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Global deployment of large capacity stationary fuel cells

Drivers of, and barriers to, stationary fuel cell deployment

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Abstract

The long history of stationary fuel cell development and deployment has culminated in a strong growth during the last 10 years. Whether this will lead to full commercialisation independent of governmental incentives, and for which technologies, is as yet uncertain. Stationary fuel cells with capacities >200 kW have been installed in several regions of the world (mainly Europe, Japan, South Korea and the USA), but at widely varying volumes and rates. They can be deployed in the commercial and industrial sectors, to generate power or for cogeneration.

Based on a literature and internet study, information was gathered regarding the installed capacity of the different types of fuel cells and a database was constructed. More than 800MW of large stationary fuel cell systems with a rated power above 200kW[1] have been installed globally for power generation and combined heat power applications prior to 2018. The global deployment of large-scale fuel cells is currently dominated by the US and South Korean market, which together make up almost 95% of installed capacity. Within the US, there are major differences in the approach taken at state level, with the majority of the capacity installed in only two states (California and Connecticut). Worldwide, three technologies dominate: MCFC, SOFC and PAFC. Furthermore, one specialist company dominates the production of each FC type.

To understand the drivers of, and barriers to, large-scale capacity fuel cell deployment, technology and policy/regulatory aspects need to be considered, as well as the respective energy system of the geographical region. The study attempts to identify some key factors influencing deployment and to relate them to the trends observed in specific countries/regions. These factors include: energy and climate policies, FC funding programmes, competing technologies, the presence of FC system manufacturers and energy prices (spark spread). It is clear that considerable financial incentives would be required if the levels of implementation observed in the US and South Korea are to be realised in Europe where companies are currently focussing on small to medium scale applications. However, it should also be considered that there are not the same drivers present in Europe as in South Korea or selected parts of the US, such as high levels of air pollution or an unreliable electricity grid.

[1] Wherever possible, kW_e has been used, although it is not clear for every database entry if this is case.

1 Introduction

This report provides a short overview of the deployment of different fuel cells technologies used in large-scale stationary applications. Stationary fuel cells with large capacities >200 kW[2] have been installed in several regions of the world (mainly Europe, Japan, South Korea and the USA), but at widely varying volumes and rates. Firstly, the number and capacity of fuel cell systems that have been installed worldwide will be assessed, as there is no single, central source for this information[3]. Drawing on a large number of sources, a database has been constructed and figures describing the deployment of stationary fuel cells in the period 2007 - 2017 are provided (based on cumulative capacity installed from the year 2000 onwards). To understand the drivers of, and barriers to, large-scale capacity fuel cell deployment, technology and policy/regulatory aspects will be considered, as well as the respective energy system of the geographical region. Clearly this is a complex issue, and to identify all the underlying causes of the relative deployment rates is a difficult undertaking. In this report, an attempt has been made to identify some key drivers for deployment and to relate them to the trends observed in specific countries/regions. This will be addressed in the final section of the report (section 5). The explanation of the data gathering methodology is given in section 2, followed by an overview of global deployment figures in section 3. The historical technology development of the different fuel cell types and their relative global deployments are discussed in section 4.

Stationary fuel cells in the >200 kW range can be deployed in the commercial and industrial sectors, to generate power or for cogeneration[4]. The exact definition of what constitutes "large-scale" stationary applications differs within the literature. In the Multiannual Workplan (MAWP) of the Fuel Cells and Hydrogen Joint Undertaking (FCH JU), fuel cell systems ranging from a capacity of 400 kW to 30 MW are considered within this category. For the US Department of Energy (DOE) Multi-Year Research, Development, and Demonstration Plan, fuel cell systems for CHP (combined heat and power) and distributed generation should be within the range of 100 kW to 3 MW capacity. In this study, the lower limit has been taken at 200kW for assessing global deployment numbers. No upper limit was applied.

[2] Electric power, unless noted otherwise.
[3] There is a database for fuel cell installations for the state of California http://www.casfcc.org/.
[4] Combined heat and power (CHP), or combined cooling, heat and power (CCHP).

2 Methodology

A literature and internet study was conducted to find information regarding the installed capacity of the different types of fuel cells and a database was constructed. Some examples of key sources are the annual Fuel Cell Industry Reviews [1], Fuel Cell Technologies Office (FCTO) market analysis reports [2], an overview of deployment until 2013 in the book "Fuel Cells" by N. Behling [3], as well as company presentations and press releases.

The collation of this data was based on the following two premises:

- The total size of the overall project was considered. Only individual installations totalling 200kW or greater were included in the database. For example, a commercial installation at an individual site combining 2 x 100 kW units is included; multiple small residential installations as part of a wider residential building project are not included.
- Wherever possible, the date (year) provided is when the installation came into service. Only projects which reached active service are included and no account has been taken of whether installations are still presently active, i.e. the latest cumulative capacity values are **not** the current active installation totals, but the cumulative capacity total for units which have been brought into service.

Cumulative data is shown from 2007-2017 in the following graphs. When viewing this data or comparing with other sources, the following should be considered:

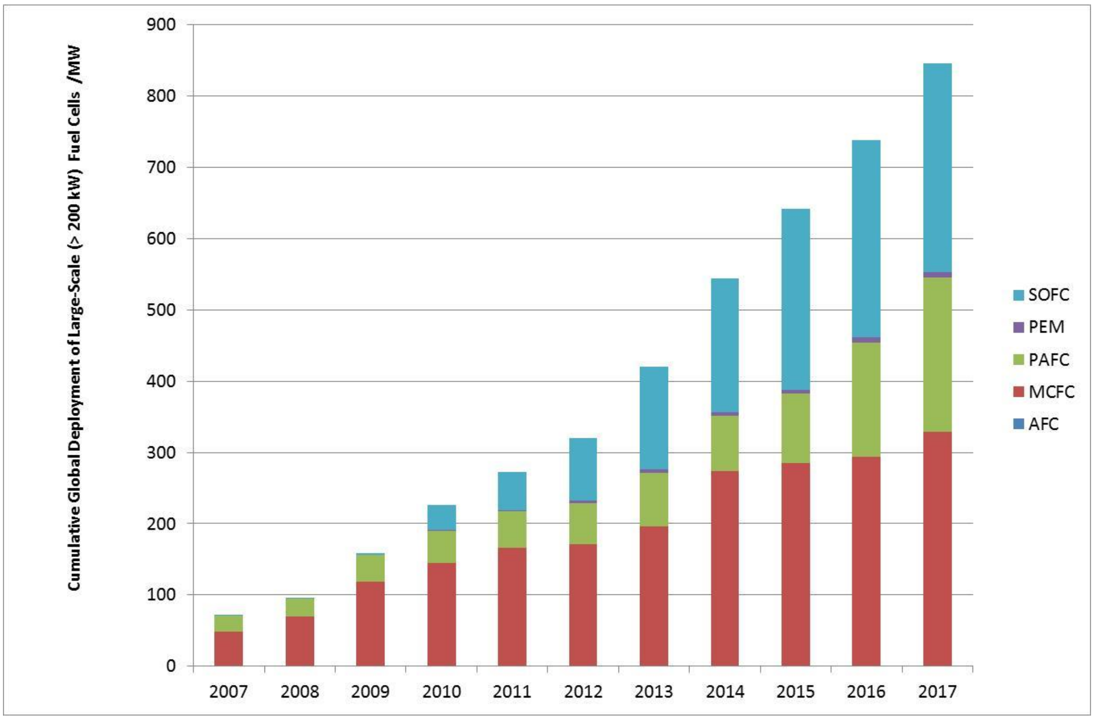
- Other sources may take a different lower capacity limit when defining large-scale stationary storage
- Installations often have a long lead time. Wherever possible, the date when the unit came in to active service is used. However, different sources may provide the date when the project was approved or when construction was begun.
- The sources used often provide different levels of detail about the stationary fuel cell installations. Therefore, whereas all effort has been made to avoid duplicates, it cannot be guaranteed that all double-counting has been avoided, especially for some smaller installations where limited public information is available.
- Only installations from 2000 onwards are considered in the database.

Whilst the authors cannot guarantee that there are not missing or incomplete entries in the database, it is sufficiently advanced to identify trends and draw conclusions. It is the authors' intention to make the database available to the FCH community to enable further refinement and updating.

3 Worldwide deployment of stationary fuel cells – an overview

More than 800MW of large stationary fuel cell systems with a rated power above 200kW [5] have been installed globally for distributed generation and combined heat power applications. The largest shares of the installations are found in the US and South Korea. Figure 1 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 Molten Carbonate Fuel Cells (MCFC) having the largest share, followed by Solid Oxide Fuel Cells (SOFC) and Phosphoric Acid Fuel Cells (PAFC). Only a small number of large capacity installations based on Proton Exchange Membrane Fuel Cell (PEMFC) and Alkaline Fuel Cell (AFC) technologies have been deployed to date. In the last 5 years, deployment trends indicate the strongest growth rate for PAFC, although plans for several multi-megawatt MCFC installations in the US have also been announced [3] (for details, see section on MCFC). Large stationary fuel cell units have been deployed by utilities and provide power for distributed generation and Combined Heat and Power (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 [1].

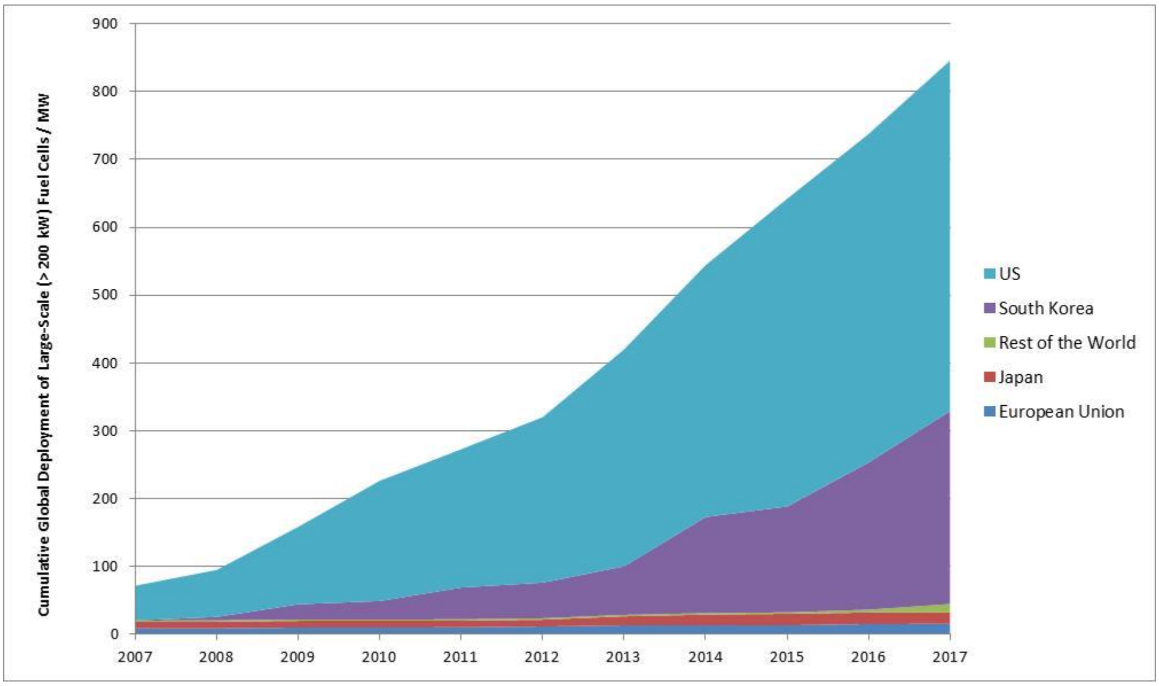
Figure 1: Cumulative global deployment of large scale stationary fuel cells shown from 2007 onwards (deployment data considered from 2000 onwards), displayed per technology



In Figure 2, the same data is displayed but related to the deployment per geographical area. It can be seen that two countries have completely dominated with regards to the installation of large scale stationary fuel cell systems (the US and South Korea) with only limited deployment occurring in other geographical locations.

[5] The fuel cell systems are typically composed of several stacks. In a report by Battelle for the US DOE in 2016, the authors concluded that 100 kWe and larger single-stacks would not be the preferred approach of manufacturers. This is because otherwise the entire stack might have to be replaced during the warranty period in the field 4. *Manufacturing Cost Analysis of 100 and 250 kW Fuel Cell Systems for Primary Power and Combined Heat and Power Applications*, *Battelle Memorial Institute*. Several manufacturers are, however, also developing large single stacks.

Figure 2: Cumulative global deployment of large scale stationary fuel cells shown from 2007 onwards (deployment data considered from 2000 onwards), displayed per geographical region



4 Fuel cell technology development

The five fuel cell technologies (PEMFC, AFC, PAFC, MCFC and SOFC) with products available at >200 kW capacity, all have different operating characteristics and can serve different segments of the CHP or power generation market. Fuel cells are typically run on natural gas, utilizing the existing gas grid infrastructure, or on biogas, usually from landfills or wastewater treatment plants. The few large scale PEM fuel cells installed tend to utilize by-product hydrogen from industrial processes. Each individual technology has advantages and drawbacks that govern its final use for specific purposes. For instance, PEM fuel cells require high purity hydrogen as fuel and their operational temperature provides only low grade heat. However, they demonstrate a fast response to change in power demand. On the other hand, SOFCs offer high electrical efficiency and high grade heat, use natural gas as fuel, but have long start-up times and slow response times. Although not discussed in detail here, one additional sector which is particularly attracting the interest of large scale fuel cell manufacturers is the maritime sector, which for larger vessels will have a similar operating regime to stationary fuel cells.

Table 1 summarises the main characteristics of the aforementioned technologies across the spectrum of their applications.

Table 1: Characteristics of the five main fuel cell technologies (adapted from FCTO [5])

Fuel Cell Type	Operating Temperature	Typical Electrical Efficiency (LHV)	Typical power range (kW)	Applications	Advantages	Challenges
Polymer Electrolyte Membrane (PEM)	<120°C	60% direct H_2; 40% reformed fuel	1 – 100	Backup power Portable power Distributed generation Transportation Specialty vehicles Grid support P2P	Solid electrolyte reduces corrosion & electrolyte management problems Low temperature Quick start-up and load following	LT PEM: Expensive catalysts Sensitive to fuel impurities
Alkaline (AFC)	<100°C	60%	1 – 100	Military Space Backup power Transportation	Wider range of stable materials allows lower cost components Low temperature Quick start-up	Sensitive to CO_2 in fuel and air Electrolyte management (aqueous) Electrolyte conductivity (polymer)
Phosphoric Acid (PAFC)	150 - 200°C	40%	5 – 400	Distributed generation	Suitable for CHP Increased tolerance to fuel impurities	Expensive catalysts Long start-up time Sulfur sensitivity
Molten Carbonate (MCFC)	600 - 700°C	50%	300 – 3000	Electric utility Distributed generation	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
Solid Oxide (SOFC)	500 - 1000°C	60%	1 – 2000	Auxiliary power Electric utility Distributed generation	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

4.1 Proton Exchange Membrane Fuel Cells

Although Figure 1 demonstrates that PEMFC provides only a relatively small contribution to the levels of global deployment of large scale stationary fuel cells, a number of important projects (in particular originating in Europe) warrants its inclusion in this report.

Global development of PEM fuel cells began with space research in the 1950's and continued for submarine applications in the 1970's. At present, the main application for PEM fuel cells is transportation, followed by small scale residential units. More than 90% of the 490 MW of PEM fuel cell systems deployed globally in 2017 were for the transport sector [1]. Most of the remaining units are likely to have been installed in Japan for small-scale stationary applications, where the residential market is strong, albeit with a reliance on subsidies. To date, over 200.000 PEMFC units have been sold as part of the Ene-Farm project. The Japanese programme had ambitious targets for both the residential and transport sector and provided support for basic research, product development and subsidies to promote sales. PEM development has been supported by public funding in Japan, but the programme does not seem to have a strong focus on upscaling to larger capacities. In terms of commercial scale systems, Toshiba offers a 100 kW PEM fuel cell [6].

The US mainly invested in PEMFC development for its application in Fuel Cell Electric Vehicles (FCEV), but after achieving a peak annual R&D budget of >80 million USD in 2009, support dropped significantly until 2013 before stabilising [3]. The PEMFC developed by General Electric for NASA was subsequently licensed to Ballard in the 1980s, who has taken up a leading role in this technology. While the main focus for Ballard is on transport applications, fuel cell systems for back-up power are also offered up to 30 kW. The large capacity ClearGen™ model, which initially provided 174 kW power (demonstrated for example in California [7]) is meanwhile available as a modular solution in 500kW increments [8]. Ballard Power Systems commissioned a 1 MW ClearGen™ fuel cell system at Toyota Motor Sales USA (TMS) to provide electricity for the sales and marketing headquarters campus in Torrance, California in 2012 [9]. The FCH JU CLEARgenDemo project aims at field demonstration of another 1 MW PEMFC system. After changing the planned location several times, a suitable site has been found on the island of Martinique where two 500 kW power banks will be running on by-product hydrogen from a refinery plant. The commissioning is expected for mid-2019. In the US, ClearEdge[6] worked on PEM fuel cell development until 2014, when the company shifted to PAFC. They had previously raised more than $136 million of funding to develop and build a PEM fuel cell for residential and small commercial applications up to 200 kilowatts, apparently unsuccessfully [10].

The Canadian based Hydrogenics Corporation sells 1 MW fuel cell units with >50% electrical efficiency. According to a financial analyst, the outlook for Hydrogenics is positive with many orders coming in, due to their cooperation on FC buses with Heijili, and three orders of 5 MW each from South Korean Kolon Water & Energy [11]. In 2014, Hydrogenics had entered into an agreement with Kolon for a joint venture on renewable power generation, and meanwhile deployed at least one PEMFC unit (of 1 MW) at Hanwha-Total's oil refinery site in Daesan, South Korea [12].

Horizon Fuel Cell Technologies of Singapore has sold a 200 kW PEM fuel cell system to Ulsan in South Korea, as part of the Ulsan Technopark (UTP) project. This project is part of the Hydrogen Town initiative which aims to achieve 1 MW of electricity generation using 'waste' hydrogen in the industrial city [13]. The company had previously tested their liquid-cooled[7] PEM fuel cells in transport applications.

In Europe the R&D funding for fuel cell technologies has increased, reaching close to 60 million Euro annually during Framework Program 6 (FP6). European research projects have largely focussed on PEMFC and SOFC technologies. However, the main focus for PEMFC has again been the transport sector. Under FP5, the 50PEM-HEAP project targeted the UPS market and sought to develop a 50 kW PEM fuel cell system. Under FP6, PEM R&D was not conducted for upscaling beyond 5kW for stationary applications (in the NextGenCell project). However, under FP7 two demonstration projects were funded, ClearGen Demo and DEMCOPEM-2MW, involving two out of the three manufacturers offering PEM FC in the MW range, i.e. Ballard and Nedstack.

The fuel cell developer Nedstack was founded in 1999 as a spin-off of Akzo Nobel and has deployed PEM fuel cell stacks around the world. A 70 kW Pilot plant at the AkzoNobel site in Delfzijl has delivered more than 2.7 GWh of electric power after 55,000 hours of operation on the local grid [14]. Solvay has installed a 1 MW PEM

[6] After taking over UTC Fuel Cells in 2012.
[7] The product line for stationary use is air cooled.

fuel cell generator for their chlor-alkali plant near Antwerp, which became operational in 2012. The Hydrogen Region Flanders-South Netherlands programme supported the realization of this project with a budget of 14 million Euro. This 1 MWe unit is recovering heat for a process flow in the plant. The project DEMCOPEM-2MW is demonstrating a PEM Fuel cell power plant (2 MW electrical power and 1.5 MW heat[8]) integrated into a chlor-alkali production plant at the site of a chemical producer in Yingkou, China, lowering electricity consumption by 20%. It is interesting that Nedstack is partly going back to the drawing board for their fuel cells with the FCH2 JU GRASSHOPPER project, which will demonstrate a 100kW pilot plant with newly developed stacks, with the idea of ultimately scaling up to MW systems. These stacks are aiming at a CAPEX of <1500 Euro/kW, as the costs of the current MW scale units is seen as too high. The optimisation efforts are geared towards improvement of MEAs, stack design and overall system balance of plant. In addition, more dynamic operation for grid support will be tested.

Overall, whilst deployment of PEMFC for large-scale stationary applications can be seen in a number of interesting projects outlined above, they have not made the wider breakthrough observed for PAFC, MCFC and SOFC technologies in this area, with the focus more on mobility and small-scale residential applications.

The development of high temperature PEM fuel cells is also being pursued in Europe. Operation at high temperatures has the advantage of better performance, higher tolerance towards carbon monoxide and simplified water management. At present there are no concrete efforts towards upscaling this technology from the kW to the MW range.

4.2 Alkaline Fuel Cells

As for PEMFC, it can be seen from Figure 1 that there has not been major or widespread adoption of AFC for large-scale stationary applications. However, it has been included here for completeness.

In 1962 the US based technology provider UTC won a contract with NASA to power the Apollo space crafts, delivering 92 systems by the 1970s [3] with a power output of approximately 1kW. UTC struggled to find terrestrial applications for AFCs, mainly due to sensitivity to CO_2, performance issues and low power density. UTC subsequently shifted its focus towards PAFC. Japanese companies such as Fuji Electric and Hitachi have conducted basic R&D into AFC in the past. Fuji developed up to 15 kW capacity fuel cells for submarine and remote power applications until 1988 [3]. In Europe, Siemens devoted much effort to developing AFC units, up to a 48 kW system intended for submarines, but the tests carried out in the late 1980s were likely unsuccessful, as Siemens later developed PEM fuel cells for this application. Alsthom developed and installed a MW scale AFC system running on by-product hydrogen from a chlor-alkali plant in the 1980s, but AFC was ultimately not seen as a suitable solution for this application [15]. The Belgian company Elenco sought to deploy AFC for transport applications, investing in R&D for close to 30 years. The company even built a pilot plant with a capacity of producing 250000 electrodes per annum in 1989, but declared bankruptcy in 1994. By the 1990s research on AFCs was largely abandoned[9].

In 2006, AFC Energy was founded, building on the know-how developed by Elenco. Their technology was demonstrated in the FCH JU project "Power-up" at an industrial gas plant in Germany. The initial plans to supply 500kW were downscaled to 240kW, and the necessary BoP was developed and installed. Only power was provided, as CHP was not deemed economically viable, with no customer for the heat in the immediate vicinity. AFC Energy sees the key advantages of this technology as the high electrical efficiency coupled with the low temperature and low pressure operating conditions, which pose fewer constraints for materials and contribute to lower costs of manufacturing. In addition, the technology is well suited to the use of low-grade, by-product hydrogen. In 2017, the company announced that preliminary engineering has begun on a 1MWe project with Covestro (hydrogen provider) in Brunsbüttel, Germany[16] and the power generated will be sold under a long-term Power Purchase Agreement (PPA) to the local grid. AFC Energy also aims to provide the UK's largest hydrogen fuel cell precinct at Peel's Protos industrial park in the north of England, with a potential 35MW to 50MW [17]. The only other AFC developer seems to be the Israel based GenCell, which offers AFC for

[8] Although conceptually foreseen, there is no plan to integrate the heat in the system.
[9] Several companies tried to develop AFC for transport applications, such as Allis Chalmers. Daihatsu Motors presented a FCEV with an AFC at the Tokyo Motor show in 2011 (https://newatlas.com/diahatsu-gets-greative-with-three-concepts-for-tokyo/20477/)

back-up power and off-grid solutions in the 5kW range. The company aims to provide an affordable primary power fuel cell solution that can replace diesel generators for rural telecom and rural electrification.

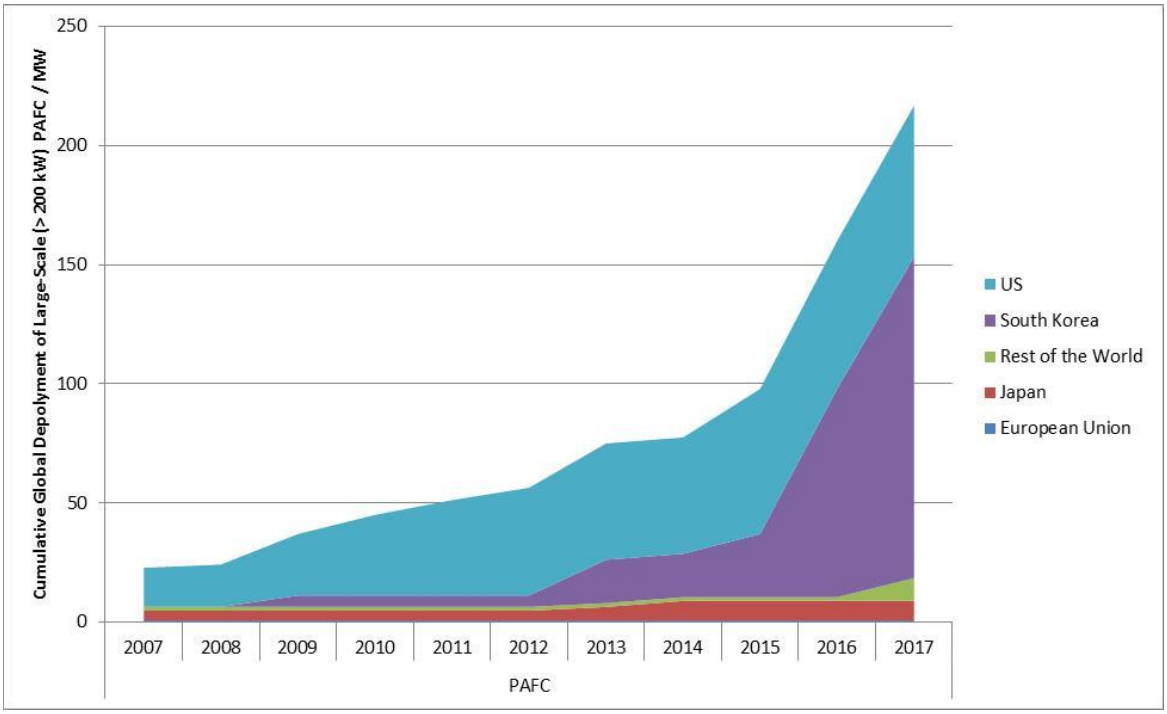
In summary, whilst there are a few projects being undertaken in Europe by AFC Energy, these are really the only deployments of this technology worldwide on the scale considered for this report.

4.3 Phosphoric Acid Fuel Cells

The deployment of stationary fuel cells for power generation began around 50 years ago in the US with the installation of PAFC for distributed power and co-generation. Unlike PEMFC and AFC, there are a significant number of installations of PAFC globally, of the order of 200 MW (see Figure 1). Up until approximately five years ago, there was quite a significant growth in installation of this technology in the US whilst more recently, the major deployments have been in South Korea (see Figure 3).

In Japan, a 1MW PAFC power plant was being tested from 1977, and a 4.5 MW plant was purchased in 1980 by TEPCO [3]. Field tests of a 11MW power plant took place between 1991 and 1997 [3]. Cost and durability issues had to be overcome, but initial tests seemed promising. An availability >95% and 40000h operation had been already reached in the 2000's [3]. However, the commercialisation of the products from companies such as Toshiba and Mitsubishi Electric has not been successful. Fuji Electric is still offering a 100 kW PAFC for the back-up market, reporting lifetimes of 15 years [18].

Figure 3: PAFC cumulative global deployment shown from 2007 onwards (deployment data considered from 2000 onwards)



In the US, the high cost and lack of reliability of these systems led to manufacturers such as Westinghouse shifting their interest towards SOFC in the 1990s. The units installed in the US were mainly from the fuel cell branch of United Technologies Corp, UTC Power. This company was taken over by ClearEdge Power in 2012, and in turn acquired by the South Korean Doosan Group in 2014. The fuel cells are manufactured in Connecticut, US, and in Iksan, Korea [6].

Close to 130 MW of PAFC systems have been installed in South Korea to date, with the main technology provider still being the Doosan Corporation. PAFC deployment in South Korea is still seeing significant growth. Recently the Doosan Corporation has announced the start of installation of a 50 MW fuel cell power plant in

Daesan, which will run on by-product hydrogen [19]. There are plans to install another 108 MW of PAFC in Korea and 20 MW in Connecticut [6]. It should be noted that Doosan are responsible for almost all large-scale (>200kW) PAFC deployments observed in the last 10 years.

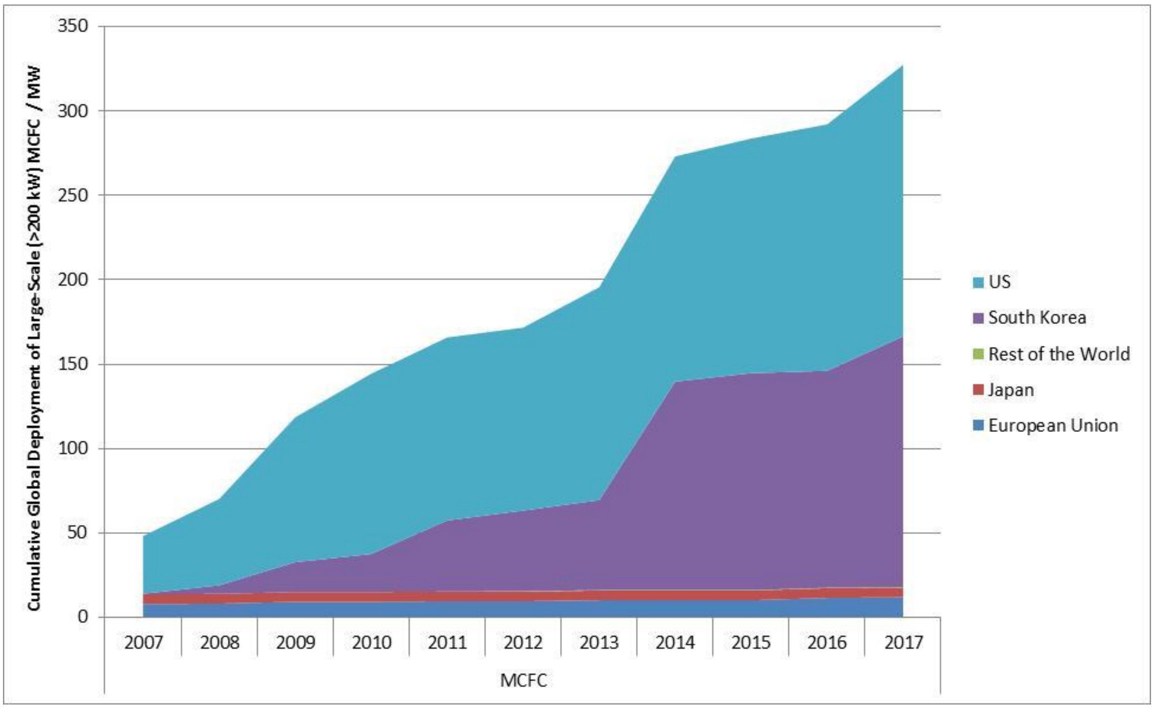
Europe financed several demonstrations of mostly smaller scale PAFC systems (in particular in the 1990s), but has conducted little of its own research, relying on the purchase of units from US or Japanese suppliers.

4.4 Molten Carbonate Fuel Cells

MCFC technology makes up a significant proportion of the deployed large-scale stationary installations worldwide (see Figure 1). MCFC are often operated on biogas, for example from waste water treatment plants, exploiting the fuel flexibility offered by the high temperature internal reforming capacity.

For MCFC technology development, the US and Japan were the main drivers, with substantial investments in the past 40 years. Fuel Cell Energy has been the main manufacturer of the technology in recent years providing almost all of the systems installed worldwide. As for PAFC the majority of the take-up of this technology has occurred in the US and South Korea in recent years (see Figure 4).

Figure 4: Global deployment of MCFC, cumulative capacity shown from 2007 onwards (deployment data considered from 2000 onwards)



The deployment of MCFC technology has been very significant in South Korea, as over half of the total of 325 MW installed fuel cell capacity is provided by MCFC. These are all sourced from FuelCell Energy through a partnership with the energy provider POSCO Energy. The steel manufacturer POSCO was initially responsible for the BoP, but has also made endeavours towards stack manufacturing [20]. As from 2010, a plant for the production of stacks was operational with a capacity of 100 MW per annum[21]. In 2012, POSCO Energy, together with a utility and gas company, began constructing a 58.8 MW fuel cell park which involves a series of 2.8 MW natural gas-fuelled fuel cells in the city of Hwaseong. The power output is enough to supply 135.000 households within the area and allow the utility involved to meet the Renewables Portfolio Standard requirements (see Section 5). This is the largest among many other similar projects throughout South Korea. A plant for the manufacturing of MCFC had been built, but currently production has been reduced or stopped, and POSCO has announced that it would exit the fuel cell business entirely during 2018[10]. In a February 2018 article, Korean business newspaper DK Ilbo reported that of the 21 fuel cell units POSCO supplied to the Gyeonggi Green Energy project, in less than two years, one third had stopped operating and required replacement, resulting in a loss to the company of 235.7 billion Korean Won since 2014[11] [22]. The durability of the fuel cells can be seen as the most critical factor for project success or failure. FuelCell Energy has recently announced a 20-year service agreement with Korea Southern Power for their 20MW CHP plant in Sinincheaon [24]. The South Korean Doosan company, active in PAFC had also developed MCFC, but seems to have discontinued their activities [20].

Close to 150 MW of MCFC have been installed in the US, and the outlook seems more positive here than for South Korea. Currently, there is an increased interest in the carbon capture capabilities of MCFC, and in 2016 FuelCell Energy and ExxonMobil announced plans to test carbon capture technology at a power plant operated by Alabama Power [25]. FuelCell Energy has patented a system concept called Combined Electric Power and Carbon-dioxide Separation, based on the utilization of CO_2 from flue gas by MCFC as a reactant for the electrochemical reaction to produce power, while also separating and transferring CO_2 from the flue gas to the anode exhaust stream [21]. Construction was set to begin in 2018, and project partner ExxonMobil sees this technology as a potential game changer for CCS [26]. The bulk of MCFC installations in the US are in the home state of FuelCell Energy, Connecticut. FuelCell Energy plans to install a further 150 MW by 2021, much of which will be located in Bridgeport, CT [27]. The company states that it faces two primary challenges, which are (i) the need to further reduce the total cost of ownership, and (ii) the continued education and acknowledgment of the value that their solutions provide. The Californian Self-Generation Incentive Program (SGIP) has funded almost 175 MW of stationary fuel cells [25], however only a small fraction of these are MCFC. Toyota has recently announced plans for a 2.35 MW capacity tri-generation plant, to be located in Long Beach, California [28]. Expected to begin operating in 2020, the facility will generate 2.35 megawatts of electricity and 1.2 tons of hydrogen per day. The Tri-Gen facility, to be built and operated by FuelCell Energy, will convert biological waste into hydrogen, heat and electricity.

Although the concept was developed in the 1950s in the Netherlands, MCFC research in Europe began in earnest in the mid to late 1980s, with ECN, MBB (later MTU Onsite) and Ansaldo Fuel Cells in the lead of the development. MTU Onsite (later Tognum, then CFC Solutions) had a technology exchange agreement with the US-based FuelCell Energy Company and successfully deployed several HotModule type plants, primarily in Germany and the UK. Throughout the Framework Programs, research focus shifted from basic research to development, demonstration and back again to basic research, indicating fundamental technological issues [3]. Insufficient lifetime and high costs appear to be the main causes of the lack of commercial success [3]. Under FP7, the MCFC-CONTEX project sought to address degradation, with FuelCell Energy components being tested. Initially, the project had both MTU Site Energy and Ansaldo FC as partners, both of which discontinued their operations mid-way through the project. MCFC-CONTEX has furthered the understanding of degradation mechanisms due to poisoning by typical gas impurities, and had attracted the interest of several companies in the technology, but there have been very few sales of MCFC systems in Europe in the recent past. As commercialisation of these products did not succeed, there is currently only one European company involved in the development of MCFCs: the MBB know-how has been transferred to FuelCell Energy, through its German subsidiary FuelCell Energy Solutions GmbH. The fate of the IP of Ansaldo Fuel cells is unclear following the demise of the company. Given the experience of POSCO Energy discussed above, a focus on increasing the robustness and thereby lifetime of MCFC seems a highly relevant research direction. In Germany, FuelCell Energy is deploying a 400kW CHP plant for a hotel in Frankfurt, funded by a national CHP support scheme. In 2016 a 1.4 MW plant was installed in Mannheim at a company producing ceramics and other materials, providing up to 60% of the energy requirement of the production process [29].

In summary, the recent deployment of large-scale stationary MCFC has followed a similar pattern to that of PAFC with one company (in this case FuelCell Energy) producing almost all the units being distributed. Again, the US and South Korea are the main geographical regions where the technology is being deployed.

[10] The company does seem to continue its collaboration with FuelCell Energy at some level, due to the intervention of the South Korean Government 1. *Fuel Cell Industry Review*, 2017, E4Tech.

[11] It should be noted that the article referenced was written by an employee of Bloom Energy, and that JRC was not able to track down the original source. 235 billion Korean Won are approximately 180 million EUR at today's exchange rates.

4.5 Solid Oxide Fuel Cells

SOFC also make up a significant contribution to the installed large-scale stationary fuel cells worldwide, as shown in Figure 1. However, the take-up of this technology has almost exclusively occurred in the US, as demonstrated in Figure 5, below.

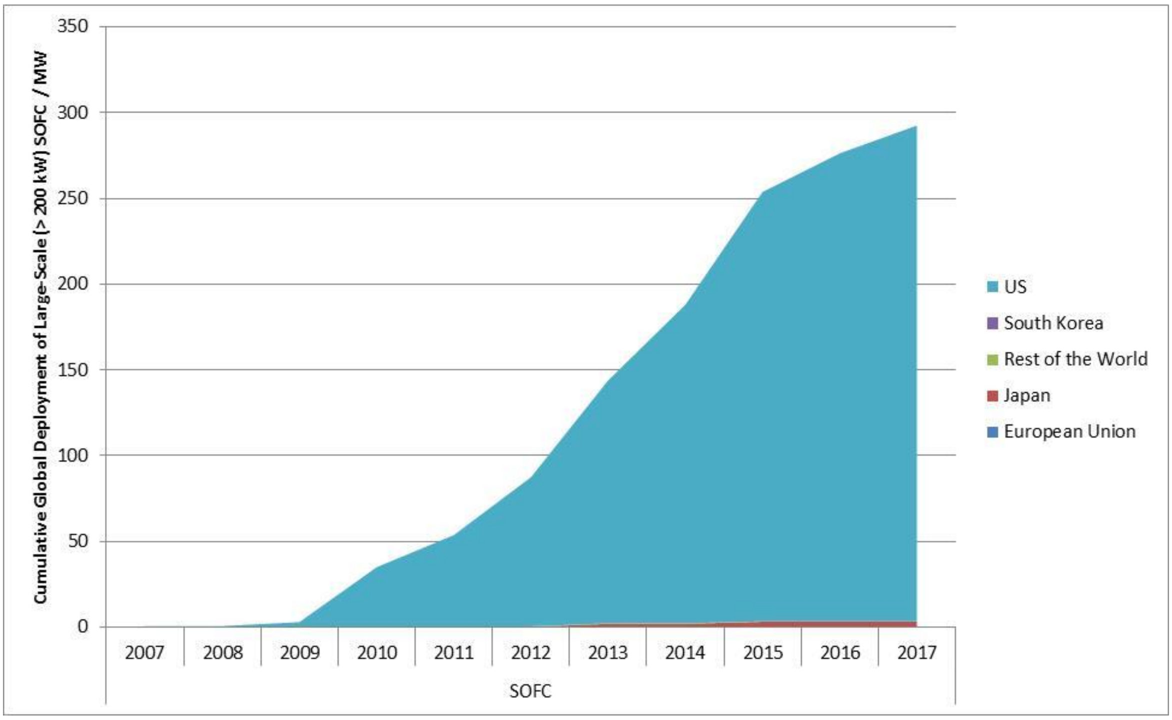
R&D on SOFC began in the US in 1977. Research into tubular SOFC had received 250 million USD of funding by 2005, about half of the funding allocated to MCFC research [3]. After Siemens acquired Westinghouse technology for 1.5 billion USD and further developed their technology, the first field tests of a 100kW unit were conducted in Denmark in 1997. A lifetime of close to 40kh was reached. 250kW units were operated in the early 2000s, and plans were in place for building 1MW hybrid plants with a micro-turbine. The tubular technology did not achieve sufficient power densities and durability, nor did it reach the required cost targets and in 2010 Siemens closed down its SOFC activities. The US Department of Energy subsequently supported research on planar design by launching the Solid State Energy Conversion Alliance (SECA) programme. SECA has supported a range of R&D projects, with a budget of 600 million USD from 2000 to 2014 [43] and has covered topics from basic research to manufacturing. The current programme aims to reach stack cost targets of 175 USD/kW combined with 40kh durability, and has recently awarded 13.5 million USD in funding [30]. In the US, companies such as Acumentrics, Atrex, LG Fuel Cells System Inc.[12], Bloom Energy, FuelCell Energy and Ceramatec/OxEon are still actively involved in SOFC development. GE had successfully advanced planar SOFC technology, but has meanwhile significantly reduced their activities. Their current work seems to be at a more basic research level, looking into metal-supported stacks with ceramic anodes [31]. FuelCell Energy is also involved in SOFC development and is preparing to field test a 200 kW unit which it is seeking to upscale to utility level within the next 10 years [32]. Apart from Bloom and FuelCell Energy, only LG Fuel Cells is investing in the development of larger scale systems (Acumentrix work on UPS systems from 250W – 2kW; Atrex on remote power generation to 10kW; Ceramatec/OxEon produce 10kW modules). LG Fuel Cell Systems (LGFCS) was formerly known as Rolls Royce Fuel Cell Systems (RRFCS) until it was taken over in 2012. With the support of the SECA programme, this company is developing a MW scale SOFC Power Plant, which is at commercial demonstration level for a 250 kW unit [33] and has also invested in manufacturing, namely a multi-MW/year printed tube line. They received a DOE grant of almost 1M$ in July 2018 to perform a techno-economic analysis of their MW class system for distributed power generation [34].

Bloom Energy is often showcased as a success story for stationary fuel cells, and has been successful raising investment in the company (e.g. [35]). They have recently made an initial public offering at 15 USD per share, raising 270 million USD, after years of announcements. After keeping cost information closely under wraps for many years, this is now available since Bloom is a publically traded company. The cost per installed kW is stated to be between 5040 and 5390 USD [36]. The company has installed over 200 MW of their units almost entirely in the US, and is the reason that the US completely dominates global large scale SOFC deployment as previously indicated. However, they are now targeting the Korean market [22] and have recently installed an 8.35 MW fuel cell for a utility near Seoul, in a partnership with Koreas' SK Engineering and Construction. Commercial operation began in late 2018 [37]. The design claims to be the world's most energy-dense power plant, generating 13.7 kW/m^2 [38]. SK Engineering and Construction will become a distributor of Bloom fuel cell systems for South Korea [39]. Bloom Energy has installed several MW of their fuel cells in data centres, for high profile clients such as Apple. Recently, the Apple site installation in North Carolina has been criticised by the local press, as Bloom Energy apparently did not comply with environmental regulation for disposing of their desulphurisation filters. Furthermore, the concept used by Apple to increase the share of renewables for their data centre has been questioned, as the biogas from a nearby landfill is not actually used by the fuel cells[13], but injected into the gas grid, and moreover the fuel cells do not supply energy to the centre at all, but provide electricity to a utility in an offsetting scheme [40].

[12] Formerly Rolls Royce Fuel Cell Systems (US), now a subsidiary of LG Electronics.

[13] The fuel cells are run on natural gas.

Figure 5: Global deployment of SOFC, cumulative capacity shown from 2007 onwards (deployment data considered from 2000 onwards)



Bloom Energy disclosed that two customers accounted for 53% of revenue, but it is not clear which are those customers [19]. Bloom Energy has formed a partnership with the utility Southern Company and its subsidiary PowerSecure for project investment and joint technology development. PowerSecure will acquire about 50MWe of Bloom Energy Servers [2]. The business model of Bloom Energy is often based on power purchase agreements (PPA) instead of actually selling the fuel cells[14]. The fuel cells systems were typically eligible for tax breaks and state subsidies, except in 2017, when tax credits were unavailable. In California, Bloom customers have benefitted from the Self Generation Incentive Program (230 million USD in the period 2001-2015 [41]).

SOFC development is very active in Japan, however mostly for residential applications of approximately 1kW. This technology has a strong market in Japan with several highly active companies (such as Mitsubishi Heavy Industries, Fuji Electrics, Kyocera and NGK). Research and development has been supported by public funding. The research programme saw an interesting shift in focus in 2008 by returning to fundamental research, in order to tackle the issue of degradation [3]. A post programme evaluation had found that, although the previous programme had furthered the understanding of the causes of degradation, the solutions to overcome them were still missing. The current programme is still seeking to address this issue [42]. Japanese SOFC developer Kyocera started to develop tubular stacks without any public funding in 1985, and began mass production in 2011 for the ENE-FARM type S[15]. SOFC technology is gaining traction in this market, as while in 2015 less than 10% of Ene-farm units were SOFC, in 2017 a 40% share was foreseen [1]. It should be noted that the company does not seem to have plans to scale up beyond the 3kW range. However, Mitsubishi Hitachi Power Systems has demonstrated a tubular SOFC 250kW fuel cell and is also targeting power generation at the MW level [6, 43, 44]. Their hybrid technology (integrated with steam/gas turbine) is reported to have an electrical efficiency of 55%. The high grade heat from the flue gas of the SOFC can be used to heat steam which is used in a turbine.

In Europe, research on SOFC has received significant public support, supporting companies such as ABB, Haldor Topsoe (TOFC), Rolls Royce Fuel Cell Systems (RRFCS), Wärtsilä, Sulzer/Hexis and Siemens. Several research institutions, for example Risø (Denmark) and Jülich (Germany) have conducted breakthrough research and development. Although Jülich has reduced their activities in this field, long term testing has continued after

[14] Recently Fuel Cell Energy seems to have followed suit 1. *Fuel Cell Industry Review*, 2017, E4Tech.
[15] The sale of the ENE-FARM type S units is subsidised.

the end of the FP6 REAL-SOFC project, and a 10 year lifetime has been demonstrated [45]. Some of the above-mentioned companies have since stopped their SOFC development, but SolidPower/HTCeramics, Staxera/Sunfire, Elcogen, Wärtsila/Convion, Hexis/Viessman and Ceres Power are still active. The effect of the volatility of the market for fuel cell manufacturers is also evidenced by the many mergers and acquisitions with subsequent changes of company names. SolidPowerSpA has acquired the IP of the Australian CFCL, which had seen its main business opportunities in Europe and had already established a supply and manufacturing base there [3, 46]. At lower capacity level, but moving towards medium scale installations, SolidPower will supply fuel cells for Microsoft in Seattle [47]. This is a promising development for a European company, as previously only Bloom Energy has been active in this segment in the US.

Apart from Convion, none of these companies are targeting the large scale stationary market. Ceres Power has entered into a partnership with the US based company Cummins, and is also evaluating the market for data centre applications in the US. Although scalable, at 5 kW the current capacity is still not geared towards large units [48]. They are also aiming to produce a 10 kW fuel cell in partnership with Bosch [49]. The FP6 project Large-SOFC sought to overcome the challenges related to upscaling through cooperation between industry partners RRFCS, Convion and TOFC. The results of this project were used to implement the design of the WFC50kW fuel cell unit and brought Convion fuel cells closer to commercialization in terms of product cost, performance, manufacturability, assembly, lifetime and availability. The long term goal was to move to 250 kW basic units, but this does not seem to have been accomplished to date. RRFCS had announced plans to develop a 1MW GT-SOFC hybrid system. The project concluded that significant advances had been achieved, but further development work for commercialisation would be needed [50]. In another FP6 project (FELICITAS), an attempt was made to adapt the RRFCS 1MW pressurised SOFC design for a 250 kW APU, for maritime applications, apparently without success. It is not clear whether the upscaling to 1 MW had actually been achieved.

The ongoing FlexiFuel-SOFC project (H2020-LCE-2014-1) will develop a highly efficient and fuel flexible micro-scale biomass CHP technology consisting of a small-scale gasifier, a compact gas cleaning system and an SOFC. The technology will be developed for a capacity range of 25-150 kW and is characterised by fuel flexibility. HyGear BV is the fuel cell system provider involved.

The FCH JU DEMOSOFC project is demonstrating the largest SOFC system to date in Europe, a 174 kW Convion fuel cell system at a wastewater treatment plant in Turin[16], Italy. The integration of the fuel cell with micro gas turbines was investigated. Wastewater treatment consumes up to 1% of electricity in Europe [51]. The biogas conversion efficiencies could be improved through the deployment of SOFC, and thermal and electrical self-sufficiency rates of 25% for the facility were reached [17]. The FCH JU project INNO-SOFC will demonstrate the next generation of the Convion fuel cell, a 60kWe power plant with a European value chain and aims to reduce system costs below 4000 Euro/kW. The industry partners are Convion and Elcogen. European R&D efforts are, however, largely geared towards the residential segment, with companies such as Solid Power, Ceres Power, Sunfire, Hexis/Viessmann targeting commercialisation of products in the 1-5 kW range. According to the Fuel Cell Industry review, Sunfire will install 50 kW units in China [6]. Furthermore, Solid Power and Sunfire are now in the EU demonstration project ComSos targeting larger installations (although still less than 100 kW) [52].

It can be concluded that whilst there is significant development currently ongoing in the SOFC field, large-scale installations of SOFC are almost uniquely produced by a single company (Bloom Energy) in a way that mirrors the market dominance of a single producer in PAFC (Doosan Corporation) and MCFC (FuelCell Energy). Contrary to the other two technologies, Bloom Energy have not yet made major inroads in South Korea, having focussed almost exclusively in the US, although they are now beginning to target this market.

[16] To date two modules of 58 kWe out of the three expected have already been commissioned

5 Drivers of, and barriers to large-scale stationary fuel cell deployment

This section intends to identify reasons behind the varying levels of stationary fuel cell deployment in different countries/regions. These reasons may be related to energy and climate policies, to the characteristics of the energy market and infrastructure and/or to the presence of FC system manufacturers and potential customers, as well as the state of art of competing technologies in terms of cost, efficiency and reliability.

Energy and climate policies pursue the improvement of energy system efficiency, the reduction of dependence on energy imports and the reduction of emissions, by means of regulations that could represent a policy-pull for the deployment of FC technologies. The implementation of these regulations can be assisted by funding programmes to support competitiveness, by financial incentives or by providing access to financing.

The deployment of FC systems for large-scale stationary applications in a specific region or country can also be influenced by the presence of a FC system manufacturer in the area that could raise awareness with potential customers regarding the benefits of the technology they provide versus competing technologies (e.g. diesel-based generation).

Another potential driver for the deployment of large-scale stationary fuel cell systems can be the presence of end-users that need a large, steady electricity supply (e.g. data centres) in regions with poor grid reliability.

The characteristics of the energy market will strongly influence the deployment of FC systems, for instance, the existence of Power Purchase Agreements (PPAs) as opposed to direct sales of fuel cells. With this formula the end user only has to pay for electricity at the price established in the agreement, while the company offering the service takes care of the deployment, operation and maintenance of the system. This option liberates end users from potential problems of a promising but still not well-established technology.

Energy prices (electricity and gas) are a decisive factor for the implementation of FC technology in stationary applications. The "spark spread" refers to the difference between the price of electricity and the price of natural gas. If this difference is large enough (with the price of electricity greater than the price of natural gas), the option of producing electricity from natural gas (by means of gas engines or fuel cell systems) instead of purchasing the electricity could be more attractive from an economic point of view. This will depend on the electrical efficiency of the technology chosen along with other factors such as CAPEX, maintenance and operational cost, reliability and lifetime.

In the case of fuel cells, efficiencies ranging from 40 to 60% can be considered, depending on the technology and on the need for an external fuel processor (e.g. PEM fuel cells). Regarding the CAPEX of fuel cell systems, it is possible to find literature values that range from 2000 to 10000 €/kW for the same fuel cell technology. One of the reasons for this disparity is that different system sizes and manufacturing volumes are considered. A similar situation can be found regarding the lifetime of FC systems. Values found in literature can range from 10000 h to 40000 h. In addition, it is not clear whether the lifetime reported corresponds to commercial or laboratory-scale systems.

With these uncertainties, it is difficult to determine the minimum spark gap that would make a fuel cell system an attractive solution. In a first approximation, the spark spread (€/kWh) should at least be larger than the ratio between the CAPEX (€/kW) and lifetime (h) of the fuel cell system to be deployed (considering a lifetime equal to the operational hours at 100% of the nominal power). These calculations do not consider a potential benefit coming from the use of the heat produced by the fuel cell system in the case of CHP systems. Considering the range of possible efficiencies (40-60%), the ratio of the electricity to the natural gas price being above 1.7-2.5 could in principle encourage the deployment of fuel cell technologies, at least from the operational cost point of view (not considering maintenance costs).

The analysis to identify reasons behind the different levels of deployment of stationary fuel cell systems in several countries/regions presented in the following subsections will include a study of the spark spread. It should be noted that energy prices have been obtained from different sources, OECD (for Japan and Korea), Energy Information Administration (for the USA) and Eurostat (for Europe). This hinders the comparison, as the prices considered could include different contributions (e.g. taxes) depending on the source. Furthermore, the thresholds for power and energy consumed used to attribute consumers to a particular sector (industrial, residential or commercial) vary between countries.

5.1 South Korea

South Korea is the world's eighth-largest consumer of energy [53], a major energy importer[17] and emits a large amount of GHG (690 million tonnes in 2015). Air quality is a concern, as according to the Organization for Economic Cooperation and Development the country has the worst air quality among the 35 developed economies [54]. The government has therefore issued a policy targeting a reduction in GHG emissions of 37%, versus business as usual (BAU) levels by 2030) which requires a decarbonisation of the energy generation sector (which will have to contribute a reduction of 64.5 million tonnes of CO_2 [55]). The share of renewable energy is still low at 7.24% (2016) for power generation [56] and only 2% of primary energy, with limited potential for expansion. For the past decade, power generation has increasingly depended on natural gas (power generation accounted for about half of the natural gas sales in 2016 [57]), and practically all natural gas has to be imported from overseas with LNG tankers. Power generation is centralized and currently relies on coal and nuclear power, but the shares of both are to decrease, with more power to be generated from renewable energy sources and natural gas, according to the 8th electricity plan[58]. The Korean Electric Power Corporation (KEPCO) manages 97% of the Korean electrical grid. The reserve margin (difference between peak capacity and demand) has increased to more than 11% since 2014, but was previously lower than 10%, resulting in major brown-out events in 2011 [53, 59]. Reserve margins in the 15% range would be more typical, as found for example in the US electricity system [60].

Fuel cells are considered a new and renewable energy (NRE) source by the South Korean Government. The Renewable Portfolio Standard (RPS) calls for electric utilities and independent power producers (>500 MW generating capacity) to either install NRE technologies or to buy renewable energy credits. This programme started in 2012 and superseded the previous non-technology neutral feed-in tariff (FIT) scheme. The programme has a target of 5% electricity production from renewable energy in 2018, increasing to 10% by 2023. The qualifying NREs are solar, biomass, wind, hydro, fuel cells (regardless of fuel type and origin), gasification or liquefaction of coal, ocean, waste, geothermal, and hydrogen energy. Credits can be purchased through renewable energy certificates, which are allocated for produced electricity according to the technology. There is a weighting scheme to off-set the higher cost of new technologies, with fuel cells receiving a multiplier of 2 (for comparison: off-shore wind: 2, hydro: 1) [61]. Prior to 2012, fuel cells were supported by fixed feed-in tariffs of ~15-18 Euroct/kWh (biogas or other fuels) [62]. The change in policy from FIT to RPS does not seem to have had a negative effect on fuel cell deployment, which has continued to grow. The public investment in this technology has been effective, according to a recent analysis [63]. Electricity generated through new and renewable power plants that have a capacity less than 1MW, can be sold through the Korea Power Exchange (KPX) or through the execution of power purchase agreements (PPA) via the Korea Electric Power Corporation (KEPCO) [64].

In South Korea a high energy demand, coupled with ambitious plans for integration of renewables, seems to have paved the way for its position as world leader in utility scale fuel cell power generation [22, 65]. In Figure 6 it can be seen that the cumulative deployment of large scale stationary fuel cells has reached a total installed capacity of approximately 300 MW with considerable additional projects planned for the coming years. The ministry of trade, industry and energy new electricity supply plan foresees further deployment of fuel cells from the current 300 MW to 600 MW by 2022 [38]. As an example, Hanwha Energy has begun construction of a 50 MW PAFC electric power station in the Daesan Industrial Complex which should begin operation in June 2020 [66].

In South Korea, the total capacity is split quite evenly between PAFC and MCFC but PAFC has been expanding rapidly in the last few years.

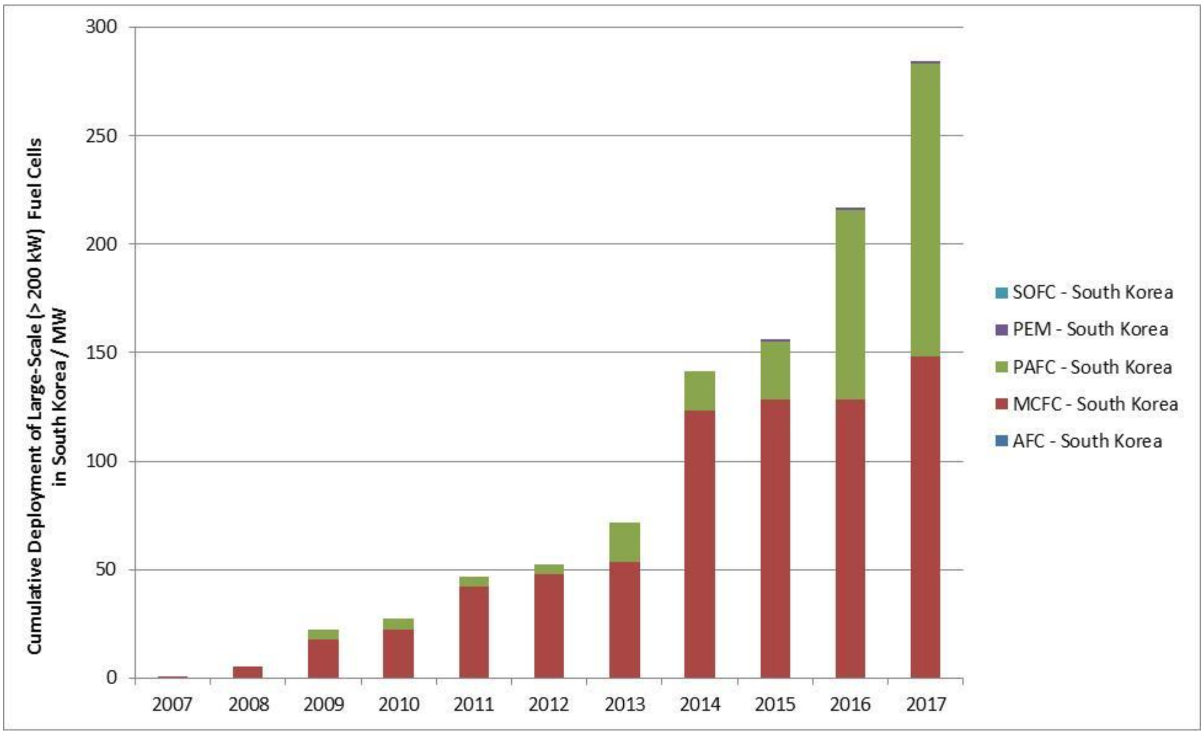
The South Korean Government provides subsidies for the installation of fuel cells, which can be up to 80% of the costs for demonstration projects [67]. Other policies supporting fuel cells are the mandatory share of renewables for public buildings and pilot projects such as H-Town[18] which was implemented in Ulsan. Utility companies have to develop energy infrastructure to renewable portfolio standards.

Apart from offering subsidies, South Korea has also supported R&D for fuel cells. The level of investment in fuel cell technology development (averaged value from 2009-2013) has been >47 billion KRW (~35 million Euro) [63].

[17] South Korea is the second-largest importer of liquefied natural gas in the world.
[18] In the H-Town project, hydrogen produced from biogas and by-product hydrogen is used.

As mentioned before, the fuel cell power plants installed in South Korea are all based on US technology[19]. Recently the Doosan Group has been involved in a fuel cell development project supported by South Korea's Ministry of Knowledge Economy, which seeks to strengthen the domestic development of technology for MW-class fuel cells for operation in conjunction with power plants [2].

Figure 6: Cumulative deployment of large scale stationary fuel cells in South Korea shown from 2007 onwards (deployment data considered from 2000 onwards)

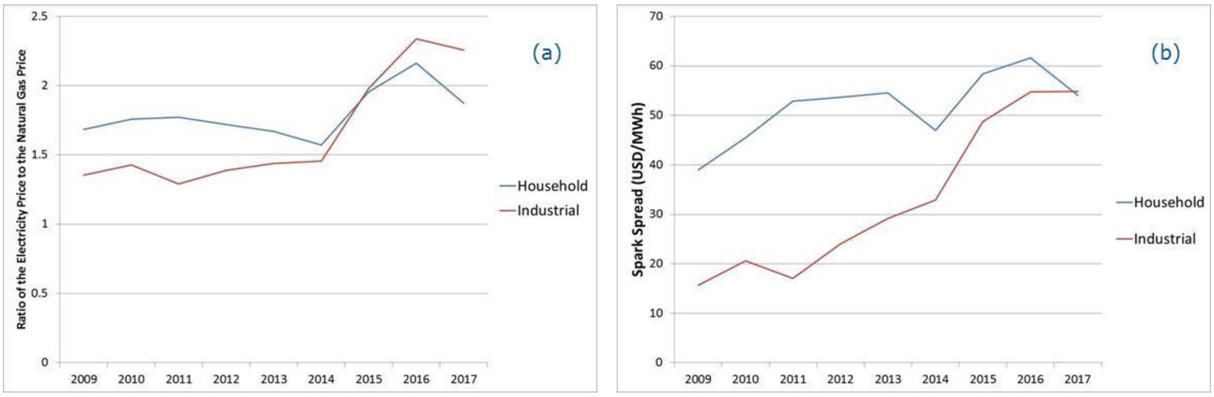


According to Doosan Fuel Cell, enabling national regulations are contributing to the adoption of the technology [68]. The company also mentioned the low space requirement of fuel cells as an additional positive factor. The success of fuel cell deployment in South Korea is also due to the fact that distributed generation is feasible thanks to a well-developed natural gas grid. District heating as a sink for the heat produced in CHP applications exists. Whether industrial processes are benefiting from the high-grade heat from MCFC is not clear, but could also help to explain why this technology has attained such a large share of the fuel cell market.

Regarding energy prices, the ratio between electricity prices and natural gas prices were of the order of 1.3-2.3 in the period 2009-2017, both for industrial and household users, as shown in Figure 7. (a). The spark spread has been increasing in South Korea during the period from 2009-2017 (Figure 7 (b)). Initially, it was greater for residential users but in recent years the spark spread for industrial users has increased significantly, reaching the same values as in the residential case (54 USD/MWh). However, these values remain too low to make a strong business case for the production of electricity using FC systems, due to the current CAPEX and lifetime of state of the art FC systems. Hence, incentives have been necessary to make the use of fuel cells attractive for electricity production.

[19] With the exception of Hydrogenics, which is gaining a small market share for PEM fuel cells, see section 4.1

Figure 7: (a) Ratio Electricity / Natural Gas Prices (b) Spark spread; for South Korea 2009-2017



5.2 Japan

Japan has invested heavily in fuel cell technologies since the 1970s with large R&D projects such as the Moonlight and Sunshine programmes. A further example, the Millennium Project, was implemented in 1999 to boost the development of fuel cells in transport and in residential cogeneration systems. The Ministry of Economy, Trade and Industry (METI) started a four-year fuel cell development strategic plan (2000–2004) to develop and commercialize fuel cell technology, which was subsequently extended to 15 years. Policy initiatives were started in parallel with the fuel cell R&D program. The governmental allocation for fuel cell R&D activities was 3.3 billion USD for the 10-year period from 2005 to 2015 [9], representing the highest level of public support for fuel cells in the world [3]. The annual budget has varied, but has reached peaks of 352 million USD in 2005 and close to 400 million USD in 2014.

The main motivations for Japan to invest heavily in these technologies come from it being, like South Korea, a net importer of energy due to a lack of its own indigenous energy resources. Furthermore, Japan is strongly committed to reducing GHG emissions and to enhance its energy security in particular following the Fukushima nuclear disaster. It is therefore seeking diversification of energy sources and an increased resilience in the face of natural disasters.

With these key drivers in mind, Japan intends to reform its existing energy supply structure and transition to a new energy system. Hydrogen is seen as a means to utilize renewable energy resources.

Hence, Japan has developed a dedicated Hydrogen Strategy [69] in a commitment to achieve the world's first "Hydrogen Society". Goals of the strategy are to decrease the overall carbon footprint of the energy supply, including that of hydrogen. There is a strong focus on developing hydrogen supply chains with direct reference to hydrogen imported from abroad[20]. The Basic Hydrogen Strategy mentions that "fuel cells, although appreciated for their ability to reduce energy costs, are seen only as representing efficient energy use at present". Fuel cells are regarded as promising for small scale distributed generation. The strategy foresees that hydrogen-based power generation will consume massive amounts of hydrogen and is therefore the most important application to develop, together with the supply chain. The strategy document refers only to combustion, not fuel cells, for power generation purposes. However, Japan plans to clarify whether hydrogen power generation can be classified as a non-fossil power source in the Energy Supply Sophistication Act. This differs from the approach taken by certain US states and South Korea where fuel cells are considered a renewable energy resource, regardless of the source of hydrogen.

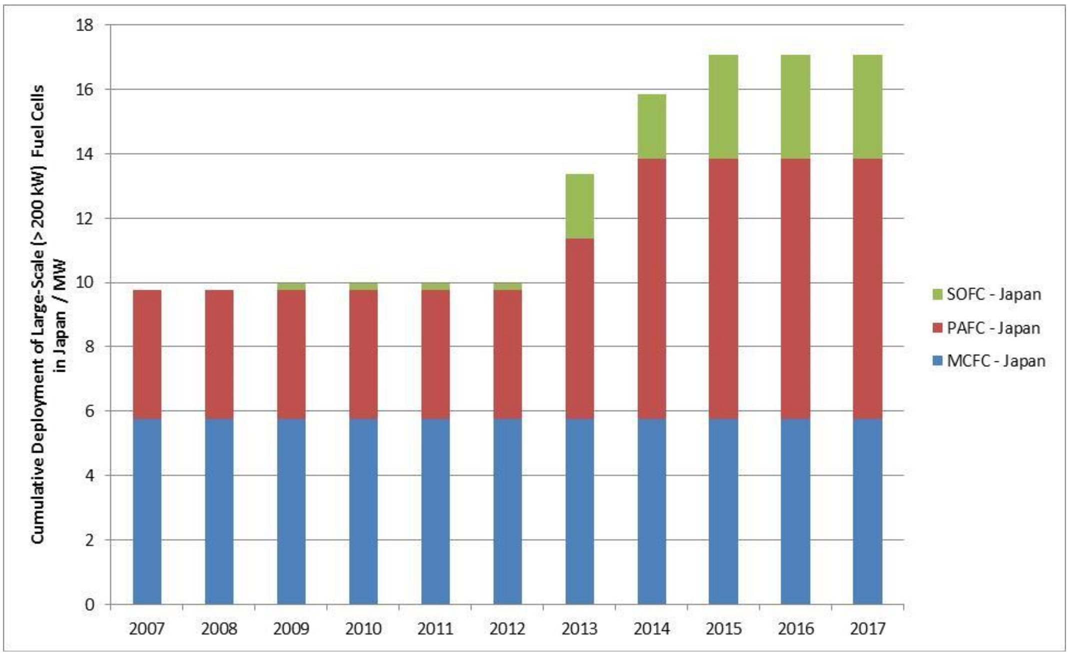
In the current strategy document, Japan states, regarding the topic of stationary fuel cells, that it will promote the introduction of commercial and industrial fuel cells for users with low heat-to-power ratios. Japan will also promote technological development to increase the fuel cell power generation efficiency above 60% for sophisticated, gas-turbine-combined-cycle (GTCC) power plants. It remains to be seen how these plans will be put into action, as presently the main focus for Japan is on creating a market for residential fuel cells. Activities seem to be devoted to PEMFC and SOFC, mainly for residential applications in the 1kW range. The Ene-Farm project, as mentioned previously, has deployed over 250.000 fuel cells, but market readiness has not been entirely achieved. The ability of residential fuel cells to supply heat maybe a particular strength in a country with little district heating capacity [71].

The 2017 budget for the Hydrogen Society allocated 310 million EUR for various programmes, such as subsidies for residential fuel cells. Further deployment of residential fuel cells is planned. The Strategic Road Map for hydrogen and fuel cells [72] from 2014 mentioned the release of fuel cells for commercial and industrial use as part of the first of three phases.

However, activities on stationary fuel cells in the 5kW+ capacity range are rare. Large-scale deployment in the range of >200 kW it is even rarer, with less than 10 MW total capacity being added since 2007, as shown in Figure 8.

[20] The Basic Hydrogen Strategy mentions "unused energy resources from overseas that it has so far failed to use due to the fact that Japan is an island nation. Coupled with CCS…", which is referring to the plans to import hydrogen from coal gasification. There is a joint project with Australia to build a supply chain based on LH2 70. *Hydrogen Energy Supply Chain*. 2019; Available from: https://hydrogenenergysupplychain.com/..

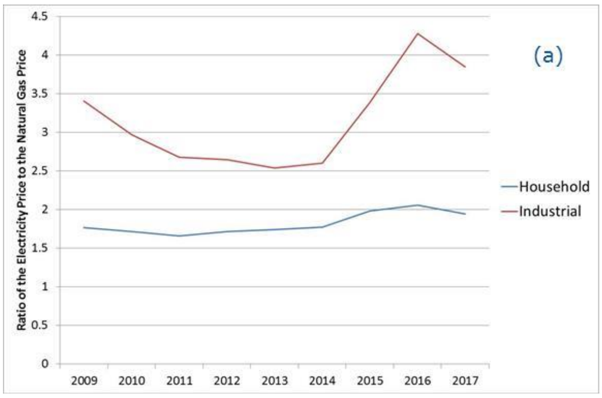
Figure 8: Cumulative deployment of large scale stationary fuel cells in Japan shown from 2007 onwards (deployment data considered from 2000 onwards)

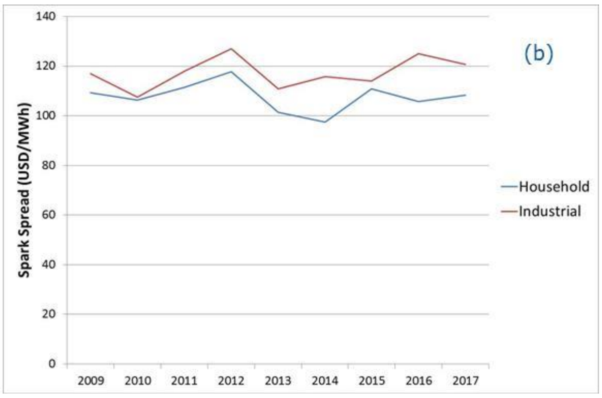


It should be noted that the manufacturing landscape in Japan differs from that found in the US and in Europe. In Japan, huge conglomerates such as Toshiba, Mitsubishi and Panasonic are investing in fuel cell development, with presumably little effect on their overall bottom line. In the U.S. and Europe it is mainly companies dedicated to fuel cells, such as Bloom Energy, Fuel Cell Energy, Nedstack, SolidPower and Convion.

The ratio of the electricity to the natural gas price, and associated spark spread for Japan are displayed in Figure 9. The spark spread in Japan has remained stable for the period 2009-2017 at a large value, offering opportunities for FC solutions. As in South Korea, the household and industrial spark spreads have similar values. Regarding the spark spread ratio (Figure 9 (a)), it seems that for industrial users, electricity production with a FC system could be an attractive solution, as the ratio of the electricity to the natural gas price approaches 4.

Figure 9: (a) Ratio Electricity / Natural Gas Prices (b) Spark spread; for Japan 2009-2017



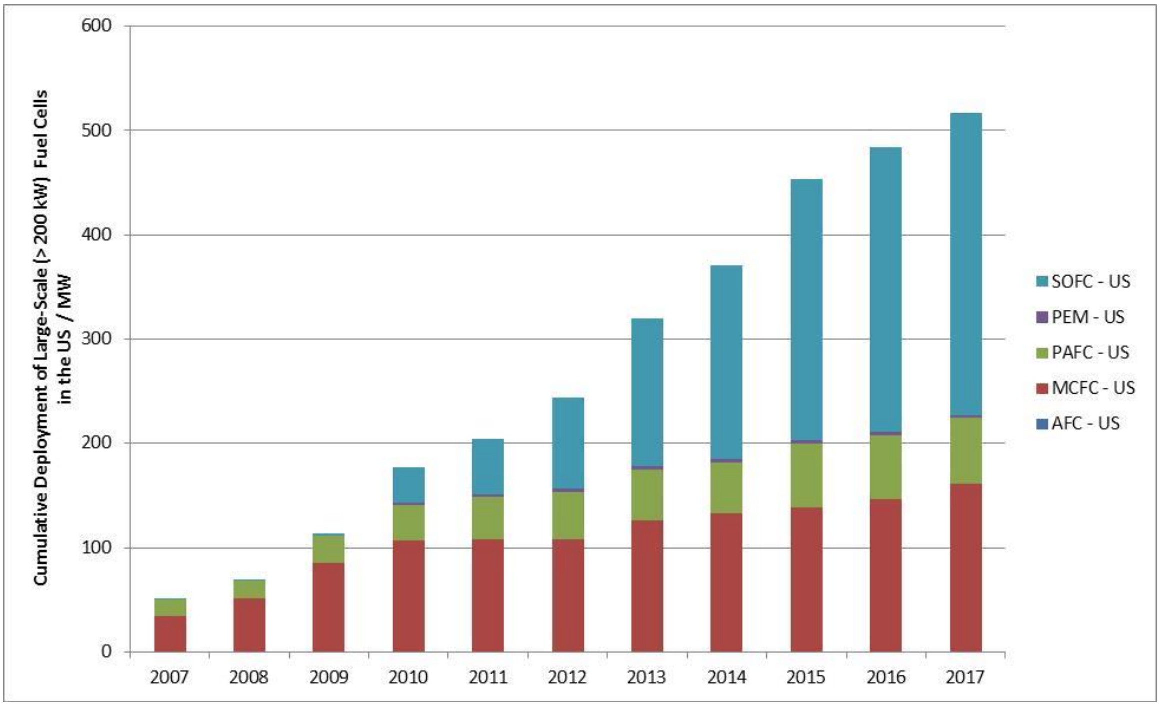


In summary, Japan has invested heavily in fuel cells for many years. However, there has never been a concerted focus on large-scale stationary applications. The focus on transport, and especially small-scale residential applications, has dictated the selection of the technologies used.

5.3 United States

In the US, more than 500 MW of large-scale stationary storage capacity has been installed to date as shown in Figure 10. Almost half of the fuel cell capacity (>240 MW) is installed in California, followed by Connecticut. In the US fuel cell systems in the >200 kW power range are primarily serving medium to large commercial buildings, data centres, hospitals, naval bases, warehouses, product distribution centres and light industrial fabrication/manufacturing sites [2].

Figure 10: Cumulative deployment of large scale stationary fuel cells in US shown from 2007 onwards (deployment data considered from 2000 onwards)



The main technologies deployed in this segment are molten carbonate, phosphoric acid and solid oxide fuel cells. Alkaline and proton exchange membrane fuel cells currently still play a much smaller role for this type of application. There are multiple policy drivers for the strong growth of large-scale stationary FC technology, as outlined below, with one likely non-policy related factor being that the natural gas grid, from which fuel cells can be supplied, is perceived as being more reliable than the electrical grid. Extreme weather events are causing power system performance problems or even damage to infrastructure [73]. The average US customer went without power for an average of almost eight hours in 2017 [74], compared to customers in Japan experiencing power failures for four minutes per year[21] [75]. 80% of power outages were related to weather events in the period from 2003-2012, with Michigan experiencing the highest number of all states with 71 major weather-related power outages (for reference the states with the highest installed fuel cell capacity: California 46 events, New York 32 events and Connecticut 10 events) [76].

In 2016, the three major U.S. fuel cell manufacturers, Bloom Energy, Doosan Fuel Cell America (formerly ClearEdge Power Inc.) and FuelCell Energy, announced sales, installations, or agreements for almost 100 MW of fuel cell systems. The majority of these systems (75 MW) were to be shipped to South Korea to produce power for the electric grid [2]. In spite of the promising sales figures, market readiness has not been fully achieved as much of the deployment is subsidised or supported by grants (both in South Korea and the US).

[21] Although Japan has also experienced major blackouts, for example in 2011 and 2018.

Public funding for research and innovation on fuel cell technologies has been provided in the US through the Department of Energy (DOE), mainly coordinated by the Fuel Cell Technologies Office (FCTO). The Solid State Energy Conversion Alliance (SECA) program is responsible for coordinating efforts on solid oxide fuel cells, which are funded through the DOE's Office of Fossil Energy. In the decade from 2005-2015 the US federal government invested approximately 2.1 billion USD in FC&H technology development [77].

There are also deployment initiatives at individual state level with significant funding levels. Incentives are provided in California, Connecticut and other states, from programmes with aims to achieve reduced greenhouse gas (GHG) emissions, improved power reliability, enhanced energy efficiency, and lowered consumer demand on the electric grid [78]. State policies on increasing the share of renewable energy in California, Connecticut and New York have strongly contributed to the deployment of stationary fuel cells, and are therefore analysed in more detail below.

California

California suffered an electricity crisis in 2000-2001 when it experienced high energy prices (including via market manipulation) and rolling blackouts. Since then, California has regulated to ensure this does not happen again, and has diversified its energy supply to include the highest levels of renewable energy in the US [79]. However, as mentioned above, grid reliability is still an issue to date. California has the second highest energy demands after Texas, despite having one of the lowest per capita rates of energy consumption in the US [80], due to the mild weather conditions.

According to the California Stationary Fuel Cell Collaborative, as of March 2018, more than 220 MW of fuel cell systems were installed in close to 200 cities in California. [22]

The majority of these installations have received support from California's Self Generation Incentive Program (SGIP) for the deployment of distributed energy systems. The programme has provided support of up to 4,500 USD/kW for fuel cell systems that use biogas, and half as much for natural gas-powered fuel cells [81]. The funding rates have since been reduced, with up to 1200 USD/kW support currently being given to fuel cells supplied with biogas (600 USD/kW for natural gas). Since 2001, more than 450 fuel cell systems have been installed in California with SGIP support. As of January 2017, the total fuel cell capacity was 188 MW, with 45.5 MW of CHP fuel cell systems and 142.7 MW of electric-only fuel cells [78]. The SGIP program currently has a budget of 61 million USD allocated to renewable generation [82]. Recent revisions of the program have been made, and 75% of the budget is now reserved for energy storage technologies. By 2020, power generation based on natural gas has to be replaced by 100% biogas to be eligible for funding.

An analysis into the effect of the SGIP programme on fuel cell system costs found that there was actually little or no effect on installed costs (around 10000 USD/kW for SOFC and 8000 – 9000 USD/kW for PAFC and MCFC) [83]. For reference, the state of the art 2015 DOE value for installed cost with natural gas is 3000-4000 USD/kW, and the 2017 SoA CAPEX of the FCH JU 3000-3500 EUR/kW. In the report, the lack of cost reduction was attributed to either the flat part of the experience curve being reached or a US marketplace with limited competition. In the US only three OEMs are active, one in each of the technology areas, which in the opinion of the authors of this report provides less pressure on pricing and also limits the development of a diverse supply chain. It should be noted that of the three companies that are active, Bloom Energy is based in California and has been responsible for approximately 60% of the installed capacity in the state.

Public support for fuel cell deployment has not only been financial. In California, the Air Resources Board (CARB) considered the low emissions of fuel cells when considering permit requirements and other certifications [84]. Some fuel cells have received certification that they meet the state's emission standards, and are exempt from air permitting requirements (for example DFC® products by FuelCell Energy [21]).

[22] This is potentially a good benchmark for the accuracy of our database which provides a total for California of 244 MW. The higher value in our instance may be due to a number of factors: the most likely of which is the inclusion in our database of some projects which may not yet be fully deployed, although some double-counting where projects are not clearly defined may also provide a contribution.

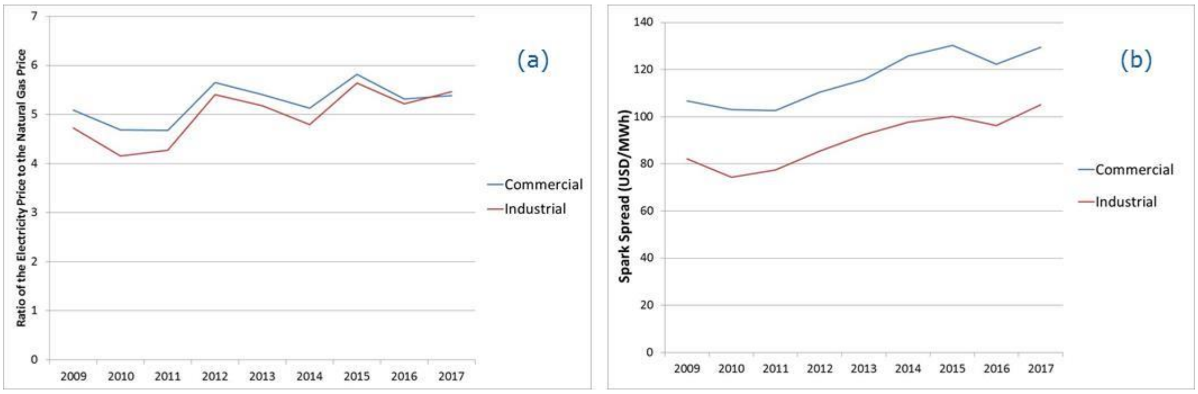
California's Renewables Portfolio Standard (RPS) has set targets for retail sellers of electricity and local publicly owned electric utilities. They must increase the amount of renewable energy they procure such that 50 percent of their retail sales are from eligible renewable energy resources by December 31, 2030. Facilities using fuel cell technology may qualify for RPS certification if the facility uses either an RPS-eligible renewable energy resource, or hydrogen produced from renewables [85].

Although most fuel cells installed in California seem to be running on natural gas, there are examples of biogas utilisation, in particular for MCFC [23]. Many of these fuel cells utilize anaerobic digester gas (ADG) from wastewater treatment facilities which are required to reduce emissions by California air quality regulations. The excess heat of the fuel cells can be used in anaerobic digesters to generate ADG, which can then be fed back into the fuel cell.

CARB has granted conditional certification for FuelCell Energy's renewable hydrogen generation at wastewater treatment facilities. The Orange County 2.3 MW MCFC installation is operating in tri-generation mode, also providing hydrogen for fuel cell vehicles. The renewable hydrogen supplied for vehicle fuelling is eligible for a Low Carbon Fuel Standard credit that can be sold or traded to offset carbon-intensive petroleum fuel usage [78].

Figure 11 shows how the price ratio for electricity/natural gas and the spark spread have varied for California in the period 2009-2017. A slight increase in the spark spread has been observed, both for commercial and industrial users. Values of the spark spread for commercial users are more attractive than in the industrial case (almost 130 USD/MWh), with values that could offer economic viability to FC solutions for their current state of the art. Figure 11 (a) shows the evolution of the ratio of the electricity to the natural gas price in the period from 2009-2017. Its value has remained stable during this period, but with very high values in both markets, with prices of electricity more than 5 times higher than natural gas prices. In these cases, if CAPEX could be reduced by means of funding support, FC electricity production could provide considerable savings when compared with electricity purchase. Historically, California has suffered from a lack of a secure electricity supply which may contribute to these higher prices, and provide an incentive for fuel cell power generation.

Figure 11: (a) Ratio Electricity / Natural Gas Prices (b) Spark spread; for California 2009-2017



Connecticut

Currently, Connecticut has around 50 MW of installed capacity of fuel cells, but will expand to ~100MW as projects for the deployment of Bloom Energy, Doosan Fuel Cell America and Fuel Cell Energy fuel cells have recently been selected for funding[24] [86].

The Connecticut Renewable Portfolio Standard (RPS) requires electricity providers to obtain a specified percentage or amount of the energy they generate from renewable sources. Utilities are mandated to generate

[23] For example in Fountain Valley, Ontario, Moreno Valley, Perris, La Jolla, Point Loma, South Bay (water reclamation), Riverside (water quality control plant).

[24] It should be noted that our database provides a total in the region of 96 MW for Connecticut which suggests that many of these more recently approved projects have been included in the figures to 2017, as no double-counting is evident.

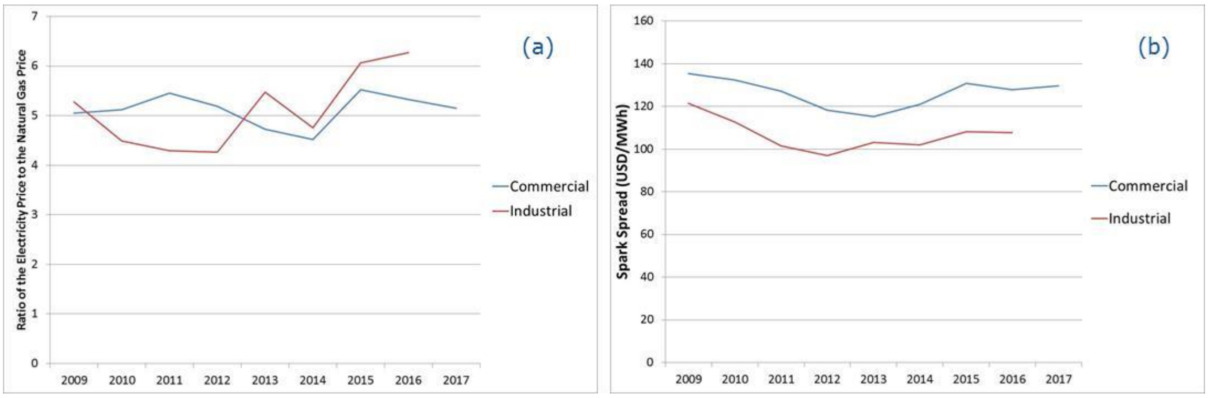
no less than 17% of the total output from Class I renewables, with targets rising to 40% by 2030. Fuel cells are considered a Class I renewable energy source, without further specification of the fuel. The Connecticut energy policy specifically mentions fuel cell projects, which should receive no less than 50% of energy credits in the Class I energy credits programme, provided the fuel cell is manufactured in the state [87]. It should be noted that both FuelCell Energy and Doosan Fuel Cell America are based in the state and have been responsible for approximately 95% of the capacity installed or approved for installation to date.

The Low-Emission Renewable Energy Credits Program enables participants to sell Class I Renewable Energy Credits created from renewable projects to the utilities. In Connecticut, legislation has been passed enabling the utilities to recover the costs of installing fuel cells to the end customer [88].

Connecticut also started a micro-grid grant programme following weather-related power outages in 2012, under which fuel cells have been installed in critical facilities[25] [84]. As in California, waste water treatment plants (WWTP) are becoming increasingly interested in fuel cell technology. In 2017, three fuel cell systems from Doosan Fuel Cell America were installed at WWTPs, and another is to be installed in 2018 [84].

Connecticut has very interesting values for spark spread and ratio of the electricity to the natural gas price, both in commercial and industrial markets. In Figure 12 these values are displayed for the period 2009-2017 for commercial users whilst industrial market values are only currently available to 2016. Spark spread and the ratio of the electricity to the natural gas price values have remained very constant in the period considered. As in the case of California, the energy price situation could offer economic viability to FC solutions.

Figure 12: (a) Ratio Electricity / Natural Gas Prices (b) Spark spread; for Connecticut 2009-2017



New York

Between 2000 and 2017, New York State has seen the deployment of more than 16 MW of large scale stationary fuel cells making it the U.S. state with the third largest level of deployment. The New York State Energy Research and Development Authority (NYSERDA) has funded 24 continuous-duty stationary power fuel cell systems representing 7.1 MW as of March 2018, and is supporting 12 other projects under development that are expected to add 2.5 MW [89]. Furthermore, an additional 15 million USD has been made available for the time period of 2018/2019 for systems supporting critical infrastructure facilities including hospitals, police and fire stations, as well as supermarkets.

Fuel cell systems can provide resilience by supplying power to critical building loads during a power failure. Distributed generation is seen as a solution to the lack of reliability of the power grid, and fuel cells are regarded as particularly advantageous as they can also provide heat and hot water, reducing the vulnerability to power outages [90]. Resilience in the face of extreme weather, and reducing greenhouse gas emissions by

[25] Defined as hospitals, police stations, fire stations, water treatment plants, sewage treatment plants, public shelters or correctional facilities, any commercial area of a municipality, [or] a municipal centre.

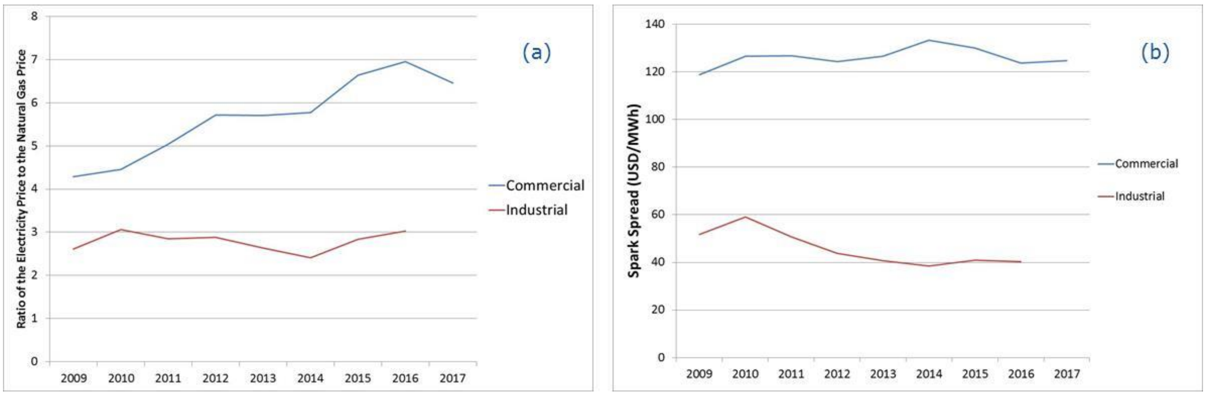
40% by 2030 are the key drivers for fuel cell deployment in the state of New York. According to the New York State Clean Energy Standard (CES), fuel cells using either renewable or non-renewable fuels may be certified for Tier 1 of the renewable energy standard if they meet all other requirements. This certification enables the project to obtain renewable energy certificates that can then be used to demonstrate compliance to the renewable energy targets by the load serving entities[26] (LSE) [91]. The CES requires that 50 percent of New York's electricity comes from RES by 2030 and requires every LSE in New York State to procure renewable energy credits (RECs) associated with new renewable energy resources—known as Tier 1—for their retail customers.

In 2016, the Long Island Power Authority approved the Fuel Cell Resources Feed-in Tariff IV for interconnection of fuel cell equipment sized from 1 MW to 20 MW [78]. The PSEG Long Island Fuel Cell Resource Feed-in Tariff program provides a formula rate for all the electricity generated over a 20 year term by the eligible fuel cell system. The program has a goal to install 40 MW of fuel cells, which will be provided by FuelCell Energy for electrical substations [84]. Systems that use less than 100% renewable energy sources are also eligible to participate. The program will purchase all of the electricity generated by the fuel cell system at a fixed price plus a variable cost of fuel. The rate will be determined through a bidding process [92].

The spark spread and ratio of the electricity to the natural gas price for New York State are shown in

Figure 13. It can be seen that the business case for FC systems is clearly more favorable in the commercial market. In fact, with the values obtained for the industrial case, it does not seem that there is a business case in this sector for electricity production with FC.

Figure 13: (a) Ratio Electricity / Natural Gas Prices (b) Spark spread; for New York State 2009-2017



US in General

Programs supporting the installation of fuel cells also exist in other states, such as Massachusetts and Pennsylvania. Notable are the differences in the specification of the feedstock for the fuel cell – the state with the highest installed capacity, California, actually calls for biogas or hydrogen produced from renewables. Connecticut and New York do not mandate renewable fuel. From a policy perspective, fuel cells contribute towards renewable energy targets. From a practical perspective they provide additional grid resilience through Transmission and Distribution (T&D) deferral. This is particularly important as it is claimed that the US electricity grid is suffering from insufficient investment (e.g. in [93]).

[26] Typically utilities or other energy providers.

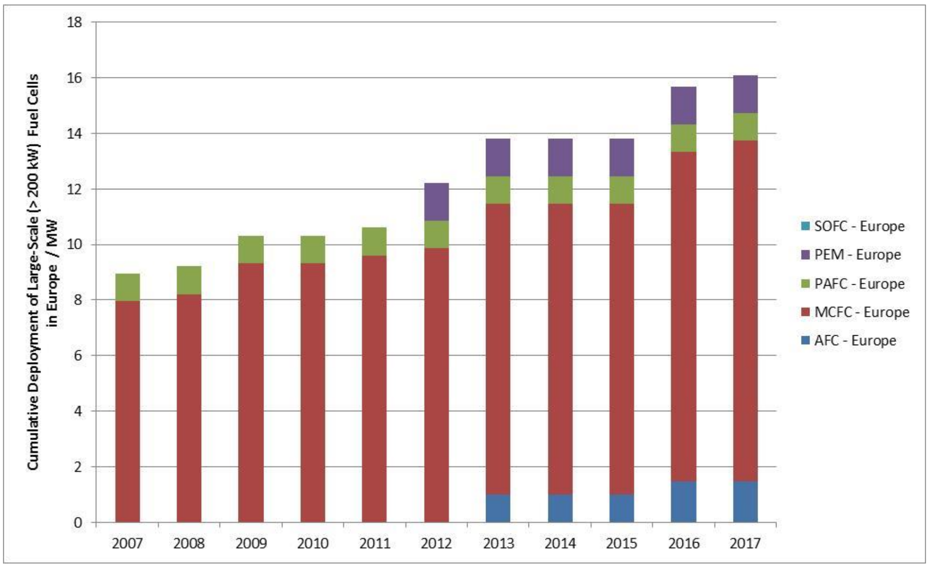
5.4 Europe

Through the renewable energy directive, it is clear that Europe is strongly committed to promoting the use of energy from renewable energy sources, specifically identifying the need to support the integration of energy from renewable sources into the transmission and distribution grid and the use of energy storage systems for integrated variable production of energy from renewable sources [94]. However, historically, the investment levels specifically targeting large-scale stationary fuel cells for power generation and CHP are low.

Currently there is only around 16 MW installed capacity of large scale fuel cells in Europe (Figure 14). A study conducted by Roland Berger for the FCH JU in 2015 analysed the potential demand for prime power and combined heat and power (CHP) in Europe [95]. The study revealed a substantial potential market for the large scale segment: 1.4GW of installable capacity at data centres and 5.6GW of CHP systems. Large addressable markets are seen, for example, in the UK for data centres, and Germany for chemical and pharmaceutical production facilities, breweries and wastewater treatment facilities. Considering the potential deployment in Europe, Italy, UK and Germany seem promising in terms of the penetration of the gas grid, allowing for stationary fuel cells to commercialise using already existing infrastructure. Considering this positive potential, it is striking that the actual deployment has been so limited, especially considering that the European funding for fuel cells and hydrogen R&D has steadily increased under FP4 – FP7, up to a total of around 2 billion Euro [3], which is complemented by national funding, for example the NIP program in Germany[27]. Under Horizon 2020, the funding for stationary fuel cells in the industrial and commercial segment has amounted to 34 M Euro to date [96]. The German National Innovation Programme (NIP) is also supporting fuel cell development, but has a focus on the automotive sector, the residential sector and increasingly on maritime applications, for which large capacity fuel cells are needed. However, unlike in certain other regions, in Europe there has not been any incentive programme for distributed generation or installation of renewable energy sources from which fuel cell manufacturers were able to directly benefit.

The business base in Europe has been stated to be weak due to low electricity prices and good reliability of the electrical grid in Europe (see extract from MAWP – Annex A) with correspondingly lower customer demand for back-up power. For example in Germany the average customer was affected by power outages on average for 15.3 minutes in 2015 (which saw some extreme weather events) [16].

Figure 14: Cumulative deployment of large scale stationary fuel cells in Europe (EU-28 countries) shown from 2007 onwards (deployment data considered from 2000 onwards)



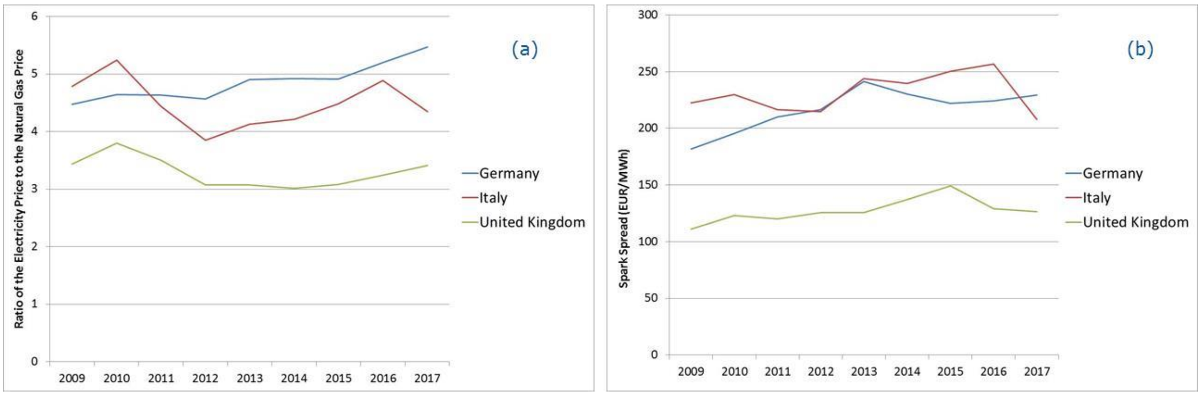
[27] The German programme supporting Hydrogen and Fuel cells, NIP, is not currently supporting stationary fuel cells of medium to large capacity.

Prices in the European energy market vary from country to country. Regarding the industrial market, Spain has the highest differences in prices between electricity and natural gas, with a spark spread of over 230 EUR/MWh and a ratio of the electricity to the natural gas price greater than 6 (in 2017). Finland, on the other hand, is the European country where the implementation of FC solutions to produce electricity from gas natural seems the least feasible, with a spark spread below 4 EUR/MWh and a ratio of the electricity to the natural gas price of approximately 1.5 (in 2017). As mentioned above, Germany, Italy and UK are countries where the penetration of the gas grid could make the use of FC to produce electricity an attractive proposition.

Figure 15 shows the spark spread and ratio of the electricity to the natural gas price for those countries in the period from 2009-2017, which suggest that Italy and Germany are better positioned to deploy FC solutions, with a very high spark spread and ratio of the electricity to the natural gas price. Although the values for the UK are lower than for Germany and Italy, they are high enough to demonstrate a business case for electricity production with FC systems.

In general, the situation of energy prices for industrial customers in Europe in recent years appears to be more attractive for this kind of application than in the other countries considered in this report; however the level of deployment is significantly lower in Europe. Europe has not had a concerted program of incentives from which fuel cell manufacturers in the large-scale stationary segment are able to directly benefit. This has been the major tool to facilitate adoption of large-scale stationary fuel cells in other geographical regions discussed above.

Figure 15: (a) Ratio Electricity / Natural Gas Prices (b) Spark spread; prices for industrial customers for selected EU countries 2009-2017



5.5 Summary

The landscape of adoption of large-scale stationary fuel cells according to the main geographical regions can be summarised as follows:

United States:

- Considerable financial support for deployment projects from public funding at state level (in particular in CA and CT)
- Main drivers appear to be green energy targets and lack of reliability of electricity grid supply
- Main applications are in electrical supply and back-up; customers often large public service providers
- All three main technologies (MCFC, SOFC, PAFC) are active and manufactured within the US
- Only California makes the distinction that the fuel must be from a renewable source.

South Korea:

- Ambitious plans for renewables due to high GHG emissions and poor air quality.
- Fuel Cells are designated as part of the "New and Renewable Energy" program **regardless of fuel source** and hence qualify for Governmental financial support.
- Deployment is eligible for significant public funding support. South Korea does not seem to be concerned with the origin of the technology and IP (which is largely from the US).
- Many projects are by major power producers who receive Government incentives.
- PAFC and MCFC dominate.

Japan:

- Very few large-scale stationary projects.
- Focussing more on transport and residential applications.
- Large conglomerates invest in fuel cell development (elsewhere, it is mainly companies dedicated to fuel cells).

European Union:

- Very few large-scale stationary projects.
- Products not yet fully developed in the medium range (5-400 kWe).
- Reliant on global know-how for large-scale stationary applications (especially from the US).
- There does appear to be an economic case supporting implementation as evidenced by the spark spread calculations, at least for certain countries.

In Table 2 below, a summary has been made of the main drivers for the adoption of large-scale stationary fuel cells for the key geographical areas discussed above, along with a subjective rating for each geographical region, indicating the positive or negative influence of this driver on the adoption of the technology. It should be noted that drivers refer specifically to **large-scale fuel cell implementation** and not to other fuel cell applications (e.g. Japan is rated low for Governmental incentives specifically for implementation of large-scale stationary fuel cells, although it is supporting micro-scale adoption at a very high level).

Table 2: A Summary of the Key Drivers for Adoption of Large-Scale Stationary Fuel Cells per Geographical Region. The final column shows the actual level of adoption to date

Country (State)	Manufacturer	Lack of a reliable Electrical Grid	Government Incentives	Spark spread	Commitment to Lower GHG Emissions	Air Quality Issues	Energy Security Concerns	**Level of Adoption**
US (CA)	+	++	++	++	++	o	o	**High**
US (CT)	++	+	++	++	++	o	o	**High**
US (NY)	-	++	+	o	++	o	o	**Medium**
S.Korea	+	o	++	-	++	++	++	**High**
Japan	-*	o	-	o	++	o	++	**Low**
Europe	-*	- -	-	- **to** ++#	++	o	o **to** +	**Low**

* Whilst there are no manufacturers at the scale needed, there are manufacturers with experience of the relevant technologies, albeit for smaller scale applications.

The spark spread has been calculated for several EU states in the relevant section, however it is quite variable from country to country

6 Conclusions

The long history of stationary fuel cell development and deployment has culminated in a strong growth during the last 10 years, but whether this will lead to full commercialisation, and for which technologies, is as yet uncertain.

The global deployment of large-scale fuel cells is currently dominated by the US and South Korean market, which together make up almost 95% of installed capacity. Within the US, there are also major differences in the approach taken at state level, with the majority of the capacity installed in only two states. In fact, California, Connecticut and South Korea combined, are responsible for > 70% of the world's installed stationary fuel cell capacity.

Worldwide, three technologies dominate: MCFC, SOFC and PAFC. Only limited large-scale application of AFC and PEMFC has been initiated. Furthermore, one specialist company dominate the production of each FC type: FuelCell Energy (MCFC), Bloom Energy (SOFC) and Doosan Fuel Cells (PAFC).

Fuel cell manufacturers are still largely dependent on public funding in order to support deployment activities of large-scale stationary fuel cells, whether through technology push or market pull measures. The main barriers at this stage seem to be reliability (availability and lifetime) and cost of the fuel cells. A lack of fundamental understanding of electro-chemical processes has been cited as one of the causes of the many setbacks suffered by the fuel cell industry [3]. It is interesting that the type of state financial support provided in the US and South Korea does not appear to have led to the selection of a particular fuel cell technology, but has helped multiple technologies to expand. As there is only one manufacturer operating for each FC technology it is important that there is some form of competition to drive cost reduction, both for the product and within the supply chain. Currently, this competition must come from an alternative FC technology.

It is clear that considerable financial incentives would be required if the levels of implementation observed in the US and South Korea are to be realised in Europe. There is EU know-how in the field of large-scale stationary fuel cells but in general fuel cell companies are focussing on small to medium scale applications. This knowledge base, particularly in SOFC and PEMFC, could be utilised for increased levels of upscaling. However, if Europe should seek to deploy large-scale stationary fuel cells then it may be necessary to provide incentives for:

- Programs which specifically encourage the upscaling of existing technologies, for specific applications, inside the EU
- Large-scale deployment projects which do not rely on technologies developed inside the EU (This would be analogous to the approach taken by South Korea).

It may be more difficult to justify projects using technology produced outside of the EU (mainly in the US) than if the technology was produced within Europe, but the benefit could be seen through long-term development of a supply chain or manufacturing base in Europe.

On the other hand, there are not the same drivers present in Europe that there are in South Korea or selected parts of the US. In particular, Europe benefits from a stable electrical power grid. Investing in technology development to achieve the targets of the FCH JU programme (see Annex B) would be beneficial towards overcoming some of the remaining barriers, specifically lowering cost and improving reliability and durability. Europe has a strong manufacturing base for stationary fuel cells for the residential segment which provided with the correct incentives could be expanded to the larger scale. The spark spread analysis suggests that there could be a business case in certain European countries.

Annex A: MAWP targets

MAWP 2014 addendum 2018

Likewise, the much larger market of centralised power generation has not yet properly developed due to the low electricity prices for large industrial customers in EU (the Fuel cell industrial segment in Europe has struggled to find applications with viable business cases). There are however identified business opportunities for using European products in overseas territories or overseas markets that can serve as stepping stones for cost reduction and longer term strengthening of European industry. A number of projects around the world showcase large sized CHP installations such as the FCH 2 JU DEMCOPEM-2MW project[39] which deployed a 2 MW CHP system in China, the 1.4 MW project by E.ON and FuelCell Energy Solutions in Manheim[40], Germany and the 750 KW stationary system installed in New York, USA by Bloom Energy[41].

Industrial: Large scale installations for industrial use and grid support and district use (1 - 30 MW)

With the technology used in current demonstration projects it is unlikely that the KPI's for the industrial large scale segment will be achieved with European technology within the frame of the FCH 2 JU programme. Therefore longer-term actions might be required to open this segment to European technology and value creation. In this regard, new research activities have started within the FCH JU aiming at developing the next-generation MW-size Fuel cell Power Plant unit (FCPP) with reduced CAPEX and with grid services capabilities. Against this background, the focus of this segment in 2018-2020 should be on considerations of strengthening the supply chain for all system components with other sectors, including electrolysis, to benefit from mass-volume cost reduction and increased technical maturity

Annex B: State of the Art and Future Targets

State-of-the-art and future targets **large scale** FC installations, converting hydrogen and renewable methane into power in various applications (0.4 - 30 MW). From the MAWP 2014-2023 Addendum 2018.

No.	Parameter	Unit	SoA		FCH 2 JU target		
			2012	2017	2020	2024	2030
1	CAPEX	€/kW	3,000 4,000	3,000 - 3,500	2,000 - 3,000	1.500 - 2500	1,200 1750
2	Lifetime	years of plant operation	n/a	15	25	25	25
3	Availability	% of the plant	98	98	98	98	98
4	Durability of key component (stack)	khrs	15	20-60	20-60	20-60	25-60
5	Reliability	MTBF (hrs)	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%	-	100%/1 min	-

1) Cost of manufacturing (labour, materials, utilities) of the m-CHP unit at current production levels (exclude monetary costs, e.g. overheads, profits, rebates, grants, VAT, insurances, taxes, land).
2) Lifetime (years) that the m-CHP unit, with its major components/parts being replaced, e.g stack, is able to operate until the End-of-Life.
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 fuel cell 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 - Low Heating Value (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) Time required to reach the nominal fuel cell rated output when starting the system from shut-down mode (at ambient temperature).

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List of abbreviations and definitions

ADG	Anaerobic Digester Gas
AFC	Alkaline Fuel Cell
APU	Auxiliary Power Unit
CAPEX	Capital Expenditure
CARB	Californian Air Resources Board
CC	Carbon Capture
CCS	Carbon Capture and Storage
CES	Clean Energy Standard
CHP	Combined Heat and Power
DOE	Department of Energy (of the US)
ECN	Energy Research Centre of the Netherlands
EUR	Euro (currency)
FC	Fuel Cell
FCEV	Fuel Cell Electric Vehicle
FCH JU	Fuel Cells and Hydrogen Joint Undertaking
FCPP	Fuel Cell Power Plant
FCTO	Fuel Cells Technology Office
FC & H	Fuel Cells and Hydrogen
FIT	Feed-in Tariff
FP	Framework Program
GE	General Electric
GHG	Greenhouse Gas
IP	Intellectual Property
KRW	Korean Wan (currency)
LSE	Load Serving Entities
MAWP	Multi-annual Work Program
MCFC	Molten Carbonate Fuel Cell
METI	Ministry of Economy Trade and Industry (in Japan)
NASA	National Aeronautics and Space Administration (of the US)
NIP	National Innovation Programme (of Germany)
NRE	New and Renewable Energy
NYSERDA	New York State Energy Research and Development Authority
P2P	Power to Power
PAFC	Phosphoric Acid Fuel Cell
PEMFC	Proton Exchange Membrane Fuel Cell
POSCO	(formerly known as) Pohang Iron and Steel Company

REC	Renewable Energy Credits
RPS	Renewables Portfolio Standard
R & D	Research and Development
SECA	Solid State Energy Conversion Alliance
SGIP	Self-Generation Incentive Program (of California)
SOFC	Solid Oxide Fuel Cell
TCO	Total Cost of Ownership
UK	United Kingdom
US	United States of America
USD	United States Dollar (currency)
UTC	UTC Power, formerly part of United Technologies Corporation
UTP	Ulsan Technopark (in South Korea)
WWTP	Waste Water Treatment Plants

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