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Historical Analysis of FCH 2 JU Stationary Fuel Cell Projects

Progress of Key Performance Indicators against the State of the Art.

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Abstract

As a part of its knowledge management activities, the Fuel Cell and Hydrogen Joint Undertaking 2 (FCH 2 JU) has commissioned the Joint Research Centre (JRC) to perform a series of historical analyses by topic area, to assess the impact of funded projects and the progression of its current Multi-Annual Work Plan (MAWP; 2014-2020) towards its objectives. These historical analyses consider all relevant funded projects since the programme's inception in 2008.

This report considers the performance of projects against the overall FCH 2 JU programme targets for stationary Fuel Cells (FCs), using quantitative values of Key Performance Indicators (KPI) for assessment. The purpose of this exercise is to see whether and how the programme has enhanced the state of the art for stationary fuel cells and to identify potential Research & Innovation (R&I) gaps for the future. Therefore, the report includes a review of the current State of the Art (SoA) of fuel cell technologies used in the stationary applications sector.

The programme has defined KPIs for three different power output ranges and equivalent applications: (i) micro-scale Combined Heat and Power (mCHP) for single family homes and small buildings (0.3 - 5 kW); (ii) mid-sized installations for commercial and larger buildings (5 - 400 kW); (iii) large scale FC installations, converting hydrogen and renewable methane into power in various applications (0.4 - 30 MW). Projects addressing stationary applications in these particular power ranges were identified and values for the achieved KPIs extracted from relevant sources of information such as final reports and the TRUST database (Technology Reporting Using Structured Templates). As much of this data is confidential, a broad analysis of performance of the programme against its KPIs has been performed, without disclosing confidential information. The results of this analysis are summarised within this report.

The information obtained from this study will be used to suggest future modifications to the research programme and associated targets.

1 Introduction

The Fuel Cell and Hydrogen Joint Undertaking (FCH JU) was established according to a European Council Regulation of 30th May 2008 as a Public Private Partnership (PPP) between the European Commission, European Industry and Research Organisations [1]. The FCH JU has distributed European Union (EU) funds for projects related to fuel cells and hydrogen, first under the EU's 7th Framework Program for Research and Innovation (FP7) from 2008-2013 and, as the Fuel Cell and Hydrogen Joint Undertaking 2 (FCH 2 JU), under the Horizon 2020 Program (H2020) from 2014 onwards.

At the time of writing[1], 262 projects have been funded, with the goal of accelerating fuel cell and hydrogen technologies to the marketplace, hereby assisting in the transition to a carbon-clean energy system.

Funding from the FCH 2 JU is distributed according to two main pillars, Energy and Transport, as identified in the Multi-Annual Work Plan (MAWP) [2]. In addition, there are cross-cutting activities which perform general activities relevant to both main pillars (for example educational or safety-related work). Furthermore, there are projects that are labelled "over-arching" because they are relevant to both Energy and Transport and therefore receive part of their funding from each pillar. Ongoing projects funded by the FCH 2 JU are assessed each year as part of the Programme Review. This is carried out by a team of experts at the JRC who assess the project portfolio against key objectives of the programme. For the purpose of the Programme Review, the projects are split across six panels that look at specific areas of Fuel Cell and Hydrogen (FCH) development. The Pillars and Panels are defined in Table 1. This report considers the quantitative performance of projects against the overall Programme Targets for stationary fuel cell Key Performance Indicators (KPI). The purpose of this exercise is to see how the programme has enhanced the state of the art and to identify potential R&I gaps to be covered in the future.

Table 1: Programme Review Panels – Names and Topics

PILLAR/ACTIVITY	PANEL NAMES	TOPICS
Transport	1 - Trials and Deployment of Fuel Cell Applications	Projects targeting the demonstration and proof of concept (PoC) of FCH applications in the transportation pillar
	2 - Next Generation of Products	Basic and applied research projects tackling subjects related to the transportation pillar
Energy	3 - Trials and Deployment of Fuel Cell Applications	Projects targeting the demonstration and PoC of FCH stationary heat and power applications in the energy pillar
	4 - Next Generation of Products	Basic and applied research projects tackling subjects related to FCH stationary heat and power applications
	5 - Hydrogen for Sectorial Integration	All projects addressing hydrogen production, distribution and storage issues
Cross-Cutting	6 - Support for Market Uptake	Projects addressing cross-cutting issues

Source: Programme Office of the FCH 2 JU, 2020.

[1] Including FCH 2 JU Call 2019

2 Methodology of Historical Project Review

The purpose of this historical project review is to determine whether and how FCH JU projects (from here on covering both FCH JU and FCH 2 JU projects) have played a role in advancing the state of the art in the field of stationary fuel cells. In particular, the main aim was to use KPIs for the different stationary fuel cell technologies to evaluate how funded projects have performed against the SoA and overall Programme Targets. In order to perform this task, the following steps were undertaken.[2]

Firstly, the projects involving stationary fuel cells were identified through a database, which has been developed for the purpose of classifying all FCH 2 JU projects according to keywords [3]. The projects considered are those which have been included in Panel 3 - Trials and Deployment of Fuel Cell Applications (projects targeting the demonstration and proof of concept of fuel cell and hydrogen stationary heat and power applications in the energy pillar) and Panel 4 - Next Generation of Products (basic and applied research projects tackling subjects related to fuel cell and hydrogen stationary heat and power applications). A full list of projects is given in Annex 1, Table 9.

The main KPIs for stationary fuel cell applications identified in the MAWP have been separated based on three different sizes of application: (i) mCHP for single family homes and small buildings (0.3 - 5 kW); (ii) mid-sized installations for commercial and larger buildings (5 - 400 kW); (iii) large scale FC installations, converting hydrogen and renewable methane into power in various applications (0.4 - 30 MW). Therefore, projects were classed according to which of these three power ranges they addressed. Additionally, the projects were classified according to the fuel cell technology that they utilised. Most of the projects involved Proton Exchange Membrane Fuel Cell (PEMFC) or Solid Oxide Fuel Cells (SOFC). A small number of projects addressed Alkaline Fuel Cells (AFC), Protonic Ceramic Fuel Cells (PCFC) or Molten Carbonate Fuel Cells (MCFC).

The assessment was performed during 2019 (autumn period). Projects were divided into "completed" and "ongoing" projects. Completed projects were considered to be those with a completion date before the end of December 2018. For these projects, the primary source for the project KPIs was the final report (which is generally submitted within 3 months of the end of the project). The full methodology outlined below was performed for completed projects, whilst a simplified methodology was performed for ongoing projects.

Templates were created for each of the three main classes of stationary fuel cell applications containing a series of KPIs mainly based on the list of programme targets given in the Addendum to the Multi-annual Work Plan (MAWP) from 2018 [4]. The KPI template was filled in for each completed project, using data obtained from the following sources, in order of priority:

- Project final report
- The latest update of the TRUST database (data available from 2015-2018)
- Intermediate project reports
- Other source documents.

For ongoing projects, a simplified procedure was followed where the latest figures recorded for the specific KPIs were obtained from the TRUST database. These were then supplemented with any known values that had been achieved by the projects since the latest TRUST update.

The KPI values obtained for the relevant projects were then compared against the SoA and target values and used to derive the summary tables presented in the relevant sections below.

[2] Note: The same methodology has also been applied to FCH JU electrolyser projects for a separate historical analysis.

3 Review of Fuel Cell Technologies for the Stationary Applications Sector

The stationary fuel cells applications sector involves a range of different applications. In general, stationary FC provide electricity and sometimes heat, and are not designed 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)).

In terms of number of units deployed, the more common types are PEMFC, MCFC, Phosphoric Acid Fuel Cells (PAFC) and SOFC. 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.

Fuel cells stacks for stationary applications are typically installed in systems with external or internal reformers and run on natural gas or biogas. A few large-scale PEMFC are operated on by-product hydrogen from industrial processes. A sub-type of PEMFC, the direct-liquid (most commonly methanol) fuel cells, supply the liquid fuel directly to the electrodes, without prior reforming. 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.

In terms of commercialisation of fuel cells, the largest market share globally, both in terms of number of units and capacity, are for PEMFC, but close to 70% of the capacity has been supplied to transport applications [5]. In terms of installed capacity for stationary applications, both MCFC and PAFC have large shares in the segment above 200 kW [6]. The stationary fuel cell market in general, for all FC sizes, saw sales of around 240 MW capacity in 2018, and is dominated by the US and Asia, both in terms of manufacturers and place of deployment [7].

Each individual technology has advantages and drawbacks, which will determine the application they are best suited for. An overview is provided in Table 2.

Table 2: Characteristics of the fuel cell technologies considered in this report (adapted from [7-9]).

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	30-40%	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
Direct Methanol (DMFC)	50-130°C	30-50%	0.025 - 1	Portable power generation Back-up power Off-grid power supply Military	Fuel storage and delivery Thermal management	Power density Slow kinetics Fuel cross-over Flooding Fuel toxicity Water management

Fuel Cell Type	Operating Temperature	Typical Electrical Efficiency (Lower Heating Value)	Typical power range (kW)	Applications	Advantages	Challenges
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
Phosphoric Acid (PAFC) [3]	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
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

[3] This technology is not covered further in this report, as there have not been any R&D projects on this technology funded by the FCH JU.

Fuel Cell Type	Operating Temperature	Typical Electrical Efficiency (Lower Heating Value)	Typical power range (kW)	Applications	Advantages	Challenges
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
Proton Ceramic (PCFC)	400-600°C	Under development		Auxiliary power Distributed generation CHP	Lower temperature than SOFC	Materials issues. Sensitive to CO_2

Source: JRC based on [7-9]

3.1 PEMFC

3.1.1 Operating Principle

Polymer electrolyte membrane fuel cells are characterized by a polymeric proton conducting membrane (e.g. Nafion™, Fumapem™) separating the porous electrodes. The membrane has the function of conducting protons, electronic insulation, and separating the gases (H_2 and O_2). The electrodes consist of a gas diffusion layer coated with a catalyst material, and a microporous layer. The Membrane Electrode Assembly (MEA) is composed of bipolar flow plates and membrane, together with the electrodes. The hydrogen oxidation reaction and oxygen reduction reaction take place at the anode and cathode, respectively, and are catalysed by platinum, which is a key cost driver for this technology. As the catalyst is easily poisoned, high purity hydrogen needs to be used. PEM fuel cells typically operate in the temperature range of 60-80°C.

The chemical reactions can be stated as follows:

Anode: $H_2 \rightarrow 2H^+ + 2e^-$

Cathode: $\frac{1}{2} O_2 + 2H^+ + 2e^- \rightarrow H_2O$

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. Membranes based on hydrated sulfonic acids, such as Nafion, are not suitable for use at elevated temperatures, as they may lose mechanical stability. Other types of membranes, for example based on Polybenzimidazole (PBI) polymers, can be used at temperatures above 100°C, but finding a proper balance between conductivity and mechanical strength is still a topic of ongoing research. A HT-PEMFC has a CO tolerance of up to 5% in pure hydrogen at 180°C, which reduces the fuel processing needed significantly [10].

The Balance of Plant (BoP) of a PEM fuel cell comprises the peripheral equipment, an external reformer (when supplied with natural gas), water and thermal management, air blowers, humidifiers, control and operating systems and power conditioning.

Direct liquid fuel cells are also based on polymer electrolyte membranes, the most common type being DMFC. DMFC operate in a similar manner to PEMFC, with protons as charge carriers, transported across a polymer membrane. Methanol is used directly in the fuel cell without reforming. The catalyst material is based on platinum group metals (PGM). Research on DMFC is primarily driven by the ease of use of the liquid methanol fuel.

The anode and cathode reactions in a DMFC are:

Anode: $CH_3OH + H_2O \rightarrow 6\ H^+ + 6e^- + CO_2$

Cathode: $1\frac{1}{2}\ O_2 + 6H^+ + 6e^- \rightarrow 3\ H_2O$

Due to the many intermediate steps involved in the oxidation of methanol, the efficiency of the DMFC is low, and the sluggish reactions need a considerably higher amount of catalyst material than for PEMFC (up to ten-fold [11]).

3.1.2 State of the Art

LT-PEM fuel cells for stationary fuel cell applications have achieved a high level of technological readiness, with the main challenges for market uptake being cost and durability.

The Japanese EneFarm programme has supported the installation of more than 200,000 PEMFC[4] for residential applications, with capacities in the 0.7–1.5 kW range. The main suppliers for these systems are Panasonic and Toshiba. The systems, including installation, have a cost around EUR 10,000 [12] and they are mostly fuelled using natural gas and an inbuilt reformer. The stationary fuel cell market also seems to be picking up in Korea, where Doosan is offering their CellVille PEM units sized from 600 W to 10 kW [5].

Supported by national and EU funding, several thousand units have been deployed in Europe, for example through the FCH JU projects ene.FIELD and PACE.[5] The German Kreditanstalt für Wiederaufbau (KfW433) programme on energy efficient housing is providing subsidies for the installation of mCHP units. The main suppliers are BDR Thermea Group (Senertec/Panasonic) [13] and Viessmann (Panasonic fuel cell) [14].

Panasonic seeks to commercialise units with an output of 5 kW, at 57% efficiency (Lower Heating Value (LHV)) supplied with H_2, which are to be used at hydrogen refueling stations and in commercial settings [15]. Helbio, based in Patras in Greece, have developed a CHP unit with an electrical capacity of 5 kW, which can operate on natural gas, propane or biogas, which it converts to hydrogen for use in the PEMFC [16]. It can produce up to 7 kW thermal energy in the form of hot water. The US company Altergy offers the Freedom Power System, with units providing up to 5 kW for telecom back-up power. Intelligent Energy offers a 4 kW system for stationary and portable use, with an efficiency of around 43% [17].

Several manufacturers are targeting the segment above 5 kW FC capacity for stationary applications. Toshiba offers a PEMFC system, the H2REX™, at 0.7, 3.5 and 100 kW capacity [5]. Powercell offer systems for sale at 5 kW, 30 kW and 100 kW scale [18]. The Canadian based Hydrogenics Corporation sells the HyPM-XR power modules with capacities between 10 and 120 kW. The (peak) efficiency is stated to be greater than 55 % (LHV), presumably based on hydrogen as fuel [19]. Larger units have been deployed for power generation in South Korea [20].

Nuvera had developed a product for the stationary market, the Forza Industrial Power Large Industrial / Stationary PEM with a capacity up to 250 kW, which had been installed in Canada and Italy in 2006 [21,22]. However, the company currently seems to focus on mobility applications.

There are four manufacturers offering PEMFC in the MW range, i.e. Ballard, Hydrogenics, Nedstack and Powercell. The Canadian company Ballard is mainly focussed on transport applications, but they also offer fuel cell systems for back-up power. Ballard offers the FCgen®-H2PM systems up to 30 kW of power, with 7,000 hours operating lifetime. The large capacity ClearGen™ model is available at 500 kW capacity [7]. Ballard Power Systems commissioned a 1 MW ClearGen™ fuel cell system at Toyota Motor Sales USA (TMS) in 2012, to provide electricity for the sales and marketing headquarters campus in Torrance, California [9]. A 1 MW ClearGen system has been installed by the FCH 2 JU CLEARGENDEMO project in Martinique at a refinery. In 2019 a technology transfer agreement has been signed between Ballard and hydrogen technology specialist Hydrogène de France to assemble Ballard FC systems in Bordeaux. The plant will have an annual production capacity of 50 MW. Production is said to start in 2022 [23].

The fuel cell developer Nedstack was founded in 1999 as a spin-off of Akzo Nobel and has installed a number of PEM fuel cell plants to generate heat and power for industrial applications. The first such plant was a 70 kW pilot unit, installed in 2007 at Akzo Nobel's chlor-alkali plant in Delfzijl [24]. In 2010, they installed a 1 MW plant at SolVin chlor-alkali plant in Antwerp-Lillo, Belgium [25] and in 2016 they provided the fuel cell modules for the world's first 2 MW PEM fuel cell plant in Yingkou, China [26].

In addition to the smaller size units mentioned above, Powercell also offer customised MW scale solutions [27].

[4] The ENEFARM programme is also supporting the installation of SOFC.

[5] It should be noted that KfW433 is a deployment subsidy, whereas the FCH JU project PACE is demonstration funding.

Horizon Fuel Cell Technologies of Singapore has sold a 200 kW PEMFC system to Ulsan in South Korea, as part of the Ulsan Technopark (UTP) project. This is part of the Hydrogen Town initiative aiming to achieve 1 MW of electricity generation using 'waste' hydrogen in the industrial city [12].

HT-PEMFC technology is being developed by several companies, such as by the (meanwhile defunct) Elcore GmbH (taken over by Freudenberg in 2017, who will keep producing the Elcore 2400 FC system), Serenergy A/S (based on reformed methanol, up to 5 kW), Danish Power Systems and Advent Technologies, with capacities ranging from 0.3 – 6 kW [28]. Serenergy states the efficiency of their methanol-based systems as being up to 45% [26].

For HT-PEMFC, 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 necessary, on the order of 2.5 times [29]. In general, catalyst degradation mechanisms present in LT-PEMFC are exacerbated at higher temperatures, which lead to a faster increase in Pt particle size. Therefore, Pt loading is much higher than that of LT-PEMFCs, and contribute to a high share of stack cost.

Mainly implemented at small capacities, direct methanol fuel cells have found a niche market for portable power solutions, for example for the military. The main research challenges are cost and efficiency issues, as well as crossover of methanol. There are also issues with water flooding. The power density of DMFCs is one order of magnitude lower than that of PEMFCs [30]. Research activity in China focusses on improved/non-PGM catalysts, and the development of DMFC at elevated temperatures to increase power density.

As one of the few profitable fuel cell manufacturers, SFC Energy has sold 40.000 units for portable power applications, back-up power and off-grid power supply. The company offers both DMFC and hydrogen fuelled systems.

3.1.3 Applications

PEM fuel cells have been deployed from the mW to MW capacity scales, for many types of applications. Due to the low operating temperature (<80°C), high dynamic response and high power density, PEMFC are the most suitable type of fuel cell for transport applications. A large share of the 590 MW of PEM fuel cell systems deployed globally in 2018 were for transport applications [5]. Most of the remaining units are likely to have been installed in Japan and to a lesser extent in Europe, for mCHP applications in the 0.7–1.5 kW capacity range. For capacities up to 200 kW, other applications are provision of back-up power, emergency power, and power generation for remote applications and telecom towers. For providing back-up power, various manufacturers state that fuel cells offer high reliability and lower total cost of ownership compared with batteries and diesel generators e.g. [19].

Two FCH JU projects have installed large capacity PEM fuel cells for power generation at sites where by-product hydrogen is available: CLEARGENDEMO [31] and DEMCOPEM-2MW [32]. One additional project (EVERYWH2ERE) is developing PEMFC based gensets for temporary power applications [33].

FCH JU is interested in exploiting the progress made by PEMFC for transport applications through R&I efforts on automotive-derivative PEMFC and applying them to stationary applications under the energy pillar.

3.2 SOFC

3.2.1 Operating Principle

A solid oxide fuel cell operates at high temperatures, above 600°C, to enable conduction of ions through a solid electrolyte material. The operation temperature mainly depends on the type of electrolyte material, which is typically yttria-stabilised zirconia (YSZ). The cathode is often a perovskite material such as strontium-doped lanthanum manganite, and the anode is a cermet of nickel and YSZ. Due to the high temperature, reaction kinetics are enhanced and non-precious metal catalysts such as nickel can be used. Fuels other than hydrogen are possible. For example, CO can also be oxidised. The high temperature of operation enables production of high quality heat for cogeneration/tri-generation[6] applications.

Anode: $H_2 + O^{2-} \rightarrow H_2O + 2e^-$

Cathode: $\frac{1}{2}O_2 + 2e^- \rightarrow O^{2-}$

An advantage of the high operating temperature is the possibility to integrate the natural gas reforming process. Two main configurations can be differentiated, systems where natural gas is internally reformed in the FC, and systems where natural gas is reformed externally. Internal reforming has advantages as to system design, but there are challenges for heat management of both processes (electrochemical and reforming). When natural gas or biogas is fed directly to the anode, problems with deposition of carbon may also occur. This can lead to deactivation of catalytic sites.

Different cell geometries have been investigated, with the main types being tubular or planar. Cell design has a high impact on performance as well as on manufacturing cost, therefore different configurations have been tested extensively. This is a complex topic which is out of scope of this report, but in general tubular cells are easier to seal, but have low power density. Planar cells have advantages in terms of power density and manufacturing.

SOFC can also be classified according to the type of cell support, for example anode- or electrolyte-supported. Common types of SOFC are electrolyte-supported with high operation temperature (~900°C) or anode-supported with a thinner electrolyte layer. This enables a lower operating temperature of 700–800°C. Another distinction can be made between low (500–650°C), intermediate (650–800°C) and high (800–950°C) temperature SOFC. A high operating temperature is beneficial in terms of performance, but there are severe challenges due to corrosion and mismatch of thermal expansion of materials.

SOFC have the possibility for utilisation in reverse mode as Solid Oxide Electrolysers (SOELs), which would be particularly useful for peak shaving of intermittent renewable energies (RE), i.e. operating in electrolyser mode when there is sufficient RE and in fuel cell mode when insufficient RE. Reversible Solid Oxide Cell (SOC) technologies are still at a lower Technology Readiness Level (TRL) than either of the individual technologies, as compromises need to be made for operating in reversible mode.

3.2.2 State of the Art

In recent years, much effort has been made to increase the lifetime of SOFC and reduce the cost of manufacturing. There has been much research activity on materials, to enhance performance and also to reduce the amount of rare earth metals in the active components. Issues with poisoning by fuel impurities such as sulphur or Cr generated by Cr-containing stack components, as well as steel corrosion, are being dealt with.

European SOFC manufacturers are SolidPower, Sunfire, Elcogen, Bosch, Wärtsila/Convion, Hexis/mPower and Ceres Power. Apart from Convion, these companies are mainly developing products for the residential and small building sectors. Ceres Power is evaluating the market for data centre applications in the US, with scalable units

[6] Co-generation: heating and electricity; Tri-generation: heating, cooling and electricity

of 5 kW [34]. They are also aiming to produce a 10 kW fuel cell in partnership with Bosch [35]. SolidPower and Sunfire are planning to develop somewhat larger installations, but still in the sub-100 kW range [36].

In the US, companies such as LG Fuel Cells System Inc., Bloom Energy and FuelCell Energy are investing in SOFC development. Most SOFC in the capacity range >100 kW are produced by Bloom Energy. The company has installed over 200 MW of their units almost entirely in the US [6]. The key applications for deployment are stated by the company as high tech, data centres and healthcare sectors [37]. The company has recently installed an 8.35 MW fuel cell for a utility near Seoul [38]. The design claims to be the world's most energy-dense power plant, generating 13.7 kW/m^2 [39]. FuelCell Energy, in addition to manufacturing MCFC, is developing a 200 kW SOFC unit and has plans to upscale to utility level within the next 10 years [40]. The Acumentrics SOFC Corporation reported that it has delivered more than 250 remote power solid oxide fuel cell generators with capacities from 250 W to 10 kW [41].

In Japan, there are several manufacturers and developers of SOFC, such as Mitsubishi Hitachi Power Systems, Fuji Electrics, Kyocera and NGK.

The combination of a SOFC with a gas turbine can result in a high overall (electrical and thermal) efficiency, as the high-grade heat from the flue gas of the SOFC can be used to heat steam which is used in a turbine. This concept has been investigated by Rolls Royce, Mitsubishi and Siemens. In the 1980s, research was conducted on tubular cells by the Siemens/Westinghouse Corporation and Kyocera. In order to increase power density, the development of flat tubular cells was pursued by Siemens in the early 2000's. Following problems with several projects where SOFC and SOFC/GT hybrid systems, the company terminated its fuel cell business in 2010 [42]. Mitsubishi Hitachi Power Systems has demonstrated a tubular SOFC 250 kW fuel cell and is targeting power generation at the MW level [43-45]. Their hybrid technology (integrated with steam/gas turbine) is reported to have an electrical efficiency of 55%. Integrated planar (IP) cells can be considered as a combination of planar and tubular design (IP-SOFCs), and were developed by Rolls Royce, Kyocera and Mitsubishi. Although this option had improved characteristics in terms of cost and performance, there were challenges with sealing [46].

3.2.3 Applications

Due to the high operating temperature, SOFC are highly suitable for CHP applications. In terms of number of units, SOFC are most commonly deployed as **mCHP** for residential applications. There is an increasing share of SOFC supported through the ENEFARM programme in Japan, for residential applications of approximately 1 kW. As a marked increase to previous years, in 2017 a 40% share for SOFC was foreseen [47]. In Europe, the ENEFIELD project has installed SOFC systems by Sunfire, Bosch and Solid Power, and the PACE project is deploying SOFC by Sunfire and Solid Power.

Regarding large-scale units (in excess of 200 kW) close to 300 MW capacity have been installed globally, almost exclusively in the US [6]. Most of these fuel cells have been sourced from US manufacturer Bloom Energy, for applications such as power supply for data centres and provision of back-up power. There do not seem to be MW range capacity SOFC installations, as at the MW range the main technologies are MCFC and PAFC. [48]The recent FCH 2 JU project RoRePower [48] involves both Sunfire and Solid Power as Original Equipment Manufacturers (OEMs) and aims to develop and demonstrate SOFC for off-grid power generation in remote regions with harsh climatic conditions and the continuous power supply of telecommunication towers.

SolidPower has also entered the data centre sector, e.g fuel cells for Microsoft in Seattle [49]. This is a promising development for a European company, as this segment has been dominated by Bloom Energy in the US.

3.3 AFC

3.3.1 Operating Principle

The alkaline fuel cell uses an aqueous solution of highly conductive potassium hydroxide (KOH) as the electrolyte, and operates in a range of 70-250°C, depending on the concentration of KOH in the electrolyte. The reactions occur at a triple phase boundary where the gas (fuel or oxidant), liquid and solid catalyst meet. The electrodes have to be durable in a highly corrosive alkaline environment, as well as in oxidising and reducing conditions at the stated temperatures. Due to the alkaline environment, the electrochemical kinetics of the Oxygen Reduction Reaction (ORR) at the cathode is enhanced and does not need noble metal catalysts. If supplied with hydrogen, the electrical efficiency can reach more than 60%.

Anode: $H_2 + 2OH^- \rightarrow 2H_2O + 2e^-$

Cathode: $\frac{1}{2}O_2 + H_2O + 2e^- \rightarrow 2OH^-$

An advantage of AFC is a higher tolerance to certain impurities. Alkaline fuel cells are not susceptible to poisoning from NH_3, and can therefore be run on hydrogen produced from ammonia, which can be more easily stored and distributed than hydrogen.

However, the alkaline environment does lead to a major drawback, as the OH^- anions can react with CO_2 from the air to form carbonate. Carbonate precipitation reduces the conductivity of the electrolyte, and may block the porous electrode. The alkaline electrolyte needs to be carefully managed to keep the KOH concentration and carbonate concentration within the proper boundaries, otherwise problems with flooding or drying can occur. Different methods have been investigated, such as recirculating and static electrolyte management systems.

3.3.2 State of the Art

AFCs were the first fuel cells deployed, for the US space program. Until recently, few technological advances have been made for this technology despite its promising characteristics. AFC have certain advantages over PEM fuel cells, e.g. higher cell voltages, cheaper catalyst materials, and improved robustness against chemical poisons. The fuel cells deployed for Gemini and Apollo spacecraft were supplied with hydrogen and oxygen, and had reached high power densities. However, operating the systems with air rather than oxygen has proven to be challenging, due to the issues with CO_2 mentioned above. Although there have been numerous efforts in the past to commercialise AFC (for example Elenco and Alstom), recently there have only been a few manufacturers investing in this technology, and little research effort.

UK-based AFC Energy are developing products in the medium to large capacity range. Their modular 10 kW systems can be up-scaled to MW range, according to the company website, with 400 kW units to be available from 2021 [50]. As mentioned, AFCs are robust against contaminants and are therefore well suited to the use of low-grade, by-product hydrogen. AFC is partnered with electrolyser manufacturer de Nora for their electrode development and manufacturing. Degradation of the electrodes still seems to be a challenge, although improvements to lifetime have been made. Their newest product, working without liquid electrolyte, is being scaled up to 10 kW prototype level, and is stated to have higher power density, high efficiency and tolerance of impurities [51]. The only other AFC developer seems to be Israel-based GenCell, which offers AFC for back-up power and off-grid solutions in the 5 kW range. The company aims to provide an affordable off-grid power fuel cell solution that can replace diesel generators for rural telecom and electrification.

In recent years, many studies have been conducted on (alkaline) anion exchange membrane fuel cells (AEMFC), in which the OH^- anion is transported from the cathode to the anode through a solid membrane. This addresses two of the main challenges of AFC, the formation of carbonate and management of the liquid electrolyte. Both liquid and gaseous fuels can, in principle, be used. Unlike AFC, this type of fuel cell does use PGM as an electrocatalyst. In the alkaline environment, the HOR is slower than in acidic media. Non-PGM catalysts are being investigated, but there are still durability issues [52]. Further development of the membranes is also still necessary, therefore this technology can be considered to have a low TRL at present. There is a high level of interest in China and the US in this technology, based on a bibliographic analysis [53].

3.3.3 Applications

AFC Energy had contracted FTI Consulting in 2018 to conduct a market study. The best opportunities are seen for replacement of off-grid diesel power generators, such as in construction, mining or military applications. The company has also demonstrated an EV fuel cell charging platform, capable of level 2 or 3 fast charging [51]. AFC Energy has an ongoing power purchase agreement with a local utility in northern Germany, as part of the POWER-UP project (see 5.2.1) [54].

A 200–400 kW fuel cell unit will be installed at the Northers Oil's biofuels refinery near Gladstone in Australia. Northern Oil is building a large industrial scale pilot plant where surplus hydrogen generated from the system is to be made available for consumption within a fuel cell [55]. As AFC can be potentially be deployed in a large capacity range, up to MW, they can in principle be used to supply power for multiple applications. The FCH JU project ALKAMMONIA developed a system for power supply to telecommunication towers, based on an ammonia fuel system. In addition, the FCH JU project POWERUP installed a sub 240 kW AFC. Both of these projects used technology provided by AFC Energy.

3.4 MCFC

3.4.1 Operating Principle

In a Molten Carbonate Fuel Cell, the electrolyte consists of a molten mixture of alkali carbonates, either Li-K or Li-Na based, and the charge carriers are carbonate ions. MCFC operate at temperatures typically between 600-700°C.

Anode: $H_2 + CO_3^{2-} \rightarrow CO_2 + H_2O + 2e^-$

Cathode: $\frac{1}{2} O_2 + CO_2 + 2e^- \rightarrow CO_3^{2-}$

The electrode material at the cathode is typically based on nickel oxide, and is exposed to a highly corrosive environment, leading to degradation of the material. The anode is composed of Ni-alloys. The efficiency of a MCFC is around 50% electrical, with an overall energy efficiency above 80% [56].

CO_2 has to be recycled from the anode to the cathode. This has the advantage that CO_2 can be easily separated from the gas stream. It is also possible to generate additional hydrogen though a so-called “tri-generation” process, where there is a local demand.

There are two types of fuel processing, either external or internal reforming. To enable heat control, an external reforming MCFC is operating at higher pressure whereas an internal reforming type would operate at atmospheric pressure.

3.4.2 State of the Art

In terms of installed capacity for stationary applications, MCFC are in the lead compared to all other FC technologies. MCFC systems are commercially available in the MW range, and are commonly deployed to provide heat and power. The development of the technology has mainly taken place in the US and Japan[7] in the

[7] Starting from 1981, the Japanese government invested USD 470 million in the development of MCFC under the moonlight programme, running until 2004. Companies such as Toshiba and Hitachi were involved [37].

past 40 years. Almost all of the systems installed in the US and South Korea have been produced by US based FuelCell Energy. Few systems have been installed in Europe. However, FuelCell Energy recently announced a collaboration agreement with E.ON Business Solutions to develop the European market of MCFC [57].

There have been MCFC research efforts in Europe since the mid to late 1980s, led by a combination of research organisations and industry, such as ECN (now TNO), MBB (later MTU Onsite) and Ansaldo Fuel Cells. MTU Onsite (later Tognum, then CFC Solutions) had a technology exchange agreement with FuelCell Energy and deployed several systems in Germany and the UK. Insufficient lifetime and high investment costs appear to be the main causes of the lack of commercial success of European MCFC development.

Internationally, there is ongoing research into the reversibility of MCFC, with experiments conducted at cell level. More efforts are needed as a high level of degradation has been observed in electrolysis mode [58]. Molten Carbonate electrolysis has been proposed for the production of commodities and of hydrogen [59]. Reverse operation of a MCFC had already been studied in the 1980s to increase CO_2 separation. The CO_2 capture capabilities of MCFC running in fuel cell mode have been explored extensively in recent years (see e.g. [60]). MCFC can be fed with flue gases emitted from power plants to retrofit CO_2 capture. The recovery of CO_2 from concentrated flue gases (>10%) seems feasible, although issues such as sulphur or particulate removal need to be accounted for. Molten Alkali Carbonate (MAC) salts are an area of interest for various sustainable energy technologies, for example as electrolytes for high temperature solar energy production. Some of the more promising types of direct carbon fuel cells (which are at low TRL) are also based on molten carbonate [59].

Other development routes have included hybridisation of MCFC with gas turbines, which could increase efficiency up to 60%. Field tests have been conducted, which have revealed problems with transient performance, such as overheating and fuel starvation. Hybridisation with Stirling engines has also been proposed [61].

3.4.3 Applications

MCFC are not used for **mCHP.** They are developed for, and deployed in, **mid-sized and large installations**. As already mentioned, MCFC technology represents a significant share of the deployed large-scale stationary fuel cell installations worldwide [62]. Of the globally installed capacity of over 325 MW, over half of those are deployed in South Korea, and the rest mainly in the US. These units are often directly connected to the natural gas grid, in particular in South Korea, and are providing heat and power to residential or commercial customers. In some installations MCFC are operated on biogas, for example from wastewater treatment plants. The excess heat of the MCFC can be used in anaerobic digesters to generate digester gas, which can then be fed into the fuel cell. Regulatory measures have been drivers in some cases, as wastewater treatment plants are required to reduce emissions (e.g. California air quality regulations), or fuel cells being considered a renewable energy source, regardless of the fuel. Another important application is uninterruptible and back-up power, for example, Connecticut has a micro-grid grant programme following weather-related power outages, under which fuel cells have been installed in critical facilities.

There has been a strong interest in recent years in the use of MCFC as post-combustion CO_2 capture technology. Current development is focused on enhancing the permeation of CO_2, which is why the term Molten Carbonate Electrochemical Membrane (MCEM) is often chosen for these applications. A number of patents have been filed for MCEMs applied in industrial environments [63]. A recent publication showed that MCFC can significantly reduce (by almost 75%) the CO_2 emissions of a steel plant, with CO_2 avoidance cost ranging from USD 25 – 65 per ton CO_2 [63] In 2016, FuelCell Energy and ExxonMobil announced plans to test carbon capture technology at a power plant operated by Alabama Power [26].

Several MCFC have been installed as Auxiliary Power Units (APUs) on ships, for example a 500 kW system on a ferry. Although this application area is not stationary, the scales of installation may be similar, as multi-MW systems would be needed to provide power to larger ships.

3.5 PCFC

3.5.1 Operating Principle

Solid oxide fuel cells have to operate at temperatures >700°C as they are using oxygen conducting electrolytes. Protons have lower activation energies than oxide ions, therefore ceramic proton conductors can operate in an intermediate temperature range (400-600°C). The lower operating temperature enables taking advantage of many of the benefits of high temperature operation, while avoiding many of the drawbacks, such as materials and sealing issues. PCFC do not need precious metal catalyst materials, and stacks are potentially less costly to manufacture than SOFC, as there are fewer high temperature firing steps. The lower overall operating temperature in general allows for the use of cheaper materials [61].

Electrolytes with high proton conductivities are perovskite oxides, such as $BaZrO_3$, and rare earth phosphates and niobates, for example $LaNbO_4$. The electrolyte membranes have to be very thin to avoid high resistance, as the conductivity of these materials is still lower than that of oxygen ion conductors. The anode materials are typically similar to those used for SOFC, nickel-cermets with protonic ceramics. Nickel can be used as anodic catalyst, but nickel-free electrodes have also been developed [64]. In this temperature range, researchers have observed that the cathode performance decreases more rapidly than the anode performance with a decrease in temperature [64]. The requirements for the cathode material are therefore especially high, as it should enable the reduction of oxygen, have high conductivity for electrons, oxide ions and protons. There are few materials with these properties, and much research effort has gone into their further development. Mixed-ion electronic conductors, for example perovskite cathode materials with the general formula ABO_3 (where A and B are cations in the crystal structure) have been investigated. Basic questions apparently remain regarding the electrochemical reaction at the cathode and the roles of oxygen ion and proton conductivity [65].

Anode: $H_2 \rightarrow 2H^+ + 2e^-$

Cathode: $\frac{1}{2} O_2 + 2e^- + 2H^+ \rightarrow H_2O$

According to the reaction given above, water is produced at the cathode, not the anode, which helps to increase efficiency as it avoids fuel dilution.

3.5.2 State of the Art

As already mentioned, the key research challenge is finding electrode materials with high electrical conductivity and electrochemical activity at intermediate temperatures. Another materials related issue is the reactivity of many protonic ceramic electrolytes with CO_2, which would have to be addressed if hydrocarbon fuels are to be used. The rate of oxygen reduction at the cathode is still limiting power densities, which are typically not higher than 200 mW/cm^2. Recent work by Northwestern University has achieved an increase to 500 mW/cm^2 at 500°C [66]. Other advancements on materials have been made: the perovskite materials developed by the Colorado School of Mines (CSM) enable the direct use of hydrocarbon fuels with PCFC. The anode supported cells have been tested for over 6,000 hours, and have shown good performance and durability (<1.5%/1,000 hours in most cases) for a variety of fuels [67]. Together with CSM, FuelCell Energy (FCE) is working to demonstrate a 500 W PCFC stack as part of a Department of Energy (DOE) Advanced Research Projects – Energy (ARPA-E) Reliable Electricity Based on ELectrochemical Systems (REBELS) funded project. The design will be based on FCE's compact solid oxide architecture stack, to allow for a low-cost and easy to manufacture stack. The stack design is based on a simple unit cell with an anode-supported cell and interconnect assembly. The aim is to allow for having fully automated stack assembly. The overall system efficiency for a 25 kW unit is estimated to be close to 58% LHV, with a Capital Expenditure (CAPEX) of USD 1137 per kW [67]. Korean, Russian and Chinese researchers are involved in more basic research on materials and electrodes (see e.g. [68], [69]). The Korea Institute of Science and Technology (KIST) is working on high power density cells, and has reported 1.3 W/cm^2 at 600°C [70]. In Europe, fundamental research is also being conducted, and a different type of architecture, namely metal supported cells, have been pursued in the METPROCELL FCH JU project.

3.5.3 Applications

The applications for PCFC are likely to be similar to SOFC, and could include CHP. CSM and FCE are aiming for natural gas supplied systems for stationary power applications.

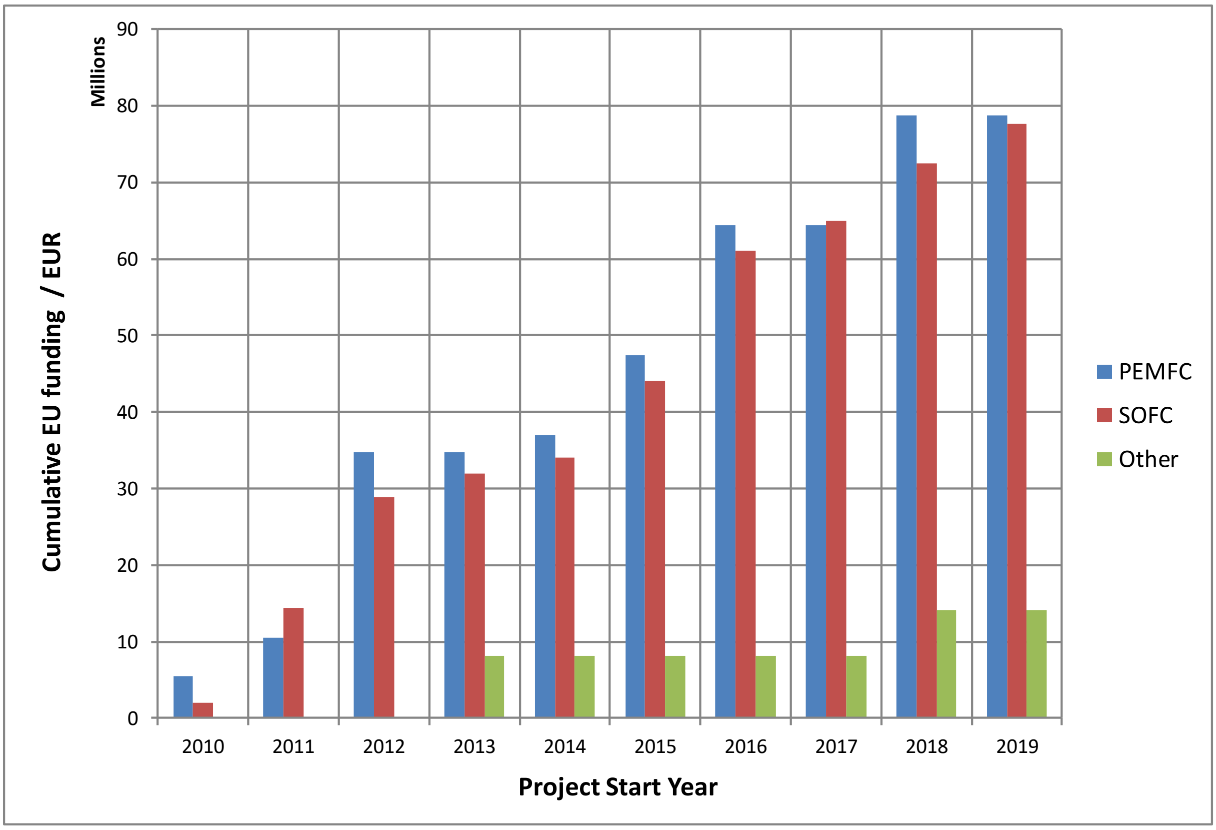
4 Fuel Cell and Hydrogen Joint Undertaking Projects

The FCH JU has been funding projects regarding stationary fuel cells since it was founded in 2008. As previously mentioned, the work on stationary fuel cells is divided into two Panels, one dealing with higher TRL projects targeting demonstrations and proofs of concept (Panel 3), and the second dealing with lower TRL Research and Development (R&D) projects (Panel 4). Most of this work has dealt with two technologies, PEMFC and SOFC. The cumulative level of EU funding from the FCH JU provided towards projects in Panels 3 and 4, according to the fuel cell technology used, are given in Figure 1 and Figure 2, respectively.

From Figure 1, it can be observed that the amount of funding provided to demonstration projects dealing with the two main technologies is evenly split. This is also the case for research activities, as shown in Figure 2, however in this case it appears that the funding for PEMFC research levels off after 2014 (i.e. from the transition from FP7 to Horizon 2020) whilst the research focus clearly remains on SOFC. An additional €3 million is spent on PEMFC research for stationary applications in this period, whereas ~€17 million is spent on SOFC research for stationary applications.

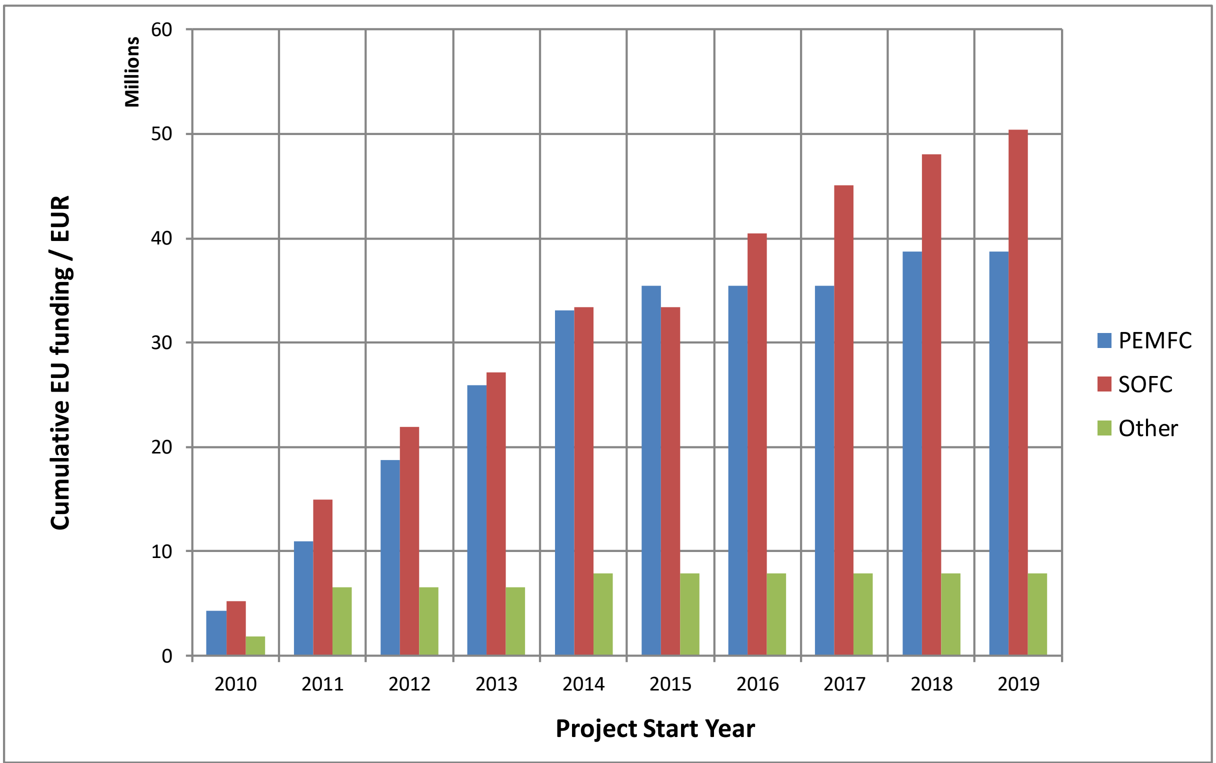
It should be noted that this spending has (variably over the course of the FCH JU) been supplemented by contributions from industry and academia. Furthermore, the Joint Research Centre of the European Commission has provided in-kind contributions to some projects, which is not counted as EU funding.

Figure 1: Cumulative FCH JU funding towards projects in Panel 3, according to the type of fuel cell technology ("other" includes AFC and MCFC)



Source: JRC based on publicly available information from the Programme Office of the FCH 2 JU, 2020.

Figure 2: Cumulative FCH JU funding towards projects in Panel 4, according to the type of fuel cell technology ("other" includes AFC, MCFC and DMFC).



Source: JRC based on publicly available information from the Programme Office of the FCH 2 JU, 2020.

The online software TIM (Tools for Innovation Monitoring) developed by the JRC has been used to provide an overview of the organisations that have taken part, or are taking part, in FCH JU projects related to stationary FCs.

TIM is a database containing three types of documents: scientific publications (articles, conference proceedings, reviews, book chapters), patents and EU projects. The scientific publications contained in the database are those published after 1996 in the Scopus database (Elsevier). The patent documents are extracted from the PATSTAT database from the European Patent Office (all patents with a priority date from 1996 onwards), and the EU projects are all those from FP5 (beginning in 1998) onwards and are extracted from the CORDIS database.

TIM uses network visualisations to display data. These contain nodes and edges (circles joined together by lines). The size of the node corresponds to the number of data items (documents) in the dataset, whilst the size of the edge corresponds to the number of items in common between the two nodes. Nodes can be assigned to communities. The colour of the node represents the community to which it belongs. TIM uses a particular algorithm (Louvain Modularity algorithm [71]) to cluster nodes together in communities. As these plots become more complex, not all low frequency nodes and edges are shown.

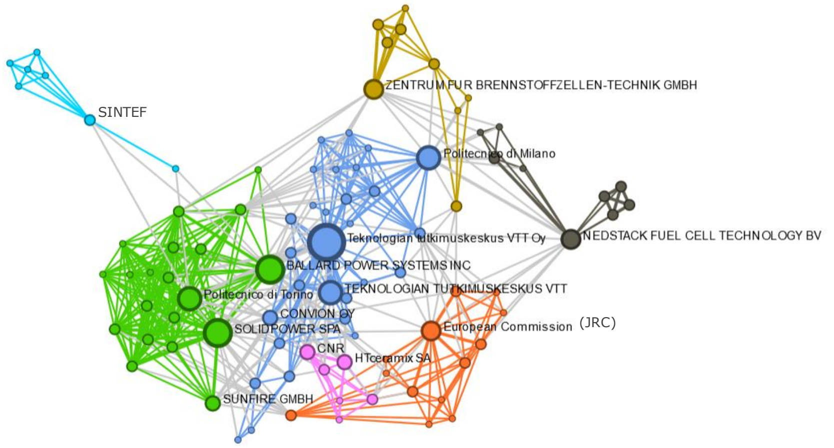
In Figure 3, the organisations that have been involved in all projects from Panel 3 are shown. The size of the node corresponds to how many projects the organisation has taken part in, whilst the thickness of the edge (link) is related to how many projects particular organisations have in common. The node size is not related to the amount of funding but simply to the number of projects. The different coloured clusters are automatically assigned by the software and relate to frequent clustering of organisations. It can be seen that the Technical Research Centre of Finland (VTT) is the most active institution involved in this area. Note, that there are two distinct nodes relating to VTT – this arises due to there being two different registered entities within the same organisation structure. In addition to VTT, a number of fuel cell manufacturers have been very active (e.g. Ballard, SolidPower, Nedstack) along with a number of other universities and research institutions.

Figure 4 shows the corresponding data for the EU member states that have been the most active within projects in Panel 3 (as defined in Table 1). Note, in this instance the size of the nodes represents the number of projects which have contained ***at least one partner*** from a particular member state. In this particular area, Italy and Germany are represented in the most projects, followed by the U.K., Belgium and the Netherlands. Finland are also prevalent. The notable presence of Finland is due to the high number of projects in which VTT is a participant. It should also be noted that of non-EU countries, Switzerland is highly active in this Panel with participation in 14 projects.

Figure 5 and Figure 6 show the equivalent data for Panel 4. Due to the lower TRL nature of the research projects present in Panel 4, there is a higher contribution of research centres and universities in the main contributors to this panel including Commissariat à l'énergie atomique et aux énergies alternatives (CEA), Europäisches Institut für Energieforschung (EIFER), Danish Technical University (DTU) and VTT. However, companies such as Haldor Topsoe, HT Ceramix and SolidPower are also well represented.[8] In terms of the EU member states which have been the most active within Panel 4, there are few surprises with the larger EU states (Germany, Italy, France and Spain) being well represented. An exception to this is the high involvement of Danish entities, mainly due to the presence of Haldor Topsoe and DTU. It should also be noted that Switzerland is involved in 14 projects, and Norway in 11 for this Panel.

[8] Haldor Topsoe has ceased all activities in fuel cells. HT Ceramix changed its name to SolidPower.

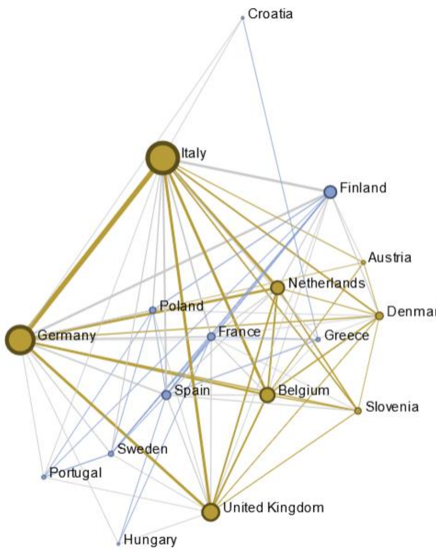
Figure 3: TIM Plot showing the participants in the 31 projects in Panel 3.[9] The table shows, by number of projects, the top five participants from the plot.



Participant	Number of projects
VTT Oy	8
Ballard	6
SolidPower	6
Politecnico di Milano	5
Politecnico di Torino	5
VTT	5

Source: JRC (TIM) based on information from the Programme Office of the FCH 2 JU 2020.

Figure 4: TIM plot showing EU member state participation in the Panel 3 projects. [10] The table shows, by number of projects, the top five countries represented.



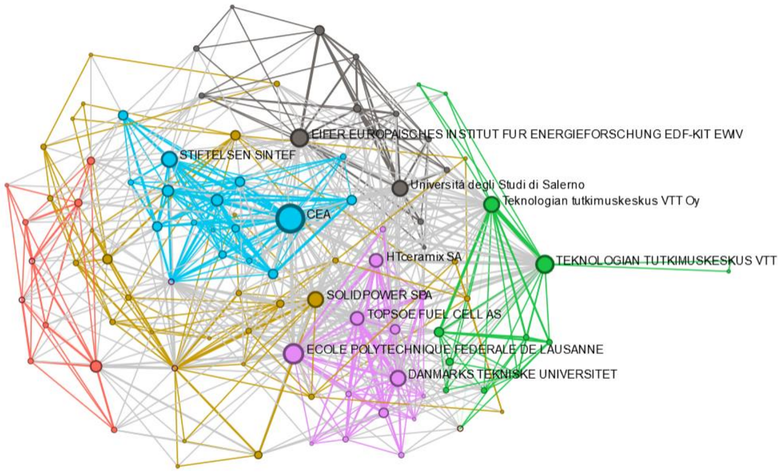
Member State	Number of projects
Italy	25
Germany	22
UK	13
Belgium	11
The Netherlands	10

Source: JRC (TIM) based on information from the Programme Office of the FCH 2 JU, 2020.

[9] The size of the node represents the number of projects a partner is involved in, whilst the thickness of the links represents the number of projects in common between the linked partners. The coloured groupings are potential clusters identified by TIM's algorithm.

[10] The size of the node represents the number of projects that has at least one participating organisation from that member state. The thickness of the links between the nodes is proportional to the number of projects those member states have in common.

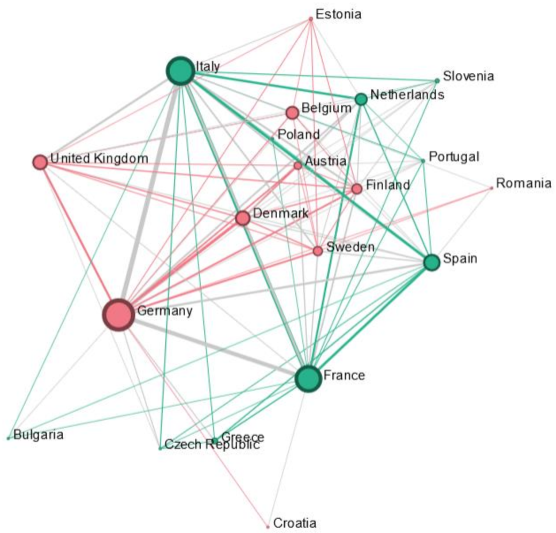
Figure 5: TIM Plot showing the participants in the 31 projects in Panel 4.[11] The table shows, by number of projects, the top five participants from the plot.



Participant	Number of projects
CEA	13
EPF de Lausanne	9
VTT	8
EIFER	8
Multiple participants	7

Source: JRC (TIM) based on information from the Programme Office of the FCH 2 JU, 2020.

Figure 6: TIM plot showing EU member state participation in the Panel 4 projects.[12] The table shows, by number of projects, the top five countries represented.



Member State	Number of projects
Germany	34
Italy	30
France	28
Spain	17
Denmark; U.K.	15

Source: JRC (TIM) based on information from the Programme Office of the FCH 2 JU, 2020.

[11] The size of the node represents the number of projects a partner is involved in, whilst the thickness of the links represents the number of projects in common between the linked partners. The coloured groupings are potential clusters identified by TIM's algorithm.

[12] The size of the node represents the number of projects that has at least one participating organisation from that member state. The thickness of the links between the nodes is proportional to the number of projects those member states have in common.

4.1 Overview of Stationary Fuel Cell Projects

In Annex 1, a table is provided that contains a summary of all the relevant projects that have been investigated for quantitative values of the KPIs considered in this report (Table 9).

In Table 3, a summary is provided showing the number of projects that were considered in the following sections, separated based on the power output of the fuel cell system, the type of fuel cell technology, and the Panel in which the project was based. Only projects that were considered relevant to advancing the MAWP KPIs were included. It should be noted that for the 0.3-5 kW scale, not all projects were specifically addressing mCHP. A number of lower TRL projects do not specify the final application whilst others are aimed at back-up applications. This is discussed in more detail in Section 5.1.1.

Table 3: Number of projects that have been assessed in this report (projects which had started before 1/1/2019)

Power Output of Fuel Cell	Type of Fuel Cell	Number of Projects (Panel 3)	Number of Projects (Panel 4)	Total Number of Projects
0.3 – 5 kW	PEMFC	4	15	19
	PEMFC & SOFC	-	3	3
	SOFC	4	10	14
	AFC	1	-	1
	PCFC	0	1	1
5-400 kW	PEMFC	4	3	7
	SOFC	8	2	10
	AFC	1	1	2
	MCFC	-	1	1
>400 kW	PEMFC	2	-	2
	SOFC	1	-	1
	Total:	25	36	61

Source: JRC based on information from the Programme Office of the FCH 2 JU, 2020.

It should be noted that certain ***projects*** from both Panels 3 and 4 were excluded in the study if they were not deemed to be performing research that would specifically advance the MAWP KPIs under consideration. Therefore, a small number of projects (mostly from Panel 4) are not included in the table. This is because some projects that operate at low TRL levels (e.g. MEA development) or perform research on fuel cell diagnostics may not contribute directly and quantitatively to the MAWP KPIs.

The projects that were not considered to provide direct quantitative improvement to the MAWP KPIs, and are not further discussed are:

Panel 4:

Diagnostics projects:	GENIUS, D-CODE, DESIGN
PEM Materials (low TRL):	DEMMEA, MAESTRO, DURAMET
SOFC Materials (low TRL):	ROBANODE, SCOTAS-SOFC, RAMSES, SOFC-LIFE, EVOLVE,
SOFC Manufacturing:	qSOFC

Panel 3:

Terminated project:	TOWERPOWER

Furthermore, it should be noted that not all projects that were reviewed on the basis of their content (and are therefore listed in Annex 1, Table 9) ended up providing usable data. Only data specifically stated to be for public release is explicitly declared within this document. This means it may not always be stated which project has achieved a particular programme target.

Additionally, several projects that were targeting a particular size of installation for the final market, only demonstrated performance for smaller scale Proofs of Concept. Therefore, the data from these projects was considered based on the size of unit that was *actually tested*, not the ultimate scale-up target size, in order to make a fair comparison.

5 Stationary Fuel Cell Project Performance Analysis

5.1 Micro-CHP

5.1.1 Overview

In this study, data from a large number of FCH JU projects was analysed. The breakdown according to technology and panel was provided in the previous section in Table 3 whilst a full list of projects is provided in Annex 1, Table 9. In general, the FCH JU defines mCHP units as those from 0.3–5 kW. Therefore, data that arises from all projects working in this power range has been considered. Some projects working at a lower TRL level may not have specified their ultimate application as mCHP and some projects may be working towards units for remote power or back-up power. However, it is the authors' opinion that certain values from these projects are relevant to measure progress against the state of the art for mCHP units, for example, projects that lead to increased stack durability.

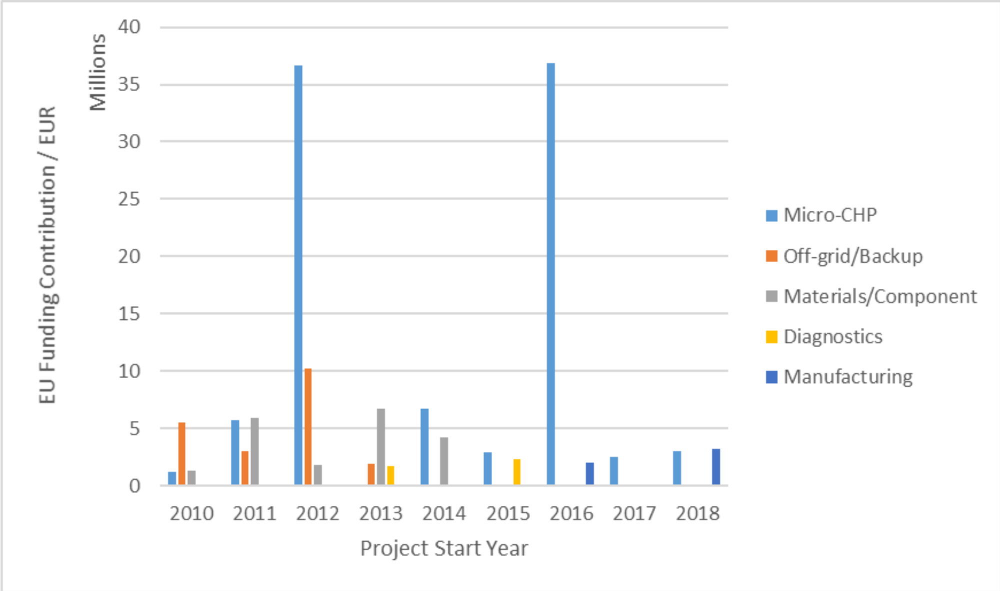
The following figures provide a breakdown of these projects considered according to their scope and technology, showing where the main funding of the FCH 2 JU has been directed.

Figure 7 shows the FCH JU funding according to the project scope. This is the application (mCHP or off-grid/backup) for the projects that targeted applications. Where no specific final application has been stated, the projects have been assigned according to whether they were lower TRL projects working on materials/component issues, FC diagnostics projects, or FC manufacturing projects. It can be seen that the majority of funding in this size range has been for mCHP units, with some earlier projects working on off-grid back-up. The two large peaks correspond to the years when ENE.FIELD (2012) and PACE (2016) started. These two large-scale demonstration projects dominate the spending of the FCH 2 JU in this field. In Figure 8, the same data is shown according to the specific fuel cell technology investigated. Here, it can be seen that the majority of funding is split between PEMFC and SOFC. Again, the two large demonstration projects, ENE.FIELD and PACE, dominate the graph. These projects deployed both PEMFC and SOFC mCHP units.

Figure 9 is a TIM plot showing all the organisations that have been involved in the projects relating to the 0.3-5 kW power range. The size of the node corresponds to how many projects the organisation has taken part in; the thickness of the edge (link) is related to how many projects particular organisations have in common. Note: the node size is not related to the amount of funding but simply the number of projects. The different coloured clusters are automatically assigned by the software and relate to frequent clustering of organisations. It can be seen that the JRC has been involved in the largest number of projects relating to this technology, whilst the company involved in the most projects has been SolidPower. This is to be expected as SolidPower has been involved in FCH JU projects from the beginning at a research level, and is now offering commercial products. Ballard has been very active from the PEMFC side. Figure 10 shows the equivalent data for the EU member states that have been the most active in this field. Note, in this instance the size of the nodes represents the number of projects that contain at least one partner from a particular member state. It is clear that the most active countries involved are Germany and Italy. It should be noted that the UK is not included in this plot as it was prepared after the official Brexit date of 31st January 2020. The UK was involved in 11 projects.

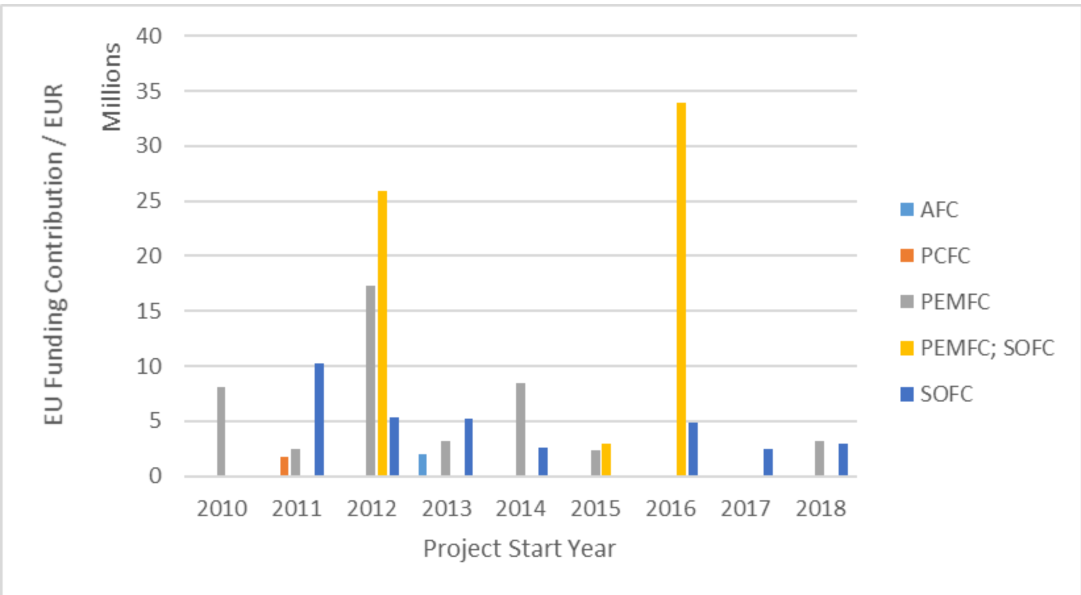
Please note that this series of figures 7–10 has only been established for the mCHP section as there are considerably fewer projects in the mid-size and large stationary fuel cell sections.

Figure 7: FCH JU Funding according to project scope for projects providing data to the 0.3-5 kW size range.



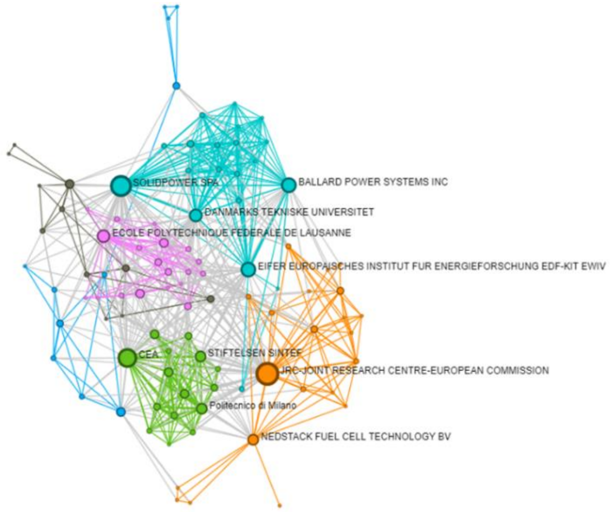
Source: JRC based on information from the Programme Office of the FCH 2 JU, 2020.

Figure 8: FCH JU funding according to technology for projects providing data to the 0.3-5 kW size range.



Source: JRC based on information from the Programme Office of the FCH 2 JU, 2020.

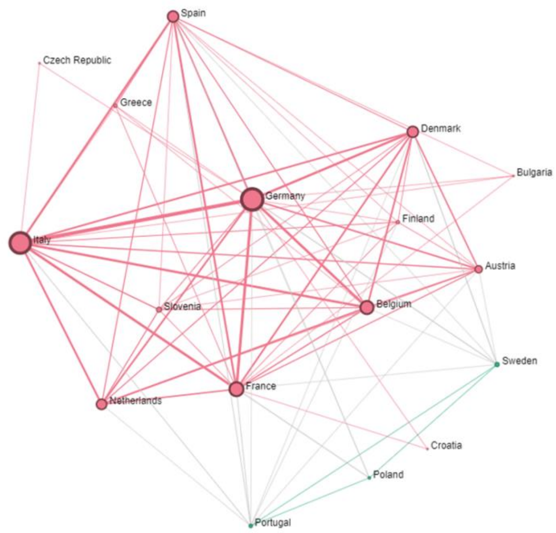
Figure 9: TIM plot showing the participants in the projects regarding 0.3-5 kW size range. [13] The table shows by the number of projects the top five participants from the plot.



Participant	Number of projects
JRC	11
SolidPower	10
CEA	9
EIFER	7
Ballard	7

Source: JRC (TIM) based on information from the Programme Office of the FCH 2 JU, 2020.

Figure 10: TIM plot showing EU member state (excluding UK, see text) participation in the projects regarding 0.3-5 kW size range.[14] The table shows by the number of projects the top five countries represented.



Member State	Number of projects
Germany	27
Italy	26
France	17
Belgium	16
Denmark; Spain	13

Source: JRC (TIM) based on information from the Programme Office of the FCH 2 JU, 2020.

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

[14] The size of the node represents the number of projects that has at least one participating organisation from that member state. The thickness of the links between the nodes is proportional to the number of projects those member states have in common.

The following paragraphs summarise the projects that have been reviewed for this section of the report.

For ***PEMFC***, there have been a large number of basic and applied research projects funded throughout the lifetime of the FCH JU, targeting consecutive generations of PEMFC products in the 0.3-5 kW power range. Several lower TRL projects considered materials development and aimed to improve on the existing cell and stack technologies. LOLIPEM worked towards long-life high temperature (>100°C) mCHP systems through development of novel MEAs, EURECA aimed to develop the next generation of mCHP systems using advanced PEM stack technologies and MATISSE aimed to develop improved stacks and cells for a range of stationary applications including mCHP, using advanced materials solutions.

Several projects focussed on the durability issues of PEMFC, including DEMSTACK, which investigated the degradation mechanisms of HT-PEMFC stacks whilst attempting to optimise key components. KEEPEMALIVE used accelerated stress test protocols, a sensitivity matrix and lifetime predication models to provide greater understanding of degradation and failure mechanisms for PEMFC for mCHP. PREMIUM ACT, and the follow-up project SECOND ACT, combined experimental work regarding the durability of PEMFC systems, stacks and MEAs, with modelling and simulation, to better understand the degradation mechanisms occurring in mCHP systems and improve their durability.

Two further projects developed diagnostic tools for PEMFC. HEALTH-CODE aimed to develop a monitoring and diagnostic tool for mCHP based on electrical impedance spectroscopy analysis. SAPPHIRE developed an integrated prognostics and health management system (both hardware and software) to increase the lifetime for both heat and power producing low temperature PEMFC systems.

Several projects focussed on the reformer part of the system, providing H_2 to the PEMFC. BEINGENERGY looked at integrating low temperature methanol steam reforming with a high temperature PEMFC. REFORCELL aimed to develop a highly efficient PEMFC mCHP system through an advanced novel and more efficient reformer and associated BoP, whilst FLUIDCELL developed an advanced m-CHP fuel cell system based on a novel bio-ethanol fluidized bed membrane reformer. FERRET developed a flexible natural gas membrane reformer for mCHP applications.

More recently, manufacturing has become an increased focus of the FCH JU. The project MAMA-MEA has been working on an additive layer manufacturing process for the mass manufacture of MEAs using high-speed deposition processes.

As previously mentioned, a number of projects dealing with systems providing back-up power have also been considered in this chapter, as they may have provided some input which assists in achieving certain KPIs relevant to the mCHP MAWP targets. The project LIQUIDPOWER was an early FCH JU research project that aimed to develop new generation fuel cell systems for back-up power/telecom with onsite methanol reforming.

As well as the above-mentioned research projects (Panel 4), a range of projects focussing on the trial and deployment of PEMFC technologies for low power applications have been undertaken (Panel 3). They also include a number of projects demonstrating back-up technologies, in particular for the telecom industry. FCPOWEREDRBS was a demonstration project providing power supplies to telecom stations using PEMFC technology, FITUP was a field test demo of PEMFC systems for UPS/backup power in the telecommunications and hotel industries, whilst NH34PWR aimed to produce an ammonia-based fuel cell power system for off-grid cell phone towers. A further project, FLUMABACK aimed to improve the performance and cost of BoP components for back-up PEMFC systems.

The majority of data presented within this section comes from three projects that involve both PEMFC and SOFC mCHP systems trial and deployment. D2SERVICE was a project that aimed to simplify residential and commercial FC systems for easy, fast and safe system service and maintenance. ENE.FIELD deployed more than 1000 residential FC mCHP systems across 11 European countries [15]. PACE is a further project continuing the roll-out of this technology across Europe. It intends to deploy 2800 new FC mCHP units with customers enabling a scaling-up of the production process.

[15] U.K., France, Italy, Germany, Belgium, The Netherlands, Luxembourg, Slovenia, Denmark, Austria and Switzerland.

For ***SOFC***, again there have been a significant number of basic and applied research projects under Panel 4 considering the next generation of SOFC products in the 0.3-5 kW power range. Several projects have considered novel materials in low TRL projects. METSAPP aimed to develop novel cells and stacks based on a robust and reliable, scalable, metal-supported SOFC technology, whilst SCORED 2:0 developed novel steel coatings for reducing degradation in SOFC. HEATSTACK aimed to reduce the cost of the fuel cell stack and heat exchanger through the optimisation of design, materials and the production process.

The durability issues of SOFC were investigated in the ENDURANCE project, which developed predictive models to estimate the long-term performance and probability of failure of SOFC stacks, based on existing materials and design. INSIGHT involved the implementation of a monitoring and diagnostic tool for SOFC stacks for mCHP applications, in order to increase their lifetime (using Electrochemical Impedance Spectroscopy and Total Harmonic Distortion as monitoring techniques).

Several projects addressed novel designs and manufacturing approaches. The project T-CELL developed a radical new triode approach to SOFC technology together with a novel, advanced architecture for cell and stack design, in order to solve durability issues associated with SOFC running directly on hydrocarbon fuels. MMLRC=SOFC addressed a novel design solution for lightweight SOFC stacks that decoupled the thermal stresses within the stack and allowed for optimal sealing and contacting. This design was highly suitable for manufacturing and automated assembly. OXIGEN aims to develop an innovative next generation SOFC stack and hotbox solution for small stationary applications. PROSOFC aimed to improve the robustness, manufacturability, efficiency and cost of SOFC stacks using cost-optimal reliability based design (COPRD) with production optimisation. The SOSLEM project aimed to improve production processes by developing and applying novel manufacturing technologies for SOFC stacks.

As well as the above-mentioned research projects (Panel 4) a range of projects focussing on the trial and deployment of SOFC technologies for low power applications have been undertaken (Panel 3). ASTERIX3 was a project initiated to evaluate HTCeramix's SOFC technology[16] for residential mCHP applications, validating the technology and developing and testing a PoC fulfilling market requirements. LOTUS aimed at building a prototype of a new generation SOFC system based on novel materials and running at lower temperatures. SOFT-PACT validated SOFC mCHP technology in a real market environment. The project aimed to deploy 100 units in occupied residential locations, and a small number in test homes to provide reference data. TRISOFC aimed to develop and evaluate the performance of a 1.5 kW LT-SOFC tri-generation prototype system, tested in the laboratory and low-carbon homes/buildings. As also mentioned above, the three projects D2SERVICE, ENE.FIELD and PACE involve both PEMFC and SOFC technology in demonstration projects.

Data from the project SOFCOM has also been included in this section. Whilst the project aims towards technical feasibility for large-scale Combined Cooling Heat and Power (CCHP) plants fed on biogenous primary fuels, two Proof of Concept (PoC) units were built, one which was 5 kW and the other only given as 5-10 kW (the final size was not clear). It was therefore decided to group the data from SOFCOM with the mCHP data. This project was followed up by DEMOSOFC, which is discussed under mid-size installations.

The majority of data collected regarding the MAWP KPIs in this section is regarding either PEMFC or SOFC units, and the results will be discussed separately for these technologies. In general, the largest quantity of relevant data has been obtained from the two mCHP large demonstration projects ENE.FIELD and PACE. Two other stationary power projects have developed units for within this power range using other fuel cell technologies: ALKAMMONIA which worked towards developing alkaline fuel cells for remote power applications and METPROCELL which was developing PCFC system for Auxiliary Power Unit (APU) and mCHP applications. These will be referred to where they have provided relevant public data. Overall, only 46% of the data points collected for mCHP were provided as "public data". This value was considerably higher for PEMFC mCHP (63%) than SOFC mCHP (30%). This means it is often difficult to plot significant data for a public report as crucial data cannot be included. Therefore, plots have only been included for electrical and thermal efficiencies where the vast majority of the data submitted was declared as public.

[16] HTCeramix is now part of SolidPower.

The targets originating from the Addendum to the Multi-Annual Work Plan of the FCH 2 JU [4] relating specifically to residential mCHP for single family homes and small buildings (0.3-5 kW) are summarised in Table 4 at the end of this section. This table also includes SoA values for 2012 and 2017. The values provided in this table originate from agreement between the Programme Office, Hydrogen Europe members and Hydrogen Europe Research members.

Table 4 shows whether a target has been achieved to date. It should be noted that this assessment was performed in 2019 and the Programme is still ongoing. Therefore, where a target has not been reached and the SoA has not been improved upon to date, it is indicated by a “Work in Progress” sign. Where it has been reached, it is indicated by a green tick. In certain cases, the SoA has been improved upon but not to the extent of achieving the target. Here, a grey tick is shown. It should also be noted that projects should provide data, wherever feasible, under standard boundary conditions (as defined in the notes to Table 4). In general, it has not been possible to establish whether all data provided has been given under these standard conditions.

5.1.2 Progress against State of the Art - Micro-CHP

CAPEX (€/kW)

This is defined as the cost of manufacturing (labour, materials, utilities) of the mCHP unit at current production levels per kW of rated electrical production. Despite a modest reduction in the state of the art cost of mCHP units between 2012 and 2017 (from 16,000 €/kW to 13,000 €/kW), the programme is targeting an almost four-fold reduction in cost between 2017 and 2030 (to 3,500 €/kW). In the TRUST database, projects are required to submit the cost of manufacturing of the fuel cell system[17] at current production levels and an estimated CAPEX at an assumed up-scaled production level. The projects are allowed to specify this level themselves.

The target for 2020 (≤ 10,000 EUR/kW) has been achieved by manufacturers of mCHP in FCH JU projects, however these values have been submitted as confidential so the exact CAPEX will not be presented here. A few other low TRL projects also submitted values that achieved the 2020 target, however these are unlikely to be representative of the full fuel cell system. The most relevant values considered are those of the units deployed within the high TRL demonstration projects.

Although it is not a specific MAWP target, the CAPEX estimated at mass production levels has been included as a KPI in TRUST. There is general optimism that both technologies can achieve the 2030 cost targets at mass production in the long term, although the range of predicted values is considerably broader for PEMFC units than SOFC (again many of these values are confidential so cannot be presented here). However, the KPI does not require for it to be stated *when* mass production could be achieved by. Therefore, it is difficult to conclude whether the programme is on track to achieve the stated target by 2030, even though some predicted mass production CAPEX values are below this target.

Lifetime (years of appliance operation)

The lifetime is defined as the time that the fuel cell system, with its major components/parts being replaced is able to operate until End of Life, with the projects being able to provide their own end of life criteria. It should be noted that this is generally a rated value provide by the OEM for high TRL commercial systems, whilst lower TRL projects tend to provide the time for which the system has been operated to date. A modest increase in lifetime from 12 to 15 years between 2017 and 2030 is targeted.

[17] It should be noted, that the term “module” is used in the MAWP, whilst the term “system” tends to be used in TRUST for the equivalent KPIs, suggesting these are interchangeable. In general, the values are referring to system values, unless specifically clarified.

Some units already have a rated lifetime equivalent to the value required for 2030. In general, lifetimes for high TRL PEMFC systems range from 9 to 18 years, whilst for SOFC this range is from 9 to 15 years. For comparison, the AFC unit from ALKAMMONIA has a rated lifetime of 20 years.

Availability (of the appliance, %)

The availability of the appliance is the ratio of time that the module is available divided by the time it was expected to operate. The number of systems and locations averaged to get the individual value submitted to TRUST seems to vary considerably. A state of the art value of 97% is assumed and a slight increase to 98% targeted by 2030.

In general, whilst this data was often confidential, the bulk of projects reported availabilities between 92-100%. The issue with this particular KPI is that the value may mean different things in the case of different projects. For example, for a low TRL project where the system is based in the laboratory, response times for the maintenance worker may be immediate, leading to shorter downtimes and higher values of availability. In the case of demonstration projects such as ENE.FIELD and PACE, it may take some time to arrange to travel to a particular unit that is experiencing downtime. Furthermore, for low TRL projects, the time the system is expected to operate could be low, leading to high availability.

It could be argued that the availability KPI is only relevant for field tests. Furthermore, availability is often averaged over a number of units around a particular geographical location. The number of units included in the data from different projects is therefore not consistent between data points.

Durability of Key Component: Stack (hrs)

The durability of the stack is the mean time it can operate before reaching its end of life criterion. The manufacturer is allowed to define this criterion. The state of the art value provided by FCH JU for 2017 is 40,000 hours, with a target of 80,000 hours for 2030. Whilst a wide range of values is indicated by the projects, a number of manufacturers already state a stack durability equal to, or in excess of, 40,000 hours and up to a maximum of 80,000 hours stack durability.

Unlike for System Lifetime where Demonstration projects were clearly declaring higher values than Research projects, no clear trend is observed in the case of Stack Durability. This is because many research projects are operating at stack level, as opposed to system level.

Reliability: MTBF (hrs)

The *Mean Time Between Failures (MTBF)* refers to the average time between failures that render the system inoperable and is a metric for the reliability of a fuel cell module. A state of the art value of 30,000 hours is assumed for 2017 with a target of 100,000 hours in 2030.

Only very limited data is available for this parameter. Values have been submitted that exceed the SoA but do not yet achieve the 2020 target.

With time more statistical data of this nature should become available. It may be useful to assess this KPI only for demonstration projects with a minimum number of units in order for the reported values of the KPI to be statistically reliable. Also, the indicator MTBF applies at system level whereas most failures will be due to a critical component within the system. From the perspective of an end-user they will not care why a system does not work, simply that it does not. However, from a technical perspective MTBF does not give an indication of the root cause of frequent failures, which, until the MTBF is significantly higher, will be the most critical point to consider and cannot be captured using the KPI.

Electrical and Thermal Efficiencies (% LHV)

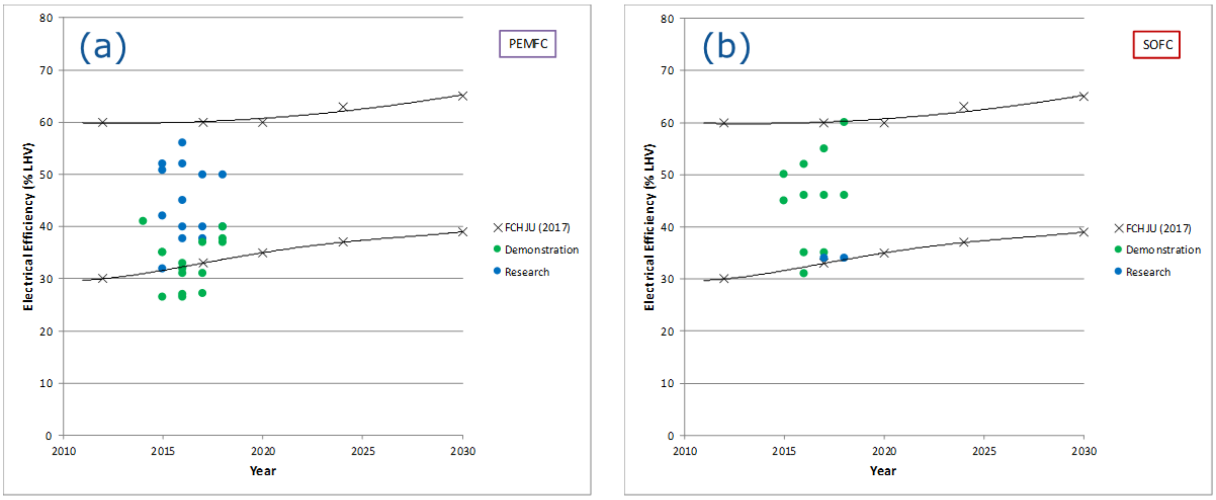
The MAWP provides separate targets for the electrical and thermal efficiencies of the mCHP modules. These are defined “at the rated capacity for the FC module as % of electrical output vs energetic content of fuel – LHV”. As the total efficiency of the unit is effectively the sum of the electrical efficiency and the thermal efficiency, ranges rather than a single target value are provided for these parameters. Interestingly, no single target value for total efficiency is given. It should be noted that in general, systems with low electrical efficiency will tend to have higher thermal efficiency. Reporting of these values was often inconsistent. In certain cases, the values for electrical and thermal efficiency totalled over 100%. Revisiting the definitions for these parameters and ensuring they are being applied correctly is recommended.

Contrary to the other MAWP KPIs the vast majority of submitted values were not labelled as confidential. Therefore, in Figure 11 the electrical efficiencies reported by the projects concerning both PEMFC and SOFC small modules (< 5 kW) are provided. The corresponding data for thermal efficiencies are given in Figure 12. Not all projects that have provided electrical efficiency data have provided corresponding thermal efficiency data. In general, the rated values of the efficiencies were used wherever available. The rated values provide the performance under nominal steady state conditions, although the system may be less efficient under operational duty cycles. For lower TRL projects the rated value and the operational value were usually the same (as no specific rated value could be declared).

All submitted public data has been included, and a distinction has been made between research (Panel 4) and demonstration (Panel 3) projects. In general, the modules can achieve efficiencies in the required range for both PEMFC and SOFC technologies. However, it is evident that the demonstration projects for PEMFC modules show electrical efficiencies at the low end of, or below, the range required whilst the “next generation” PEMFC CHP modules being developed in research projects in Panel 4 have enhanced electrical efficiency. Some variation would be expected due to the different requirements of mCHP units in terms of electricity and heat demand and it is evident from Figure 12(a) that these PEMFC units display correspondingly higher thermal efficiencies. It is important to understand whether the higher electrical efficiencies achieved in lower TRL projects can be transferable to higher TRL projects.

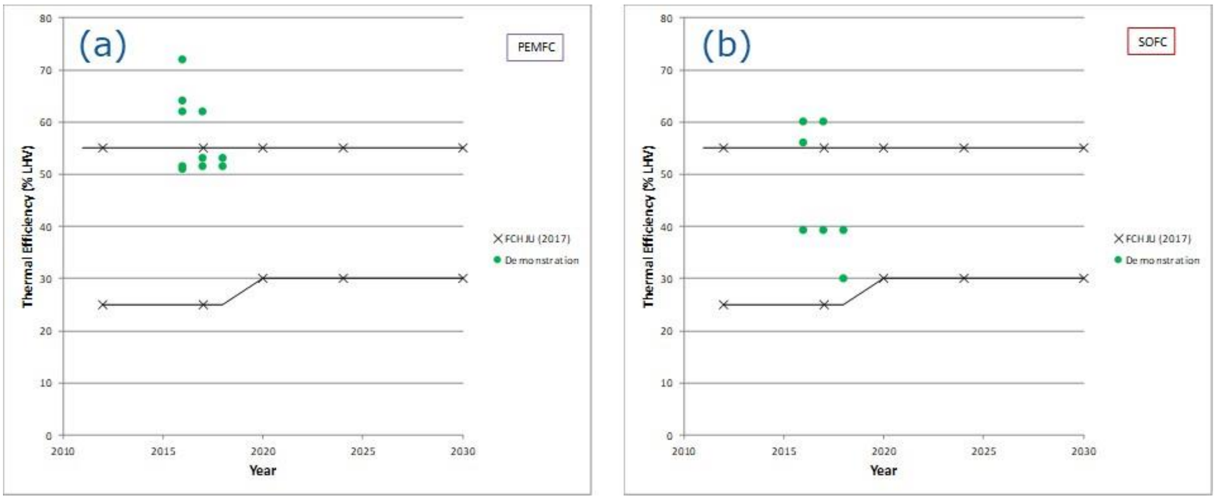
In the case of the SOFC technology, most of the submitted data comes from demonstration projects, and in this case, it is clear that modules achieving the full ranges of electrical and thermal efficiencies outlined in the MAWP targets have been produced.

Figure 11: Electrical Efficiency of mCHP modules versus year, for Research and Demonstration projects using (a) PEMFC (b) SOFC technology



Note: The lines on the plots show the lower and upper ranges for the SoA and targets provided in the MAWP document.
Source: JRC, based on data provided by the Programme Office of the FCH 2 JU, 2020.

Figure 12: Thermal Efficiency of mCHP modules versus year, for Research and Demonstration projects using (a) PEMFC (b) SOFC technology



Note: The lines on the plots show the lower and upper ranges for the SoA and targets provided in the MAWP document.
Source: JRC, based on data provided by the Programme Office of the FCH 2 JU, 2020.

Maintenance costs (€ Ct/kWh)

These are defined as the operation and maintenance costs per kWh of electricity produced (including stack replacement) but excluding the cost of the fuel, insurances and taxes.[18] The state of the art value, according to the FCH JU has halved in the period from 2012 to 2017 from 40 to 20 € Ct / kWh, however, for wide-scale

[18] Whilst the definition states "operating and maintenance costs" i.e. O&M costs, the KPI is given the name "Maintenance costs" only. To be consistent with the MAWP, this identifier will be used throughout the report.

adoption to occur a considerable further drop of almost an order of magnitude to 2.5 € Ct / kWh by 2030 is required.

In general, progress against the state of the art value from 2017 has been observed with values under 10 €Ct/kWh reported. One project has reported a value that even improved on the 2030 target. However, for this parameter the bulk of the data submitted was confidential.

Similarly as for the KPI MTBF, it is recommended that a minimum number of units be installed before this parameter is given, for it to have sound statistical meaning.

Tolerated hydrogen content in NG (Vol. %)

This is the amount of hydrogen that can be blended into the hydrocarbon feed (usually natural gas) allowing normal functioning of the SOFC module. A target of 100% hydrogen is foreseen for 2020.

Whilst a number of modules were reported that can tolerate a certain amount of hydrogen within the natural gas supplied, to date only one manufacturer stated that their SOFC unit can tolerate 100 % hydrogen (which is the target set for 2020).

It is presumed that this is a more general KPI, intended also for methane reformers operating with PEMFC. However, in the case of PEMFC it is not clear whether projects are reporting in TRUST the hydrogen content prior to a reformer, or hydrogen purity entering the fuel cell. We would therefore recommend that the KPI definition is reviewed accordingly.

Installation volume/unit (l/kW)

This is the volume of the FC module per kW of rated electrical production. The state of the art value provided by the FCH JU for 2017 is 240 l/kW. Only a slight improvement in this value is required by 2030 (to 220 l/kW) which suggests that the requirement is more to retain the state of the art value while providing improvements in the other targeted KPIs.

From the data submitted to TRUST for PEMFC and SOFC modules it was determined that the values declared by projects do not improve on the 2017 state of the art. It is clear from the projected targets that only a slight improvement on the state of the art is foreseen, and presumably it is more a case that mCHP units should achieve the other targets provided in this section without leading to increasing volume of the unit over the current value. However, as the range of unit sizes considered are from 0.3-5 kW of electrical power (i.e. more than an order of magnitude in variation), it raises the question as to whether the volume per kW is a fair comparison. Perhaps any future target should simply consider a maximum volume for a unit, which is suitable for residential use.

5.1.3 Summary - Micro-CHP

In Table 4, a summary is given showing which MAWP 2020 KPI targets have been achieved by one or more projects for mCHP technologies. A green tick shows where the target has been fully achieved by at least one project (i.e. best in class). A grey tick shows where improvement has been made on the SoA but the target has not yet been achieved and a "work in progress" sign demonstrates where work is ongoing but as yet the projects have not submitted values better than the 2017 SoA. In general, it can be seen that the mCHP units under development through the FCH JU programme have been delivering on the bulk of the KPIs declared within the MAWP. The only KPIs where neither technology has advanced the SoA versus the 2017 values and achieved the 2020 targets are in terms of reliability (specifically MTBF) where there is currently a dearth of long-term statistical data to make a fair assessment, and installation volume where the use of the unit of l/kW is perhaps not providing a fair assessment of smaller units which still need the relevant BoP. It should be noted that reliability will be critical for end-users (small commercial and domestic) and thus for the eventual success of fuel cell mCHP systems in these markets.

The addendum to the MAWP states that fuel cell m-CHP is becoming increasingly established in early markets and can provide reduced emissions, high efficiency and increasingly sufficient economic payback [4]. The ENE.FIELD project installed in excess of 1,000 mCHP units, whilst a further 2,800 are being deployed during the PACE project. This technology is also being taken up by member states. For example, the German KfW 433 subsidies programme is providing financial support (subsidies) to end-users which should lead to the installation of approximately 60,000 units by the end of 2022, leading a number of manufacturers to begin scaling up to mass manufacture. This can be compared to Japan, where more than 300,000 units have already been installed (the majority under the ENEFARM programme). Based on the progress that has been made, the statement was made in the revised MAWP addendum of 2018 that FC mCHP applications would not require further demonstration in the field in the remaining period of the FCH 2 JU [4]. However, a deeper analysis of the outcomes of the ongoing PACE project would be required to determine the correct form of support for this application in any future funding programme.

Several of the targets of 2030 have already been achieved by certain projects. It would therefore be worth considering whether any of these targets need reviewing. It is possible that it is simply necessary to continually achieve these targets whilst ensuring the remaining targets are met. However, it should be considered, for example, whether additional R&I efforts are required regarding material improvements for reduction of efficiency losses at stack level or whether more longer-term system-level testing is required to verify rated lifetimes, for example.

Finally, the programme should consider whether achievements in the lower TRL projects (e.g. PEMFC electrical efficiencies) are being transferred from these research projects to higher TRL demonstrations.

Table 4: MAWP objectives and achievements of projects for mCHP for single family homes and small buildings (0.3-5 kW)

No.	Parameter and Unit	SoA 2012	SoA 2017	Target 2020	Achieved?	Target 2024	Achieved?	Target 2030	Achieved?
1	CAPEX (€/kW)	16,000	13,000	10,000	✓	5,500		3,500	
2	Lifetime (years)	10	12	13	✓	14	✓	15	✓
3	Availability (%)	97	97	97	✓	97	✓	98	✓
4	Durability of stack (hours)	25,000	40,000	50,000	✓	60,000	✓	80,000	✓
5	Reliability MTBF (hours)	10,000	30,000	50,000		75,000		100,000	
6	Electrical Efficiency (% LHV)	30-60	33-60	35-60	✓	37-63	✓	39-65	✓
7	Thermal Efficiency (% LHV)	25-55	25-55	30-55	✓	30-55	✓	30-55	✓
8	Maintenance Costs (€ Ct/kWh)	40	20	5	✓	3.5	✓	2.5	✓
9	Installation volume (l/kW)	330	240	230		225		220	
10	Tolerated hydrogen content in NG (%)	5	5	100	✓	100	✓	100	✓

Source: JRC, based on the Addendum to the MAWP of the Programme Office of the FCH 2 JU (2018) and data provided by the Programme Office of the FCH 2 JU, 2020.

Notes:

1. Cost of manufacturing (labour, materials, utilities) of the mCHP unit at current production levels (exclude monetary costs, e.g. overheads, profits, rebates, grants, value-added tax (VAT), insurances, taxes, land).
2. Lifetime (years) that the mCHP unit, with its major components/parts being replaced, e.g stack, is able to operate until the EoL.
3. Ratio of the time that the FC module was able to operate minus downtime divided by the time that was expected to operate. Downtime is the time that the FC is not able to operate - includes time for (un)scheduled maintenance, repairs, overhaul etc
4. Time that a maintained FC stack is able to operate until End-of-Life criterion - as specified by the OEM.
5. Mean time between failure of the FC that render the system inoperable without maintenance or average time between successive failures leading to downtime: time that the FC is not able to operate includes (un)scheduled maintenance, repairs, overhaul etc
6. Electrical efficiency at rated capacity for the FC module as % of electrical output vs energetic content of fuel - LHV.
7. Thermal efficiency at rated capacity for the FC module as % of electrical output vs energetic content of fuel - LHV.
8. Operation and maintenance costs per kWh of electricity produced - Including running, overhaul, repair, maintenance labour costs and costs of stack replacement; excluding: fuel cost, insurances, taxes, etc.
9. Volume of fuel cell module as is available for installation in its basic configuration, in l/kWe.
10. Percent amount of hydrogen that can blended into the hydrocarbon feed (usually natural gas) allowing normal functioning of the fuel cell module.

5.2 Mid-Sized Installations

5.2.1 Overview

According to the addendum to the MAWP, mid-sized installations (5 to 400 kW) suitable for commercial and larger buildings are currently less mature compared to the mCHP sector. This is attributed to a lack of upscaling of the current stacks available [4]. However, a number of demonstrations are underway across Europe in order to validate the technology at this scale.

The projects considered for this section are listed in Annex 1, Table 9. Again, the majority of projects consider either PEMFC or SOFC technologies.

At the Research and Development level (Panel 4) a number of projects have developed technologies for ***PEMFC*** on this scale. STAYERS focussed on extending the lifetime of PEM fuel cells beyond five years by combining advanced materials research and development (R&D) with modelling and accelerated tests. CISTEM aimed at the construction of improved MEAs and stacks for long-term stable modular CHP units, in particular for large-scale peak shaving systems. The project targeted an electrical output of 100 kW. The GRASSHOPPER project is aiming to create a next-generation MW-size FC Power Plant unit, which is being demonstrated in the field as a 100 kW sub-module pilot plant with newly developed MEAs, stacks and BoP.

In terms of Demonstration projects (Panel 3) a number of mid-size projects relating to PEMFC have been undertaken. PEMBEYOND aimed to demonstrate a PEMFC based power system operating on crude bioethanol for back-up and off-grid power generation. AUTORE aimed to create the foundations for commercialising an automotive derivative PEMFC system in the 50-100 kW range for CHP applications in commercial and industrial buildings. Two further projects are ongoing. EVERYWH2ERE is integrating PEMFC stacks and low weight pressurised hydrogen technologies into transportable gensets, which will be tested at construction sites, music festivals and urban public events. REMOTE is demonstrating two fuel-cell based hydrogen energy storage solutions (an integrated power to power (P2P) system and a non-integrated P2G plus gas to power (G2P) system). These are being tested in isolated micro-grid or off-grid remote areas.

In the case of ***SOFC*** only a couple of Panel 4 (Research) projects have been included in this section, along with a number of Panel 3 (Demonstration) projects.

DIAMOND was a project aiming to improve SOFC performance for CHP applications using innovative strategies for monitoring and control, to provide information on the state of health of SOFC systems. NELLHI combined existing know-how regarding cells, coatings, seals and stack design to produce a 1 kW stack and 10 kWe PoC, with the target being stationary and residential CHP production based on natural gas.

A number of Panel 3 projects focussed on the development of sub-systems for mid-size applications. The ASSENT project focussed on the development of fuel and water management, whilst the CATION project developed and optimised the cathode subsystem to provide solutions for future 250 kWe SOFC systems.

The STAGE-SOFC project developed a PoC SOFC system for stationary power and CHP applications. The novel developments focussed on the reformer of the system, incorporating a serial connection of an exothermal catalytic partial oxidation (CPOx) stage with an endothermic steam reforming stage.

A number of projects have been aiming to validate mid-size SOFC systems. The INNO-SOFC project aimed to develop, manufacture and validate a next-generation innovative 50 kW SOFC system. ONSITE operated a novel SOFC-battery integrated hybrid for telecommunication energy systems. This consisted of the construction and operation of a containerised system of >20 kW power.[19] The COMSOS project is demonstrating and validating mid-size SOFC CHP systems in the 10-12, 20-25 and 50-60 kW power ranges for the commercial sector. The

[19] ONSITE data was also included in the 0.3-5 kW section, as data was also provided through TRUST for a 2.5 kW module.

DEMOSOFC project is demonstrating a larger distributed CHP system fed with biogas from a wastewater treatment plant.

Finally, the CH2P project is aiming to build a transition technology for hydrogen refuelling stations (HRS). The system will co-generate hydrogen, heat and electricity using SOFC technology fuelled by natural gas or bio-methane.

Three projects have implemented fuel cell technologies other than PEMFC or SOFC in this size range. LASER CELL and POWER UP use AFC technology and MCFC CONTEX uses MCFC technology. LASER CELL was a manufacturing project, which aimed to develop a novel mass-producible AFC and stack design for stationary industrial applications relevant to mid-scale applications. The POWER UP project aimed to generate electrical power from an AFC system running on untreated industrial waste H_2 from a hydrogen plant in Germany. This project was originally classed as a large-scale project as it was due to demonstrate a 500 kWe system, however, according to reported data, only a 240 kWe plant was realised. The MCFC CONTEX project aimed to tackle the issue of degradation caused by contaminants in fuels for MCFC by investigating poisoning mechanisms, in principle with mid-range systems in mind.

The majority of data collected regarding the MAWP KPIs in this section is regarding either PEMFC or SOFC units, and the results will be discussed separately for these technologies. Overall, only 44% of the data points collected for mid-sized systems were provided as "public data". This value was similar for PEMFC (43%) and SOFC (45%). Again, this means it is difficult to plot significant data for a public report as crucial data cannot be included. Hence, only data for the electrical efficiency is shown.

The targets originating from the Addendum to the Multi-Annual Work Plan of the FCH 2 JU [4] relating specifically to mid-size installations for commercial and larger buildings (5-400 kW) are summarised in Table 5 and Table 6 at the end of this section. This table also includes SoA values for 2012 and 2017. The values provided in this table originate from agreement between the Programme Office, Hydrogen Europe members and Hydrogen Europe Research members.

Table 5 (for PEMFC) and Table 6 (for SOFC) also show whether a target has been achieved to date. It should be noted that this assessment was performed in 2019 and the Programme is still ongoing. Therefore, where a target has not been reached and the SoA has not been improved upon to date, it is indicated by a "Work in Progress" sign. Where it has been reached, it is indicated by a green tick. In certain cases, the SoA has been improved upon but not to the extent of achieving the target. Here, a grey tick is shown. This needs to be considered in the context regarding the scale of the project and the conditions under which the particular performance was achieved. It should also be noted that projects should provide data, wherever feasible, under standard boundary conditions (as defined in the notes to Table 5 and Table 6). In general, it has not been possible to establish whether all data provided has been given under these standard conditions.

5.2.2 Progress against State of the Art: Mid-Sized installations

CAPEX (€/kW)

This 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). For mid-size units a range of CAPEX costs have been given (presumably due to the broad range of unit sizes included). A state of the art value of 5,000-8,500 €/kW in 2017 is targeted to drop to 1,500-4,000 €/kW in 2030. These values are lower than those predicted for mCHP.

Projects have submitted CAPEX values for both the current production levels and estimated at mass production. CAPEX values currently being achieved by the projects relating to PEMFC technology are within the target range, and indeed in certain cases ahead of the 2020 targets. In the case of SOFC, all projects submitted a current CAPEX value in excess of the targets. However, it should be noted that when considering the longer-term cost at mass production both technologies give a similar range of values in between the 2020 and 2030 targets. However, no related time-scale is given as to when the prediction will actually be achieved.

All values submitted by AFC projects were confidential but it should be noted that the cheaper cost of alkaline fuel cells is one of their main advantages.

Lifetime (years of plant operation)

This is defined as the time that the plant, with its major components/parts being replaced, is able to operate until End of Life. The projects are allowed to define their own end of life criterion. Contrary to the mCHP values, a target giving a range of lifetimes is provided for the mid-range starting from 6-20 years in 2017 to 15-20 years in 2030. This seems an unconventional way to define a lifetime target, but it is again presumably due to the wide range of product sizes concerned.

In general, declared lifetimes for PEMFC mid-size plants fall between 10-20 years whereas SOFC systems fall between 7-15 years. By comparison, the AFC project POWER UP states a lifetime of 25 years in TRUST.

In general, progress seems to be in line with the programme targets (i.e. they fall within the required range), however it is not at all clear why a range has been provided for this target and not simply a minimum target value. This should be revisited.

Availability (of the plant, %)

This is the ratio of the time that the plant is expected to operate minus downtime, divided by the total time it was expected to operate. As for m-CHP, the value increases from a state of the art value of 97% in 2017 to 98% targeted by 2030.

Only a very limited amount of data has been submitted for this KPI. SOFC projects provided limited data mostly in the region of 95-100% but no reported data that achieves the SoA for PEMFC. In general, more statistical data is needed before drawing any conclusions on this particular parameter.

Durability of key component: stack (hrs)

This is the mean time that the stack can operate before reaching its end of life criterion. The manufacturer is allowed to define this criterion. The state of the art is assumed to be 35,000 hours in 2017 and a target of 80,000 hours is given for 2030.

For PEMFC technology, there are no projects reporting higher stack durability than the 2017 state of the art. For SOFC one project has declared a rated durability of the fuel cell stack that has achieved the 2020 target of 50,000 hours, although the precise value is given as confidential.

The MAWP states that the reason for currently lower penetration by mid-size units compared to mCHP is due to a lack of upscaling of the stack technology. However, the targets for stack durability are identical for mCHP and mid-size installations. However, the mid-size projects are lagging behind. This seems to be particularly the case for PEMFC. If PEMFC are going to have a future in larger scale systems then the durability at larger stack sizes will need to be addressed.

Reliability: MTBF (hrs)

This refers to the average time between failures that render the system inoperable. A state of the art value of 20,000 hours is assumed for 2017 with a target of 80,000 hours in 2030.

To date, only a small number of data points have been obtained for the MTBF for either PEMFC or SOFC projects and all those were submitted as confidential values. For PEMFC no submitted data has exceeded the 2017 SoA value, whilst for SOFC, one value has exceeded the SoA but not quite achieved the 2020 target of 30,000 hours. It will be necessary to obtain additional data over the coming years to obtain sufficient statistical information in order to make any conclusions on this parameter.

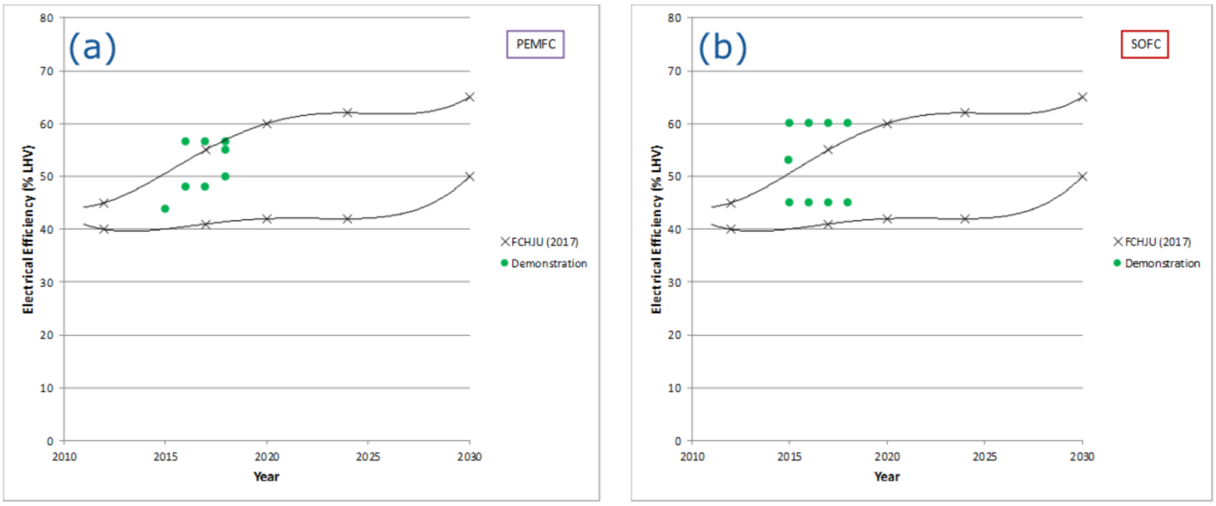
Electrical and Thermal Efficiencies (% LHV)

As for the mCHP modules, the MAWP provides separate targets for the electrical and thermal efficiencies of the mid-size installations. These are defined “at rated capacity for the FC module as % of electrical output vs energetic content of fuel - Low Heating Value (LHV)”. As the total efficiency of the unit is effectively the sum of the electrical efficiency and the thermal efficiency, no single target value for either is provided for these parameters.

In Figure 13, the electrical efficiencies reported publicly by the projects concerning both PEMFC and SOFC mid-size installations are provided. Some additional data was provided confidentially by projects but do not change the range of data that can be observed. For both PEMFC and SOFC it can be seen that data has been submitted within the ranges targeted for 2020. However, one of the targets of this KPI is to have higher electrical efficiencies (up to 65%) by 2030. Currently, the highest system electrical efficiencies for mid-size installations reported are 57% for PEMFC and 60% for SOFC.

For thermal efficiencies, less data has been submitted and it is mostly confidential, however for PEMFC, the reported values are actually higher than the SoA range and the range of targets for 2020, and correspond more closely to the range of values foreseen for 2030 (as given in Table 5). For SOFC a wide range of thermal efficiencies covering all target ranges are observed.

Figure 13: Electrical Efficiency of mid-size installations versus year, for projects using (a) PEMFC (b) SOFC technology



Note: The lines on the plots show the lower and upper ranges for the SoA and targets provided in the MAWP document.
Source: JRC, based on data provided by the Programme Office of the FCH 2 JU, 2020.

Maintenance costs (€ Ct/kWh)

These are defined as the operation and maintenance costs per kWh of electricity produced (including stack replacement), but excluding the cost of the fuel, insurances and taxes. The state of the art value, of 8.6 € Ct/kWh, is considerably lower than for mCHP, with a target of 1.2 € Ct/kWh set for 2030.

At the time of this analysis, no projects in the range of 5 kW to 400 kW installation size have submitted any data regarding maintenance costs. As more demonstrations start it is expected that more information will be submitted.

Land use/ footprint (m^2/kW)

This is the base surface area (width x depth) occupied by the stationary fuel cell module per unit of rated electrical capacity. A drop from the current state of the art value of 0.25 m^2/kW to 0.06 m^2/kW by 2030 is foreseen.

For PEMFC, only one project has submitted a value that is an improvement on the SoA. For SOFC, several projects have improved on the state of the art and are close to achieving future targets.

Tolerated hydrogen content in NG (% (Volume))

This is the amount of hydrogen that can blended into the hydrocarbon feed (usually natural gas) allowing normal functioning of the (SO) fuel cell module. A target of 100% hydrogen is foreseen for 2020.

Several projects have supplied data and the highest tolerance achieved has been 50% H_2. However, no project has to date advanced this KPI beyond the SoA value of 50% for mid-size systems.

5.2.3 Summary: Mid-Sized installations

In Table 5 and Table 6, a summary is given showing which MAWP 2020 KPI targets have been achieved by one or more projects for mid-size PEMFC and SOFC technologies. Based on the data submitted to date, a much more mixed picture is seen than for mCHP, hence the data has been displayed according to technology. In the case of PEMFC technologies, the CAPEX targets have been achieved, along with the lifetime target and electrical efficiency targets. The thermal efficiency was slightly out of range (high) but close to being achieved. The key issues seem to be with the durability of the stack and the availability/reliability of the system. This is despite the fact that the lifetime of systems has been achieved according to the rated values given. In the case of SOFC, the lifetime, durability of stack and system availability targets have all been achieved, and systems have been produced with electrical and thermal efficiencies in the required ranges. The main issue in this case seems to be achieving a breakthrough CAPEX value.

According to the addendum to the MAWP, mid-sized installations (5 to 400 kW) suitable for commercial and larger buildings are currently less mature when compared to the mCHP sector. This is supported by the data compiled for this section and is attributed to a lack of upscaling of the current stacks available [4]. The demonstration projects that are mentioned above will need to demonstrate clear progress in particular on the durability of PEMFC at this scale. Factors that affect this durability relate to the need for frequent start-ups and shut-downs and variable demand during operation. This is not captured by the KPI as it is not of a purely technical nature. From this point of view, the need for upscaling stacks could be alleviated by a higher degree of modularity, i.e. using a higher number of smaller stacks. This would, however, impact the complexity of the required balance of plant, and lead to higher CAPEX. The demonstration projects will also have to show improved cost-effectiveness of SOFC technology. The cost-effectiveness may be improved by optimising the use of co-generated heat, i.e. locating the unit in proximity to a site with suitable heat demand.

It should be noted that for certain KPIs, the targets for 2030 have already been achieved (lifetime; electrical and thermal efficiency). It is worth considering whether these targets need reviewing and updating or whether it is simply necessary to maintain this achieved target whilst optimising the other parameters.

Table 5: MAWP objectives and achievements of PEMFC projects for mid-sized installations for commercial and larger buildings (5 - 400 kW)

No.	Parameter and Unit	SoA 2012	SoA 2017	Target 2020	Achieved?	Target 2024	Achieved?	Target 2030	Achieved?
1	CAPEX (€/kW)	6,000 – 10,000	5,000 – 8,500	4,500 – 7,500	✓ [20]	3.500 – 6.500	✓	1,500 - 4,000	
2	Lifetime (years)	2 - 20	6 - 20	8 - 20	✓	8 - 20	✓	15-20	✓
3	Availability (%)	97	97	97	⚠	97		98	
4	Durability of stack (hours)	25,000	30,000	50,000	⚠	60,000		80,000	
5	Reliability MTBF (hours)	10,000	20,000	30,000	⚠	50,000		80,000	
6	Electrical Efficiency (% LHV)	40-45	41-55	42-60	✓	42-62	✓	50-65	✓
7	Thermal Efficiency (% LHV)	24-40	24-41	24-42	⚠	24-42		30-50	✓
8	Maintenance Costs (€ Ct/kWh)	8.6	7.6	2.3	⚠	1.8		1.2	
9	Land use/ footprint (m^2/kW)	0.25	0.15	0.08	⚠	0.07		0.06	

Source: JRC, based on data provided by the Programme Office of the FCH 2 JU, 2020.

[20] It should be noted that this has been achieved by PoC projects at lower TRL and not Demonstration projects

Table 6: MAWP objectives and achievements of SOFC projects for mid-sized installations for commercial and larger buildings (5 - 400 kW)

No.	Parameter and Unit	SoA 2012	SoA 2017	Target 2020	Achieved?	Target 2024	Achieved?	Target 2030	Achieved?
1	CAPEX (€/kW)	6,000 - 10,000	5,000 – 8,500	4,500 – 7,500	⚠	3,500 – 6,500		1,500 - 4,000	
2	Lifetime (years)	2 - 20	6 - 20	8 - 20	✓	8 - 20	✓	15-20	✓
3	Availability (%)	97	97	97	✓	97	✓	98	✓
4	Durability of stack (hrs)	25,000	30,000	50,000	✓	60,000		80,000	
5	Reliability MTBF (hrs)	10,000	20,000	30,000	✓	50,000		80,000	
6	Electrical Efficiency (%LHV)	40-45	41-55	42-60	✓	42-62	✓	50-65	✓
7	Thermal Efficiency (%LHV)	24-40	24-41	24-42	✓	24-42	✓	30-50	✓
8	Maintenance Costs (€ Ct/kWh)	8.6	7.6	2.3	⚠	1.8		1.2	
9	Land use/ footprint (m^2/kW)	0.25	0.15	0.08	✓	0.07		0.06	
10	Tolerated H2 content in NG (%)		50	100	⚠	100		100	

Source: JRC, 2020. Based on Addendum to the MAWP of the Programme Office of the FCH 2 JU, 2018 and data provided by the FCH JU.

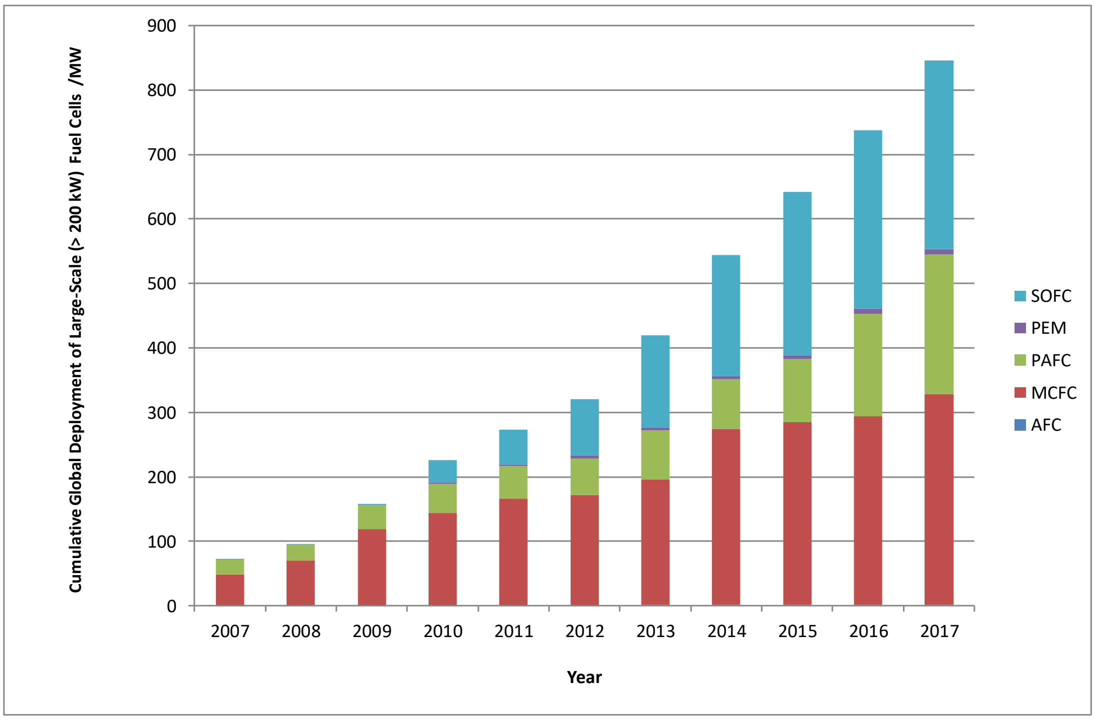
Notes: For 1-8 and 10 please refer to the definitions of Table 4. For 9, base surface (width x depth) occupied by the stationary FC module per unit of rated electrical capacity.

5.3 Large-Scale Installations

5.3.1 Overview

According to a recent report prepared by JRC, more than 800 MW of large stationary fuel cell systems with a rated power above 200 kW have been installed globally for distributed generation and combined heat power applications [7]. The largest shares of the installations are found in the US and South Korea. Figure 14 shows the relative share of the different large capacity fuel cell technologies installed up to the end of 2017. It can be seen that this is dominated by three technologies, with MCFCs having the largest share, followed by SOFCs and PAFCs. Only a small number of large capacity installations based on PEMFC and AFC technologies have been deployed to date. Large stationary fuel cell units have been deployed by utilities and provide power for distributed generation and CHP applications, the latter particularly in Asia. Whilst a large number of the installed units generate both heat and electricity, there is also a market for electricity only systems, for example those installed to provide back-up power for US customers. According to the report, the motivation for introducing large-scale fuel cell technologies in Europe is not as clear, as the main reasons for applying the technology in South Korea (poor air quality) and the US (unreliable electricity grid) are not as pressing in European markets.

Figure 14: Cumulative global deployment of large-scale stationary fuel cells shown from 2007 onwards (deployment data considered from 2000 onwards), displayed per technology.



Source: Weidner, E., Ortiz Cebolla, R. and Davies, J., Global deployment of large capacity stationary fuel cells – Drivers of, and barriers to, stationary fuel cell deployment, EUR 29693 EN, Publications Office of the European Union, Luxembourg, 2019, ISBN 978-92-76-00842-2, doi:10.2760/787370, JRC115923.

Furthermore, according to the MAWP addendum, the market for centralised power generation has not yet properly developed in the EU due to the low electricity prices for large industrial customers [4]. In general, the fuel cell industrial segment has struggled to find applications with viable business cases. Whilst the CLEARGENDEMO project has installed a 1 MW system in Martinique at a refinery, the DEMCOPEM-2MW system was deployed in China (project completed in December 2018). These projects are the two sources of data discussed in the following section. Both projects consider PEMFC technology. Please note that the GRASSHOPPER project is also aiming to create a next-generation MW-size Fuel Cell Power Plant unit. However, it is being demonstrated in the field as a 100 kW sub-module pilot and therefore has been included in the mid-size section.

Note, two other projects have been aiming towards large-scale units using other technologies. SOFCOM aimed to demonstrate the technical feasibility of CCHP plants based on SOFC fed by biogenous fuels. The data was included in the mCHP section because a PoC unit of 5 kW was produced, however the technology is targeting SOFC units up to 1 MW in size for combination with Waste Water Treatment Plants (WWTP). Furthermore, the project POWER UP was due to install an AFC unit of 500 kW size, however, only data for a 240 kW unit have been declared, therefore this has been included in the mid-size section.

As mentioned above, the data discussed in this section is regarding PEMFC units. In this chapter, 78% of the data points collected for large-scale installations was provided as “public data” but originated from only two projects. For this reason, detailed plots of the data are not given.

The targets originating from the Addendum to the Multi-Annual Work Plan of the FCH 2 JU [4] relating specifically to “large scale fuel cell installations, converting hydrogen and renewable methane into power in various applications (0.4-30 MW)” are summarised in Table 7 at the end of this section. This table also includes SoA values for 2012 and 2017. The values provided in this table originate from agreement between the Programme Office, Hydrogen Europe members and Hydrogen Europe Research members. As the reference sources for SoA values are not provided, it is unclear whether these values are technology specific, or whether they apply only to Europe or globally. As mentioned, the majority of large-scale FC installations globally are PAFC, MCFC and SOFC. It would be good to understand whether the SoA and targets take into account all of these technologies.

Table 7 also shows whether a target has been achieved to date. It should be noted that this assessment was performed in 2019 and the Programme is still ongoing. Therefore, where a target has not been reached and the SoA has not been improved upon to date, it is indicated by a “”Work in Progress” sign. Where it has been reached, it is indicated by a green tick. In certain cases, the SoA has been improved upon but not to the extent of achieving the target. Here, a grey tick is shown. It should also be noted that projects should provide data, wherever feasible, under standard boundary conditions (as defined in Table 7). In general, it has not been possible to establish whether all data provided has been given under these standard conditions.

5.3.2 Progress against State of the Art: Large-Scale Installations

CAPEX (€/kW)

This is defined as the cost of manufacturing (labour, materials, utilities) of the mCHP 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 a range of CAPEX costs have been provided (again presumably due to the broad range of unit sizes included in this class). A state of the art value of 3,000-3,500 €/kW in 2017 is targeted to drop to 1,200-1,750 €/kW in 2030. These values are lower than for the mid-size systems.

Current CAPEX values for both projects are given as confidential values, however the DEMCOPEM-2MW project states that cost can be reduced to a state of the art value of 3,000 €/kW at mass production levels. However, it is clear that some improvements will be necessary to achieve the lower end of the CAPEX range provided. This is one of the main objectives of the GRASSHOPPER project previously mentioned, which intends to achieve a CAPEX < 1500 €/kWe at a yearly production of 25 MWe.

It is not clear why a range has been provided for this particular parameter, although most likely it is due to the range of size of systems that are being considered (0.4-30 MW). It would be good to clarify whether the lower range corresponds to the larger installation size and the upper to the smaller size, in order to fairly judge the installations that are being deployed under the FCH 2 JU program.

Lifetime (years of plant operation)

This is defined as the time that the fuel cell plant, with its major components/parts being replaced is able to operate until End of Life. The projects are allowed to define their own end of life criterion. An increase in lifetime from 15 to 20 years is targeted from 2017 to 2030. A single value target is stated (in a similar way to mCHP) rather than the range that was provided for mid-size applications, indicating inconsistencies in target setting between the different scales. The rated lifetime of the systems declared for large-scale PEM projects have increased in the course of the project reporting, with DEMCOPEM-2MW providing a lifetime of 10 years in 2018 in TRUST. CLEARGENDEMO states a lifetime of 20 years, which is in excess of the 2017 state of the art but still short of the 2020 target of 25 years.

Availability (of the plant, %)

This is the ratio of the time that the plant is available to operate minus downtime, divided by the total time it was expected to operate. A state of the art value of 98% is assumed and this is required to be maintained by 2030. The state of the art availability for large-scale systems in 2017 is deemed to be higher than for mCHP or mid-size units presumably because large-scale installations are not expected to operate as often under fluctuating load, and therefore do not experience so many cyclically induced phenomena that can reduce availability. Availability of 95% was achieved in 2017 and 2018 for the DEMCOPEM-2MW project, just short of the 98% target.

Durability of key component: stack (hrs)

This is the mean time that the stack can operate before reaching its end of life criterion. The manufacturer is allowed to define this criterion. Contrary to mCHP and mid-size installations, a range of durability values are provided, both for the state of the art and the future targets. The state of the art is assumed to be 20,000-60,000 hours in 2017 and a target of 25,000-60,000 hours is given for 2030. The origin of this range is not clear.

A durability of 20,000 hours has been stated for the CLEARGEN DEMO stacks and 16,000 hours for the DEMCOPEM stacks, which puts the stacks at the lower end of the state of the art range. As mentioned previously, it is unclear why a range is given for the future durability of stacks for large-scale installations rather than a single value as given for mCHP and mid-size applications. The values presented at the large-scale are similar to several projects demonstrating PEM technologies at the mid-scale.

Reliability: MTBF (hrs)

This refers to the average time between failures that render the system inoperable. For this particular parameter, no value has been provided as the state of the art, apparently because insufficient numbers of units have been installed to provide statistical data. Whilst this may be true within Europe where the adoption of large-scale FC technologies is limited, it is certainly not the case worldwide. However, whether such information is publicly available is not clear. A target of 75,000 hours is given for 2030. DEMCOPEM-2MW has publicly reported a reliability in terms of the mean time between failures of 8,500 hours (in 2018). This is still far short of the 2020 target of 25,000 hours.

Electrical and thermal efficiencies (% LHV)

As for the other size ranges, the MAWP provides separate targets for the electrical and thermal efficiencies of the large-scale installations. These are again defined “at rated capacity for the FC module as % of electrical output vs energetic content of fuel - Low Heating Value (LHV)”. As the total efficiency of the unit is effectively the sum of the electrical efficiency and the thermal efficiency, no single target value for either is provided for these parameters. It should be noted that a single target value is provided for the electrical efficiency of large-scale installations, whereas a range is given for the thermal efficiency. Both projects report rated electrical efficiencies in excess of the state of the art. The DEMCOPEM-2MW project states an electrical efficiency of 50% LHV, which corresponds to the target for 2030 whilst CLEARGENDEMO has declared an electrical efficiency of 46.6% which exceeds the 45% target for 2024. Furthermore, the DEMCOPEM-2MW project achieves a thermal efficiency within the required range (at 35%). The CLEARGENDEMO thermal efficiency was declared confidential.

Maintenance costs (€ Ct/kWh)

These are defined as the operation and maintenance costs per kWh of electricity produced (including stack replacement, but excluding the cost of the fuel, insurances and taxes). The state of the art value, according to the FCH JU in 2017 was 2.8-5 € Ct/kWh. A drop to 2 € Ct/kWh by 2030 is targeted. Values for the maintenance cost KPI could not be found in any of the available sources.

Start/Stop characteristics

This is defined as the time required to reach the nominal fuel cell rated output when starting the system from shut-down mode (at ambient temperature). The state of the art is defined as 4 hours to go from 0-100% nominal output in 2017. A target of one minute is given for 2030. Whilst the start/stop characteristics for both projects are confidential it can be stated that both projects have shown good progress against the SoA and towards the future target.

5.3.3 Summary – Large-Scale Installations

In Table 7, a summary is given showing which MAWP 2020 KPI targets have been achieved by one or more projects for PEMFC large-scale technologies. These projects have achieved some of the important targets such as stack durability and electrical and thermal efficiency. However, there are still several MAWP targets which need to be met.

As for the other sections, it is clear that the 2030 targets have been achieved for some KPIs, which would suggest it may be necessary to review these targets.

Table 7: MAWP objectives and achievements of large-scale FC installations, converting hydrogen and renewable methane into power in various applications (0.4 - 30 MW)

No.		SoA 2012	SoA 2017	Target 2020	Achieved?	Target 2024	Achieved?	Target 2030	Achieved?
1	CAPEX (€/kW)	3,000 - 4,000	3,000 - 3,500	2,000 - 3,000	⚠	1,500 - 2,500		1,200 1,750	
2	Lifetime (years)	n/a	15	25	✓	25		25	
3	Availability (%)	98	98	98	⚠	98		98	
4	Durability of stack (hours)	15	20-60	20-60	✓	20-60	✓	25-60	
5	Reliability MTBF (hours)	n/a	N/A	25,000	⚠	30,000		75,000	
6	Electrical Efficiency (% LHV)	45	45	45	✓	45	✓	50	✓
7	Thermal Efficiency (% LHV)	20	20-40	22-40	✓	22-40	✓	22-40	✓
8	Maintenance Costs (€ Ct/kWh)	n/a	2.8-5	3	⚠	3		2	
9	Start/Stop characteristics	-	4 hrs, 0-100%	-	✓	1 min, 100%	✓	-	

Source: JRC, based on data provided by the Programme Office of the FCH 2 JU, 2020 and the Addendum to the MAWP of the FCH 2 JU, 2018.

Notes:

*insufficient number of units installed to get statistically supported figure

From 1) to 8) please refer to the definitions of Table 4; 9) Time required to reach the nominal fuel cell rated output when starting the system from shut-down mode (at ambient temperature).

6 Literature and Patenting Trends in Stationary Fuel Cell Technologies

6.1 Literature and Patent Searching Methodologies

This section gives a general overview regarding the trends in literature and patenting for the main technologies used in the field of Stationary FCs, i.e. PEMFC and SOFC. The aim is to provide the FCH 2 JU with information regarding how Europe is performing against other regions of the world in terms of scientific output. To determine the level of literature and patent activity regarding these technologies by geographical region, statistics have been obtained from a number of sources and subsequently analysed using two different methodologies, which provide different information and have different advantages.

The first methodology is outlined in [72] and uses the most up-to-date available information from the PATSTAT database. PATSTAT is the European Patent Office's (EPO) Worldwide PATent STATistical Database, which has been specifically developed for use by government/intergovernmental organisations and academic institutions.

Due to the time lags involved in the patenting process, data is shown up to 2016, which was the last fully completed year available at the time of the analysis. There are three main reasons for the significant lag in the patent data observed in PATSTAT: (i) Patent documents are published 18 months after their application; (ii) Cleaning and processing of the data coming from authorities other than the EPO takes significant time; (iii) The EPO database is only released twice a year. Therefore, in general, 100% coverage can only be assumed at least 4 years in advance of the analysis (this data was analysed in early 2020, so the last complete year was 2016).

Statistics have been obtained for relevant classifications according to the Cooperative Patent Classification (CPC) [73]. Within the classification "Y tags" are used, an additional class used in parallel to the traditional CPC classes, which was created specifically for low-carbon, sustainable and climate change mitigation technologies. The statistics provided in this document are for the tags Y02E 60/521 and Y02E 60/525, which are derived from the CPC hierarchy as shown in Table 8.

Y02E 60/521 is the tag relating to Proton Exchange Membrane Fuel Cells (PEMFC), whilst Y02E 60/525 is the tag relating to Solid Oxide Fuel Cells. It should be noted that the tag ***does not distinguish the application*** of the technology.

Statistics are given for patent families, which involve all the granted patent applications relevant to a distinct invention, preventing multiple counting of that invention. A fraction of the family is allocated to each applicant and linked to the country where the applicant organisation is registered. For this reason, it is possible to have non-integer numbers within this study. For a detailed description of how these fractional counts are calculated please refer to [72].

Table 8: Explanation of the patent classification hierarchy for Y02E 60/521 & Y02E 60/525

Tag	Description
Y	General tagging of new technological developments; General tagging of cross-sectional technologies spanning over several sections of the International Patent Classification (IPC)
Y02	Technologies or applications for mitigation or adaptation against climate change
Y02E	Reduction of greenhouse gas (GHG) emissions, related to energy generation, transmission or distribution
Y02E 60/00	Enabling technologies or technologies with a potential or indirect contribution to GHG emissions mitigation
Y02E 60/50	.Fuel cells
Y02E 60/52	. .characterised by type or design
Y02E 60/521	. . .Proton Exchange Membrane Fuel Cells [PEMFC]
Y02E 60/525	. . .Solid Oxide Fuel Cells [SOFC]

Source: JRC, adapted from CPC Patent Classifications, 2020.

The second tool/methodology that has been used for gaining information regarding not only patents but also literature is TIM, developed by the JRC. TIM's database contains three types of documents: scientific publications (articles, conference proceedings, reviews, and book chapters), patents and EU projects. The scientific publications contained in the database are those published after 1996 in the Scopus database (Elsevier). The EU projects are all those from FP5 (beginning in 1998) onwards and are extracted from the CORDIS database. The patent documents are extracted from the PATSTAT database from the EPO (all patents with a priority date from 1996 onwards). Contrary to the methodology used above, all patent applications are included (up to 2019) however, the same lag in terms of completeness of data will be observed as for the methodology mentioned above, as the source is the same.

TIM has been used to provide complementary results. It provides useful network visualisations to display data. These contain nodes and edges (circles joined together by lines). The size of the node corresponds to the number of data items (documents) in the dataset, whilst the size of the edge corresponds to the number of items (documents) in common between the two nodes. Nodes are assigned to communities. The colour of the node represents the community to which it belongs. TIM uses a particular algorithm (Louvain Modularity algorithm) to cluster nodes together in communities. As part of the Framework Contract with the FCH 2 JU, JRC has prepared a tailor-made version of TIM, capturing technologies relevant to FCH 2 JU activities using specific keyword searches. Data deriving from FCH JU projects cover calls 2008-2017. The TIM plots contained within this section have been prepared using this tailor-made version of TIM (supplemented where mentioned by search strings created by the authors of this report).

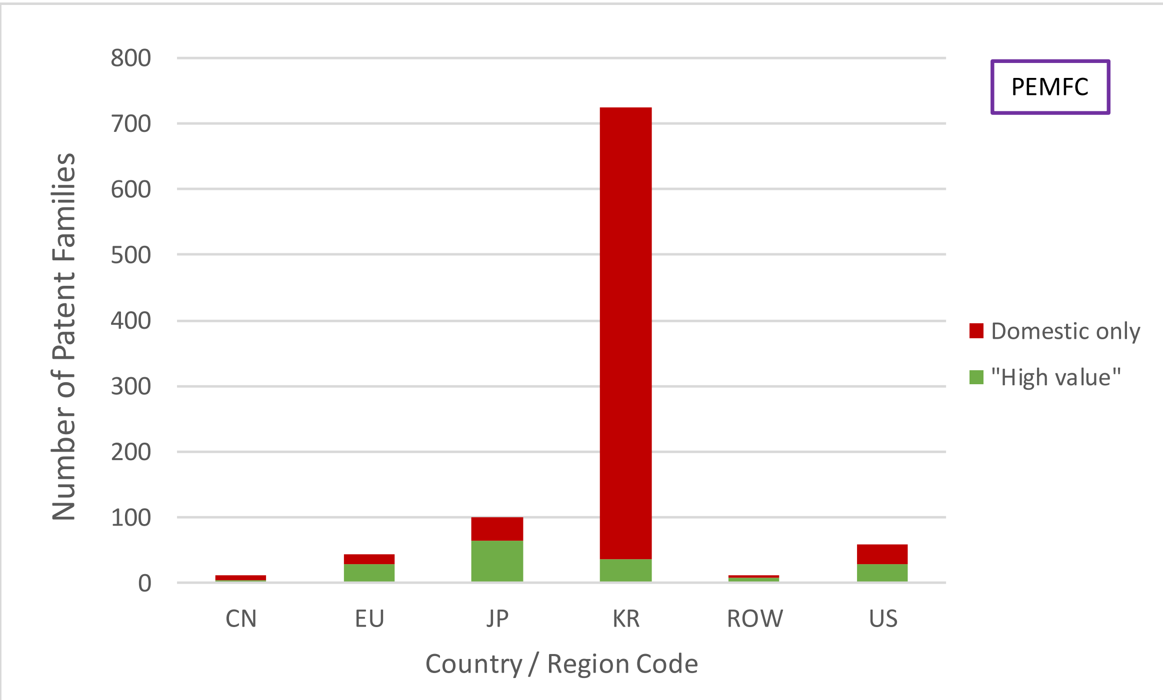
6.2 Patent data trends based on the CPC Classification

Figure 15 shows the number of patent families filed versus country/region code in total for the period from 2000-2016. High value patents families are those filed in more than one patent office (i.e. not just domestically) and are shown in green. The remaining patents shown in red are only filed domestically in the country/region of origin.

It can be seen that for the technology of PEMFC, the majority of patent families filed are from South Korea, although the majority of these patents are domestic (the reasons for this trend are not clear). South Korea is known for having a poor degree of internationality to its patent applications as it is too expensive a process for many companies [74]. In terms of high value patent families, Japan performs the best, whilst more than half of the patent families filed in the EU are high value. It should again be emphasised that this includes all patents submitted under the code Y02E 60/521 which relates to PEMFC technology, and is not application specific, i.e. many of these patents in the PEMFC field may be related to automotive applications. However, it is also true that many patents regarding materials or components do not limit themselves to specific applications as this would reduce the coverage of the patent which is generally kept as broad as possible.

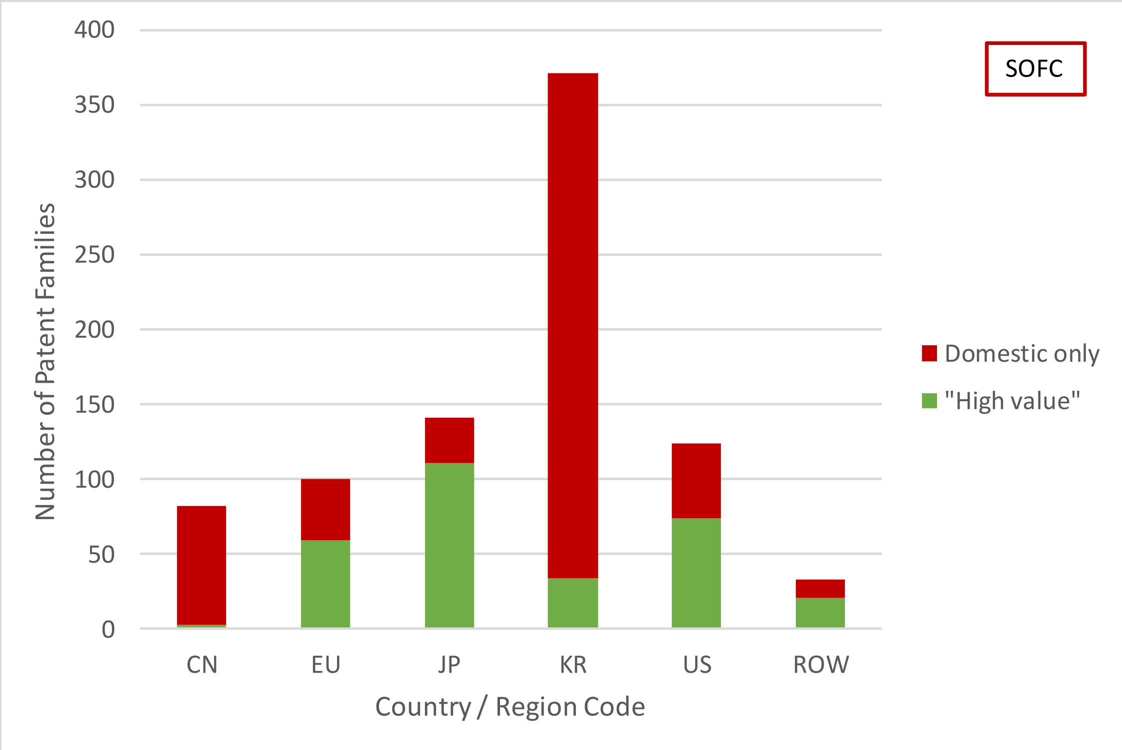
Figure 16 shows the equivalent data regarding the tag Y02E 60/525 which refers to SOFC. A similar trend is observed with the highest number of patent families being filed in South Korea and again the proportion of high value patents being low. Japan has the highest number of high value patent families, and again more than 50% of the EU patent families filed are high value.

Figure 15: Number of patent families filed versus country/region for the tag Y02E 60/521 (PEMFC) from 2000-2016. ROW refers to Rest of the World.



Source: JRC, based on EPO Patstat data, 2020.

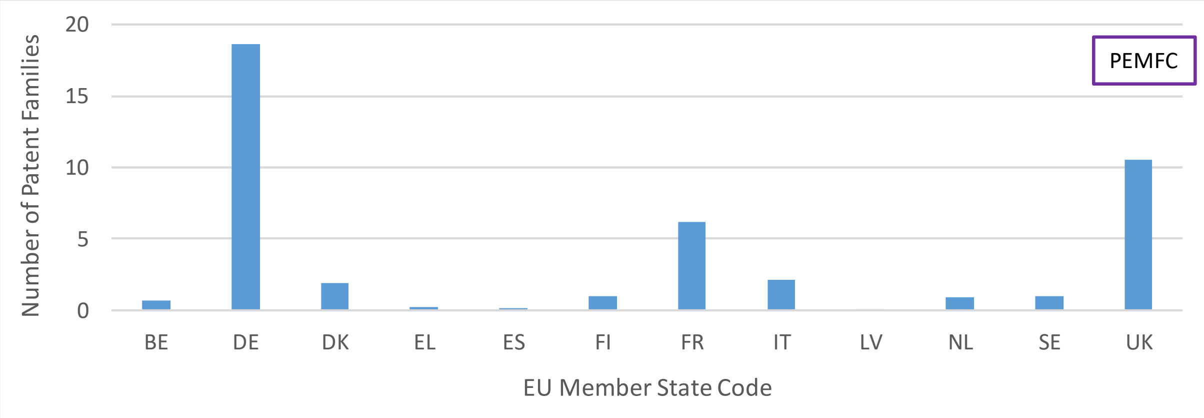
Figure 16: Number of patent families filed versus country/region for the tag Y02E 60/525 (SOFC) from 2000-2016. ROW refers to Rest of the World.



Source: JRC, based on EPO Patstat data, 2020.

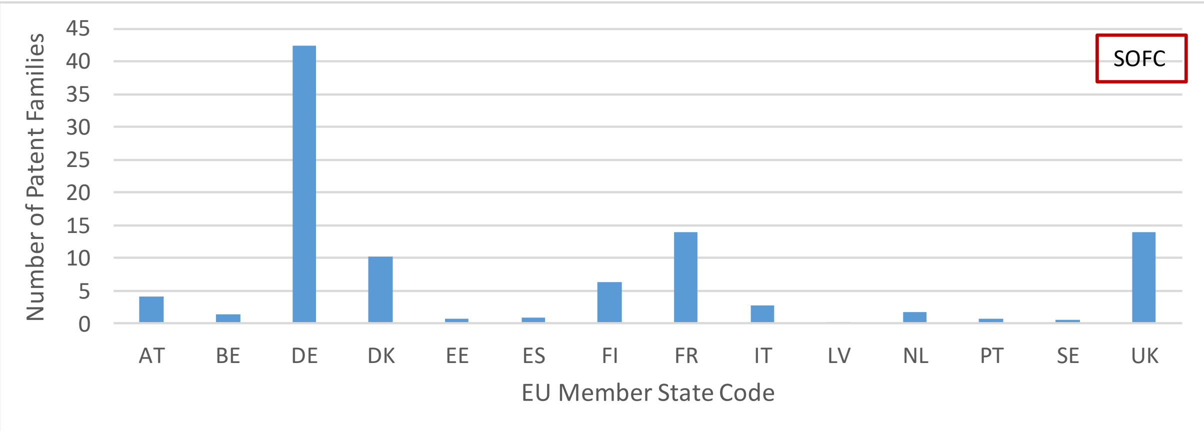
Figure 17 and Figure 18 display the number of patent families filed in the EU-28 countries for the tags Y02E 60/521 (PEMFC) and Y02E60/525 (SOFC), respectively, for the total period from 2000-2016. General observations are that there have been considerably more patents filed in the SOFC field than PEMFC in that time period, and that Germany, France and the United Kingdom, unsurprisingly lead the way in terms of the number of patents filed. In the area of SOFC, Denmark could be considered to be punching above their weight in terms of activity versus the size of the country. This is due to a significant contribution from three organisations: Topsøe Fuel Cells, the Technical University of Denmark and Risø National Laboratories (Risø became part of DTU in 2007).

Figure 17: Number of patent families filed in EU-28 countries for the tag Y02E 60/521 (PEMFC) from 2000-2016



Source: JRC, based on EPO Patstat data, 2020.

Figure 18: Number of patent families filed in EU-28 countries for the tag Y02E 60/525 (SOFC) from 2000-2016



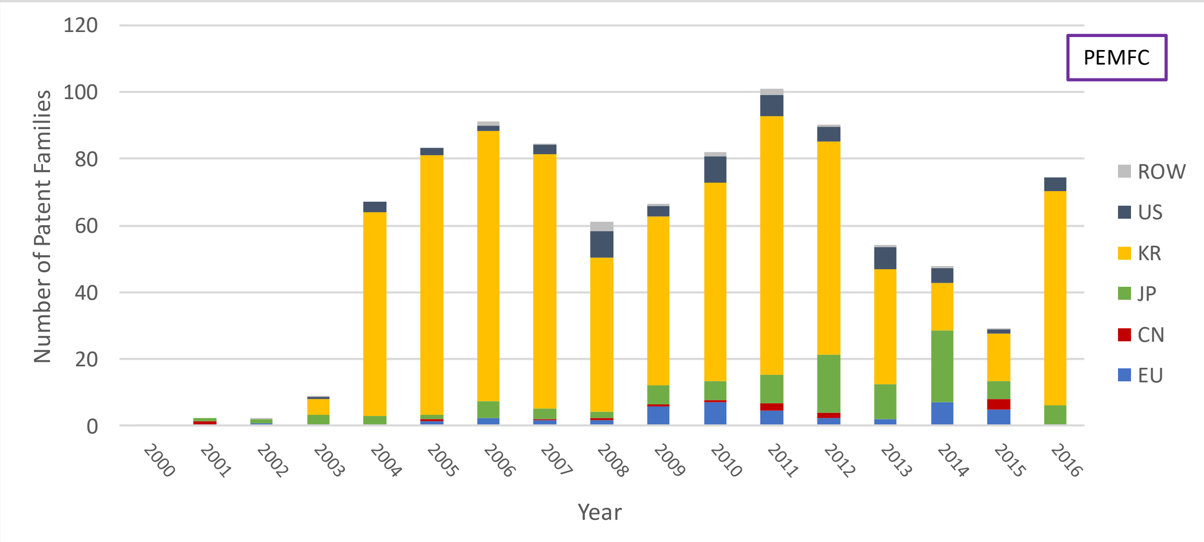
Source: JRC, based on EPO Patstat data, 2020.

It should be noted that the contribution to these EU patents for PEMFC are: 80% of patent families have been filed by private companies, 12% by government non-profit organisations and 7% by universities (the balance of 1% is given as “unknown”). In the case of SOFC the split is slightly different with 65 % of patent families filed in the EU by private companies, 18 % by government non-profit organisations and 14 % by universities (the balance of 3% is again “unknown”).

Figure 19 and Figure 20 show how the number of filed patent families has evolved in the period from 2000-2016 for PEMFC and SOFC, respectively. It seems that there was some kick-start in South Korea in 2004, and in 2009 for Japan, the US and the EU. However, there are clearly some peaks and troughs within this 16 year period which would require further analysis to determine the causes, which is outside of the scope of the current report.

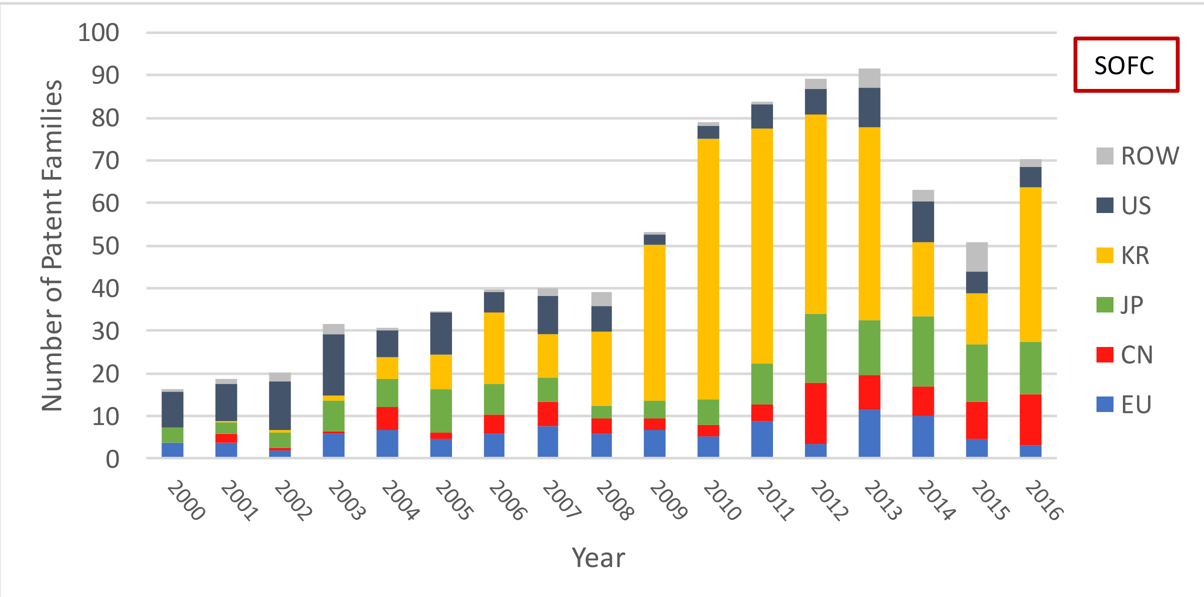
The increase observed for SOFC is much smoother with a step in activity again around 2009, although this appears to be dominated by South Korea. Similarly as for PEMFC, a significant drop in the period from 2012-2015 is observed.

Figure 19: Number of patent families filed per year for the tag Y02E 60/521 (PEMFC) from 2000-2016



Source: JRC, based on EPO Patstat data, 2020.

Figure 20: Number of patent families filed per year for the tag Y02E 60/525 from 2000-2016

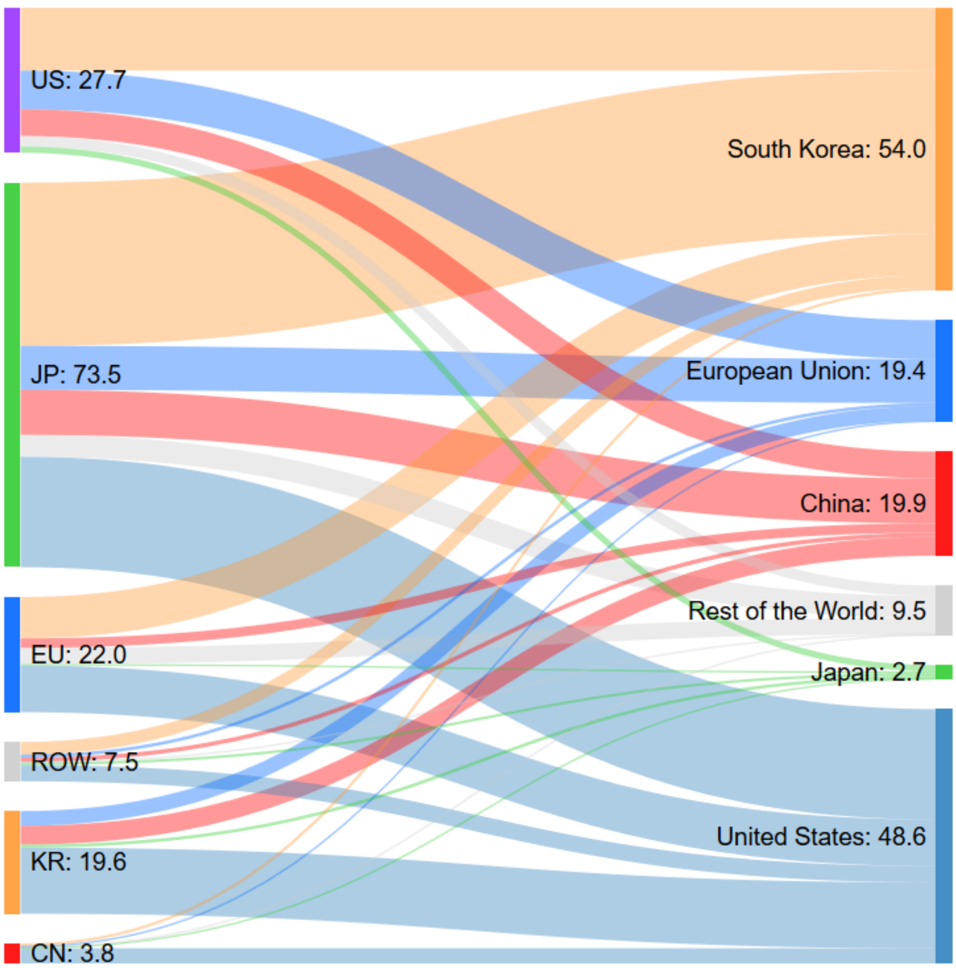


Source: JRC, based on EPO Patstat data, 2020.

Due to the long-term nature of the patenting process, it is difficult to relate trends in public/private sector funding to trends in patenting. However, the drop in patenting observed in 2011-2015 (PEMFC) and 2013-2015 (SOFC) could be a delayed reaction to the global financial crisis in 2008, leading to a drop in R&D spending.

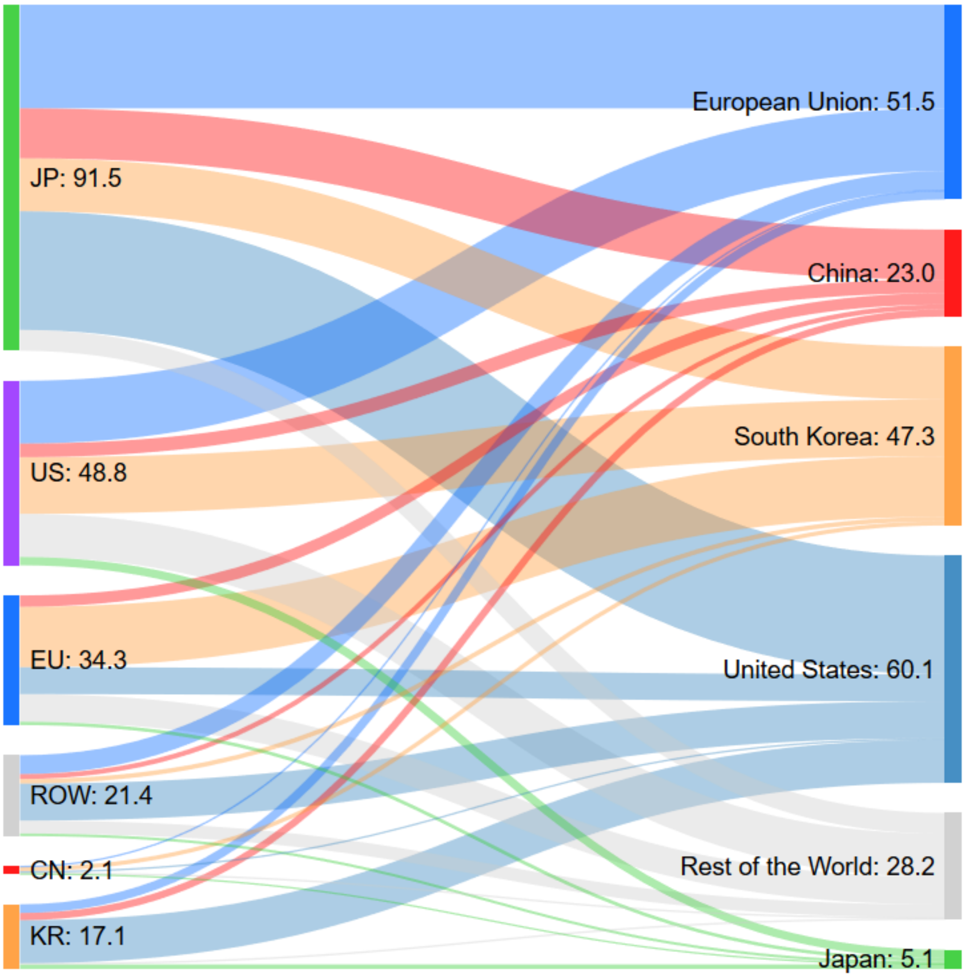
A further interesting aspect relates to the flow of inventions. This shows in which other non-domestic patent offices, patents are being filed. Figure 21 shows the flow of inventions (from left to right) for PEMFC for the period 2000-2016. For example, the plot shows that 22.0 patent families originating in the EU are being filed in other jurisdictions in the ratio shown by the flow. In this technology, it is interesting to see that Japan is patenting widely across all other geographical regions, whilst very few other countries are protecting their inventions in Japan. The opposite is due, to a certain extent for both South Korea and China. A similar pattern of behaviour is observed for SOFC (see Figure 22).

Figure 21: Sankey diagram showing the flow of inventions by geographical region for the tag Y02E 60/521 (PEMFC) for 2000-2016.



Source: JRC, based on EPO Patstat data, 2020.

Figure 22: Sankey diagram showing the flow of inventions by geographical region for the tag Y02E 60/525 (SOFC) for 2000-2016.

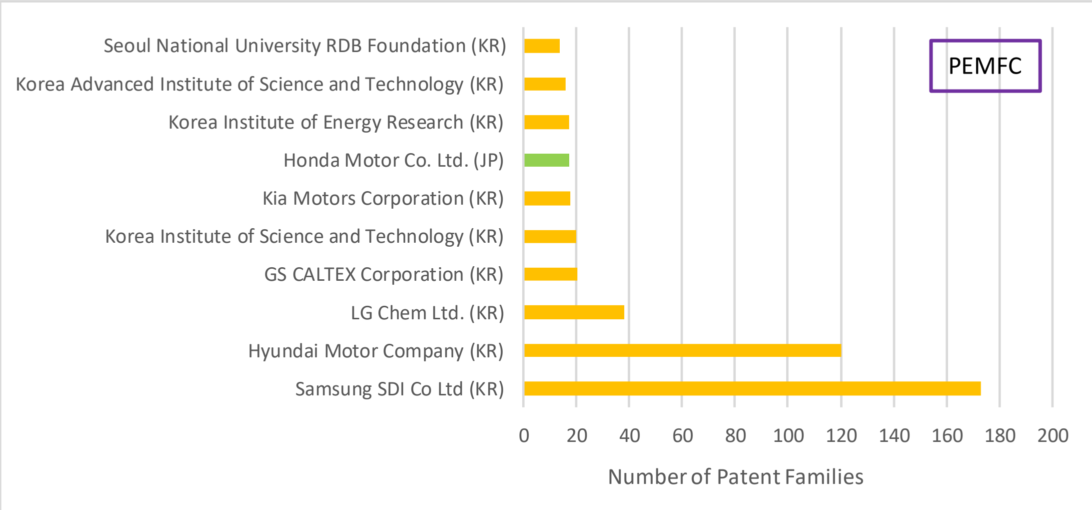


Source: JRC, based on EPO Patstat data, 2020.

Finally, Figure 23 and Figure 24 show the top 10 leading organisations with filed patent families (high value and domestic) for PEMFC and SOFC respectively, for the period from 2000-2016. For PEMFC, it can be seen that South Korean companies completely dominate the top 10 leading organisations, with Samsung having the largest number of inventions in this field. Their interest was related to low temperature fuel cells for portable electronics, however, and it should be noted that Samsung SDI sold all of its fuel cell IP to Kolon in 2016 [75]. It is clear that a number of car companies have made the top 10 (Hyundai, Kia and Honda) which again shows that the code Y02E 60/521 is providing data for all applications relating to PEMFC technology. A more extensive study would be required in order to identify which of these inventions relate particularly to stationary applications. In the top 10, only organisations South Korea and Japan are represented. The leading five EU organisations are: 33. Intelligent Energy Limited (UK, 4.7 patent families); 38. BASF (DE, 4.1); 47. Siemens (DE, 3.4); 50. Volkswagen AG (DE, 3.2); 71. CEA (FR, 2.2).

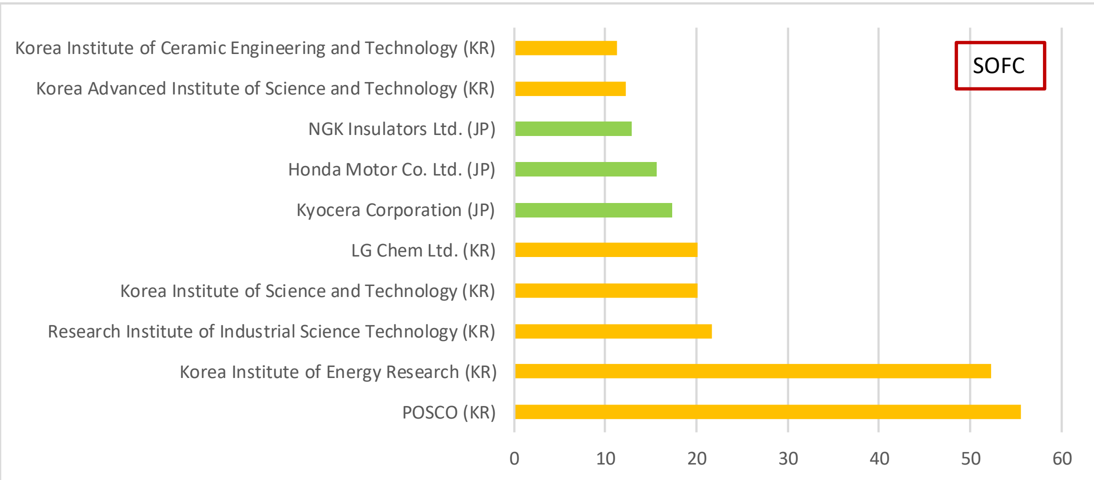
For SOFC it is likely that the majority of inventions are related to stationary applications, although it is interesting to see that the Honda Motor Company also makes the top 10 in this field (in the past they have worked on SOFC for cogeneration e.g. with NGK Spark Plug in 2012 [76]). Again, the top 10 exclusively consists of South Korean and Japanese organisations. The leading five EU organisations are: 18. Ceres IP Co. Ltd. (UK, 8.5 patent families); 28. Robert Bosch Gmbh. (DE, 6.2); 34. Kernforschungsanlage Jülich (DE, 5.6); 37. Technical University of Denmark (DK, 5.0); 47. Convion (FI, 3.2).

Figure 23: Top 10 organisations with filed patent families for the tag Y02E 60/521 (PEMFC) for 2000-2016.



Source: JRC, based on EPO Patstat data, 2020.

Figure 24: Top 10 organisations with filed patent families for the tag Y02E 60/525 (SOFC) for 2000-2016.



Source: JRC, based on EPO Patstat data, 2020.

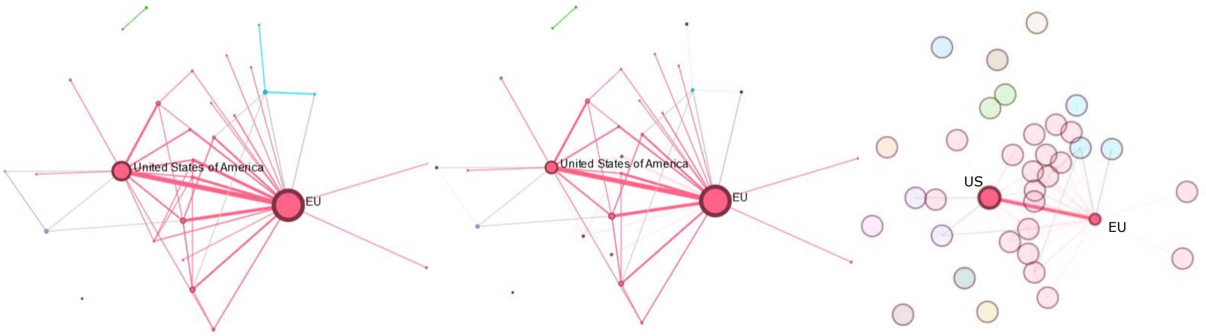
6.3 Literature and Patenting Visualisations using TIM

In order to relate geographic factors to specific fuel cell technologies and applications, the tailor-made version of TIM produced specifically for the FCH 2 JU has been used (in particular the TIM datasets related to SOFC and PEMFC, and stationary applications). Note that the datasets include all information in the TIM database which runs from ***1996 to the current date***. The current plots were prepared prior to Brexit, so the UK is included in the EU.

The following set of plots, shown in Figure 25 correspond to searches related to “PEM Fuel Cells” and “Stationary” in the title, abstract and keywords of the relevant documents.

It can be observed (see Figure 25(a)) that this search led to 599 documents (articles, conference proceedings, reviews, book chapters, patents and EU projects) being identified, the majority of which are produced within the European Union. The United States of America are the second most active region. When considering only peer-reviewed articles (excluding book chapters, reviews, patents, projects and conference proceedings) a very similar pattern is observed as shown in Figure 25(b) suggesting that the EU is world-leading regarding research in this area. Only five patents were found when using these search parameters. This may be due to the fact that when patenting, organisations do not wish to restrict the applications to which their technology can be applied any more than necessary. Therefore, it would be less likely to specify at a high level that a technology was only suitable for a stationary application.

Figure 25: TIM plots (for 1996-2019) for EU/World regarding the number of publications relating to PEM Fuel Cells and Stationary applications. The node size corresponds to the number of publications whilst the thickness of the links related to the number of co-authored documents between organisations from different geographical locations.

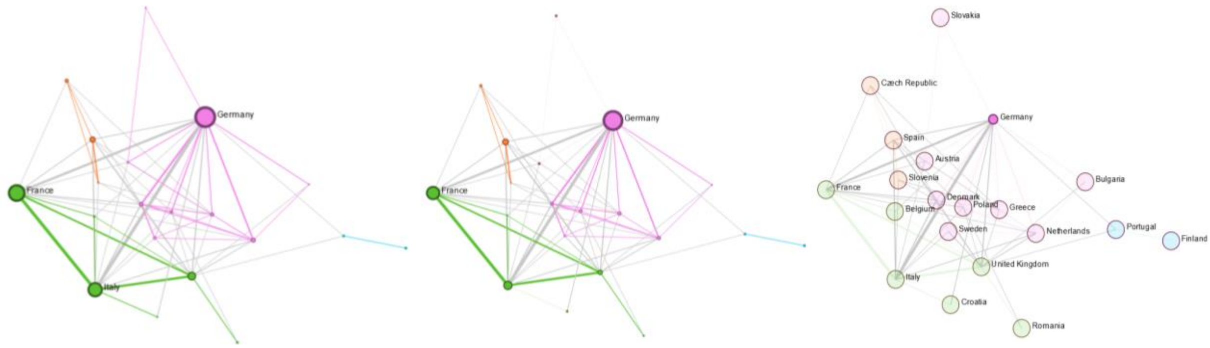


(a) All documents (599) (b) Articles (285) (c) Patents (5)

Source: JRC (TIM), based on FCH 2 JU TIM spaces, 2020.

In Figure 26 the corresponding data for EU member states is provided, demonstrating that the bulk of the publications originating in this area arise in Germany, with other significant contributions from Italy and France. Only one patent is identified by this search.

Figure 26: TIM plots (for 1996-2019) for EU member states regarding the number of publications relating to PEM Fuel Cells and Stationary applications.



(a) All documents (276) (b) Articles (144) (c) Patents (1)

Source: JRC (TIM), based on FCH 2 JU TIM spaces, 2020.

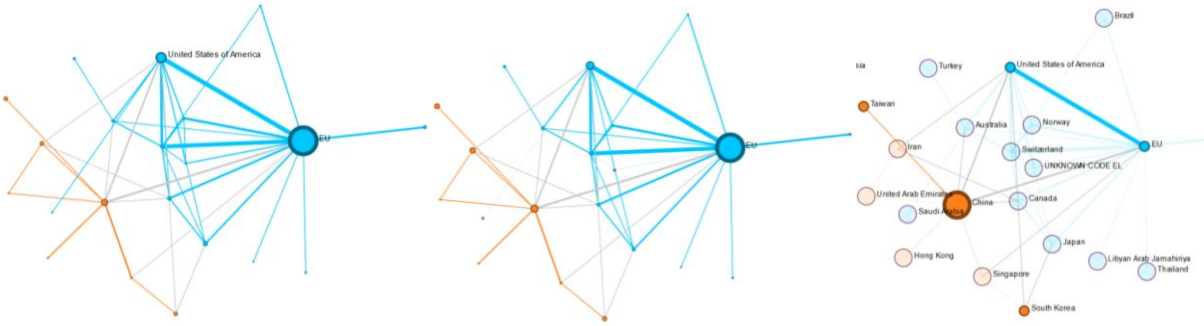
A second series of plots were produced corresponding to searches related to “PEM Fuel Cells” and “Combined Heat and Power” in the title, abstract and keywords of the relevant documents.

In this instance, 457 documents were identified (see Figure 27). Again, the implication is that the European Union is world leading with regards to research related to PEM Fuel Cells for Combined Heating and Power applications, as the EU provides the greatest contribution in terms of overall publications and peer-reviewed journal publications (followed by the US). However, again this search provided only very limited information regarding patents (9 in total) which is clearly not capturing the relevant information in this area.

Figure 28 shows the same data set only for EU member states demonstrating that the countries demonstrating the greatest productivity in terms of research activities in this area have been Italy, followed by Germany and France.

In general, it can be seen that this keyword methodology provides very useful insight regarding scientific publications and research articles, but provides unrealistically low numbers of patents, most likely due to the patents not specifying an application in the Title, Abstract or Keyword fields.

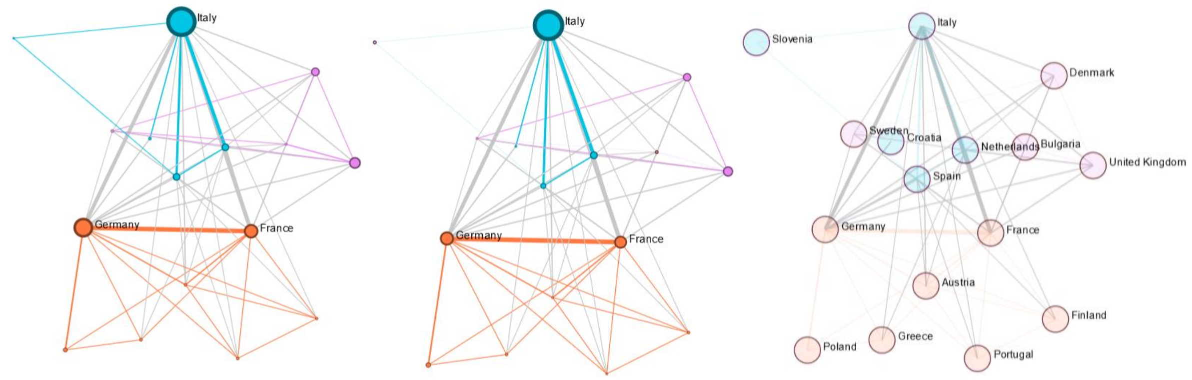
Figure 27: TIM plots (for 1996-2019) for EU/World regarding the number of publications relating to PEM Fuel Cells and CHP.



(a) All documents (457) (b) Articles (266) (c) Patents (9)

Source: JRC (TIM), based on FCH 2 JU TIM spaces, 2020.

Figure 28: TIM plots (for 1996-2019) for EU member states regarding the number of publications relating to PEM Fuel Cells and CHP.



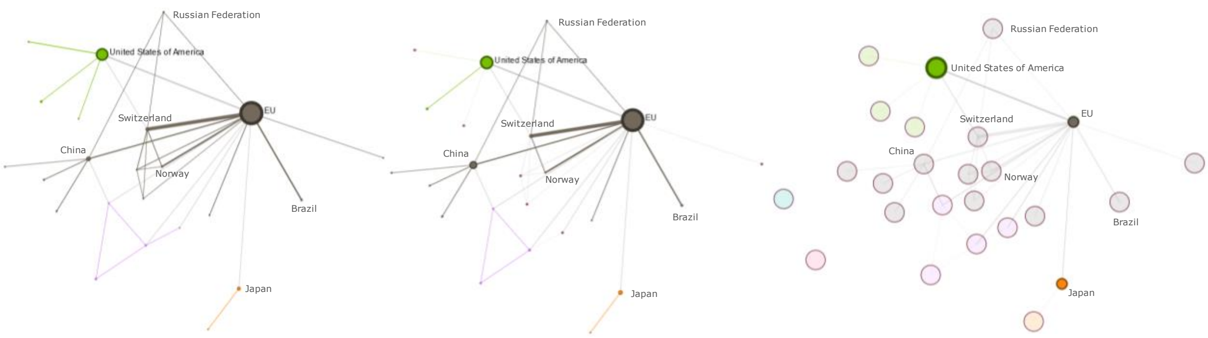
(a) All documents (223) (b) Articles (128) (c) Patents (1)

Source: JRC (TIM), based on FCH 2 JU TIM spaces, 2020.

The following set of plots, shown in Figure 29 correspond to searches related to "Solid Oxide Fuel Cells" and "Stationary" in the title, abstract and keywords of the relevant documents.

It can be observed (see Figure 29 (a)) that this search led to 450 documents (articles, conference proceedings, reviews, book chapters, patents and EU projects) being identified, the majority of which are produced within the European Union. The United States of America are the second most active region. When considering only peer-reviewed articles (excluding book chapters, reviews, patents, projects and conference proceedings) a very similar pattern is observed as shown in Figure 29 (b) suggesting that the EU is world-leading regarding research in this area. Only 7 patents were found when using these search parameters. This is again likely to be because, when patenting, organisations do not wish to restrict the applications to which their technology can be applied any more than necessary. Therefore, it would be less likely to specify at a high level that a technology was only suitable for a stationary application.

Figure 29: TIM plots (for 1996-2019) for EU/World regarding the number of publications relating to Solid Oxide Fuel Cells and Stationary applications.

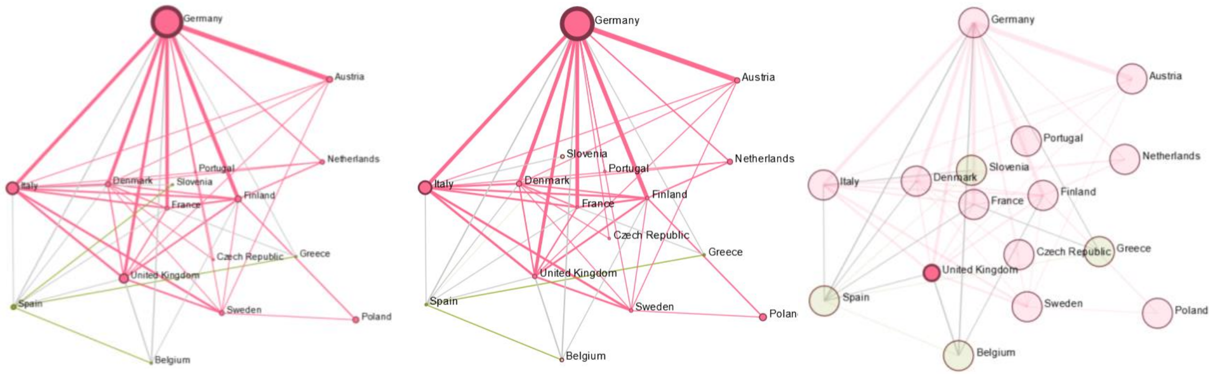


(a) All documents (450) (b) Articles (185) (c) Patents (7)

Source: JRC (TIM), based on FCH 2 JU TIM spaces, 2020.

In Figure 30 the corresponding data for EU member states is provided, demonstrating that the bulk of the publications originating in this area arise in Germany, with other significant contributions from Italy and the UK. Only one patent is identified by this search.

Figure 30: TIM plots (for 1996-2019) for EU member states regarding the number of publications relating to Solid Oxide Fuel Cells and Stationary applications.



(a) All documents (221) (b) Articles (75) (c) Patents (1)

Source: JRC (TIM), based on FCH 2 JU TIM spaces, 2020.

A second series of plots were produced corresponding to searches related to “Solid Oxide Fuel Cells” and “Combined Heat and Power” in the title, abstract and keywords of the relevant documents.

In this search, a greater number of overall documents were identified, 899 in total (see Figure 31). Again, the implication is that the European Union is world-leading with regards to research related to Solid Oxide Fuel Cells for Combined Heating and Power applications, as the EU provides the greatest contribution in terms of overall publications and peer-reviewed journal publications (followed by the US, China and Japan). However, it should be noted that this search revealed 56 patents, the majority of which originate from Japan and China.

Figure 32 shows the same data set only for EU member states demonstrating that the countries with the greatest productivity in terms of research activities in this area have been Italy, followed by Germany and the United Kingdom.

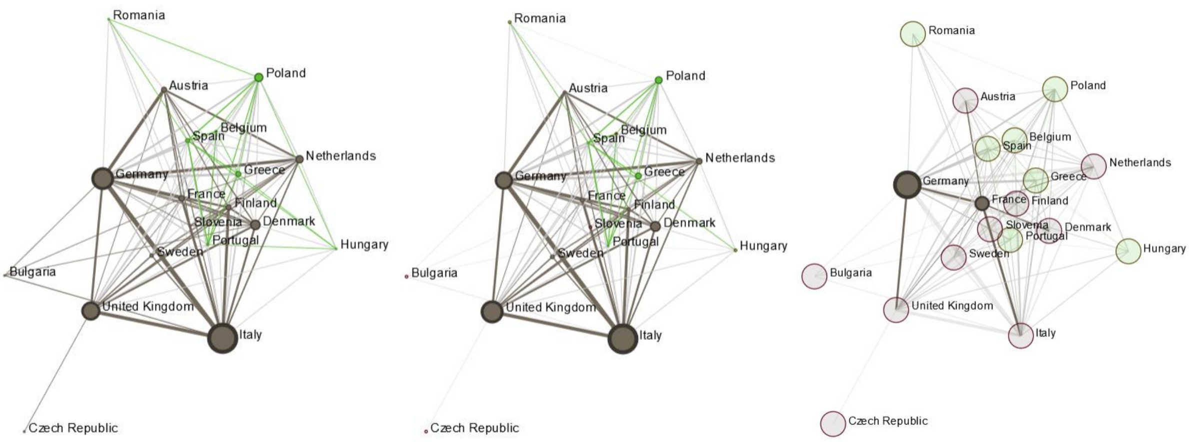
Again, it can be seen that this keyword methodology provides very useful insight regarding scientific publications and research articles, but provides unrealistically low numbers of patents, most likely due to the patents not specifying an application in the Title, Abstract or Keyword fields.

Figure 31: TIM plots (for 1996-2019) for EU/World regarding the number of publications relating to Solid Oxide Fuel Cells and CHP.

(a) All documents (899) (b) Articles (445) (c) Patents (56)

Source: JRC (TIM), based on FCH 2 JU TIM spaces, 2020.

Figure 32: TIM plots (for 1996-2019) for EU member states regarding the number of publications relating to Solid Oxide Fuel Cells and CHP.



(a) All documents (412) (b) Articles (188) (c) Patents (4)

Source: JRC (TIM), based on FCH 2 JU TIM spaces, 2020.

7 Conclusions and Recommendations

In the summary sections (5.1.3, 5.2.3 and 5.3.3) conclusions were made concerning the progress against the individual MAWP KPIs for each technology scale.

In this section, a series of recommendations is made based on specific analysis of project achievement against the MAWP targets. It should be noted that the programme runs until 2020 whereas a series of longer-term targets for 2030 are given in the MAWP. Clearly, to achieve 2030 targets additional activities should be expected over the current programme. Therefore, the following text includes suggestions relating to potential future activities of the FCH 2 JU regarding stationary fuel cell technologies.

Technical Recommendations relevant to all technology scales

- In general, there are some MAWP KPIs where targets are not being achieved across the different capacity scales. These tend to be targets which require long-term testing or widespread implementation of a technology at a high TRL (either through demonstration or deployment). Reliability is an example which requires both long-term testing and sufficient data to supply reliable statistics. Maintenance Costs also require significant levels of deployment to drive down values. Lifetime and Availability also require long-term testing. It is an issue for these specific MAWP targets, that to really determine operational values project durations longer than 3-5 years would be necessary (or continued reporting after the official completion of the project). In this regard, and to be able to obtain data over longer operational hours, it may be advisable to request that high TRL projects, such as PACE, continue to provide operational data via the online platform TRUST even after the project is ended.
- In the longer term, in order to achieve targets of full decarbonisation, the role of natural gas will need to be significantly reduced. Therefore, more emphasis on adapting SOFC technologies to run on pure hydrogen should be considered. This focus is even more important considering the increased focus on injection of hydrogen into the gas grid.
- It should be considered whether the ranges for electrical and thermal efficiency KPIs really provide targets to drive innovation. Their current format seems to be simply providing wide operation ranges that are not necessarily suited to end user needs, e.g. ratio of heat to power demand.
- Target setting should also take into account the respective present day incumbent technologies which would compete with FC technologies.
- Are there ways to increase the degree of cross-fertilisation between the different projects at different power ranges and from low TRL to high TRL projects? In addition to AUTORE, are there other possibilities for transferring knowledge from the automotive to the stationary sector.
- An increased focus on HT-PEMFC research and demonstration could encourage fuel flexibility.

Micro-CHP:

In general, good progress is being made towards the MAWP targets for mCHP applications with the majority of targets for 2020 (and in certain cases beyond) being achieved for both PEMFC and SOFC technologies. There are still a few areas where recommendations can be made, however:

- For both PEMFC and SOFC technologies, the 2020 target for CAPEX has been achieved, and future CAPEX targets are claimed to be achievable when manufacturing at scale. The use of volume manufacturing, modularity, standardised stacks and off the shelf BoP components should all contribute to improvements over current CAPEX values. However, this is yet to be demonstrated and improvements in manufacturing and reduction in use of expensive materials will still need focus to achieve 2030 goals. This may require further activities at a research level to reduce the use of expensive materials, and additional projects focussing on manufacturing and scale-up. Due to the relatively widespread deployment of the technology, future cost targets should be set in line with CAPEX of incumbent technologies.
- When considering the electrical and thermal efficiencies achieved for PEMFC, it is clear that lower TRL projects have achieved higher electrical efficiencies than are currently displayed in large demonstration projects. Further demonstration projects would be required to determine whether these next stage technologies really can achieve this performance at a higher TRL.
- Neither technology has achieved the required target for installation volume. Currently, the unit chosen for this KPI is l/kW. This is particularly unfavourable for lower kW units that still require similar BoP. It is our recommendation that the unit of this KPI be simply a volume (litres) for a residential application and fixed at a sensible maximum size appropriate for a family home while considering (thermal) energy need and available space.
- Several of the targets for 2030 have already been achieved by certain projects. It is therefore worth considering whether any of these long-term targets need reviewing.

Mid-size:

- It is clear that mid-size SOFC units are currently a long way off the CAPEX targets, although projects are optimistic about achieving these targets at mass production. Depending on the cause of these high CAPEX values, further research may be needed to reduce the cost of materials and components or projects looking specifically at volume manufacturing. Further demonstration would seem to be required. The cost-effectiveness of the SOFC installation may be improved by optimising the use of co-generated heat, i.e. locating the unit in proximity to a site with suitable heat demand.
- For PEMFC, it is clear that the durability of the stack is still a considerable issue on up-scaling. Ongoing demonstrations will need to show clear progress in this area, or further investment will be needed. Factors that affect this durability relate to the need for frequent start-ups and shut-downs and variable demand during operation. This is not captured by the KPI as it is not of a purely technical nature. The need for upscaling stacks could be alleviated by a higher degree of modularity, i.e. using a higher number of smaller stacks. This would, however, impact the complexity of the required balance of plant, and lead to higher CAPEX.

Large-scale:

- For large-scale PEMFC it is clear that there are still many of the MAWP targets that need to be achieved. To date, only the electrical and thermal efficiencies, plus the durability of stack targets for 2020 have been achieved. Clearly, further demonstration activities are necessary.
- Especially for large-scale installations, the SoA values seem to be based on technologies under development in Europe in particular (e.g. no value stated for MTBF due to "lack of statistical data" – this implies a lack of large-scale units whereas there is considerable adoption of PAFC, MCFC and SOFC worldwide). It is recommended that in defining SoA, the horizon is set globally and not

restricted to Europe. Concerning targets, internal EU considerations may apply (e.g. gas versus electricity prices, CAPEX and O&M of incumbent technologies etc.).

- Further to this point, MCFC has the potential to act as a carbon capture technology. Since MCFCCONTEX, there has been no European activity in this field which is dominated by the US. MCFC is particularly suited to large-scale installations and could be reconsidered for the future.

References

1. Fuel Cells and Hydrogen Joint Undertaking. Available from: https://fch.europa.eu/.
2. Fuel Cells and Hydrogen Joint Undertaking. Multi-Annual Work Plan 2014 - 2020, 2014.
3. Davies, J.C., Keyword Analysis and Project Classification of FCH 2 JU Projects, EUR 30187 EN, Publications Office of the European Union, Luxembourg, 2020, ISBN 978-92-76-18817-9, doi:10.2760/527632, JRC119839.
4. Addendum to the Multi-Annual Work Plan 2014-2020 of the Fuel Cells and Hydrogen 2 Joint Undertaking (FCH 2 JU), 2018.
5. The Fuel Cell Industry Review 2018, E4tech, Editor.
6. Weidner, E., Ortiz Cebolla, R. and Davies, J., Global deployment of large capacity stationary fuel cells – Drivers of, and barriers to, stationary fuel cell deployment, EUR 29693 EN, Publications Office of the European Union, Luxembourg, 2019, ISBN 978-92-76-00842-2, doi:10.2760/787370, JRC115923.
7. Comparison of Fuel Cell Technologies, 2016, US DOE FCTO.
8. Stolten, D., R.C. Samsun, and N. Garland, eds. Fuel Cells. Data, Facts and Figures. 2016, Wiley-VHC.
9. Sharaf, O.Z. and M.F. Orhan, An overview of fuel cell technology: Fundamentals and applications. Renewable and Sustainable Energy Reviews, 2014. 32: p. 810-853.
10. Liu, Y., et al., A review of high-temperature polymer electrolyte membrane fuel-cell (HT-PEMFC)-based auxiliary power units for diesel-powered road vehicles. Journal of Power Sources, 2016. 311: p. 91-102.
11. Gong, L., et al., Recent development of methanol electrooxidation catalysts for direct methanol fuel cell. Journal of Energy Chemistry, 2018. 27(6): p. 1618-1628.
12. Tokyo Fuel Cell Expo 2019 - 300.000 Ene-Farms. 2019; Available from: https://fuelcellsworks.com/news/fcw-exclusive-tokyo-fuel-cell-expo-2019-300000-ene-farms/.
13. https://www.heizungsjournal.de/aufschwung-bei-brennstoffzellen-heizgeraeten-haelt-an_16092?p=2
14. FLUIDCELL: D2.3 Industrial and market introduction requirements for bio-ethanol fuelled Fuel Cell CHP system, 2016.
15. Panasonic to Commercialize Hydrogen Fuel Cell Generator. 2018; Available from: https://news.panasonic.com/global/press/data/2018/11/en181101-6/en181101-6.html.
16. H2PS-5: 5 kW Combined Heat & Power Unit: https://helbio.com/5-kw-combined-heat-and-power-system-chp/
17. Intelligent Energy Data Sheet: FCM-804 Power Unit, PEM hydrogen fuel cell module (FCM) 48V/24V DC; 4.0kW/2.88kW.
18. Powercellution: https://powercellution.com/stationary
19. Hydrogenics: Telecom & Data Centre Backup Power. Available from: https://www.hydrogenics.com/hydrogen-products-solutions/fuel-cell-power-systems/stationary-stand-by-power/telecom-data-centre-backup-power/.
20. Kolon-Hydrogenics-Starts-Commercial-Operation-of-Megawatt-Fuel-Cell-System-in-South-Korea. Available from: https://globenewswire.com/news-release/2015/11/03/782828/10154916/en/Kolon-Hydrogenics-Starts-Commercial-Operation-of-Megawatt-Fuel-Cell-System-in-South-Korea.html.
21. Nuvera ships Forza unit to Canadian waste hydrogen project. Fuel Cells Bulletin, 2007. 2007(4): p. 8.

22. Nuvera Installs First Forza Fuel Cell System at a Chlorate Plant. Fuel Cell Today, 2006.

23. Comment Hydrogène de France va produire des piles à combustible géantes à Bordeaux, in L'Usine Nouvelle 2019.

24. Nedstacks PEM Power Plant passes 40,000 hrs of operation. Available from: https://nedstack.com/en/news/nedstacks-pem-power-plant-passes-40000-hrs-operation.

25. Largest emission free power plant 1 MW PEM FC Power plant. 2010; Available from: https://nedstack.com/en/news/largest-emission-free-power-plant-1-mw-pem-fc-power-plant.

26. Ynnovate in China installs 2MW PEM fuel cell power plant. 2016; Available from: https://nedstack.com/en/news/ynnovate-china-installs-2mw-pem-fuel-cell-power-plant.

27. Powercellution: Power Generation MW Solutions; https://powercellution.com/power-generation-mw-solutions

28. Araya, S.S., et al., A comprehensive review of PBI-based high temperature PEM fuel cells. International Journal of Hydrogen Energy, 2016. 41(46): p. 21310-21344.

29. Methanol fuel cells: Clean, simple and sustainable power source & energy storage. Available from: https://serenergy.com/products-and-services/systems/.

30. Xia, Z., et al., Recent advances in multi-scale design and construction of materials for direct methanol fuel cells. Nano Energy, 2019. 65: p. 104048.

31. https://www.cleargen.eu/

32. https://demcopem-2mw.eu/

33. https://www.everywh2ere.eu/

34. Vesely, C. and B. Dosanjh, METAL-SUPPORTED CERIA ELECTROLYTE-BASED SOFC STACK FOR SCALABLE, LOW COST, HIGH EFFICIENCY AND ROBUST STATIONARY POWER SYSTEMS, in 19th Annual Solid Oxide Fuel Cell Project Review2018.

35. Bosch forms strategic collaboration with fuel-cell expert Ceres Power. 2018; Available from: https://www.bosch-presse.de/pressportal/de/en/stationary-fuel-cell-bosch-plans-to-start-full-scale-production-in-2024-221952.html

36. Comsos: Commercial Scale SOFC Systems. 2019; Available from: https://www.comsos.eu/.

37. Bloom Energy Shareholder Letter Q3 2018. Available from: https://s22.q4cdn.com/122868703/files/doc_financials/2018/q3/Bloom-Energy-Q3-Shareholder-Letter.pdf.

38. Press Release: Bloom Energy and SK E&C Announce New Projects with KT Corporation and Korea Midland Power Company. 2019; Available from: https://www.bloomenergy.com/newsroom/press-releases/bloom-energy-and-sk-ec-announce-new-projects-kt-corporation-and-korea.

39. Bloom Energy and SK E&C Announce Strategic Partnership To Bring Clean, Reliable, always-on Electric Power To South Korea. 2018; Available from: https://www.bloomenergy.com/newsroom/press-releases/bloom-energy-and-sk-ec-announce-strategic-partnership-bring-clean-reliable.

40. Ghezel-Ayagh, H., SOFC Development Update at FuelCell Energy, in 19th Annual Solid Oxide Fuel Cell (SOFC) Project Review Meeting 2018.

41. Acumentrics delivers 250+ SOFC units to remote power users. Fuel Cells Bulletin, 2015. 2015(6): p. 5.

42. Behling, N.H., Fuel Cells: Current Technology Challenges and Future Research Needs 2013: Elsevier.

43. Lundin, M. and S. Eriksson, Hydrogen Technology Market in Japan 2016, EU - JAPAN CENTRE FOR INDUSTRIAL COOPERATION

44. Kobayashi and Yoshinori, Development of Next-Generation Large-Scale SOFC toward Realization of a Hydrogen Society. Mitsubishi Heavy Industries Technical Review, 2015. 52(2).

45. Choi, S., T.C. Davenport, and S.M. Haile, Proton ceramic electrochemical cells for hydrogen production and electricity generation: exceptional reversibility, stability, and demonstrated faradaic efficiency. Energy Environ. Sci., 2019. 12: p. 206.

46. Timurkutluk, B., et al., A review on cell/stack designs for high performance solid oxide fuel cells. Renewable and Sustainable Energy Reviews, 2016. 56: p. 1101-1121.

47. Fuel Cell Industry Review, 2017, E4Tech.

48. https://rorepower.com/

49. SOLIDpower fuel cell generators commissioned at Microsoft datacenter in Seattle. Available from: https://www.solidpower.com/en/news/all-news/details/news/solidpower-fuel-cell-generators-commissioned-at-microsoft-datacenter-in-seattle/.

50. AFC Energy products: HydroX-Cell (L)™. Available from: https://www.afcenergy.com/products/hydrox-cell_l/.

51. AFC ENERGY Annual General Meeting Presentation, 2019.

52. Pan, Z.F., et al., Advances and challenges in alkaline anion exchange membrane fuel cells. Progress in Energy and Combustion Science, 2018. 66: p. 141-175.

53. Vijayakumar, V. and S.Y. Nam, Recent advancements in applications of alkaline anion exchange membranes for polymer electrolyte fuel cells. Journal of Industrial and Engineering Chemistry, 2019. 70: p. 70-86.

54. Weltweit größte Alkalische Brennstoffzelle steht in Stade. 2015.

55. Gladstone refinery to utilise hydrogen power. 2018.

56. Mehmeti, A., et al., Exergetic, environmental and economic sustainability assessment of stationary Molten Carbonate Fuel Cells. Energy Conversion and Management, 2018. 168: p. 276-287.

57. FuelCell Energy Inc. and E.ON Business Solutions GmbH Announce an Agreement to Develop the European Market. 2019; Available from: https://investor.fce.com/press-releases/press-release-details/2019/FuelCell-Energy-Inc-and-EON-Business-Solutions-GmbH-Announce-an-Agreement-to-Develop-the-European-Market/default.aspx.

58. Perez-Trujillo, J.P., et al., A numerical and experimental comparison of a single reversible molten carbonate cell operating in fuel cell mode and electrolysis mode. Applied Energy, 2018. 226: p. 1037-1055.

59. Frangini, S. and A. Masi, Molten carbonates for advanced and sustainable energy applications: Part II. Review of recent literature. International Journal of Hydrogen Energy, 2016. 41(42): p. 18971-18994.

60. Milewski, J., et al., Experimental investigation of CO2 separation from lignite flue gases by 100 cm2 single Molten Carbonate Fuel Cell. International Journal of Hydrogen Energy, 2014. 39(3): p. 1558-1563.

61. Sánchez, D., et al., Stirling based fuel cell hybrid systems: An alternative for molten carbonate fuel cells. Journal of Power Sources, 2009. 192(1): p. 84-93.

62. Weidner, E., et al., CEN - CENELEC sector forum energy management Working group hydrogen: final report 2015.

63. Mastropasqua, L., et al., Molten Carbonate Fuel Cells retrofits for CO2 capture and enhanced energy production in the steel industry. International Journal of Greenhouse Gas Control, 2019. 88: p. 195-208.

64. Song, S.-H., et al., A high-performance ceramic composite anode for protonic ceramic fuel cells based on lanthanum strontium vanadate. International Journal of Hydrogen Energy, 2014. 39(29): p. 16534-16540.

65. Shin, E., et al., Catalysts for composite cathodes of protonic ceramic fuel cells. Ceramics International, 2018. 44(7): p. 8423-8426.

66. Choi, S., et al., Exceptional power density and stability at intermediate temperatures in protonic ceramic fuel cells. Nature Energy, 2018. 3(3): p. 202-210.

67. Braun, R.J., et al., Development of kW-Scale Protonic Ceramic Fuel Cells and Systems. ECS Transactions, 2019. 91: p. 997.

68. Plekhanov, M.S., et al., New mixed ionic and electronic conductors based on LaScO3: Protonic ceramic fuel cells electrodes. Journal of Power Sources, 2020. 449: p. 227476.

69. Zhang, L., et al., Cerium and Gadolinium co-doped perovskite oxide for a protonic ceramic fuel cell cathode. International Journal of Hydrogen Energy, 2019. 44(51): p. 27921-27929.

70. An, H., et al., A 5 × 5 cm2 protonic ceramic fuel cell with a power density of 1.3 W cm–2 at 600 °C. Nature Energy, 2018. 3(10): p. 870-875.

71. Blondel, V.D., et al., Fast unfolding of communities in large networks Journal of Statistical Mechanics: Theory and Experiment 2008 10(P10008).

72. Fiorini, A., et al., Monitoring R&I in Low-Carbon Energy Technologies. EUR 28446 EN, Publications Office of the European Union, Luxembourg. ISBN 978-92-79-65591-3, doi: 10.2760/434051, 2017.

73. Cooperative Patent Classification; European Patent Office / United States PTO. Available from: http://www.cooperativepatentclassification.org/cpcSchemeAndDefinitions/table.html

74. Suk-yee, J. Most South Korean Patents Lack Internationality. 2019; Available from: http://www.businesskorea.co.kr/news/articleView.html?idxno=32561.

75. Yoo-Chul, K. Samsung to drop fuel cell business. 2016; Available from: http://www.koreatimes.co.kr/www/news/tech/2016/04/133_202485.html.

76. Honda strives to achieve the world's top-level power generation efficiency for a SOFC-powered cogeneration unit. 2012.

List of abbreviations and acronyms

(in alphabetical order of the abbreviation/acronym)

AEMFC	Anion Exchange Membrane Fuel Cell
AFC	Alkaline Fuel Cell
APU	Auxiliary Power Unit
ARPA-E	Advanced Research Projects Agency – Energy
BoP	Balance of Plant
CAPEX	Capital Expenditure
CEA	Commissariat à l'énergie atomique et aux énergies alternatives (French Alternative Energies and Atomic Energy Commission)
CCHP	Combined Cooling Heat and Power
CE	Conformité Européene
CHP	Combined Heating and Power
COPRD	Cost-optimal Reliability-based Design
CORDIS	Community R&D Information Service (of the European Commission)
CPC	Cooperative Patent Classification
CPOx	Catalytic Partial Oxidation
CSM	Colorado School of Mines
DMFC	Direct Methanol Fuel Cell
DOE	Department of Energy (US)
DTU	Danish Technical University
EIFER	Europäisches Institut für Energieforschung (European Institute for Energy Research)
EIS	Electrical Impedance Spectroscopy
EoL	End-of-Life
EPO	European Patent Office
EU	European Union
EUR	Euro (currency)
EV	Electric Vehicle
FC	Fuel Cell
FCE	FuelCell Energy
FCH	Fuel Cells and Hydrogen
FCH JU	Fuel Cell and Hydrogen Joint Undertaking
FCH 2 JU	Fuel Cell and Hydrogen 2 Joint Undertaking
FCTO	Fuel Cell Technologies Office

FP	Framework Program (for Research & Innovation of the EU)
G2P	Gas to Power
GHG	Greenhouse Gas
GT	Gas Turbine
H2020	Horizon 2020
HHV	Higher Heating Value
HOR	Hydrogen Oxidation Reaction
HT	High Temperature
IP	Integrated planar
IP-SOFC	Integrated Planar Solid Oxide Fuel Cell
IPC	International Patent Classification
JRC	Joint Research Centre (of the European Commission)
KfW	Kreditanstalt für Wiederaufbau (German subsidy programme)
KIST	Korea Institute of Science and Technology
KPI	Key Performance Indicator
LHV	Lower Heating Value
LT	Low Temperature
MAC	Molten Alkali Carbonate
MAWP	Multi-Annual Work Plan (of the FCH JU)
MCEM	Molten Carbonate Electrochemical Membrane
MCFC	Molten Carbonate Fuel Cell
mCHP	Micro-scale Combined Heat and Power
MEA	Membrane Electrode Assembly
MTBF	Mean Time Between Failures
NG	Natural Gas
OEM	Original Equipment Manufacturer
ORR	Oxygen Reduction Reaction
P2G	Power to Gas
P2P	Power to Power
PAFC	Phosphoric Acid Fuel Cell
PATSTAT	EPO Worldwide PATent STATistical Database
PBI	Polybenzimidazol
PCFC	Protonic Ceramic Fuel Cell
PEM	Proton Exchange Membrane / Polymer Electrolyte Membrane
PEMFC	Proton Exchange Membrane Fuel Cell

PGM	Platinum Group Metal
PoC	Proof of Concept
PPP	Public Private Partnership
R&D	Research and Development
PRD	Programme Review Days (of the FCH JU)
R&I	Research and Innovation
REBELS	Reliable Electricity Based on ELectrochemical Systems
RBS	Radio Base Station
RE	Renewable Energy
ROW	Rest of the World
SoA	State of (the) Art
SOC	Solid Oxide Cell
SOEL	Solid Oxide Electrolyser
SOFC	Solid Oxide Fuel Cell
SPFC	Solid Polymer Fuel Cell
TIM	Tools for Innovation Monitoring
TMS	Toyota Motor Sales
TRL	Technology Readiness Level
TRUST	Technology Reporting Using Structured Templates
UK	United Kingdom of Great Britain and Northern Ireland
UPS	Uninterrupted Power Supply
US	United States of America
USD	United States Dollar (currency)
UTP	Ulsan Technopark
VAT	Value Added Tax
VTT	Valtion Teknillinen Tutkimuskeskus (Technical Research Centre of Finland)
WWTP	Waste Water Treatment Plants
YSZ	Ytttria-stabilised Zirconia

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Annex 1

Table 9: Summary of Projects Considered in this Report

Size	Technology	Project	Panel	Start/End	Project Title
0.3-5 kW	PEMFC	BEINGENERGY	4	2012-2016	Integrated low temperature methanol steam reforming and high temperature polymer electrolyte membrane fuel cell
		DEMSTACK	4	2013-2016	Understanding the degradation mechanisms of a HT-PEMFC Stack and optimization of the individual components
		EURECA	4	2012-2015	Efficient use of resources in energy converting applications
		FCPOWEREDRBS	3	2012-2015	Demonstration project for power supply to telecom stations through FC technology
		FERRET	4	2014-2017	A flexible natural gas membrane reformer for m-CHP applications
		FITUP	3	2010-2014	FC field test demo of economic and environmental viability for portable generators, backup and UPS power system applications
		FLUIDCELL	4	2014-2018	Advanced m-CHP fuel cell system based on a novel bio-ethanol fluidized bed membrane reformer
		FLUMABACK	3	2012-2015	Fluid management component improvement for back up fuel cell systems
		HEALTH-CODE	4	2015-2018	Real operation PEM fuel cells HEALTH-state monitoring and diagnosis based on dc-dc COnverter embeddeD Eis
		KEEPEMALIVE	4	2010-2013	Knowledge to Enhance the Endurance of PEM fuel cells by Accelerated LIfetime Verification Experiments
		LIQUIDPOWER	4	2012-2016	Fuel cell systems and hydrogen supply for early markets
		LOLIPEM	4	2010-2012	Long-life PEM-FCH CHP systems at temperatures higher than 100°C
		MAMA-MEA	4	2018-2020	Mass manufacture of MEAs using high speed deposition processes
		MATISSE	4	2014-2017	Manufacturing improved stack with textured surface electrodes for stationary and CHP applications
		NH34PWR	3	2010-2013	Ammonia based, fuel cell power for off-grid cell phone towers
		PREMIUM ACT	4	2011-2014	Predictive Modelling for Innovative Unit Management and Accelerated Testing Procedures of PEFC
		REFORCELL	4	2012-2015	Advanced multi-fuel reformer for fuel cell CHP systems
		SAPPHIRE	4	2013-2016	System automation of PEMFCs with prognostics and health management for improved reliability and economy
		SECOND ACT	4	2014-2017	Simulation, statistics and experiments coupled to develop optimized and durable µCHP systems using accelerated tests.
	PEMFC/SOFC	D2SERVICE	3	2015-2018	Design of 2 technologies and applications to service
		ENE.FIELD	3	2012-2017	European-wide field trials for residential fuel cell micro-CHP
		PACE	3	2016-2021	Pathway to a Competitive European FC mCHP market

Size	Technology	Project	Panel	Start/End	Project Title
0.3-5 kW	SOFC	ASTERIX3	3	2011-2014	Assessment of SOFC CHP systems build on the technology of HTceRamIX 3
		ENDURANCE	4	2014-2017	Enhanced durability materials for advanced stacks of new solid oxide fuel cells
		HEATSTACK	4	2016-2019	Production Ready Heat Exchangers and Fuel Cell Stacks for Fuel Cell micro-CHP
		INSIGHT	4	2017-2019	ImplementatioN in real SOFC Systems of monItoring and diaGnostic tools using signal analysis to increase tHeir lifeTime
		LOTUS	3	2011-2014	Low Temperature SOFC for micro-CHP applications
		METSAPP	4	2011-2015	Metal supported SOFC technology for stationary and mobile applications
		MMLRC=SOFC	4	2012-2015	Working towards mass manufactured, low cost and robust SOFC stacks
		OxiGEN	4	2018-2020	Next-generation Solid Oxide Fuel Cell stack and hot box solution for small stationary applications
		PROSOFC	4	2013-2017	Production and reliability oriented SOFC cell and stack design
		SCORED 2:0	4	2013-2017	Steel coatings for reducing degradation in SOFC
		SOFT-PACT	3	2011-2015	Solid oxide fuel cell micro-CHP field trials
		SOSLeM	4	2016-2019	Solid Oxide Stack Lean Manufacturing
		T-CELL	4	2012-2016	Innovative SOFC architecture based on triode operation
		TRISOFC	3	2012-2015	Durable solid oxide fuel cell tri-generation system for low carbon buildings
	AFC	ALKAMMONIA	3	2013-2018	Ammonia-fuelled alkaline fuel cells for remote power application
	PCFC	METPROCELL	4	2011-2015	Innovative fabrication routes and materials for metal and anode supported proton conducting fuel cells
5–400 kW	PEMFC	AutoRE	3	2015-2018	AUTomotive deRivative Energy system
		CISTEM	4	2013-2016	Construction of Improved HT-PEM MEAs and Stacks for long term stable modular CHP units
		EVERYWH2ERE	3	2018-2022	Making hydrogen affordable to sustainably operate Everywhere in European cities
		GRASSHOPPER	4	2018-2020	GRid ASsiSting modular HydrOgen Pem PowER plant
		PEMBEYOND	3	2014-2017	PEMFC system and low-grade bioethanol processor unit development for back-up and off-grid power applications
		REMOTE	3	2018-2021	Remote area Energy supply with Multiple Options for integrated hydrogen-based TEchnologies
		STAYERS	4	2011-2014	Stationary PEM fuel cells with lifetimes beyond five years
	SOFC	ASSENT	3	2010-2012	Anode sub-system development & optimisation for SOFC systems
		CATION	3	2011-2014	Cathode subsystem development and optimisation
		CH2P	3	2017-2020	Cogeneration of Hydrogen and Power using solid oxide based system fed by methane rich gas

Size	Technology	Project	Panel	Start/End	Project Title
5–400 kW	SOFC	ComSos	3	2018-2021	Commercial-scale SOFC systems
		DEMOSOFC	3	2015-2020	Demonstration of large SOFC system fed with biogas from WWTP
		DIAMOND	4	2014-2017	Diagnosis-aided control for SOFC power systems
		INNO-SOFC	3	2015-2018	Development of innovative 50 kW SOFC system and related value chain
		NELLHI	4	2014-2017	New all-European high-performance stack: design for mass production
		ONSITE	3	2013-2017	Operation of a novel SOFC-battery integrated hybrid for telecommunication energy systems
		STAGE-SOFC	3	2014-2018	Innovative SOFC system layout for stationary power and CHP applications
	AFC	LASER CELL	4	2011-2014	Innovative cell and stack design for stationary industrial application using novel laser processing techniques
		POWER-UP	3	2013-2017	Demonstration of 500 kWe AFC system with heat capture* *note: whilst POWER-UP was due to implement a 500 kWe system, reported data suggests only 240 kWe was achieved, therefore this is included in the medium-size section.
	MCFC	MCFC CONTEX	4	2010-2014	MCFC catalyst and stack component degradation and lifetime: Fuel Gas CONTaminant effects and EXtraction strategies
> 400 kW	PEMFC	CLEARGEN-DEMO	3	2012-2020	The Integration and demonstration of Large Stationary Fuel Cell Systems for Distributed Generation
		DEMCOPEM-2MW	3	2015-2018	Demonstration of a CHP 2 MWe PEM fuel cell generator and integration into an existing chlorine production plant
	SOFC	SOFCOM	3	2011-2015	SOFC CCHP with poly-fuel: operation and maintenance

Source: JRC, based on information from FCH 2 JU, 2020.

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