation seen in the last decade, the current rate of deployment increase in passenger cars is slowing down. The reasons behind this trend could be the higher operational costs of these vehicles compared to other decarbonised road transport options or the closing gap in terms of range and refuelling/recharging time due to the advances of battery electric vehicles. The energy crisis of 2022 has further affected the financial viability of hydrogen-powered transport by increasing hydrogen fuel costs. The supply chain for components remains fragile, with limited flexibility to ramp up production or expand spare parts inventory. Additionally, the lack of an extensive refuelling infrastructure is hindering the deployment of hydrogen mobility in some regions. However, as the global interest in sustainable transportation technologies grows, it is expected that the application of fuel cells will continue to expand and diversify across various sectors, with heavy-duty transport remaining the primary focus.

The JRC projections for EU fuel cell deployment and fuel cell installed capacity (GW) and global overnight investment cost are based on the models POTEnCIA (for the EU) and POLES-JRC (for the world). Annex 3 summarises the energy system model and scenarios modelled for the CETO 2024.

Figure 8 shows the projections on fuel cell deployment (Figure 8a) and fuel cell installed capacity (Figure 8b) in the EU based on the POTEnCIA CETO 2024 scenario. The uptake of fuel cell vehicles accelerates from 2035, with passenger cars dominating the growth of fuel cell deployments in 2050 (73 %), followed by trucks/heavy goods vehicles (HGV) with 15.5 % and light commercial vehicles (LCV) with 10.4 %. Fuel cells units in buses/coaches and in power generation (stationary applications) are significantly lower with 0.1 % and 0.01 % of the stock, respectively. In terms of fuel cell installed capacity (GW), passenger cars dominate again with 55 % of the installed capacity in 2050, followed by HGVs (32.4 %), LCVs (9.4 %), buses/coaches (2.4 %) and power generation (0.7 %). Although in absolut numbers there are more fuel cell vehicles in passenger cars, their relative share within the passenger car sector is projected to remain considerably low. In contrast, for LCV and trucks, with projections of over 1 million fuel cell vehicles by 2050 for each, the relative share reaches 15% of the road freight transport sector. For international long distance freight transport, the FCEV share of total stock rises to almost 40%.

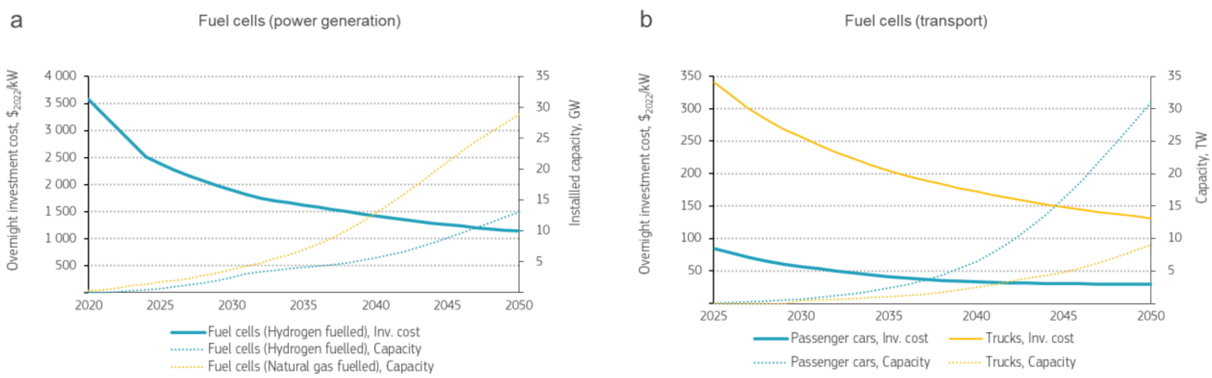
Figure 8. (a) Projections for fuel cell stock in the EU , (b) Projections for fuel cell installed capacity in the EU



Source: JRC analysis based on POTEnCIA CETO 2024 Scenario

Figure 9 shows the evolution of global average overnight investment cost for fuel cells in power generation (stationary applications) and in transport (mobility applications), according to the *Global CETO 2°C scenario 2024* calculated with the POLES-JRC model. As fuel cell types in power generation, POLES-JRC considers two generic fuel cell types using hydrogen or natural gas. Investment cost for both types is assumed to be the same. Overnight investment cost is projected to decrease steeply from today's 3045 $/kW by about 63 % by 2050. In terms of fuell cells in mobility applications, overnight investment cost is also projected to decrease for both passenger cars and trucks from today's 91 $/kW and 360 $/kW, respectively. By 2050, overnight investment cost will decrease about 68 % in the case of passenger cars and 64 % in the case of trucks.

Figure 9. (a) Projections for global overnight investment cost for fuel cells in power generation (stationary applications), (b) Projections for global overnight investment cost for fuel cells in transport (mobility applications).



Source: JRC, Global CETO 2°C scenario 2024 (POLES-JRC model)

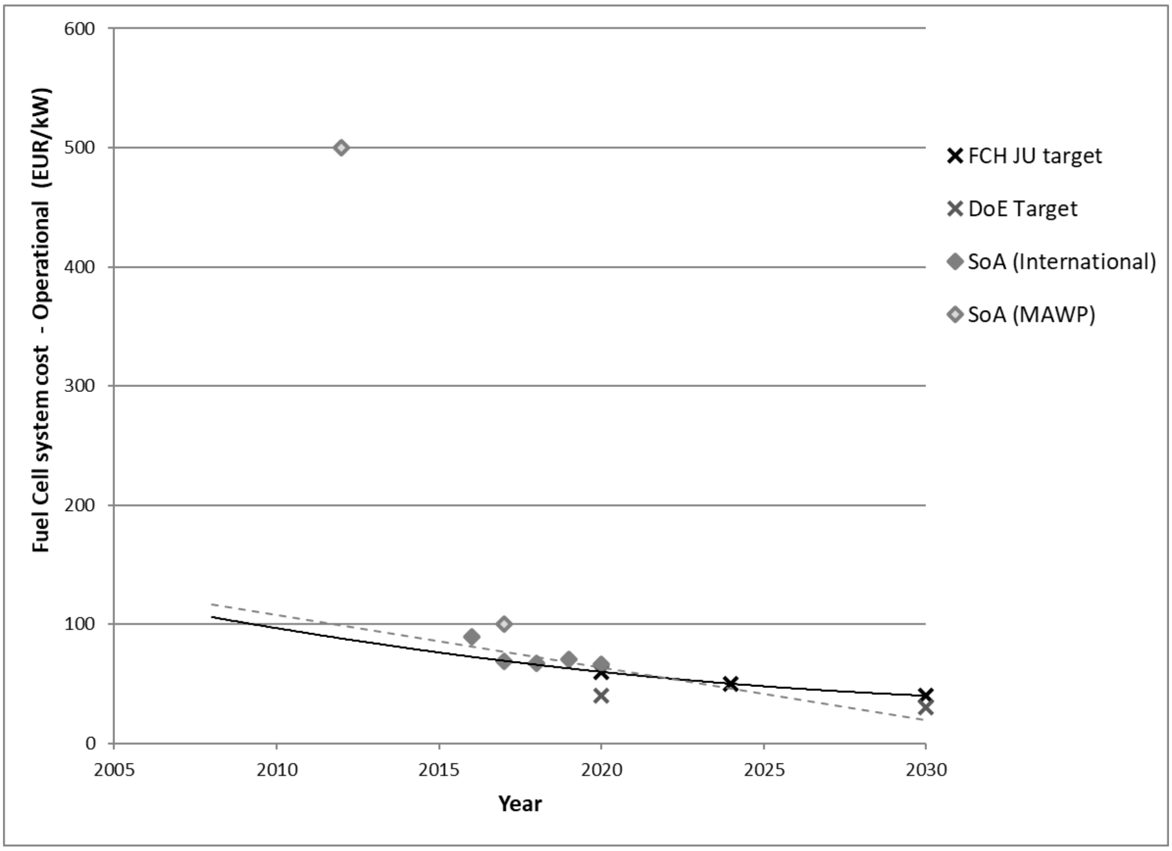
2.3 Technology Costs

2.3.1 Fuel cells for mobility applications

2.3.1.1 Fuel Cell Electric Vehicles (FCEVs)

There is not enough data reported on fuel cell system costs from manufacturers to conduct an in-depth analysis for FCEVs. Figure 10 shows the projections on fuel cell system costs over the years in EUR/kW. The fuel cell system costs are defined as the cost of the fuel cell system excluding overheads and profits, assuming 100 000 systems/year as cost calculation basis [1]. The target values from the Multi-annual Work Programme (MAWP) of the Clean Hydrogen Partnership and the US Department of Energy are shown for comparison as FCH JU target and DoE target, respectively. These targets are denoted in the figure by "X" markers. Two sets of targets, defined in the 2015 and 2017 updates of the MAWP, are also included to show the State of Art (SoA). The SoA points are denoted in the figure by diamond markers and showing values of 500 EUR/kW and over 100 EUR/kW for 2015 and 2017, respectively. The projections on fuel cell system costs from the US DoE show a value of 66.65 EUR/kW for 2020. The FCH JU target was 60 EUR/KW for 2020 [1]. The data from European demonstration projects is really scarce and confidential. However, it is safe to say that the costs reported by those projects significantly surpassed the FCH JU and DoE targets for 2020. These are not included in Figure 10 due to confidentiality concerns. Further efforts are required to lower the fuel cell system costs.

Figure 10. Fuel cell system costs (EUR/kW) versus year for FCEV demonstration projects



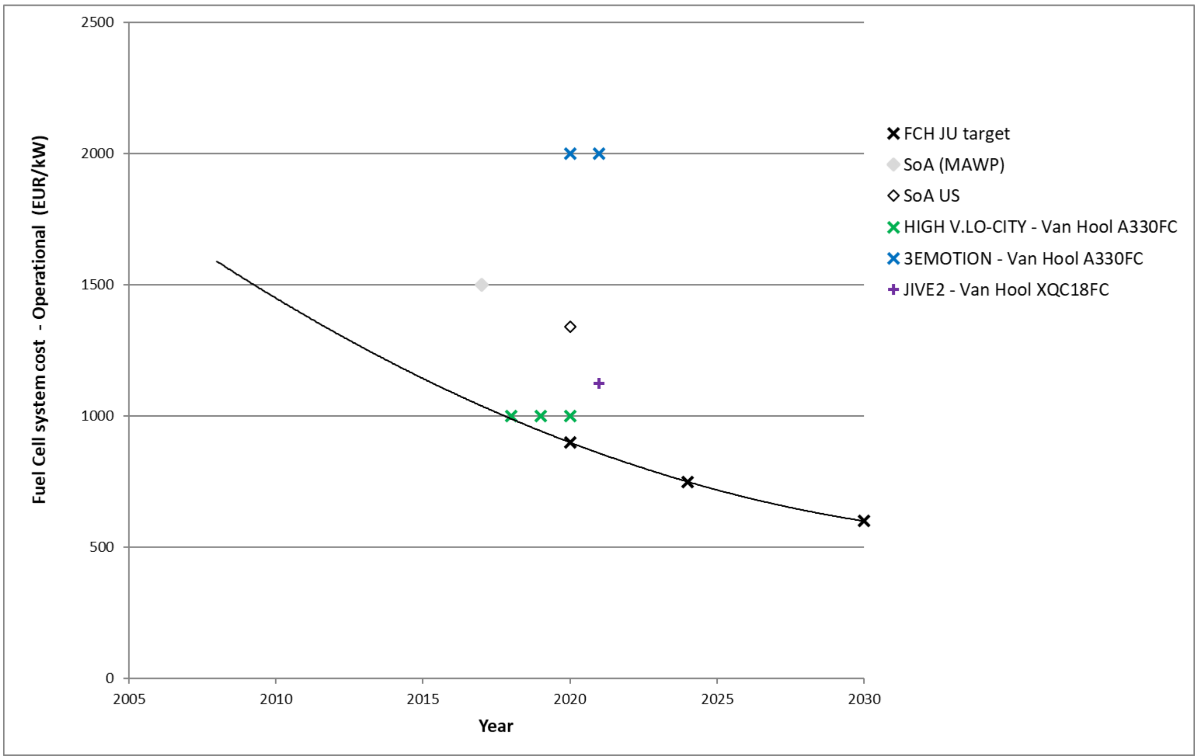
Source: JRC based on Clean Hydrogen JU data, 2024, [1]

For the analysis of the yearly maintenance costs for FCEVs (spare parts and labour for the drivetrain maintenance in EUR/km), data from the European demonstration projects was consulted. Unfortunately, very few vehicles reported reliable information on maintenance costs. The values reported showed very low maintenance costs ranging 0.01 - 0.025 EUR/km, below the FCH JU targets and in line with the costs reported by US National Renewable Energy Laboratory (NREL) in their study [1]. It is worth mentioning that project participants pointed out that one of the major factors of variability in the maintenance costs were the differences in labour costs among countries.

2.3.1.2 Fuel Cell Electric Buses (FCEBs)

Similar issues are encountered when analysing fuel cell system costs for FCEBs as there is not enough data reported by the manufacturers to conduct an in-depth analysis. For FCEBs, the fuel cell system costs (EUR/kW) are defined as the actual cost of the fuel cell system excluding overheads and profits subject to yearly overall fuel cell bus module volume as stated [1]. The US targets for fuel cell system costs for FCEBs are not given per kW but as overall costs and therefore excluded from the analysis. The FCH JU target was 900 EUR/KW for 2020. The data from European FCEB demonstration projects is really scarce, available only for some FCEB models of the projects HIGH V.LO-CITY, 3EMOTION and JIVE2 [1]. The costs reported by those projects surpassed the FCH JU target for 2020. Figure 11 shows the fuel cell system costs reported for HIGH V.LO-CITY Van Hool A330FC, 3EMOTION Van Hool A330FC, and JIVE2 Van Hool XQC18FC with best values of 1 000 EUR/kW. It should be noted that these costs are observed for small fleets in demonstration projects and not at mass production level. The common trend is that in all cases the costs have surpassed the FCH JU targets, even if only slightly in the case of the HIGH V.LO-CITY Van Hool A330FC. Further efforts are required to lower the fuel cell system costs of FCEBs.

Figure 11. Fuel cell system costs (EUR/kW) versus year for FCEB demonstration projects



Source: JRC based on Clean Hydrogen JU data, 2024, [1]

In the case of FCEBs, few European demonstration projects reported yearly maintenance costs (spare parts and labour for the drivetrain maintenance in EUR/km). The maintenance costs have decreased significantly in recent projects (0.5 EUR/km) compared to early ones (2.7 EUR/km) [1]. The lessons learned from the early projects included changes to the maintenance strategy (preventive and corrective maintenance, building a spare parts shop at the depot, etc.).

2.3.1.3 Fuel Cell Electric Trucks (FCETs)

There is not enough data reported to conduct a thorough fuel cell system cost analysis for FCETs. The Clean Hydrogen Partnership has published in 2022 updated targets for fuel cells in heavy-duty applications in their Strategic Research and Innovation Agenda (SRIA) 2021-2027 [13]. The SRIA updated the 2020 MAWP target for fuel cell stack cost from 60 EUR/kW to over 100 EUR/kW based on the SoA values. These targets refer to the cost of the fuel cell system excluding overheads and profits, assuming 100 000 systems/year. The new targets set for 2024 and 2030 are 75 and 50 EUR/kW, respectively. Additionally, the SRIA assumed a FC module CAPEX of 1 500 EUR/kW for the SoA in 2020 and set targets for 2024 and 2027 of 480 and 100 EUR/kW, respectively. US DoE cost projections for a 275-kW_{net} PEMFC system for a Class 8 long haul heavy-duty truck based on next-generation laboratory technology and operating on direct hydrogen is projected to be \$179/kW_{net} when manufactured at a volume of 50 000 units/year (\$170/kW_{net} when manufactured at a volume of 100 000 units/year) [14]. For FCET there is not enough information publicly available on maintenance costs.

2.3.2 Fuel cells for stationary applications

2.3.2.1 *Micro-CHP*

CAPEX for micro-CHP (below 5 kW_e) is defined as the cost of manufacturing (labour, materials, utilities) of the micro-CHP unit at current production levels per kW of rated electrical production. Despite a modest reduction in the state of the art cost of micro-CHP units between 2012 and 2017 (from 16 000 EUR/kW to 13 000 EUR/kW), the Clean Hydrogen Partnership programme is targeting an almost four-fold reduction in cost between 2017 and 2030 (to 4 000 €/kW for PEM and to 3 500 for SOFC by 2030) [13]. The target for 2020 stated in the MAWP (≤ 10 000 EUR/kW) was achieved by manufacturers of micro-CHP in Clean Hydrogen Partnership projects early on [4]. The targets were updated by the SRIA in 2022, assuming the new SoA values for 2020 of 6 000 EUR/kW for PEM and 10 000 EUR/kW for SOFC [13]. As of 2024, some manufacturers have achieved the SRIA 2024 targets (5 000 EUR/kW for PEM and 6 000 EUR/kW for SOFC). However, the specific values have been submitted as confidential so the exact CAPEX will not be presented here.

The operation and maintenance costs per kWh of electricity produced (including stack replacement) but excluding the cost of the fuel, insurances and taxes have halved in the period from 2012 to 2017 for the Clean Hydrogen partnership projects, from 40 to 20 EUR Ct / kWh. However, for wide-scale adoption to occur a considerable further drop of almost an order of magnitude to 4 EUR Ct / kWh for PEM and to 2.5 EUR Ct / kWh for SOFC by 2030 is required (2030 SRIA targets) [13].

2.3.2.2 *Mid-size CHP*

CAPEX for mid-size CHP systems (5 – 50 kW_e) is defined as the cost of manufacturing (labour, materials, utilities) of the mid-size installation at current production levels (exclude monetary costs, e.g. overheads, profits, rebates, grants, value-added tax (VAT), insurances, taxes, land). A state of the art value of 2 500 EUR/kW for PEM and 10 000 EUR/kW for SOFC in 2020 is targeted to drop to 1 200 EUR/kW for PEM and 2 500 EUR/kW for SOFC, respectively, in 2030, according to the SRIA. These values are lower than those predicted for micro-CHP. As of 2024, some SOFC manufacturers have achieved the SRIA 2024 target (5 000 EUR/kW for SOFC) but not yet the PEM 2024 SRIA target (1 800 EUR/kW).

Operation and maintenance costs per kWh of electricity produced (including stack replacement), but excluding the cost of the fuel, insurances and taxes have been reported in the SRIA [13]. The state of the art values for 2020 are 10 and 12 EUR EUR/kWh for PEM and SOFC, respectively. These are set to decrease to 3 and 2 EUR/kW, for PEM and SOFC, respectively, according to the SRIA targets for 2030.

2.3.2.3 *Large scale CHP installations*

CAPEX for large scale CHP installations (51 – 500 kW_e) is defined as the cost of manufacturing (labour, materials, utilities) of the CHP unit at current production levels (exclude monetary costs, e.g. overheads, profits, rebates, grants, value-added tax (VAT), insurances, taxes, land). For large-scale fuel cell applications CAPEX costs have been provided for 2020 in the SRIA [13]. The state of the art value of 1 900 EUR/kW for PEM and 10 000 EUR/kW for SOFC in 2020 is targeted to drop to 900 EUR/kW for PEM and 2 000 EUR/kW for SOFC in 2030. These values are lower than for the mid-size systems. As of 2024, some SOFC manufacturers have achieved the SRIA 2024 target (5 000 EUR/kW for SOFC) but not yet the PEM 2024 SRIA target (1 200 EUR/kW).

Operation and maintenance costs per kWh of electricity produced (including stack replacement, but excluding the cost of the fuel, insurances and taxes) have been reported in the SRIA for large scale CHP systems [13]. The state of the art values, according to the SRIA in 2020 were 5 and 12 EUR Ct/kWh for PEM and SOFC, respectively. A drop to 2 EUR Ct/kWh by 2030 is targeted for both technologies.

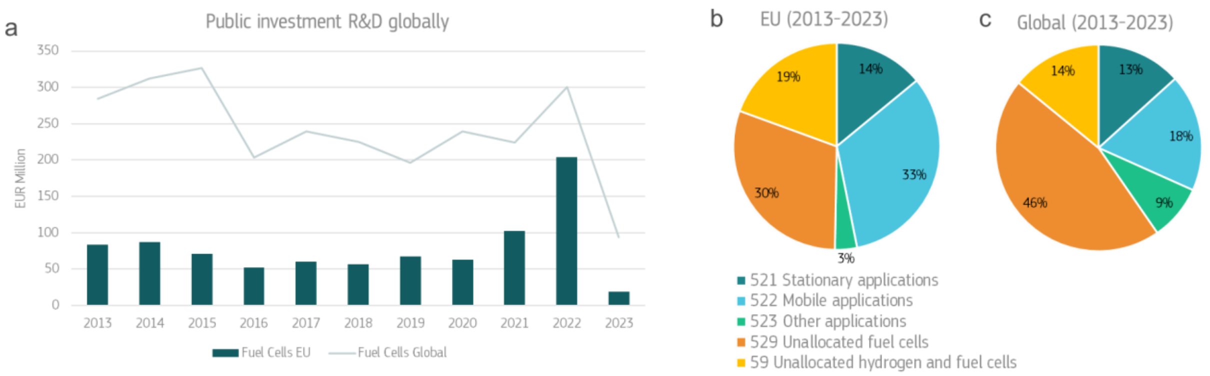
2.4 Public RD&I Funding and Investments

The public investment in fuel cells at EU and global level from 2013 until 2023 is illustrated in Figure 12a. It must be noted that the 2022 and 2023 values are provisional.

Overall, EU public investments in fuel cells increased sharply in 2022, by 69 % in comparison to 2020 levels, and by 50 % in comparison to 2021. It seems 2022 was the peak in fuel cell investments with EUR 204 million (68 % of the global public investment). This trend is shared with other technologies, such as photovoltaics. By contrast, the investment decreased sharply in 2023. There is a general public investment decrease in 2023 across all technologies as well. Between 2013 and 2021 the investments were kept constant below EUR 100 million at EU level. At global level, fuel cell public investments reached the highest level in the 2013-2015 period with EUR 327 million in 2015. Following these years, public investments were kept constant in the range of EUR 200 – 250 million until 2022 when the investment went up to EUR 300 million. The investment decreased in 2023 back to the plateau years (2016 - 2021). The year 2022 was a peak investments year both at EU and global level.

Regarding the share across fuel cell applications it is difficult to draw conclusions due to some IEA categories not being specific ("529 unallocated fuel cells" and "59 unallocated to hydrogen and fuel cells"). If we focus on the allocated funding (cool colours), similarities are observed between the distribution of the funding across categories at EU (Figure 12b) and global (Figure 12c) levels. The majority of the allocated funding is dedicated to mobile applications, followed by stationary applications.

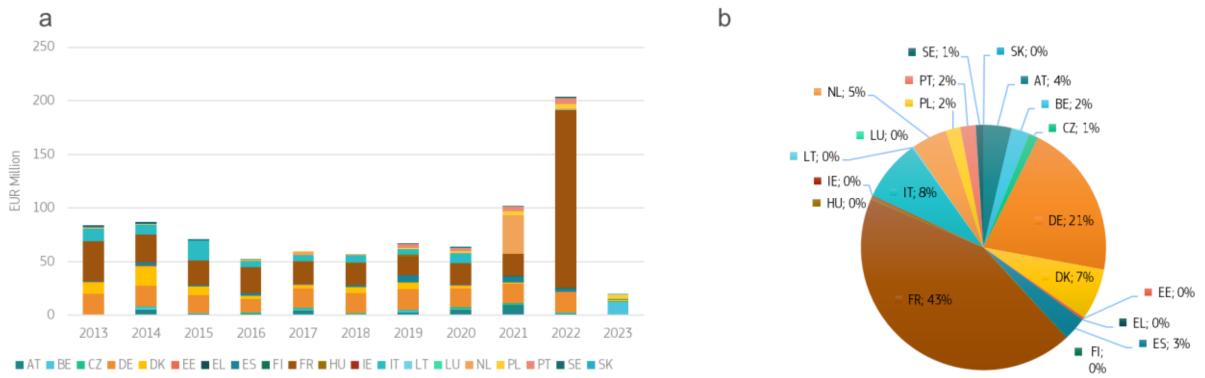
Figure 12. (a) EU and global public investment in Solar and PV R&D, (b) EU and (c) global allocation of solar energy technologies for the period 2010-2019.



Source: JRC based on IEA

Figure 13a and b present MS' public investments in the broader technology group of fuel cells, yearly (Figure 13a) and by percentage of cumulative funding over the period 2013-2023 (Figure 13b). Values for 2022 and 2023 are provisional.

Figure 13. (a) Yearly EU public investment per MS and (b) Cumulative EU public investment (2013-2013) per MS.

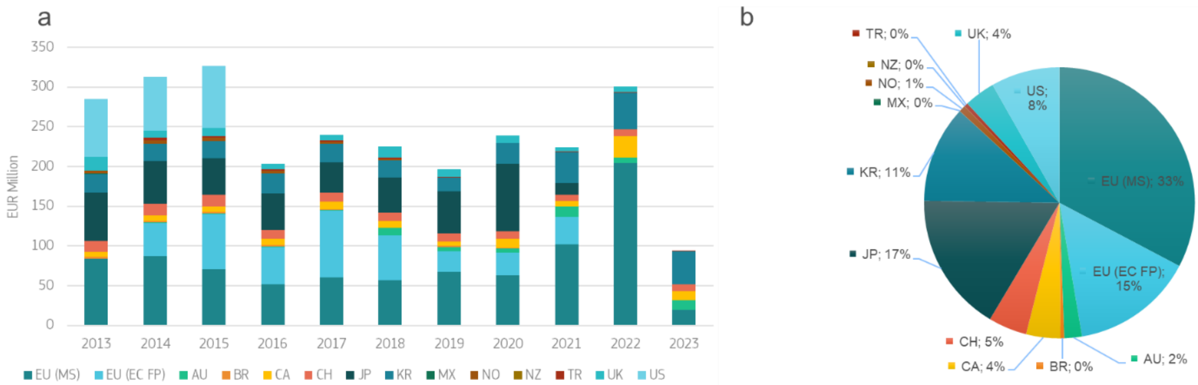


Source: JRC based on IEA

France, Germany, Italy, the Netherlands and Austria are the top five EU countries with the highest public investment in fuel cell technologies. France and Germany have kept a nearly constant fuel cells public investment over the period 2013 - 2021. It is notable that France invested heavily on fuel cells in the year 2022 with EUR 166 million (81 % of all public investment on fuel cells at EU level that year). As 2022 was the peak year on public fuel cell investment, it is safe to say that France is in the lead, possibly driven by the Hy2Tech IPCEI, for which France set aside a large budget to support hydrogen technologies. Italy has shown a gradual decrease on fuel cells public investment over the years. In the case of the Netherlands, 2021 was the peak year on fuel cell public investment with EUR 36 million (35 % of all on fuel cells at EU level that year). 2021 was also the peak year for Austria, concerning fuel cell public investment with almost EUR 10 million (9 % of all EU public funding on fuel cells).

Figure 14a and b shows the world region's public investments in the broader technology group of fuel cells, yearly (Figure 14a) and by percentage of cumulative funding over the period 2013-2023 (Figure 14b). It must be noted that 2022 and 2023 values are provisional.

Figure 14. (a) Yearly global public investment per world region and (b) Cumulative global public investment (2013-2023) per world region.



Source: JRC based on IEA

From the Figure 14a and b, in which thirteen major economies are analysed, the EU and Japan accounted together for 65 % of the total global public investments in fuel cells cumulatively in the period from 2013 until 2023. It is remarkable that the EU accounted for almost half of the cumulative global public investment (48 %). Following Japan (17 %) are Rep. Korea (11 %), the US (8 %) and Switzerland (5 %).

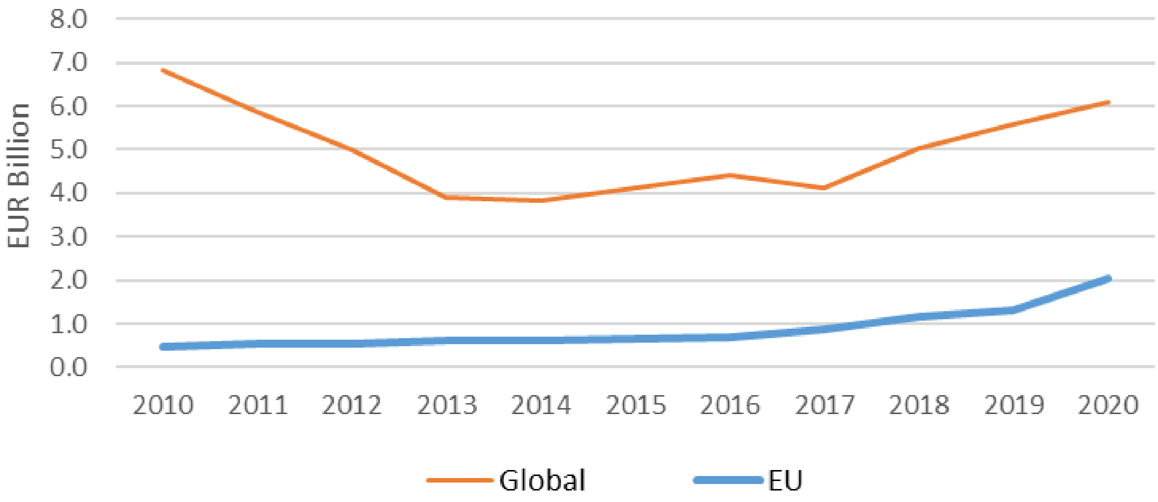
The EU has kept its public funding on fuel cells constant over the years until 2022, when it increased sharply with EUR 204 million (68 % of the global public investment that year). Japan which had also kept a significant level of public funding over the years, has decreased considerably recently (2021-2023). A similar trend is observed for US where also the public investment has decreased significantly in recent years (2022-2023). Rep. Korea and Switzerland keep constant public investment in fuel cell over the whole period analysed, including recent years (2013-2023).

2.5 Private RD&I funding

Retrieving as well as evaluating information on private funding for fuel cells is difficult as private companies do not have the obligation to disclose their financial and Research & Development (R&D) details. The following tentative analysis is based on the use of patenting output as a proxy for private funding [15], [16] and the results should therefore be interpreted with caution (especially in the case of China). Unlike public investments, the analysis is performed from 2010 until 2020 (2020 data is provisional).

While the public investments for the EU and globally ranged from EUR 52 to 137 million and from EUR 197 to EUR 456 million respectively for the period 2010-2020, the private investments in the EU and globally ranged from EUR 0.5 to EUR 2 billion and from EUR 4 to EUR 6.8 billion respectively for the same periods (Figure 15). Analysing the relationship between public and private funding from 2010 until 2020 in the EU, it is observed that public R&D funding was between 6 % and 9 % of the total R&D funding. This suggests a much higher contribution of the private sector to the fuel cells R&D funding (91 % - 97 %). Private funding at global level is similarly more important as it covers between 94 % and 95 % of the total funding.

Figure 15. EU and global private investment in fuel cells for the period 2010-2020.

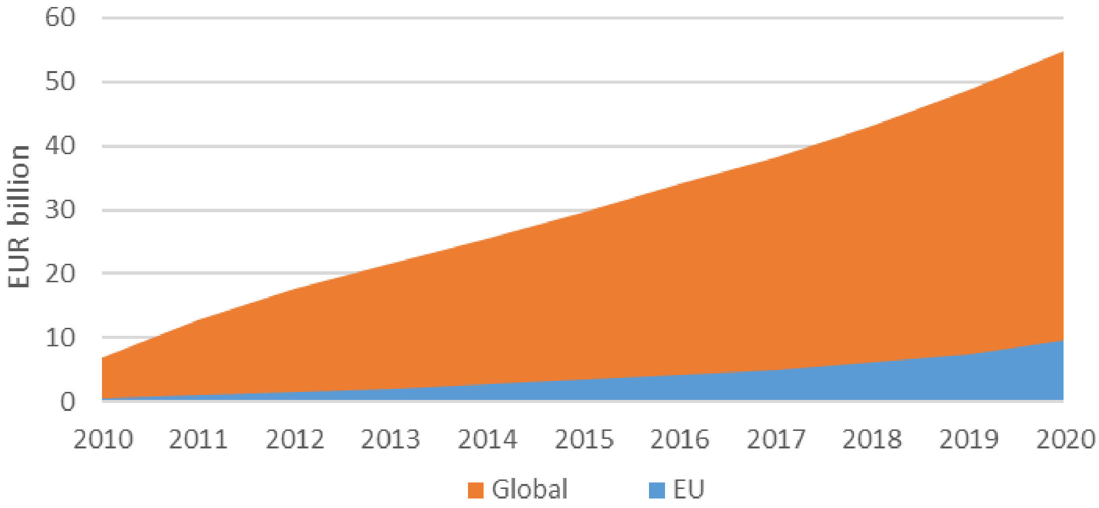


Source: JRC analysis based on [17], [18]

Between 2010 and 2020, as far as fuel cells are concerned, the indication is that the EU exhibits an extended increase in private investment while suffering a decrease in public investments (+77 % against -54 %). Over the same period, private investments at global level suffered a smaller decrease than public investments (-11 % against -47 %). Regardless of their public or private nature, investments have suffered a decrease at global level. However, this is not the case for EU private investment. There is an indication that, unlike the rest of the world, the EU had been more and more benefitting from private rather than public investments over this period.

Figure 16 shows that at global level, the cumulative private investments in fuel cells exceeded EUR 54 billion in 2020. In the same year, the EU private investments amounted to EUR 9.5 billion (17 % of the cumulative private investments at global level).

Figure 16. EU and global cumulative private investment in fuel cells for the period 2010-2020.

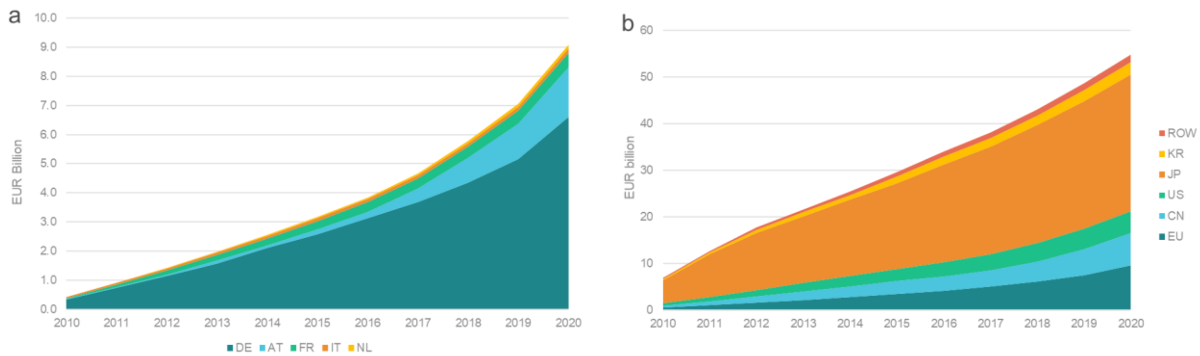


Source: JRC analysis based on [17], [18]

Figure 17a presents the five EU countries with the highest levels of cumulative private investment in the EU. These five countries account for 95.6 % of the total cumulative private investments in the EU from 2010 to 2020. Germany had the highest level of private investment in fuel cells, accounting for 69.5 % of the cumulative investments (2010-2020), followed by Austria with 17.9 % and France with 5.3 %.

Globally (Figure 17b), the cumulative private investments in fuel cells from Japan (53.7 %) represents more than half of the global cumulative private investments. The EU represents 17.3 % of the total cumulative private investments from 2010 to 2020, representing approximately EUR 9.5 billion out of a total of approximately EUR 54.8 billion. The next three regions are China (8.6 %), US (8.6 %) and Rep. Korea (4.7 %).

Figure 17. (a) EU cumulative private investment in fuel cells per MS and (b) global cumulative private investment in fuel cells (EU, top five countries and in the rest of the world for the period 2010-2020).



Source: JRC analysis based on [17], [18]

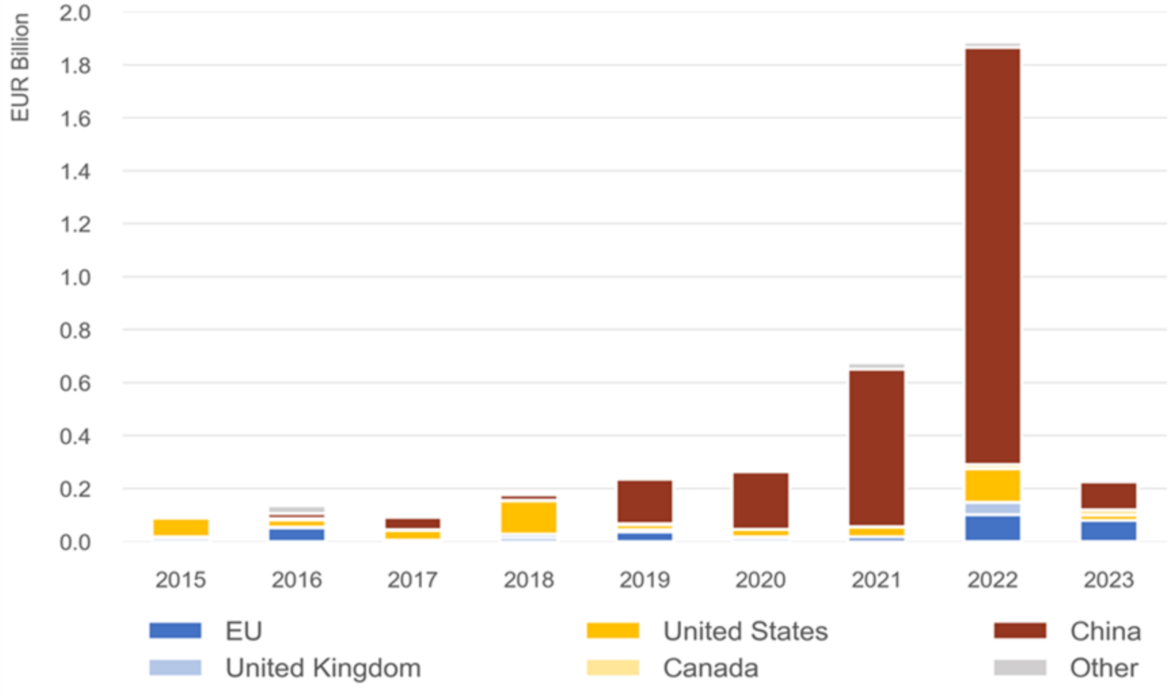
Global Venture Capital (VC) investment[10] in fuel cell start-ups and scale-ups increased sharply over the past 2 years, and specifically in 2022 (x3 compared to 2021) when they amounted to a record EUR 1.9 billion (Figure 18). This trend is essentially driven by an outstanding growth of VC investments in Chinese firms in 2021 and 2022, at both early and later stages[11], and, to a smaller extent, by the rebound of later stage investments in US firms after a long period of lower investment. Chinese companies, such as SPIC Hydrogen Energy (EUR 0.8

10 Venture capital (VC) is a form of private equity and sits at the heart of the ecosystem that finances innovative star-ups and scale-ups. The early and later stages indicators in this analysis aggregate different types of equity investments in a selection of companies and along the different stages of their growth path. For each technology, companies are selected based on their activity description.

11 For early and later stages investments, only pre-venture companies (that have received Angel or Seed funding, or are less than 2 years old and have not received funding) and venture capital companies (companies that have, at some point, been part of the portfolio of a venture capital investment firm) are included.

billion) and REFIRE (EUR 0.2 billion) raised the main share of the VC total in 2022. In a context of globally decreasing VC investment, Chinese and US-based companies developing and manufacturing fuel cells raised much less capital in 2023 (comparable to the levels seen in 2020), while VC investments in EU-based companies display a more limited -21% decrease.

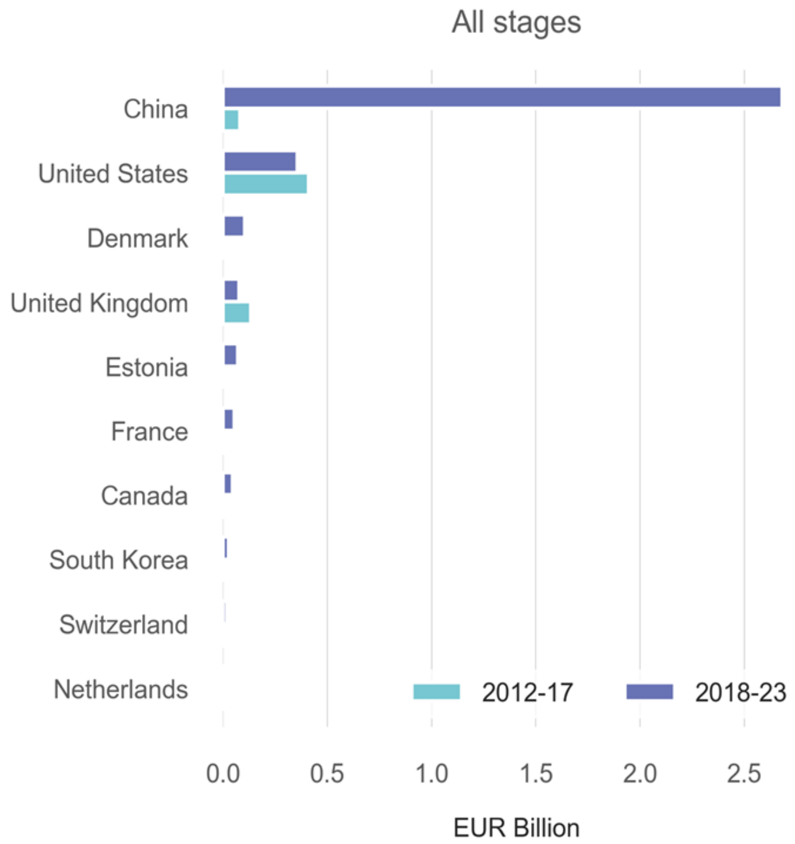
Figure 18. EU and global total Venture Capital investments for the period 2011-2023.



Source: JRC based on PitchBook

China and the US host respectively 45 % and 19 % of active start-ups and scale-ups over the 2018-2023 period, while the EU follows with 15 % of identified ventures. Regarding the total VC investments (early and later stage), China and the United States accounted for 77 % and 10 % respectively in the 2018-2023 period, while the EU accounted for 7 % of the global 2018-2023 total (see Figure 19).

Figure 19. Top ten countries total Venture Capital investments for all stages for the periods 2012-2017 and 2017-2023



Source: JRC based on PitchBook

China accounts for 64 % of global early-stage investments and 84 % of global later stage investments over 2018-2023. Later stage investments in Chinese companies have increased significantly in 2022, driven by companies such as Cemt (China), REFIRE or Sinosynergy that were founded over the 2015-2016 and are now raising capital to support their growth. The growth of early-stage investments in Chinese companies in 2022 is also notable. Early-stage investment rose sharply since 2021 and 2022, driven by investment in manufacturers of fuel cells such as SPIC Hydrogen Energy, FTXT Energy Technology, or SHTP that were founded recently (2017 - 2019) and are scaling up very fast.

Early-stage investments in EU VC companies amounted to EUR 125 million over the 2018-2023 period. After a peak in 2022, they have decreased back to their 2019 level, and, over the 2018-2023 period, the EU only accounted for 11 % of global early-stage investment. Later-stage investments in EU VC companies amounted to EUR 133 million over the 2018-2023 period (just 6 % of the global later-stage investments). EU companies however only captured 7 % of the identified grant funding[12] over the 2018-2023 period behind the United States (79 %) and the United Kingdom (11 %) and then followed by Canada (2 %). The remaining 1 % is attributed to the rest of the world. PitchBook only reports negligible (or no) amount of grant funding for Japanese, Korean or Chinese start-ups.

[12] Even though grant funding is not equity funding, grants are included among early VC stages because they are an import source of funding for start-ups.

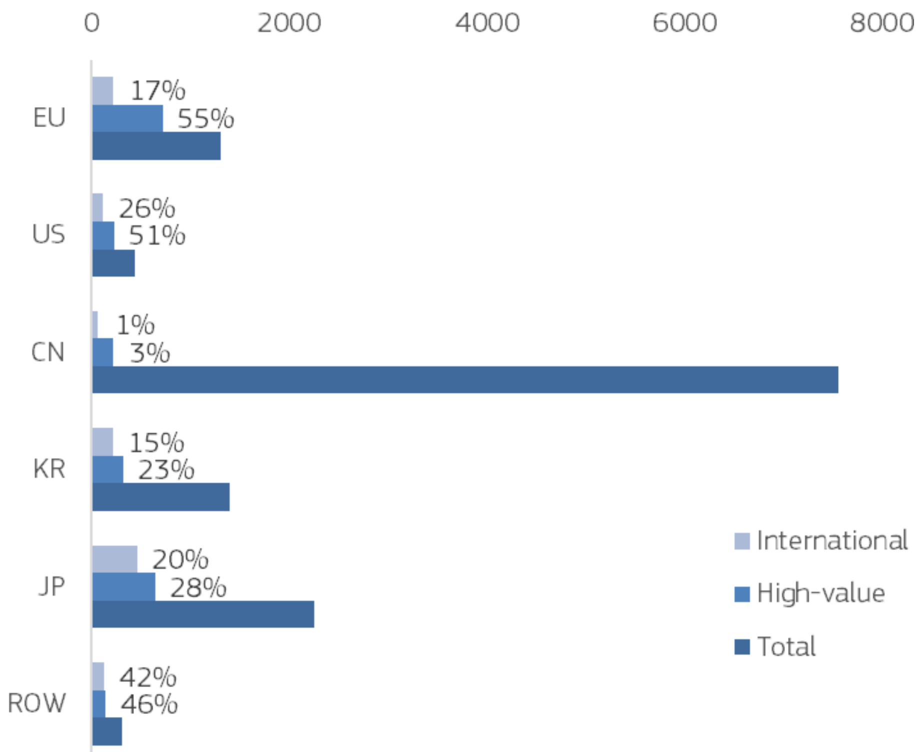
2.6 Patenting trends

Patenting trends are a valuable tool to analyse research trends in concepts that have market value. They are essentially using R&D knowledge to translate it into commercialised products. It must be noted though that in no way they may be used for R&D analysis but they can provide an insight into innovation.

The dataset used for the creation of the patent indicators [17]–[21] is based on the Cooperative Patent Classification (CPC) code: Y02E - CCMT related to energy generation, transmission or distribuiton [22]. It has to be noted though that data for 2021 is not complete.

As depicted in Figure 20 China has the largest number of patents with more than 7 545 inventions, followed by Japan and Rep. Korea. The EU is in 4th position with 1 299 inventions in total between 2019 and 2021.

Figure 20. Number of inventions and share of high-value and international activity for the period 2019-2021.



Source: JRC analysis based on EPO Patstat

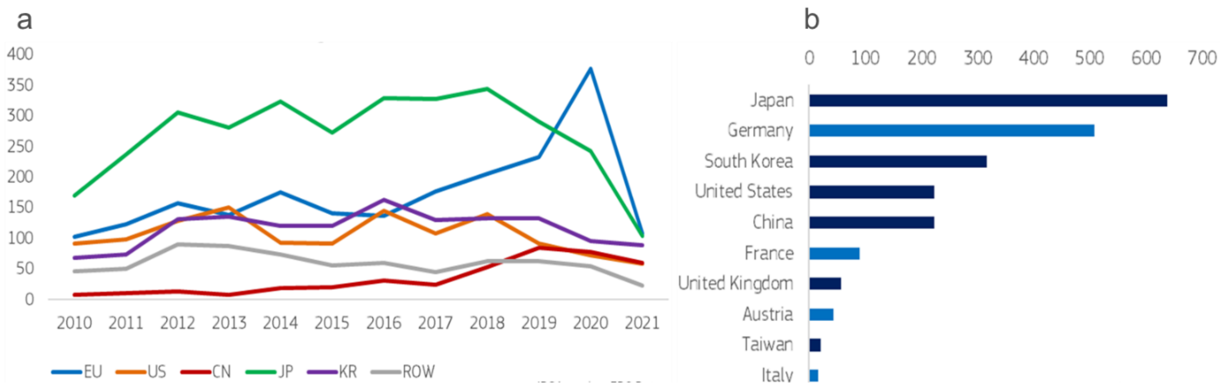
However, when only the high-value inventions[13] are taken into consideration, the EU moves first with 32 % of its total inventions being high-value inventions and China results into the fourth position tied with the US (10 % each). This suggests that the EU, unlike China, is generally filing to more than one patent office[14]. The same trend is evident also as far as international inventions[15] are concerned. The EU is aiming for patent applications outside while China appears to be concentrated on applying mainly within the country rather than internationally. Thus, the EU is leading followed by Japan and Rep. Korea regarding the international inventions. While Figure 20 shows the high-value inventions as a percentage of the total number of inventions, Figure 21a presents the number of high-value inventions in absolute numbers for each year from 2010 until 2021. A decreasing trend is observed for most countries apart from Europe in 2020 (2021 dataset is not complete). Germany, France and Austria are among the top ten countries with the highest number of high-value inventions between 2019 and 2021 (Figure 21b).

[13] High-value inventions (or high-value patent families) refer to patent families that include patent applications filed in more than one patent office. International inventions include patent applications protected in a country different to the residence of the applicant. High-value considers EU countries separately, while for international inventions European countries are viewed as one macro category.

[14] An invention is considered of high-value when it contains patent applications to more than one office.

[15] Patent applications protected in a country different to the residence of the applicant.

Figure 21. a) Number of high-value inventions and b) Top ten countries with high-value inventions for the period 2019-2021.



Source: JRC analysis based on EPO Patstat

Table 4 and Table 5 respectively present the top ten entities globally and in the EU which filed the highest number of inventions in fuel cells between 2019 and 2021.

Table 4. Global top ten entities with high-value inventions in fuel cells for the period 2019-2021.

Entities	Country	Number of high-value inventions
Robert Bosch Gmbh	DE	269
Toyota Jidosha Kabushiki Kaisha	JP	148
Honda Motor Co Ltd	JP	116
Hyundai Motor Company	KR	65
Kia Motors Corporation	KR	65
Kolon Industries Inc	KR	39
Avl List Gmbh	AT	38
Audi Ag	DE	36
Panasonic Intellectual Property Management Co Ltd	JP	31
Ceres Intellectual Property Company Limited	UK	20

Source: JRC analysis based on EPO Patstat

Almost half of the top ten entities in the field of high-value inventions are based in Europe. The rest of the top ten list includes entities from Japan and Rep. Korea (Table 4). The company Robert Bosch Gmbh has conquered the first position globally, followed by Toyota Jidosha Kabushiki Kaisha and Honda Motor Co Ltd. As far as the EU is concerned, the top ten list highlights the leadership of German entities in high-value inventions (Table 5). Robert Bosch Gmbh tops the charts in the EU top ten followed by Avl List Gmbh and Audi Ag.

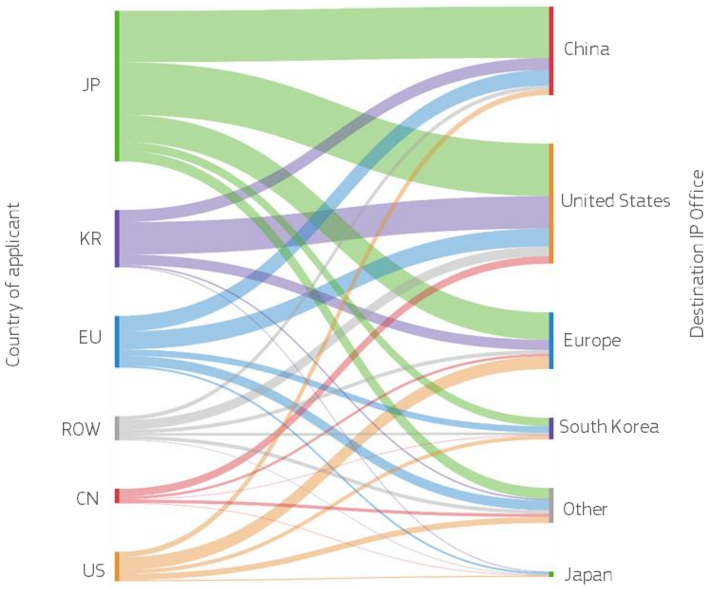
Table 5. EU top ten entities with high-value inventions in fuel cell for the period 2018-2020.

Entities	Country	Number of high-value inventions
Robert Bosch Gmbh	DE	269
Avl List Gmbh	AT	38
Audi Ag	DE	36
Mahle International Gmbh	DE	15
Schaeffler Technologies Ag Co Kg	DE	13
Reinz Dichtungs Gmbh	DE	11
Greenerity Gmbh	DE	7
Volkswagen Aktiengesellschaft	DE	6
Psa Automobiles Sa	FR	6
Voith Patent Gmbh	DE	5

Source: JRC analysis based on EPO Patstat

Figure 22 presents the countries in which patents for high-value inventions were submitted, and subsequently enjoyed patent protection, between 2019 and 2021. Japanese applicants have mainly chosen to patent their inventions in China and the US. The number of patent applications in the EU and other countries is significantly smaller. Korean inventors are mainly applying in the US and to a lesser extent in China and Europe. Chinese applicants have also US as the main destination IP office outside China. US inventors have filed their patent applications preferably in Europe and then more evenly between China, Rep. Korea and other geographical areas. The same applies also for EU inventors, where patent applications are split evenly between US, China and others. In conclusion, the US is receiving the largest number of high-value invention applications. Europe is 3rd after US and China as far as the reception of patent applications is concerned.

Figure 22. International protection of high-value inventions for the period 2019-2021.



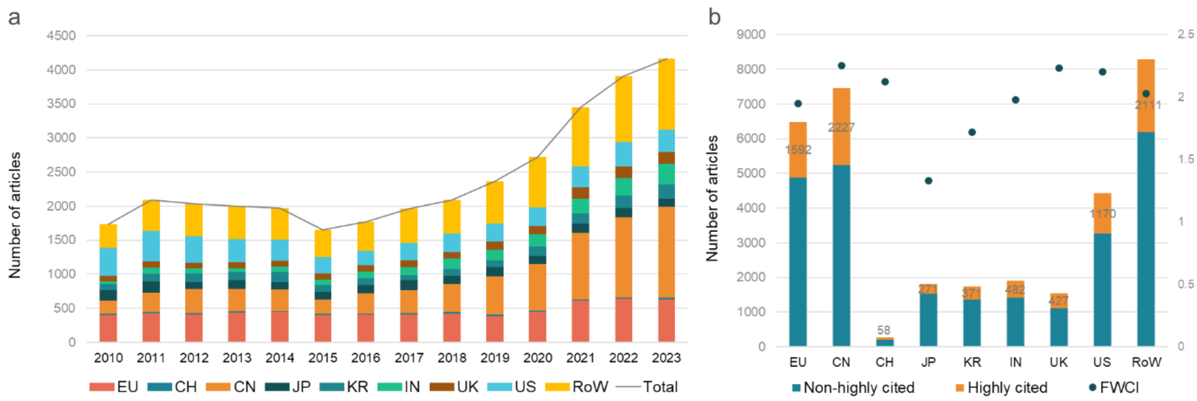
Source: JRC analysis based on EPO Patstat

2.7 Scientific publication trends

Figure 23a shows the evolution of global publications on fuel cells over the years 2010-2023. The general trend in global publications on fuel cells relies on the existence of two periods: 1) a plateau period of constant number of publications from 2010 to 2018 with about 2 000 yearly publications, and 2) a period of increase in yearly publications from 2018 to 2023 with the maximun of 4165 publications in 2023. The number of publications on fuel cell technologies has been comparable for the EU and China from 2012 until 2018. However, Chinese publications increase significantly in the period of 2018 – 2023, leading in number of publications since 2019. In the EU, the number of publications on fuel cell technologies has been constant from 2010 to 2020, increasing only slightly in recent years.

Figure 23b shows a breakdown of highly and non-highly cited publications per region, showing also the average Field-Weighted Citation Impact (FWCI) per region. On single regions, China is dominating both in total number of publications and also on highly cited publications (2 227), with the highest average field-weighted citation impact. The EU follows both on total number of publications and highly cited publications (1592). The US is third position for both with 1 170 highly cited publications.

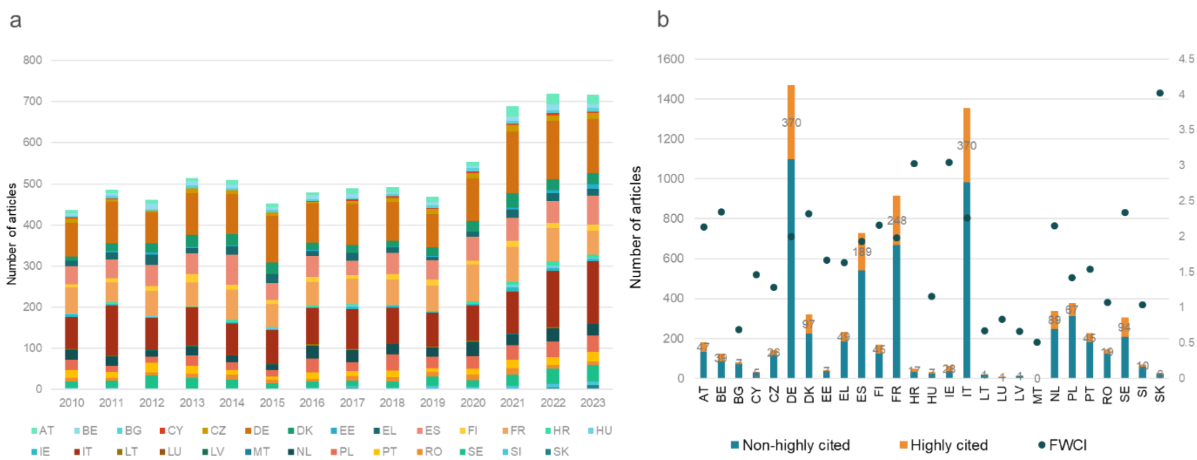
Figure 23. (a) Global publications on fuel cells for the period 2010-2023 and (b) Global highly cited publications on fuel cell and EU position for the period 2010-2023.



Source: JRC analysis, 2024

At EU level, Germany is the country with the highest number of publications and citations on all FC technologies. The other countries in the EU's top five are Italy, France, Spain and Poland (see Figure 24 a and b).

Figure 24. (a) EU publications on fuel cells for the period 2010-2023 and (b) EU highly cited publications on fuel cell and EU position for the period 2010-2023.

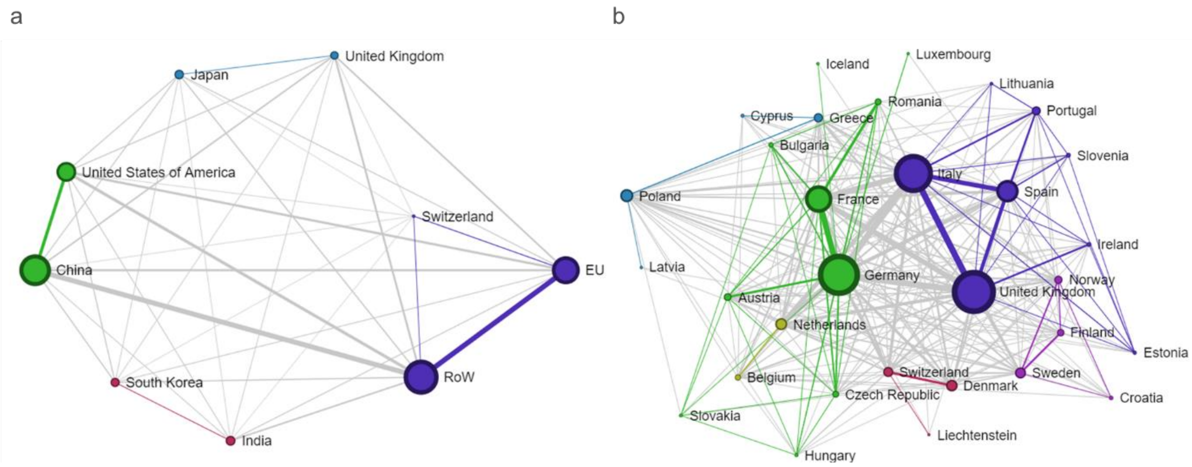


Source: JRC analysis, 2024

The online software TIM (Technology Innovation Monitoring) developed by the JRC has been used to provide an overview of the research collaborations both worldwide (Figure 25a) and at European level (Figure 25b). In the plots, the size of the nodes (circles) is proportional to the number of publications a region/country has been involved in whilst the thickness of the lines is proportional to the number of links (i.e. the number of publication two regions/countries have been involved in together). TIM uses a particular algorithm to cluster related items into a "Community". Each community has a different colour.[16] Basically, the coloured clusters identified by TIM are formed by regions/countries that collaborate more frequently with each other because they share participation in the same publications.

Figure 25a shows that China has strong bonds with the United States while the EU is mainly collaborating with other regions of the world and Switzerland but also intensively with US, Japan, China, Rep Korea, United Kingdom and India by the presence of links. Two other clusters observed are the one formed by United Kingdom with Japan and the one formed by Rep. Korea and India. At European level (Figure 25b), the countries with the highest number of publications (Germany, Italy, France and Spain) collaborate mainly with each other but it is also possible to distinguish some clusters. One of these clusters is the one formed by Germany and France with other European countries in a minor degree (Austria, the Netherlands, Czechia, Slovakia, Hungary, Bulgaria, Romania, Iceland and Luxembourg). Another important cluster is the one formed mainly by the United Kingdom, Italy and Spain, but also with other countries (Portugal, Ireland, Slovenia, Lithuania and Estonia). Four other small cluster are: 1) Belgium and the Netherlands, 2) Switzerland, Denmark and Liechtenstein, 3) Sweden, Norway, Finland and Croatia, and 4) Greces, Cyprus, Poland and Latvia.

Figure 25. (a) TIM plot showing the collaborations on research publications between word regions and (b) collaboration among EU MS.



Source: JRC analysis, 2024

2.8 Assessment of R&I project developments

At European level, this dimension is currently mostly covered by the Annual Programme Technical Assessment Review performed by the European Commission Joint Research Centre (JRC) and provided to the Clean Hydrogen Partnership under the multiannual framework contract between the two parties [23].

[16] The size of the node represents the number of research publications a region or country is involved in, whilst the thickness of the links represents the number of research publications in common between the linked regions or countries. The coloured groupings are potential clusters identified by TIM's algorithm.

3 Value Chain Analysis

The scope of this chapter mainly covers the manufacturing of fuel cells for mobility and stationary applications, as well as the manufacturing of fuel cell components. Information regarding revenue is only available for publicly traded companies focusing on fuel cells. For automotive manufacturers such as Toyota, there is no specific information regarding sales of fuel cells, but deployment numbers of FCEVs, FCEBs and FCETs, trucks and buses are provided, as available, in Section 2.2.1.1. Due to lack of information for European fuel cell manufacturers, no further breakdown or trends can be given. Key European companies are mentioned in Section 3.3. In general, there are many, but small European companies producing fuel cell components, stacks and systems, and they do not play a significant role in terms of production volume or turnover.

3.1 Turnover

3.1.1 Fuel cells for mobility applications

Hyundai[17], Toyota[18], and Honda[19] are leading the automotive industry in PEM fuel cell deployment for mobility applications. Hyundai started with the ix35 Fuel Cell in 2013 which evolved into their latest model Hyundai Nexo in 2018 and has since expanded to hydrogen-powered buses and trucks. Toyota, after limited sales of its Mirai I and Mirai II, sees commercial and heavy-duty vehicles as promising applications for hydrogen transportation and has expanded its focus to include stationary applications. Honda announced a new hydrogen-powered CR-V and collaborates with General Motors on fuel-cell module production. All three companies are now targeting larger markets by expanding into stationary and other mobility sectors. There is no information regarding turnover for fuel cell sales.

Established in 1979, Ballard Power Systems (CA) is a major supplier of PEM MEAs, with a production capacity of 1.4 GW for MEAs, 4 GW for stack production, and 3.9 GW for module production (status 2022) [24]. Ballard has partnered with OEMs like Volkswagen, Daimler, Ford and Honda for fuel cell supply contracts, primarily in the heavy-duty vehicle segment. According to the company's December 2021 annual presentation, Ballard develops around 50-60% of the global fuel cells used for fuel cell buses and trucks [25]. As a third-party supplier, including into China, Ballard generated revenues of USD 102 million in 2023, a slight decrease from USD 105.7 million in 2019 [26]. The company experienced a net loss of USD 144 million in operations. Ballard's business primarily focuses on mobility, with a significant presence in stationary applications as well. In Q3 2023, segmented revenues amounted to USD 29 million for heavy-duty mobility, USD 4.9 million for emerging applications and materials handling, and USD 12.8 million for stationary. In 2022, Ballard announced its plans

[17] Hyundai (KR) is the global leader in PEM fuel cell deployment for mobility applications. In 2013, following the testing of Hyundai's initial fuel-cell prototype, the company introduced the world's first mass-produced fuel-cell vehicle, the ix35 Fuel Cell. In 2019, Hyundai delivered of its first mass-produced hydrogen-powered electric bus, the ELEC CITY Fuel Cell. More than 11 000 NEXOs were deployed in 2022, largely in South Korea [1]. In 2023 Hyundai established its first overseas fuel cell system production facility, HTWO Guangzhou, to target the Chinese hydrogen market. The facility, with a capacity of 6 500 fuel cell systems per year, plans to expand capacity according to market demand. Hyundai is partnering with companies like Advent to improve HT-PEM technology and Gore to develop membranes.

[18] Toyota (JP) began its development of FCEV in 1992, with limited sales starting in 2002. Toyota has developed and manufactured the PEMFC in-house. After nine years since the launch of the Mirai car, Toyota has acknowledged that the vehicle has not been commercially successful and sees commercial vehicles as a more promising application for hydrogen-based transportation in the future [80]. In 2023 the company sold only around 3 500 FCEV [81]. In February 2017, Toyota introduced the first fuel cell bus to the Tokyo Metropolitan Government. It is also developing FC pick-up trucks, supported by UK funding. Toyota has a broad presence with 53 manufacturing plants in 28 countries and sells vehicles in over 170 countries. In February 2021, the company developed a fuel cell module that integrates main components into a compact package, making it suitable for upcoming bus and truck projects. Toyota has recently expanded its focus to include stationary applications, announcing its Mirai module for use in capacities up to 80 kW. Toyota announced there that in 2026 they will launch the commercialisation of 3rd generation FC stack, with a 20% increase in cruising range and 37% price reduction. The company's has a collaboration with EODev, creating custom units for the construction and marine industries. Toyota also plans to deliver a 1 MW fuel cell, built with multiple Mirai modules, to the ARIES project in Flatirons, Colorado, in a three-year DOE-funded collaboration with NREL. Additionally, Toyota is investing in research and development for PEM and solid oxide electrolysis [24].

[19] Contrary to indications of Honda (JP) shifting away from fuel cell vehicles, the end of 2022 saw the announcement of a new hydrogen-powered vehicle based on the Honda CR-V. The General Motors and Honda collaboration is being realised in an industrial park southwest of Detroit, where a jointly-owned manufacturing facility has been producing saleable fuel-cell modules since the beginning of 2024, aiming to manufacture and deliver thousands by year-end. Honda will utilise 200 of these fuel-cell modules, with approximately a quarter intended for the Honda CR-V by 2025. These hydrogen-powered CR-Vs will be configured as plug-in hybrids, but equipped with a fuel-cell stack instead of an internal-combustion engine [4]. Honda will combine its car modules into 25 kW units that can be scaled up to meet higher power requirements [1]. The company uses a 576 kW hydrogen-powered generator as a backup source for the grid- and solar-powered data centre at Honda's headquarters in Torrance, California. Additionally, Honda is preparing a Class 8 fuel cell semi-truck as a proof-of-concept in the United States [5].

to expand its manufacturing presence in Europe, the US, and China to meet growing global market demand through 2030 [24]. The company intends to invest USD 130 million in MEA production over the next three years.

First offering fuel cells for material handling application in the mid-2000s, Plug Power (US) has meanwhile expanded its portfolio to include PEM fuel cells for heavy duty vehicles, electrolysers and liquefaction. In 2022, Plug Power built a 3MW hydrogen system for Microsoft. The revenue from equipment, infrastructure, and other sales for the year ending December 31, 2023, saw a USD 152.5 million increase (27.3%) to USD 711.4 million from USD 558.9 million in 2022 [27]. This growth was mainly driven by increased revenue from hydrogen site installations, liquefiers, cryogenic equipment, and electrolyser stacks and systems. The rise in revenue from certain areas was partially offset by a decrease in revenue related to fuel cell systems, which declined by USD 36.2 million due to a reduced volume of GenDrive units sold. In 2023, 6 392 units were sold compared to 8 274 units in 2022. According to their quarterly report 3/2023, fuel cell sales accounted for less than 20% of their revenue [28]. In 2023, Plug Power has entered into an agreement with Johnson Matthey (JM), which will become a significant strategic supplier for Plug, for providing catalysts, membranes, and catalyst coated membranes [29].

Cummins (US), a major engine manufacturer, acquired Canadian-Belgian fuel cell and electrolyser manufacturer Hydrogenics in 2019. It offers a 300 kW PEMFC system for commercial vehicles. The company is developing and manufacturing both PEMFC and SOFC. 20 of their PEMFC will be delivered to Scania for FC trucks to be deployed in the Netherlands [30]. Their zero-emission engine department Accelera reported losses of USD 121 million compared to USD 81 million in sales in 2023 [31].

Nuvera (US) produces PEM fuel cells for on- and off-road segments, and is branching out into providing solutions for maritime applications. In the 4th quarter of 2023, the company had revenues of USD 0.2 million, with the operating loss decreasing to USD 8.0 million from USD 9.3 million in 2022. This was primarily due to lower product development costs resulting from US government funding received to support certain fuel cell research and development expenses [32].

Advent (US) produces HT-PEMFC for various applications, such as power generation or mobility. The company has entered a Joint Development Agreement with Siemens Energy, aiming to combine Advent's 50kW hydrogen fuel cell modules and Siemens Energy's electrification and automation solutions for hybrid and electric vessels. The collaboration seeks to develop a 500kW HT-PEM fuel cell system for maritime applications [33]. In the second quarter of 2023 Advent reported revenues of USD 1.1 million [34].

3.1.2 Fuel cells for stationary applications

Large-scale installations of SOFC technology are primarily produced by a single company, Bloom Energy, similar to the market domination of Doosan Corporation in PAFC and FuelCell Energy in MCFC. Bloom Energy (US) can be considered as one of the few success stories for stationary fuel cells, and the company went public in 2018. Bloom Energy has experienced rapid growth over the last few years. They report a revenue of USD 1 333.5 million in 2023, an increase of 11.2% compared to 2022 [35]. However, there is still an operating loss of USD 208.9 million in 2023. Product sales account for around 65% of their revenue. They have 1 GW of installations across 1 000 locations in six countries, with 228 MW of shipments in 2022. Bloom claims 80% of the US and Korean markets for large stationary fuel cells; however, each fuel cell system sold results in a loss. The company raised another USD 388 million in August 2022 and relies heavily on project financing for customer purchases and power purchase agreements [24]. In 2022, Bloom Energy completed several installations in South Korea, including a 15 MW project for Korea Western Power in Iksan, a 19.8 MW project at Daewon, and a 1.8 MW RE 100 Energy Infrastructure system at Changwon-Si, which includes hydrogen-fueled Energy Servers, hydrogen storage, and vehicle refuelling [24].

Doosan (SK) offers PAFC for power generation for the stationary market. In 2022, Doosan has launched a project to develop and test a 600 kW auxiliary power SOFC for maritime applications [36]. In 2023, Doosan Fuel Cell declared revenue amounting to approximately 261 billion South Korean won (around EUR 174 million), a decline from 381 billion SKW in 2021 [37].

Fuel Cell Energy (US), founded in 1969 has deployed MW scale MCFC mainly in South Korea and in the US. Meanwhile the company is also developing SOFC and solid oxide electrolysers (SOEC). In 2023, the company reported revenues of USD 123 million and a net loss of USD 108 million [38]. A key project is the Jwaseong Baran Industrial Complex established in 2013 with a capacity of 58.8 megawatts. The plant can supply power to approximately 13 500 homes and produce hot water for heating 2,000 homes annually. FuelCell Energy initially developed carbonate fuel cell technology for small-scale power generation using natural gas, and has collaborated on a next-generation design for large-scale CO_2 capture at industrial sites. The Rotterdam pilot project will be the first real-world application of this technology, capturing CO_2 from an operational industrial site, with the captured CO_2 stored under the North Sea through the Porthos project. Following a successful pilot, the technology could be used in other manufacturing sites and potentially commercialised for other companies to lower emissions. FuelCell Energy plans to integrate elements of the next-generation technology into current commercial modules, which will speed up market delivery while the Rotterdam demonstration is ongoing. In 2023 the company has completed the second-largest fuel cell park in North America, a 14-megawatt facility situated along the Housatonic River in Derby.

3.2 Gross value added

For the same reasons outlined for the category 'Turnover', retrieving information of gross added value it is extremely challenging.

3.2.1 Environmental and socio-economic sustainability

The main environmental impacts of PEM fuel cells have been found to occur during the manufacturing phase, rather than during the use phase [39]. The stack in PEMFCs significantly contributes to ecological impacts due to its materials, particularly platinum. A recent study [40] has identified platinum production in South Africa as the main social hotspot for the social impact categories. This is mainly linked to the high specific cost of platinum and the high sector-specific risk level in the relevant manufacturing country (South Africa), despite the low relative mass fraction of the used platinum (< 0.1% of the total mass of the stack).
The catalyst, bipolar plates, and gas diffusion layer also have a considerable environmental impact. Nafion, other polymers, and silicone are other materials with high impacts. Reducing platinum loading can significantly decrease the carbon footprint [39].

Natural gas is the most common fuel for stationary applications, whereas hydrogen is used for mobility. We consider the impacts of natural gas to be out of scope of this report. In ecological assessments, the manufacturing phase of solid oxide fuel cells (SOFCs) generally has lower global warming potential and acidification potential but higher emissions in categories like photochemical ozone formation, ozone depletion potential, and human toxicity potential compared to the operation phase. The fuel blower and slurry preparation processes contribute to most emissions in the manufacturing phase, with the balance of plant causing the most GWP emissions. Key materials with high environmental impacts in SOFCs include cerium, lanthanum-strontium-cobalt-ferrite, lanthanum-strontium-manganite, yttria-stabilized zirconia, lanthanum-chromate, and nickel [39].

In a recent social LCA of a Solid Oxide Electrolysis Cell stack [41] it was found that stainless steel production is the main social hotspot among almost all the impact categories considered. This is due to the high mass ratio, which hides the effects of lower economic flows allocated to countries with higher social risk. Mining activities in particular, were found relevant in terms of social risks and very dependent on the addressed impact category.

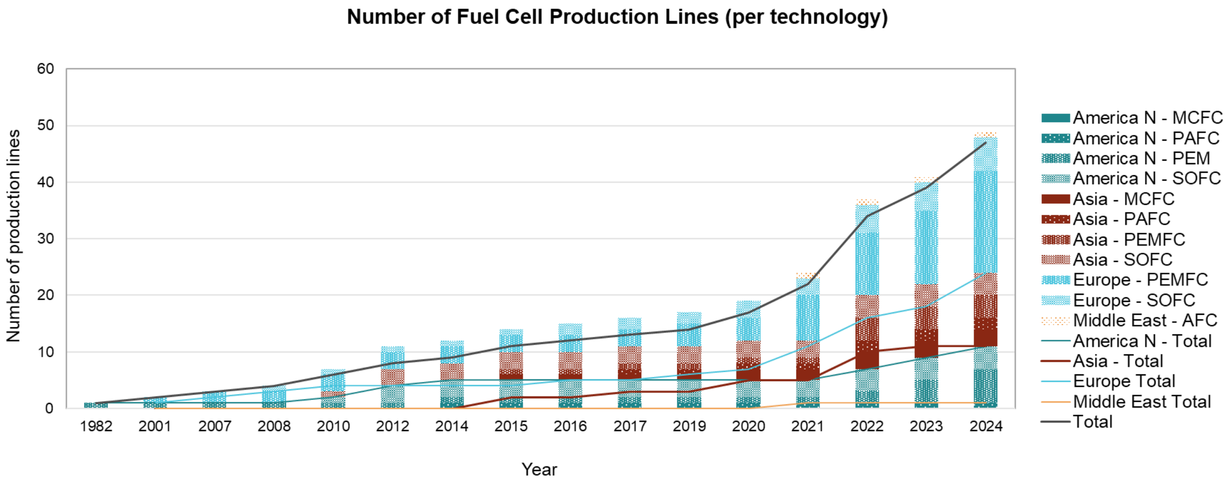
3.3 Role of EU Companies

According to Rystad Energy [42], Europe accounts for the highest number of fuel cell manufacturers in PEMFC and SOFC technologies. Europe also seems to have the highest number of production lines (see Figure 26). However, this does not translate in manufacturing capacity (see Section 2). According to Rystad Energy, which has only very few data points, therefore the data is only indicative, the manufacturing capacity of operational factories per region ranges:

- Europe: 2 000 - 10 000 fuel cell systems per factory (EKPO 10 000)
- Asia: 5 000 - 23 000 fuel cell systems per factory (Hyundai 23 000).
- America: 3 000 - 60 000 fuel cell systems per factory (Plug Power 60 000).

Notable is also the difference on factory footprints according to Rystad Energy: Europe no information, Asia 3 000 – 70 000 sqm (Toyota 70 000), America 2 000 – 38 000 sqm (Plug Power 38 000). Assessing the deployments happening worldwide, we can assume that despite the high number of European manufacturers, they do not contribute significantly to the global manufacturing capacity. However, there have been recent announcements regarding new production plants, for example Symbio FC [43] or Bosch GmbH [44], supported by the HY2TECH IPCEI (see Section 1).

Figure 26. Number of Fuel Cell Production Lines per technology and region



Source: Rystad Energy, 2024, [42]

Deployment of fuel cells for both mobility and stationary applications is limited in Europe. The lack of a market is likely a reason for the current landscape of European FC manufacturers, consisting of many small to medium size companies with limited, but growing manufacturing capacity.

3.3.1 Fuel cells for mobility applications

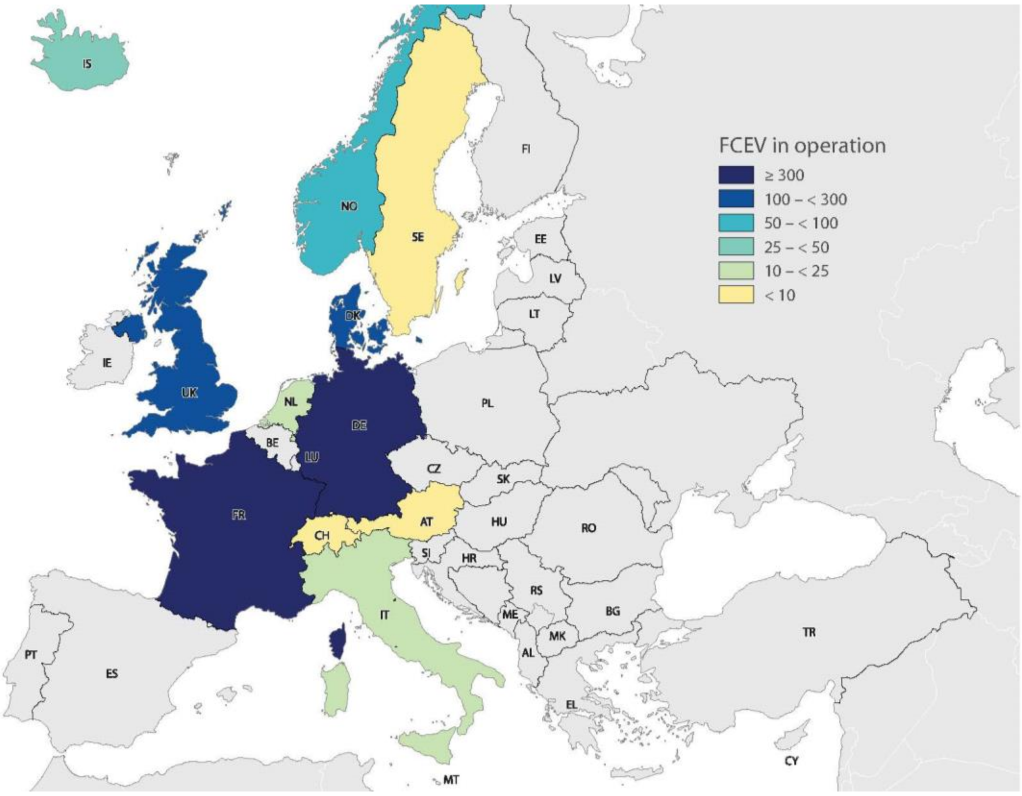
FCEVs deployment in Europe has seen a significant growth with the Clean Hydrogen JU projects, especially with H2ME and H2ME2 projects. The total FCEV fleet deployed over the 2005-2023 period by these projects surpasses the 1 300-unit milestone (see Figure 27) [1]. These initiatives have demonstrated the operational benefits and technological readiness of hydrogen-powered transport, paving the way for Europe's first hydrogen refuelling network. FCEV projects have been successful in high-mileage applications like taxi fleets, encouraging partners to expand their fleets. In spite of this, sales of FCEV are low in Europe, and constitute only a small fraction of the sales in Asia (see Figure 6 and Figure 7 in Section 2.2.1.1). According to the European Hydrogen Observatory, there are over 5 500 FCEV in operation in Europe[20].

FCEB deployment in Europe has increased, notably with Clean Hydrogen JU projects, such as JIVE and JIVE2 in 2022 and 2023. The total FCEB fleet deployed during 2005-2023 exceeds 400 units (see Figure 28), however, this is minuscule compared to China deployment numbers (see Section 2.2.1.1). Over the 17-year period, these FCEBs have collectively travelled over 17 million kilometres, showcasing the technology's maturity [1].

Both FCEVs and FCEBs face competition from battery electric alternatives, which offer lower operational costs and technological advancements. The 2022 energy crisis increased hydrogen fuel costs, impacting the financial viability of hydrogen-powered transport. The supply chain for components remains fragile, with limited flexibility for production and spare parts. FCEB challenges include long manufacturing times and slow development of hydrogen refuelling infrastructure.

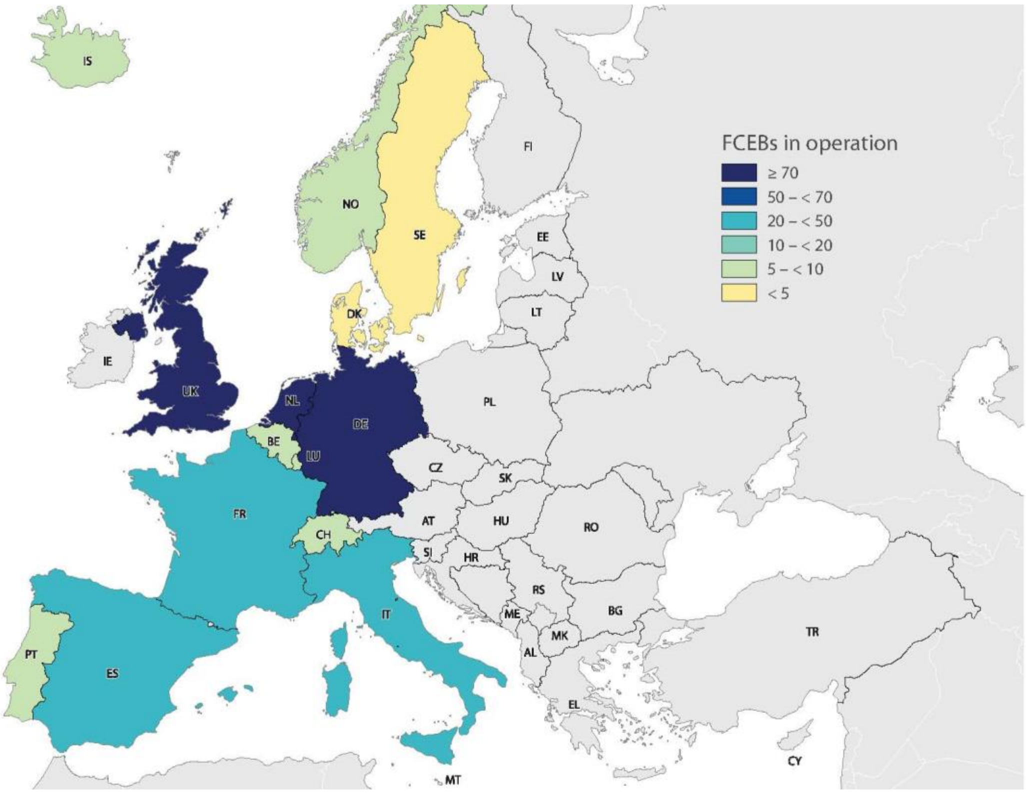
[20] Hydrogen Fuel Cell Electric Vehicles | European Hydrogen Observatory (europa.eu)

Figure 27. FCEVs deployed in Europe from 2010 to 2023. Projects: H2MOVES SCANDINAVIA, HYTEC, SWARM, HYFIVE, H2ME, H2ME2 and ZEFER.



Source: JRC based on Clean Hydrogen JU data, 2024, [1]

Figure 28. FCEBs deployed in Europe from 2005 to 2023. Projects: CUTE, HIGH:FLEET CUTE, CHIC, HIGH V.LO-CITY, HYTRANSIT, 3EMOTION, JIVE and JIVE2.



Source: JRC based on Clean Hydrogen JU data, 2024, [1]

3.3.2 Stationary fuel cells

The global deployment of large-scale fuel cells is mainly concentrated in the US and Rep. Korea. MCFC, SOFC, and PAFC are the dominant technologies, with FuelCell Energy, Bloom Energy, and Doosan Fuel Cells being the leading manufacturers. There are not the same drivers present in Europe than there are in Rep. Korea or selected parts of the US, as Europe has a stable electrical power grid and different policies regarding pubic funding for power production using natural gas. Key factors driving large-scale fuel cell deployment in the US are financial support from public funding, green energy targets, and unreliable electricity grids. Main applications include electrical supply and back-up, often used by public service providers. MCFC, SOFC, and PAFC are all deployed and produced in the US, mostly in the >100kW capacity range. Only few states such as California requires renewable sources for fuel in order to receive public funding or tax incentives. Rep. Korea has ambitious renewable energy plans due to high greenhouse gas emissions and poor air quality, with fuel cells designated as part of the "New and Renewable Energy" program. This resulted in significant public funding support for deployment, regardless of technology origin or fuel source [3]. Major power producers with government incentives drive installations, with PAFC and MCFC being the dominant technologies. In Japan the cumulative sales volume of ENE-FARM systems amounted to over 480 000 units (at around 1kW capacity) installations in the residential sector, again largely running on natural gas.

Public funding remains crucial for fuel cell deployment, and the main barriers are reliability and cost. European efforts on stationary fuel cells had in the past been focused on smaller units, but the EU's knowledge in SOFC and PEMFC could be utilised for further scaling up to target the commercial and heavy duty mobility market.

Europe has focused on the residential sector for stationary fuel cells, with very few large-scale stationary projects. European MCFC research began in the 1980s, led by organisations like ECN (now TNO), MBB (later MTU Onsite), and Ansaldo Fuel Cells. MTU Onsite (later CFC Solutions) had an agreement with FuelCell Energy and deployed systems in Germany and the UK. Short lifetimes and high costs have hindered the commercial success of European MCFC development, as well as a lack of drivers for deploying large capacity fuel cells [11]. There are few products fully developed or deployed in the medium range (5-400 kWe) or above. A large number of manufacturers were involved in the production of fuel cells for the residential sector, such as Viessmann (DE) and Bosch (DE), based on the potential for high performance (over 80% combined thermal and electrical efficiency) and CO_2 savings. The FCH JU ENE.FIELD project has installed over 1 000 micro-CHP units, with 2 600 more as part of recently ended PACE project. The PACE project found that CO_2 savings of residential fuel cells against burners running on natural gas are only 2.1 % and annual cost savings 7 % [45]. Germany's KfW 433 program supported end-users until 2023, leading to about 15 000 installations [46]. In Germany subsidies are no longer granted for residential units running on natural gas due to a change in policy. As biomethane or hydrogen are not available for most potential customers, subsidies for residential FCs are basically no longer available in Germany.

3.4 Employment

As regards to employment in the value chain, various studies show different results, due to the different methodology and assumptions adopted (for example: direct versus indirect jobs, sectors of employment including manufacturing of fuel cell vehicles, etc.). There is little information available to conduct an in-depth analysis, but some main manufacturers provide numbers on employment. These are evaluated in this section.

3.4.1 Main manufacturers

The main fuel cell manufacturers both in terms of number of systems and deployed capacity are the automotive companies Hyundai and Toyota. While there is no information on the total staff dedicated to fuel cell development and manufacturing at Hyundai, the Namyang Research Center alone has approximately 13 700 employees, including both researchers and other staff. The Jeonju Plant for heavy duty vehicle production has 5 000 employees. The Hyundai Motor Europe Technical Center in Rüsselsheim, Germany, is Hyundai's sole European R&D centre with over 400 multinational employees, contributing to R&D for European commercial vehicles. For fuel cell development and manufacturing, we can assume that there are thousands of employees. There is no information on the staffing of the Toyota fuel cell research and manufacturing units in Japan. Toyota Motor Europe (BE) is staffed by 2 700 people. Toyota launched a dedicated fuel-cell unit, the Hydrogen Factory with a staff of 1 350 in 2023 [47]. In the US Plug Power employs 3 868 people [48], mostly in the US, and Bloom Energy 2 377 [49]. Ballard (CA) had 1 173 employees in 2023, primarily based in Burnaby, Canada [25]. Other mid-sized US based manufacturers are Fuel Cell Energy (staff 591) [50] and Nuvera (staff 501) [51]

In Europe, Symbio Fuel Cell (FR) has more than 750 employees and is set to grow [52]. In the UK the key players are Ceres Power (staff 536) [53] and Intelligent Energy (staff 292) [54]. Germany has two important manufacturers in CellCentric [55] (staff 350) and EKPO Fuel Cells (staff 99) [56]. SolydEra (IT) is another mid-sized manufacturer with a staff of 270 [57]. Smaller companies in Europe are Power Cell Sweden (SE), 149 employees [58] and the recently bankrupt Nedstack (NL) with 64 employees [59]. For components, IAG (AT) has 100 employees [60].

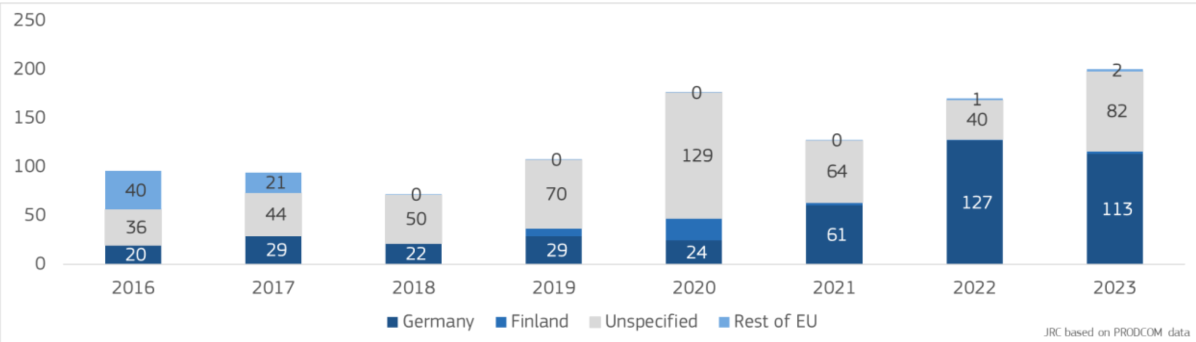
3.5 Energy intensity and labour productivity

Unfortunately, there are not yet enough fuel cell volumes being produced to calculate this. It is not possible to provide precise figures for these categories as they are not officially tracked.

3.6 EU Production Data

In 2023, the value of the EU fuel cell[21] production increased by 18%, reaching EUR 200 million (Figure 29) Germany was the top EU producer, holding more than half of the EU production in 2023. However, not all Member States disclose their production. As a result, around 40% of the EU production is confidential (the grey boxes in Figure 29).

Figure 29. EU production value of fuel cells [EUR Million]



Source: JRC based on PRODCOM data

[21] Prodcom code 27904200, available as of 2016

4 EU Market Position and Global Competitiveness

4.1 Global & EU market leaders

According to the Fuel Cells Observatory of the Clean Hydrogen JU[22], the cumulative number of FCEV in Europe reached 5 500, compared to a global deployment of over 70 000 vehicles [7], [8]. For the stationary market, the deployed capacity is mainly located in Asia and North America, and the demand is covered by manufacturers from these regions. Therefore the European market does not have an appreciable share, and European manufacturers also do not play a large role on the international market. In the following subsections an overview of the main manufacturers is provided.

As mentioned in Section 2.2.1.2, Europe is no longer supporting the deployment of residential fuel cells, likely due to the fact that they are typically operating on natural gas. There are some projects where large capacity fuel cells have been installed, but compared to the international landscape, these are not significant.

4.1.1 Fuel cell stack/system manufacturers

Although Europe had invested in the development of FCEV, there are few products with a very limited market share. BMW and Daimler are investing in this technology and are part of the Hydrogen IPCEIs. The Mercedes-Benz GLC F-CELL prototype, an electric vehicle with both fuel cell and plug-in hybrid technology, was unveiled in 2017 at the International Motor Show in Frankfurt. Initially, fleet customers utilised the car in 2018, followed by business and private customers in 2019. However, the company has meanwhile moved its focus to heavy duty mobility. Although Daimler (Mercedes Benz) and BMW have produced FCEVs, they have not manufactured fuel cells. In place for over 10 years is a partnership of BMW with Toyota, supplying the fuel cells for the I-series concept cars [61]. Daimler has shifted to heavy duty applications with first customer trials to take place in 2024 [6]. The fuel cells will be sourced from Ballard, but Daimler is also a major stakeholder in CellCentric (see below).

Intelligent Energy (UK) produces PEMFC for the mobility sector and other specialised applications such as Unmanned Aerial Vehicles (UAV). Their new, compact 157 kW fuel cell is predicted to cost around 100 GBP per kW under full-scale, high-volume manufacturing conditions by the end of the decade [62]. There is no reliable information available regarding capacity or turnover.

Bosch (DE), a major automotive supplier, has announced plans to invest EUR 2.5 billion by 2026 in hydrogen technology. Bosch's strategy encompasses the entire hydrogen supply chain, from production to hydrogen engines. The company anticipates generating EUR 5 billion in sales by 2030 and has already initiated mass production of fuel cell power modules, with Nikola Corporation, a US-based commercial electric truck maker, as the pilot customer.

CellCentric aims to manufacture and market PEM fuel cell systems for heavy-duty trucks and other similar applications. These systems will be provided to shareholders Daimler Truck AG and the Volvo Group, as well as other customers. In 2022, Cellcentric opened a facility in Burnaby, British Columbia. The Greater Vancouver area, known as the "Silicon Valley of fuel cell technology," houses many world-leading clean technology and hydrogen mobility companies. With nearby universities like the University of British Columbia and Simon Fraser University, the region boasts a strong talent pool in the fuel cell sector. Cellcentric's choice of location was influenced by easy access to this local expert network [63]. The company also plans to build a manufacturing facility in Weilheim, Germany. Again this location was chosen due to the availability of competent staff in the area. Due to substantial delays with the building of the new plant, the fuel cells will be built in an existing facility in Esslingen [64].

Owned by Michelin, Stellantis and Forvia, Symbio FC (FR) will be opening a large scale factory in Saint-Fons in 2023. It will be one of the largest fuel cell stack and system production sites in Europe and will have a total production capacity of 50 000 systems per year by 2026 [52]. The company is mainly targeting the heavy duty segment. It has produced class 8 trucks with a 400kW FC system which will be tested in central California in 2025 [65].

ElringKlinger and Plastic Omnium have recently launched a joint venture, EKPO Fuel Cells to manufacture products for the mobility market. The company offers PEM fuel cell stacks as well as components. EKPO is receiving funding of up to €177 million until 2027 under the "IPCEI Hydrogen" initiative to bring high-

[22] Hydrogen Fuel Cell Electric Vehicles | European Hydrogen Observatory (europa.eu)

performance fuel cell stack modules for heavy-duty applications to mass production level [66]. The funding is provided by the Federal Ministry of Digital and Transport and the Ministry of the Environment of the state of Baden-Württemberg. These advanced stacks will be produced in southern Germany, among other locations.

Helion (FR) offers PEMFC, mainly for rail or other mobility applications. The company was recently acquired by Alstom and plans to open its new production plant with 30 MW capacity in 2024.

Hydrogene de France Energy (FR) has launched a plant for manufacturing 1 MW+ PEM fuel cells, aimed at decarbonising heavy maritime and rail mobility, as well as producing electricity for public power grids. The company plans to start the industrial process in 2024, with the aim of producing 1 GW per year by 2030. The company has received financial support from the Nouvelle-Aquitaine Region and through the HYMOVE IPCEI [67].

Elcogen in Lithuania manufactures both SOFC and SOEC, and is set to expand considerably. The new production facility will increase its manufacturing capacity to 360 MW. Construction of the new 14 000 m^2 facility started in January 2024, with operations scheduled to commence by mid-2025.

Ceres Power (UK) and SolydEra (IT, formerly Solid Power) had developed SOFC products largely geared towards the residential segment, within the 1-5 kW range. Meanwhile Ceres Power has moved towards SOEC development, partnering with Bosch and Linde [68] and SolydEra is also expanding to SOEC and large size SOFC systems.

Nedstack (NL) deployed the world's first MW scale PEMFC at a chlor-alkali plant in Belgium, running on by-product hydrogen. In partnership with GE Power Solutions, the company was going into the maritime propulsion market. In February 2024, the company declared bankruptcy [69], in spite of potential future subsidies from the Dutch government through the Hydrogen IPCEI. The company had been a partner in several Clean Hydrogen JU projects.

Proton Motors (DE) manufactures PEMFC for various end-use sectors, most recently a 24 kW emergency back-up solution for the Deutsche Bahn. The company reported a record 1st quarter in 2020 with EUR 6.4 million in orders.

4.1.2 Fuel cell components

It is not possible to provide a comprehensive overview of fuel cell component manufacturers due to the fast dynamics and the wide heterogeneity of the market. Some prominent examples are mentioned. In Europe, several large companies are producing fuel cell components. Johnson Matthey (UK) supplies MEAs, catalyst coated membranes and catalysts to fuel cell manufacturers. Sales of these components represent 1.1 % of their sales excluding PGMs [70]. The company reported sales of GBP 55 million against a reported loss of GBP 46 million. Johnson Matthey has agreed strategic partnerships with Plug Power and Hystar (electrolyser manufacturer). Freudenberg (DE) produces fuel cell stack seals, gas diffusion layers, filters and humidifiers. The most commonly used membrane for PEMFC is Nafion, developed by DuPont (US). There are other options being developed and manufactured by Fumatech (DE) and Solvay (BE), whereas Umicore (BE) makes catalyst materials for fuel cells and electrolysers. Merck (DE) also offers fuel cell components. IAG (AT) is making bipolar plates [60], Elmarco in Czechia is producing nanofibers [71], Inea in Slovenia is focused on automation. UFI Hydrogen (IT) aims to create advanced MEAs, designed for roll-to-roll production processes. The company was recently announced to be part of the HYMOVE IPCEI.

4.2 Trade (Import/export) and trade balance

The available data on the import and export of fuel cells is limited, making it difficult to accurately assess the trade balance for this technology. This lack of information hinders the ability to understand the global market dynamics and identify potential opportunities or challenges for fuel cell trade.

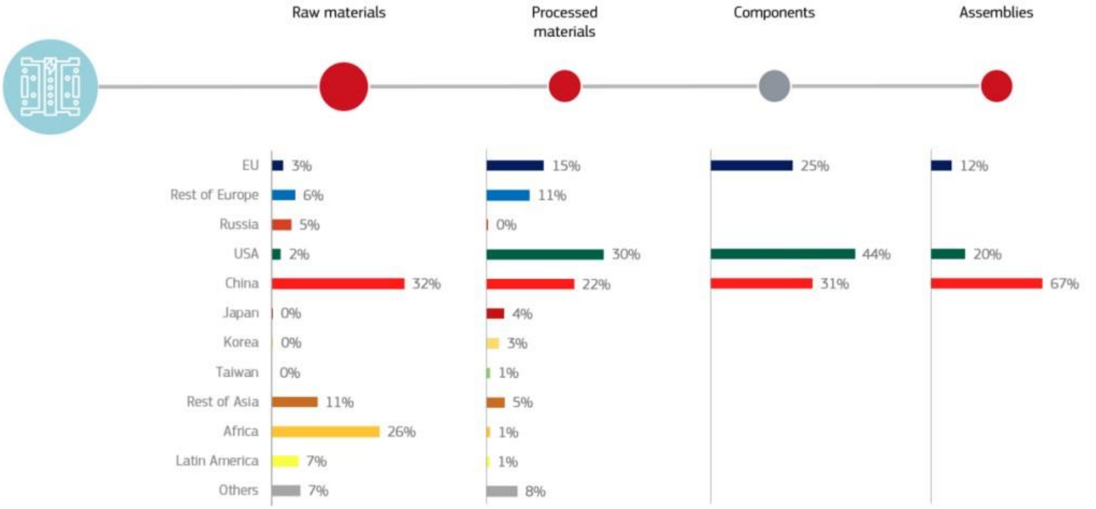
4.3 Resource efficiency and dependence in relation to EU competitiveness

According to JRC analysis [72], the greatest risk in the supply chain for fuel cells lies in the raw material stage. Europe generates only 3 % of the raw materials, 18 % of the processed materials, and 25 % of the components used in FC manufacturing. Europe's FC manufacturing for system assemblies is also comparatively low, accounting for just 12 % of the global production share, see Figure 30.

The 2022 Critical Raw Materials (CRM) list identifies 18 out of 24 materials needed for PEMFC and SOFC production as crucial for the EU economy. Europe heavily relies on foreign sources for these materials. China leads in the production of several CRMs, such as cerium (100 %), yttrium (100 %), lanthanum (over 85 %), gadolinium (over 85 %), and natural graphite (65 %). Due to competing demands from various industries and poor social governance in these source countries, the situation is unlikely to change, keeping prices high for these materials.

Asian companies dominate the supply chain steps, while Europe holds the highest share in components (25 %) and processed materials (18 %) production but does not have a clear advantage in any particular stage.

Figure 30. An overview of supply risks, bottlenecks, and key players along the supply chain of fuel cells. The color of the circles shows whether the step should be considered critical (red) or non-critical (grey). The size of the circles (small, medium or large) relates to the number of supply chain elements appearing in the step.



Note: In the case of components, the graph represents combined categories for Europe (EU27 together with Rest of Europe), North America (USA + Canada), and Asia (China, Japan, Korea, Taiwan, and Rest of Asia) presented at the level of the main source.

Source: JRC, 2023 [72]

5 Conclusions

The installed fuel cell capacity (GW) worldwide has seen a steady growth over the last decade. Asia has been leading this growth, followed by North America and Europe. Estimates from different sources showed that the total installed fuel cell capacity in 2021 ranged between 6.9 – 7.3 GW worldwide. European installed capacity (EU + UK, NO, CH) ranged between 0.5 – 0.6 GW which represented 8.1 – 8.3 % of the total worldwide capacity. The global installed capacity is stagnating recently (2021-2023), whereas in the years before there had been strong growth (see Figure 1 and Figure 2). The Asian region (mainly Rep. Korea, Japan and China) continues to lead in total fuel cell deployments with 5.6 GW (71.6 %) installed capacity, followed by North America with 1.4 GW (18.3 %).

Mobility applications (predominantly using PEMFC) accounted for approximately 73.4 – 76.7 % of the total fuel cell market share in 2021. In comparison, stationary fuel cells hold the second-largest market share with an installed capacity in the range of 23.3 – 26.5 % in 2021. Lastly, portable fuel cells account for only a negligible portion (0.05 – 0.06 %) of the total fuel cell market, as their usage is limited to small-scale applications like electronic devices, consumer products, and portable power generation.

The global fleet of FCEVs is closing in on 80 000, with Rep. Korea remaining the major market for cars and China for buses and trucks. As the global interest in sustainable transportation technologies grows, it is expected that the application of fuel cells will continue to expand and diversify across various sectors, with road transport, especially in heavy-duty applications, remaining the primary focus for now.

Asia seems to have taken the lead with 0.9 - 1.2 GW installed capacity for stationary fuel cells. For the US, which had the highest installed capacity globally up until 2018 with over 0.5 GW [11], installations seem to have stalled. In Europe, the total installed capacity is around 10% of the global capacity. Europe has primarily been concentrating on decarbonisation efforts, resulting in a lower priority for stationary fuel cell deployment. Renewable hydrogen is regarded as too precious to use for typical stationary fuel cell applications, and in any case, most fuel cells deployed globally are running on natural gas. The decarbonisation benefits are therefore somewhat limited, even though fuel cells offer a higher efficiency than incumbent technologies. In terms of using green hydrogen, Europe aims to implement it to decarbonise hard-to-abate sectors, such as heavy-duty mobility.

Manufacturing capacity of fuel cells is set to increase, which may not be matched with market demand. In Europe, fuel cell manufacturers seem to be focusing on producing stacks and systems for the heavy duty sector, and there are clear efforts toward expanding manufacturing capacity. As for electrolysers, public support for hydrogen end-use technologies will be crucial in the coming years. Despite having the highest number of production lines for fuel cells, the European manufacturing capacity remains relatively small. This is primarily due to the fact that the industry is comprised of many small to medium-sized companies, each with limited manufacturing capacity. While the region may have a significant number of production lines, these are often dispersed across a multitude of smaller facilities, rather than concentrated within a few large-scale manufacturing plants. As a result, the overall manufacturing capacity for fuel cells in Europe is relatively modest compared to other regions. This presents a challenge in terms of achieving economies of scale and cost efficiencies, which are often associated with larger, more centralized manufacturing operations. Therefore, addressing the fragmentation of manufacturing capacity within the European fuel cell industry is essential to fully leverage the potential of this technology and enhance its competitiveness on a global scale.

In terms of public investments, the analysis of thirteen major economies shows that the EU and Japan collectively accounted for 65% of the total global public investments in fuel cells from 2013 to 2023. The EU's contribution of 48% stands out as particularly significant, with Japan, Rep. Korea, the US, and Switzerland following behind in their respective contributions. These findings highlight the dominant role of the EU and Japan in global public investments in fuel cells during this period.

Using patenting output as a proxy for private funding, it is observed that private investments in the EU and globally outweigh public investments significantly. The EU exhibits a substantial increase in private investment over the period from 2010 to 2020, with Germany leading in cumulative private investments. At a global level, Japan represents the highest percentage of cumulative private investments, followed by the EU. The trend of global venture capital investments in fuel cell companies has fluctuated, with a notable increase in 2022, primarily driven by Chinese firms. However, early-stage investments in EU VC companies have continuously decreased after a peak in 2022, indicating a competitive position stagnation in the global investment race. Later-stage investments in EU VC companies also remain relatively low compared to other regions.

In spite of a weak internal market and a limited number of manufacturers with a significant turnover, Europe has a role as an international patenting actor. Europe is involved in research and development activities, demonstrating a strong global scientific presence alongside China and the US, as evidenced by their top-tier publication records.

In terms of resource efficiency, the greatest risk in the supply chain for fuel cells lies in the raw material stage. Europe generates only 3 % of the raw materials, 18 % of the processed materials, and 25 % of the components used in fuel cell manufacturing. Europe's FC manufacturing for system assemblies is also comparatively low, accounting for just 12 % of the global production share.

It is also relevant to highlight the significant shift in the importance of strategic technologies within the hydrogen field. Traditionally, fuel cells have been highly investigated due to their application in clean mobility applications. However, there is now a greater emphasis on the production of renewable hydrogen through electrolysis. This shift in focus reflects the growing recognition of the importance of renewable energy production and the role that electrolysis plays in facilitating the availability of renewable hydrogen. As a result, there is a noticeable funding shift towards the development and implementation of electrolysis technology, as fuel cell dependency on the availability of renewable hydrogen becomes increasingly apparent. This shift signifies a broader industry trend towards prioritising the production of renewable energy, and underscores the growing importance of electrolysis in driving this transition.

Despite the weak internal market and the modest European manufacturing capacity provided by small manufacturers, there has been a notable increase in industry interest in expanding the manufacturing capacity of fuel cells in recent years. This trend has been further bolstered by the implementation of Important Projects of Common European Interest (IPCEIs) for fuel cells, which aim to support and accelerate the development and deployment of key technologies within the European Union. With a renewed focus on strategic technologies and the production of renewable hydrogen, the IPCEIs provide a valuable opportunity for industry stakeholders to collaborate and invest in the advancement of fuel cell manufacturing. This signifies a significant step towards fostering a sustainable and competitive fuel cell industry, and underscores the growing momentum towards harnessing the potential of fuel cells in addressing energy and environmental challenges.

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List of abbreviations and definitions

AFC	Alkaline Fuel Cells
AFIR	Alternative Fuels Infrastructure Regulation
BoP	Balance of Plant
CBAM	Carbon Border Adjustment Mechanism
CETO	Clean Energy Technologies Observatory
CHP	Combined Heat and Power
CRM	Critical Raw Materials
EPO	European Patent Office
ETS	Emmisions Trading System
FC	Fuel Cells
FCEB	Fuel Cell Electric Buses
FCET	Fuel Cell Electric Trucks
FCEV	Fuel Cell Electric Vehicles
FCH JU	Fuel Cell Hydrogen Joint Undertaking, now Clean Hydrogen Partnership
FCH 2JU	Fuel Cell Hydrogen Joint Undertaking 2, now Clean Hydrogen Partnership
FWCI	Field-Weighted Citation Impact
GHG	Green House Gas
HD-FCET	Heavy Duty Fuel Cell Electric Trucks
HGV	Heavy Goods Vehicles
HT-PEMFC Fuel Cell	High Temperature Proton Exchange Membrane Fuel Cells or Polymeric Electrolyte Membrane
IEA	International Energy Agency
IPCEI	Important Projects for Common European Interest
IRA	Inflation Reduction Act
JRC	European Commission Joint Research Centre
LCV	Light Commercial Vehicles
LT-PEMFC Fuel Cell	Low Temperature Proton Exchange Membrane Fuel Cells or Polymeric Electrolyte Membrane
MAWP	Multi-annual Work Programme
MCFC	Molten Carbonate Fuel Cells
MD-FCET	Medium Duty Fuel Cell Electric Trucks
MEA	Membrane Electrode Assembly
METI	Japan’s Ministry of Economy, Trade and Industry
NDRC	National Development and Reform Commission
NZE	Net Zero Emissions
PAFC	Phosphoric Acid Fuel Cell
PCFC	Proton Conducting Fuel Cells or Proton Ceramic Fuel Cells
PEMFC	Proton Exchange Membrane Fuel Cells or Polymeric Electrolyte Membrane Fuel Cell
PFAS	Per- and polyfluoroalkyl Substances

R&D	Research and Development
RED	Renewable Energy Directive
RFNBO	Renewable Fuels of Non Biological Origin
R&I	Research and Innovation
RoW	Rest of the World
SET-Plan	Strategic Energy Technology Plan
SoA	State of the Art
SAF	Sustainable Aviation Fuels
SOEC	Solid Oxide Electrolyser Cells
SOFC	Solid Oxide Fuel Cells
SRIA	Strategic Research and Innovation Agenda
TEN-T	Trans-European Transport Network
TRL	Technology Readiness Level
TRUST	Technology Reporting Using Structured Templates
UAV	Unmanned Aerial Vehicles
UPS	Uninterruptible Power Systems
US DoE	United States Department of Energy
VC	Venture Capital
YSZ	Yttria-Stabilised Zirconia

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Annexes

Annex 1 Summary Table of Data Sources for the CETO Indicators

Theme	Indicator	Main data source
Technology maturity status, development and trends	Technology readiness level	JRC analysis, scientific publications, EC reports, EPO reports
	Installed capacity & energy production	JRC analysis, IEA, Rystad Energy, European Hydrogen Observatory
	Technology costs	JRC analysis, Clean Hydrogen Partnership, US Department of Energy
	Public and private RD&I funding	JRC analysis
	Patenting trends	JRC analysis, EPO
	Scientific publication trends	JRC analysis
	Assessment of R&I project developments	JRC analysis, Clean Hydrogen Partnership
Value chain analysis	Turnover	JRC analysis
	Gross Value Added	JRC analysis
	Environmental and socio-economic sustainability	JRC analysis
	EU companies and roles	JRC analysis
	Employment	JRC analysis
	Energy intensity and labour productivity	JRC analysis
	EU industrial production	JRC analysis
Global markets and EU positioning	Global market growth and relevant short-to-medium term projections	JRC analysis
	EU market share vs third countries share, including EU market leaders and global market leaders	JRC analysis
	EU trade (imports, exports) and trade balance	JRC analysis
	Resource efficiency and dependencies (in relation EU competiveness)	JRC analysis

Annex 2 Energy System Models and Scenarios: POTEnCIA and POLES-JRC

AN 2.1 POTEnCIA Model

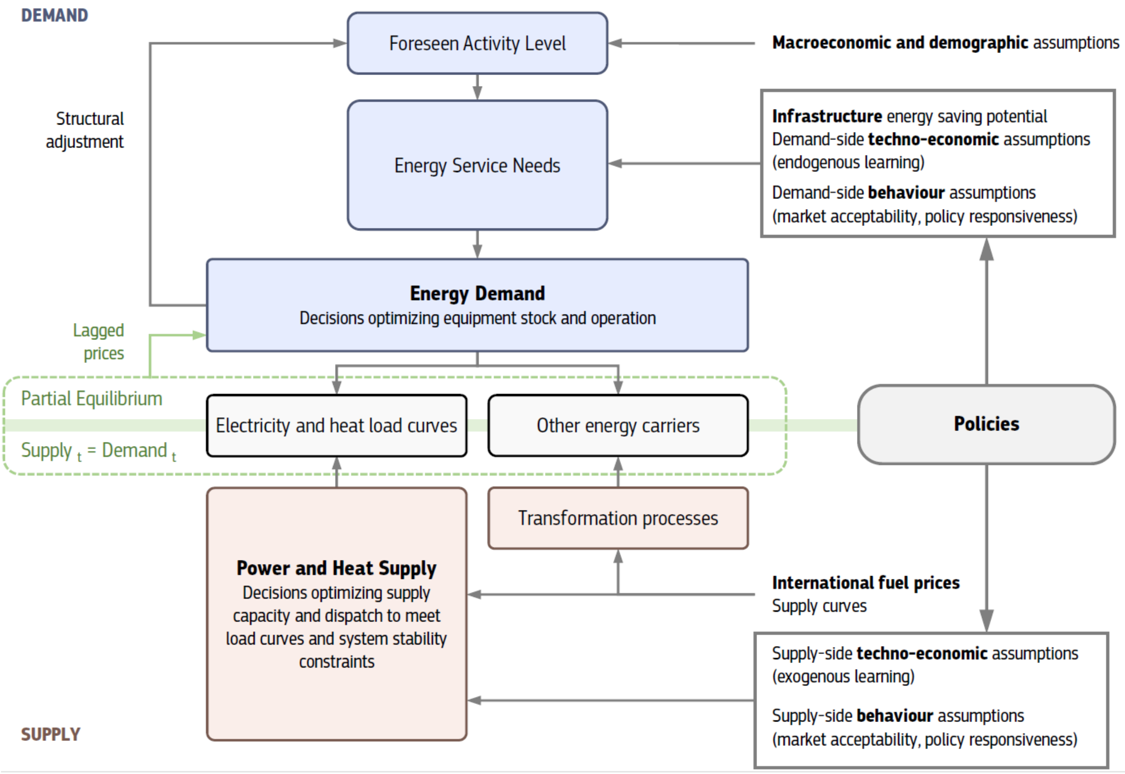
AN 2.1.1 Model Overview

The Policy Oriented Tool for Energy and Climate Change Impact Assessment (POTEnCIA) is an energy system simulation model designed to compare alternative pathways for the EU energy system, covering energy supply and all energy demand sectors (industry, buildings, transport, and agriculture). Developed in-house by the European Commission's Joint Research Centre (JRC) to support EU policy analysis, POTEnCIA allows for the joint evaluation of technology-focused policies, combined with policies addressing the decision-making of energy users. To this end:

- By simulating decision-making under imperfect foresight at a high level of techno-economic detail, POTEnCIA realistically captures the adoption and operation of new energy technologies under different policy regimes;
- By combining yearly time steps for demand-side planning and investment with hourly resolution for the power sector, POTEnCIA provides high temporal detail to suitably assess rapid structural changes in the EU's energy system;
- By tracking yearly capital stock vintages for energy supply and demand, POTEnCIA accurately represents the age and performance of installed energy equipment, and enables the assessment of path dependencies, retrofitting or retirement strategies, and stranded asset risks.

The core modelling approach of POTEnCIA (Figure 31; detailed in [73], [74]) focuses on the economically-driven operation of energy markets and corresponding supply-demand interactions, based on a recursive dynamic partial equilibrium method. As such, for each sector of energy supply and demand, this approach assumes a representative agent seeking to maximize its benefit or minimize its cost under constraints such as available technologies and fuels, behavioural preferences, and climate policies.

Figure 31. The POTEnCIA model at a glance



Source: JRC adapted from [73]

This core modelling approach is implemented individually for each EU Member State to capture differences in macroeconomic and energy system structures, technology assumptions, and resource constraints. The national model implementation is supported by spatially-explicit analyses to realistically define renewable energy potentials and infrastructure costs for hydrogen and CO_2 transport. Typical model output is provided in annual time steps over a horizon of 2000-2070; historical data (2000-2021) are calibrated to Eurostat and other official EU statistics to provide accurate initial conditions, using an updated version of the JRC Integrated Database of the European Energy System ([75]).

AN 2.1.2 POTEnCIA CETO 2024 Scenario

The technology projections provided by the POTEnCIA model are obtained under a climate neutrality scenario aligned with the broad GHG reduction objectives of the European Green Deal. As such, this scenario reduces net EU GHG emissions by 55% by 2030 and 90% by 2040, both compared to 1990, and reaches net zero EU emissions by 2050. To model suitably the uptake of different technologies under this decarbonisation trajectory, the scenario includes a representation at EU level of general climate and energy policies such as emissions pricing under the Emissions Trading System, as well as key policy instruments that have a crucial impact on the uptake of specific technologies. For instance, the 2030 energy consumption and renewable energy shares reflect the targets of the EU's Renewable Energy Directive and of the Energy Efficiency Directive. Similarly, the adoption of alternative powertrains and fuels in transport is consistent with the updated CO_2 emission standards in road transport and with the targets of the ReFuelEU Aviation and FuelEU Maritime regulations. A more detailed description of the *POTEnCIA CETO 2024 Scenario* will be available in the forthcoming report [76].

AN 2.2 POLES-JRC model

AN 2.2.1 Model Overview

POLES-JRC (Prospective Outlook for the Long-term Energy System) is a global energy model well suited to evaluate the evolution of energy demand and supply in the main world economies with a representation of international energy markets. It is a simulation model that follows a recursive dynamic partial equilibrium method. POLES-JRC is hosted at the JRC and was designed to assess global and national climate and energy policies.

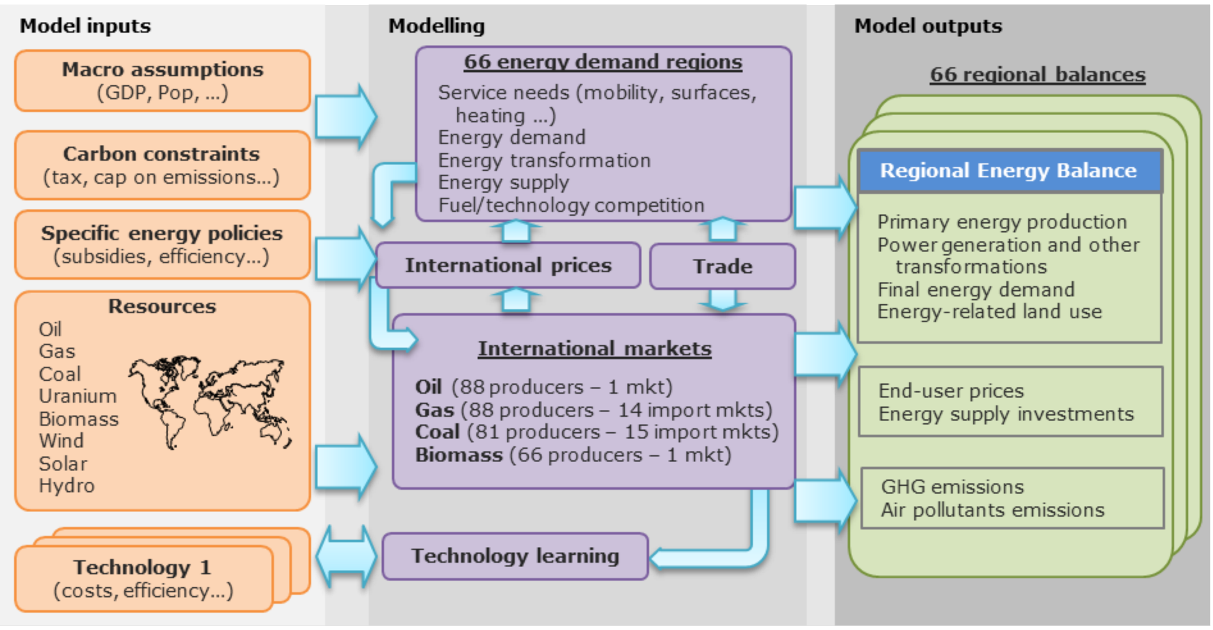
POLES-JRC covers the entire energy system, from primary supply (fossil fuels, renewables) to transformation (power, biofuels, hydrogen and hydrogen-derived fuels such as synfuels) and final sectoral demand (industry, buildings, transport). International markets and prices of energy fuels are calculated endogenously. Its high level of regional detail (66 countries & regions covering the world with full energy balances, including all detailed OECD and G20 countries) and sectoral description allows assessing a wide range of energy and climate policies in all regions within a consistent global frame: access to energy resources, taxation policy, energy efficiency, technological preferences, etc. POLES-JRC operates on a yearly basis up to 2100 and is updated yearly with recent information.

The POLES-JRC model applied for the CETO project is specifically enhanced and modified to capture learning effects of clean energy technologies.

POLES-JRC results are published within the series of yearly publications "Global Climate and Energy Outlooks" – GECO. The GECO reports along with detailed country energy and GHG balances and an on-line visualisation interface can be found at: https://joint-research-centre.ec.europa.eu/scientific-activities-z/geco_en

A detailed documentation of the POLES-JRC model is provided in [77].

Figure 32. Schematic representation of the POLES-JRC model architecture.



Source: POLES-JRC model

AN 2.2.2 POLES-JRC Model description

Power system

The power system considers all relevant power generating technologies including fossil, nuclear and renewable power technologies. Each technology is modelled based on its current capacities and techno-economic characteristics. The evolution of cost and efficiencies are modelled through technology learning.

With regard to the power technologies covered by CETO, the model includes solar power (utility-scale and residential PV, concentrated solar power), wind power (on-shore and off-shore), hydropower and ocean power. Moreover, clean thermal power technologies are taken into account with steam turbines fuelled by biomass, biomass gasification, CCS power technologies and geothermal power. Furthermore, electricity storage technologies such as pumped hydropower storage and batteries are also included.

For solar and wind power, variable generation is considered by representative days with hourly profiles. For all renewables, regional resource potentials are considered.

Electricity demand
Electricity demand is calculated for all sectors taking into account hourly fluctuations through the use of representative days. Clean energy technologies using electricity consist of heat pumps (heating and cooling), batteries and fuel cells in transport, and electrolysers.

Power system operation and planning
Power system operation allocates generation by technology to each hour of representative days, ensuring that supplying and storage technologies meet overall demand, including grid imports and exports. Capacity planning considers the existing power mix, the expected evolution of electricity demand as well as the techno-economic characeristics of the power technologies.

Hydrogen

POLES-JRC takes into account several hydrogen production routes: (i) low temperature electrolysers using power from dedicated solar. wind and nuclear plants as well as from the grid, (ii) steam reforming of natural gas (with and without CCS), (iii) gasification of coal and biomass (with and without CCS), (iv) pyrolysis of gas and biomass as well as (v) high temperature electrolysis using nuclear power.

Hydrogen is used as fuel in all sectors including industry, transport, power generation and as well as feedstock for the production of synfuels (gaseous and liquid synfuels) and ammonia. Moroever, hydrogen trade is modelled, considering hydrogen transport with various means (pipeline, ship, truck) and forms (pressurised, liquid, converted into ammonia).

Bioenergy

POLES-JRC receives information on land use and agriculture through a soft-coupling with the GLOBIOM-G4M model [78]. This approach allows to model bioenergy demand and supply of biomass adequately by taking into account biomass-for-energy potential, production cost and reactivity to carbon pricing.

Biomass is used for power generation, hydrogen production and for the production of 1st and 2nd generation of liquid biofuels.

Carbon Capture Utilization and Storage (CCUS)

POLES-JRC uses CCUS technologies in:

- Power generation: advanced coal using CCS, coal and biomass gasification with CCS, and gas combined cycle with CCS.
- Hydrogen production: Steam reforming with CCS, coal and biomass gasification with CCS, and gas and biomass pyrolysis.
- Direct air capture (DAC) where the CO_2 is either stored or used for the production of synfuels (gaseous or liquid).
- Steel and cement production in the industrial sector.
- Second generation biofuels production.

The deployment of CCS technologies considers region-specific geological storage potentials.

Endogenous technology learning

The POLES-JRC model was enhanced to capture effects of learning of clean energy technologies. To capture these effects, a one-factor learning-by-doing (LBD) approach was applied to technologies and technology sub-components, aiming at endogenising the evolution of technology costs.

POLES-JRC considers historical statistics and assumptions on the evolution of cost and capacities of energy technologies until the most recent year available (this report: 2022/2023). Based on the year and a capacities threshold, the model switches from the default time series to the endogeneous modelling with the one-factor LBD approach. Within the LBD, the learning rate represents the percentage change of the cost of energy technology based on a doubling of the capacity of the energy technology.

This generic approach is applied on a component level to capture spillover effects as well. For instance, a gasifier unit is used as component for several power generating technologies (e.g. integrated gasification combined cycle, IGCC) as well as for several hydrogen production technologies (e.g. gasification of coal and biomass). Therefore, the component-based LBD approach allows to model spillover effects not only across technologies, but also across sectors. Also, it allows to estimate costs for emerging technologies for which historical experience does not yet exist.

Moreover, for each component a floor cost is specified which marks the minimum for the component's investment cost and serves as limitation for the cost reduction by endogenous learning. Cost reductions by learning in POLES-JRC slow down when the investment cost approaches the floor cost.

The described method above applies not only for the overnight investment cost of energy technologies, but as well for operation and maintenance (OM) costs, which also decrease as technologies improve, and for efficiencies. In the model, OM costs diminish synchronously to the decrease of total investment cost of the technology. The efficiency of renewables is implicitly taken into account in the investment cost learning and the considered renewable potentials. For most technologies the efficiencies are endogenously modelled.

AN 2.2.3 Global CETO 2°C scenario 2024

The global scenario data presented in the CETO technology reports 2024 refers to a 2°C scenario modelled by the POLES-JRC model in a modified and enhanced version to address the specific issues relevant for the CETO project.

The *Global CETO 2°C scenario 2024* and its specific POLES-JRC model configuration is described in detail in the forthcoming report "*Impacts of enhanced learning for clean energy technologies on global energy system scenario*" [79].

The *Global CETO 2°C scenario 2024* is designed to limit global temperature increase to 2°C at the end of the century. It is driven by a single global carbon price for all regions that reduces emissions sufficiently so as to limit global warming to 2°C. This scenario is therefore a stylised representation of a pathway to the temperature targets. This scenario does not consider financial transfers between countries to implement mitigation measures. This is a simplified representation of an ideal case where strong international cooperation results in concerted effort to reduce emissions globally; it is not meant to replicate the result of announced targets and pledges, which differ greatly in ambition across countries.

As a starting point, for all regions, it considers already legislated energy and climate policies (as of June 2023), but climate policy pledges and targets formulated in Nationally Determined Contributions (NDCs) and Long-Term Strategies (LTSs) are not explicitly taken into account. In particular, the EU Fit for 55 and RePowerEU packages are included in the policy setup for the EU. Announced emissions targets for 2040 and 2050 for the EU are not considered.

The *Global CETO 2°C scenario 2024* differs fundamentally from the *Global CETO 2°C scenario 2023* used in the CETO technology reports in 2023 in various aspects[23]:

- The version of the POLES-JRC model used for the Global CETO 2°C scenario has been further enhanced and modified to capture effects of endogenous learning of clean energy technologies and, furthermore, several technology representations were further detailed, e.g. DAC (composition of renewable technologies, batteries and DAC unit), fuel conversion technologies (for hydrogen transport) and batteries in transport.

[23] A description of the *Global CETO 2°C scenario 2023* can be found in Annex 3 of [82].

- The techno-economic parameters have been thoroughly revised and updated taking into account the expertise of the authors of the CETO technology reports.

As a result, major scenario differences occur in the *Global CETO 2°C scenario 2024* regarding DAC, synfuels, CCS power technologies, wind power and ocean power.

AN 2.3 Distinctions for the CETO 2024 Scenarios - POLES-JRC vs. POTEnCIA

The results of both models are driven by national as well as international techno-economic assumptions, fuel costs, as well as policy incentives such as carbon prices. However, on one side these two JRC energy system models differ in scope and level of detail, on the other side the definitions of the POTEnCIA and POLES-JRC scenarios presented in this document follow distinct logics, leading to different scenario results:

- The *Global CETO 2°C scenario 2024* (POLES-JRC) scenario is driven by a global carbon price trajectory to limit global warming to 2°C, where enacted climate policies are modelled, but long-term climate policy pledges and targets are not explicitly considered. Scenario results are presented for the global total until 2100.
- The *POTEnCIA CETO 2024 scenario* is a decarbonisation scenario that follows a trajectory for EU27's net GHG emissions aligned with the general objectives of the European Climate Law (ECL) taking into consideration many sector-specific pieces of legislation. Scenario results are presented for the EU27 until 2050.

Annex 3 Countries, regions and continents coding

EU

CODE	COUNTRY
AT	Austria
BE	Belgium
BG	Bulgaria
HR	Croatia
CY	Cyprus
CZ	Czechia
DK	Denmark
EE	Estonia
FI	Finland
FR	France
DE	Germany
EL	Greece
HU	Hungary
IE	Ireland
IT	Italy
LV	Latvia
LT	Lithuania
LU	Luxembourg
MT	Malta
NL	Netherlands
PL	Poland
PT	Portugal
RO	Romania
SK	Slovakia
SI	Slovenia
ES	Spain
SE	Sweden

WORLD

CODE	COUNTRY
BR	Brazil
CA	Canada
CN	China
CH	Switzerland
EU	European Union
HK	Hong Kong
IL	Israel
IN	India
JP	Japan
KR	South Korea
MY	Malaysia
RoW	Rest of World
SG	Singapore
TW	Taiwan
UK	United Kingdom
US	United States of America
VN	Vietnam

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