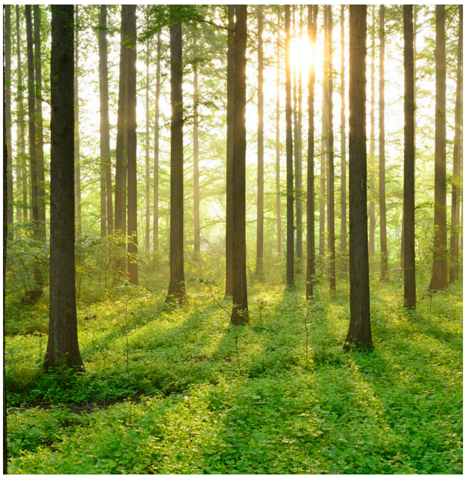
TECHNOLOGY REVIEW – SOLID OXIDE FUEL CELL

REPORT 2017:359



TEKNIKBEVAKNING
BRÄNSLECELLER

Swedish Electromobility Centre

Energiforsk

Technology review – Solid Oxide Fuel Cell

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Foreword

I syfte att koordinera teknikbevakningen, men också för att sammanställa, analysera och sprida information om utvecklingen inom bränslecellsområdet finansierar Energimyndigheten projektet **Teknikbevakning av bränsleceller**. Projektet och dess resultat vänder till svenska intressenter, främst fordonsindustrin, och genomförs under 2014 – 2016 inom ramen för kompetenscentret Swedish Electromobility Centre med Energiforsk som koordinator och projektledare.

Den här rapporten är en omvärldsbevakningsstudie av teknikläget för fastoxidbränsleceller, SOFC. Den beskriver nuvarande status samt nödvändig utveckling och de genombrytningar som krävs för att fastoxidbränsleceller ska kunna bli relevant för fordonstillämpningar.

Projektet har genomförts av Martin Andersson och Bengt Sunden på Lunds universitet.

Styrgruppen för projektet har bestått av följande ledamöter: Anders Hedebjörn och Stefan Bohatsch Volvo Cars, Annika Ahlberg-Tidblad Scania, Johan Svenningstorp AB Volvo, Bengt Ridell Sweco Energuide, Göran Lindbergh Electromobility Centre/KTH, Peter Smeds/Magnus Lindgren Trafikverket, Elna Holmberg Electromobility Centre och Bertil Wahlund Energiforsk. Energiforsk framför ett stort tack till styrgruppen för värdefulla insatser.

Samtliga rapporter från projektet kommer att publiceras och fritt kunna laddas ner från Energiforsks webbplats under Teknikbevakning bränsleceller på www.energiforsk.se och på Electromobility Centres webbplats www.hybridfordonscentrum.se.

Stockholm mars 2017

Bertil Wahlund Energiforsk AB

Swedish Electromobility Centre

Swedish Electromobility Centre, tidigare Svenskt el- och hybrid-fordonscentrum SHC, är ett nationellt kompetenscentrum för forsk-ning och utveckling av el- och hybridfordon och laddinfrastruktur. Vi enar Sveriges kompetens och utgör en bas för samverkan mellan akademi, industri och samhälle.

Sammanfattning

Kommersialiseringen av SOFC-system sker inom specifika nischmarknader, t.ex. lokal kraftgenerering till datacenters (främst i USA), småskalig kraftvärme för enskilda hushåll (främst i Japan) och för militära ändamål (exempelvis i USA). Den framtida potentialen är stor inom nämnda områden och även för t.ex. distribuerad kraftgenerering i MW-skala (förväntas starta i Japan samt Sydkorea) samt för APUer, och i vissa fall även för framdrivning, i lastbilar och andra fordon. Utvecklingen har under senare år inkluderat även elektrolys, dvs omvända elektrokemiska reaktioner för att producera vätgas och/eller metan.

Volvo har tidigare deltagit i europeiskt finansierade SOFC-projekt (expempelvis DESTA), men dessa är nu avslutade. Exempel på företag som arbetar med fordonsinriktad SOFC-utveckling är: AVL, Eberspächer och Elcogen i Europa, samt Delphi, Protonex och Ultra Electronics USSI i Nordamerika. Med militära (fordons) applikationer arbetar även Fuel Cell Energy och MSRI i Nordamerika och Catator i Europa.

En elektrisk verkningsgrad på 60 % (LHV) för ett 1,5 kW SOFC-system, som är möjligt att köpa (Solid Power), har uppnåtts, vilket kan jämföras med 72,5 % (LHV) för ett SOFC-system (under utveckling) hos SOFCMAN i Kina.

Antalet samarbeten i bräncellsbranchen ökar stadigt, exempelvis samarbetar Panasonic och Viesmann, Toshiba med BDR Thermea och Aisin med Bosch. Daimler och Ford samarbetar genom deras joint-venture AFCC-Auto. Honda och GM utvecklar gemensamt bränseceller. Honda samarbeter även med Ceres Power. VW arbetar tillsammans med Ballard.

Antalet företag som utvecklar bränslecellsystem baserade på flera olika teknologier ökar. Även antalet offentligt finansierade program (t.ex. Callux i Tyskland och ENE-FARM i Japan) som stöder flera olika bränslecellsteknologier parallellt ökar.

Den japanska regeringen använder OS 2020 i Tokyo som uppvisning för deras vätgas och bränslecellssatsningar.

Summary

The commercialization of SOFC systems starts within specific niche markets, such as on-site power generation for datacenters (mostly in USA), small-scale CHP for individual households (mainly in Japan) and in military applications (for example in USA). The future potential is enormous in the just mentioned areas as well as for APUs (or in some cases also for propulsion) in trucks and other vehicles as well as for MW-scale distributed power generation (expected to start in Japan and in South Korea). The development in recent years includes electrolysis as well, i.e., reversed electrochemical reactions to produce hydrogen and/or methane.

Volvo participated in some previous EU-funded SOFC research projects (e.g. DESTA) and is currently involved in EU-funded PEFC projects. SOFC development for the vehicle industry is carried out by AVL, Eberspächer and Elcogen in Europe, as well as Delphi, Protonex and Ultra Electronics USSI in North America. SOFC developments for military applications are carried out by Fuel Cell Energy and MSRI in North America and Catator in Europe.

An electrical efficiency of 60 % (LHV) for an SOFC system as small as 1.5 kW SOFCs (Solid Power) has been reached, compared to 72.5 % (LHV) for a 200 kW SOFC system under development by SOFCMAN in China.

The number of partnership/joint ventures is steadily increasing, so for instance Panasonic is a partner with Viesmann, Toshiba with BDR Thermea and Aisin with Bosch. Daimler and Ford are collaborating with their joint-venture AFCC-Auto. Honda and GM are jointly developing FCs. Honda is also collaborating with Ceres Power. VW is working together with Ballard.

The number of companies developing fuel cell systems based on multiple technologies is increasing. Also in public funded programs (e.g. Callux in Germany and the ENE-FARM in Japan), multiple fuel cell technologies are being installed.

The Japansese government is pushing the development to make the 2020 Tokyo Olympics a showpiece for its hydrogen and fuel cell strategy.

List of contents

1 News and Development trends (not limited to SOFC)

This chapter is based on the content of this report as well as what the authors learned from attending various conferences and IEA annex meetings (listed in chapter 7.1)

Summary of recent fuel cell (FC) developments

- Lifetime is increasing (total number of operating hours as well as achievable number of start/stops)
- For cars the level of technological maturity is higher (due to more experience) compared to commercial vehicles, which is expected to change with time. Notice that the stack power level is similar for passenger cars and medium duty trucks.
- Commercialization occurs via niche markets, where additional benefits are available (e.g., material handling devices and military equipment).
- Hydrogen increases the coupling of the energy need of transport, heat and electricity.
- Honda, Toyota and Hyundai launched FC cars.
  - × The waiting list in Japan for a Toyota Mirai is 3 years.
- Daimler, GM and BMW are expected to launch FC cars around 2020
- FC as range extender, for example to La Poste (France)
- First prototypes of FC trains are developed by Alstom.
- FCs for trams (in China) are being developed
- Over 10000 FC powered material handling devices are operating (mostly in US)
- Significant potential for unmanned aerial vehicles (UAVs), due to high system energy density, low heat signature and less vibration.
- Increased number of companies working with multiple types of FCs.
- Hydrogen infrastructure roll-out is coming, starting with Japan, California, Europe and South Korea.
- Demonstration program for FC buses in Europe with 100+ buses. Also in China and South Korea plans for FC buses demonstration program.
- The ENE-FARM mCHP subsidies were expected to terminate in 2015 but have been extended. However, decreased amount per unit.

Summary of recent SOFC development (not limited to the vehicle industry)

- Λifetimes over 78,000 hours reached for stack in laboratory environment (FZ Jülich). Note that this test is with 9 years "old technology" and even longer lifetime with technology of today is expected, but no "new" similar long-time tests have been started.
- The electrical efficiency is over 60% for a 1.5 kW SOFC CHP system that is available for purchase (SolidPower). A 200 kW SOFC system under

development by SOFCMAN in China reached 72.5 % (LHV) electrical efficiency.

- The number of companies developing fuel cell systems based on multiple technologies is increasing. Also in public funded programs (e.g., Callux in Germany and the ENE-FARM in Japan) multiple fuel cell technologies are being installed.
- Large-scale SOFC installations provided by Bloom Energy in the USA, have achieved significant deployment in USA by large companies. Unfortunately, the heat is not used. The motivation for most companies to install their own electricity generation is the relatively low grid stability, e.g., in USA.

1.1 FUEL CELL DEVELOPMENT

The numbers of patents filed for FC with automotive applications have been relatively constant the last 10 years, as can be seen in Figure 1 and the patents distributed on companies in Figure 2. Please note that all types of FCs are included [E4tech].

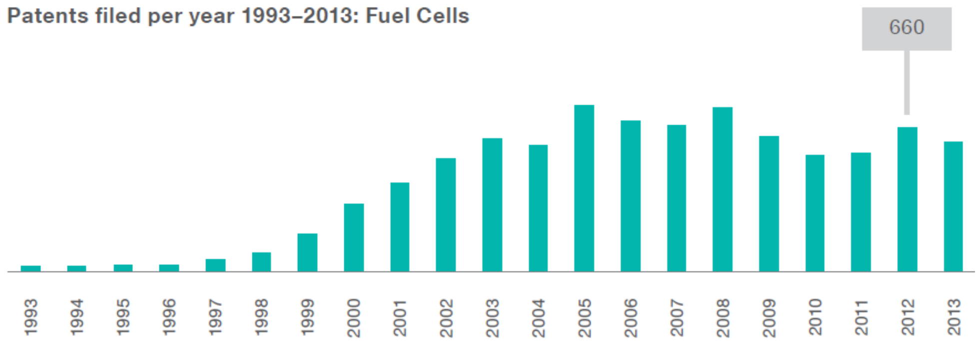

Figure 1. Filed FC for automotive applications patents per year [E4tech].

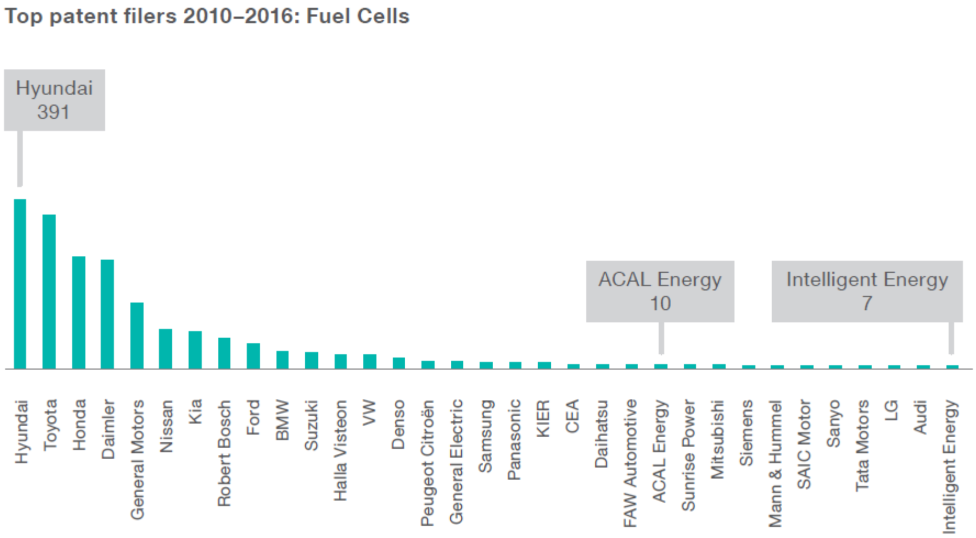

Figure 2. Patent filers connected to the vehicle industry [E4tech]

The deployment of FCs will be strongly dependent on legislation because the prices prior to mass-production are relatively high, compared to existing technologies. As an example zero-emission vehicle (ZEV) programs exist in the following US states: California, Connecticut, Maine, Maryland, Massachusetts, New Jersey, New York, Oregon, Rhode Island and Vermont [FCHEA 1]. The US DOE publishes an annual report focusing on FC customers [DOE].

A good example of government and business working together is the US DOE market transformation demonstration project with material handling FC vehicles. The governmental department funded partly 1600 units. The companies purchased additionally 13500 FC vehicles. The motivation for FCs in material handling vehicles includes improved electrical efficiency, faster refilling (compared to changing battery packs), constant reliable power and space savings (hydrogen infrastructure takes significantly less space than a battery room). Also in Europe the use of FC material handling vehicles is starting (with small numbers), for example DB Schenker (in Austria), Colryut (in Belgium), Starks construction market (in Denmark), FM Logistic (in France), IKEA (in France), BMW (in Germany), Daimler (in Germany) and Honda (in UK) [FCHEA 2].

Military applications in the power range of 1W to 100s of Ws is an attractive and potentially lucrative niche. Companies include for example Protonex (USA), Acumentrics (USA), UltraCell (USA) and SFC (Germany). FCs can be seen as the ideal power solution for UAVs, with ability to provide operating time significantly longer than for systems powered with batteries [E4tech 2]

1.1.1 Partnerships

The number of partnership is steadily increasing, e.g., Panasonic is partnering with Viesmann, Toshiba with BDR Thermea and Aisin with Bosch for microscale CHP (mCHP) [E4tech 2].

Daimler and Ford are collaborating with their joint-venture AFCC-Auto. Honda and GM are jointly developing FCs aiming for a 2020 vehicle. VW is working with FC development together with Ballard.

1.1.2 New niche markets

The niche market with FC for telecom companies is growing around the world. Examples of customers are: Jiangsu Communications Services Company (China), Ascend Telecom (India), Microqual Techno Limited (India), Reliance Jio Infocomm (India), Telkomsel (Indonesia), Digicel Group Limited (Jamaica), Vodafone (Netherlands), Warid Telecom (Pakistan), Globe Telecom (Philippines) and Vodacom (South Africa) [FCHEA 2].

The world's first hydrogen powered passenger train is planned to be launched in December 2017 with trains from Alstom (Corada iLint). Both the hydrogen tanks and the FCs are placed on the roof of the train (Figure 3). This is a part of the public funded German program, activities towards FCs onboard trains, i.e., replacing diesel engines on specific non-electrified rail routes. Reference routes are Buxtehude-Bremerhaven-Bremervörde-Cuxhaven-Buxtehude and Frankfurt-Köningstein. An advantage with train applications is that the refueling infrastructure can be made of rail tank wagons, which are then possible to move according to requirements [Alstom, EY].

Figure 3. Corada iLint [www.alstom.com]

1.1.3 Different types of fuel cells

The FC is not a new invention, because the electrochemical process was discovered already in 1838-39. Among various types of FCs, the SOFC has attained significant interests because of its high efficiency and low emissions of pollutants to the environment. High temperature operation offers many advantages, such as high electrochemical reaction rate, flexibility of using various fuels and tolerance for impurities. The main advantage of the SOFC (compared to the polymer electrolyte fuel cell (PEFC)) is the outstanding high electrical efficiency. However, it is important to point out that the PEFC is a more mature technology and also that the lower operating temperature enables a faster start-up. The lower voltage, the higher electrical efficiency is possible (Figure 4).

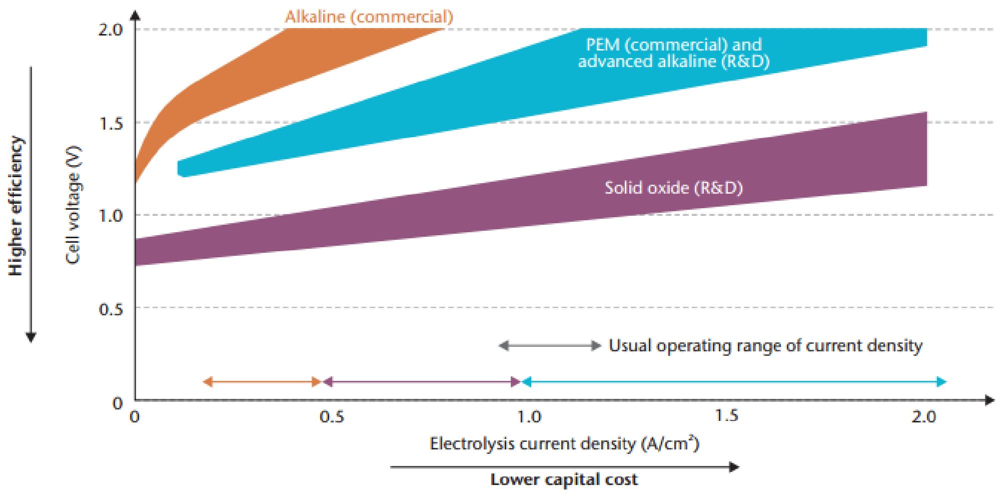

Figure 4. Sketch of the technology development potential of different electrolysers [IEA 2].

SOFCs can work with a variety of fuels, e.g., hydrogen, carbon monoxide, methane and combinations of these. Also fuels with longer carbon chains are possible, however, they need to be pre-reformed outside the anode. Oxygen is reduced in the cathode (Figure 5) and the oxygen ions are transported through the electrolyte, but the electrons are prevented to pass through the electrolyte. The participation of methane in the electrochemical reactions at the anodic TPB is negligible, instead it is catalytically converted in the methane steam reforming reaction, externally or within the anode, into carbon monoxide and hydrogen, which are used as fuel in the electrochemical reactions. Carbon monoxide can be oxidized in the electrochemical reaction, but can also react in the water-gas shift reaction.

Hybrid concept involving a combination of a gas turbine and a FC can be developed with high conversion efficiency. Also hybrid systems with batteries are promising, because the FC can be operated with an optimized load, i.e., the fuel conversion efficiency can be increased and the start-up time can also be reduced.

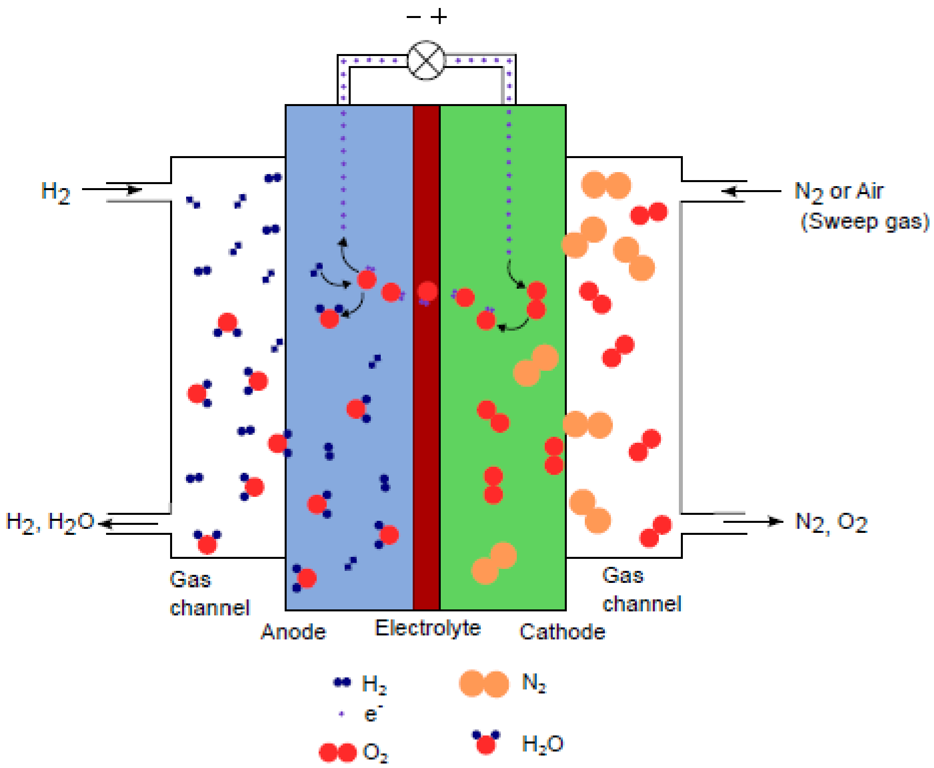

Figure 5. Sketch of the electrochemical reactions in an SOFC [MN].

1.1.4 Solid Oxide Electrolysis Cells

In a future hydrogen society, energy efficient production processes for hydrogen need to be built in very large scale, to capture surplus of electricity, e.g., when wind power is high.

Presently water electrolysis is one of the most suitable processes for hydrogen production at large scale. Water is split into hydrogen and oxygen by applying electrical energy. An increased temperature increases the total energy required for electrolysis slightly while the required electrical energy decreases. Thus, high-temperature electrolysis (HTE) might be a suitable process to consider when waste heat from other sources is available. Solid oxide electrolysis cells (SOEC) can use the waste heat from industry to decrease the heat demand from the endothermic electrochemical reactions and the electricity obtained from renewable sources, mainly solar cells or wind turbines. HTE of water takes place at temperatures between 700 and 1000 °C and the technology is based on the high-temperature cells, i.e., SOECs. A sketch of an SOEC is presented in Figure 6. An SOEC can be understood as an SOFC operating in reversed mode due to the similarity. An SOEC consists also of the same components as an SOFC, i.e., air and fuel channels, an anode, a cathode as well as an electrolyte. Also the materials are normally the same: YSZ for the electrolyte, Ni-YSZ cermet for the steam/hydrogen electrode and LSM for the oxygen-side electrode [MN]. Topsoe Fuel Cells (in Denmark) is a company working with SOEC research and development.

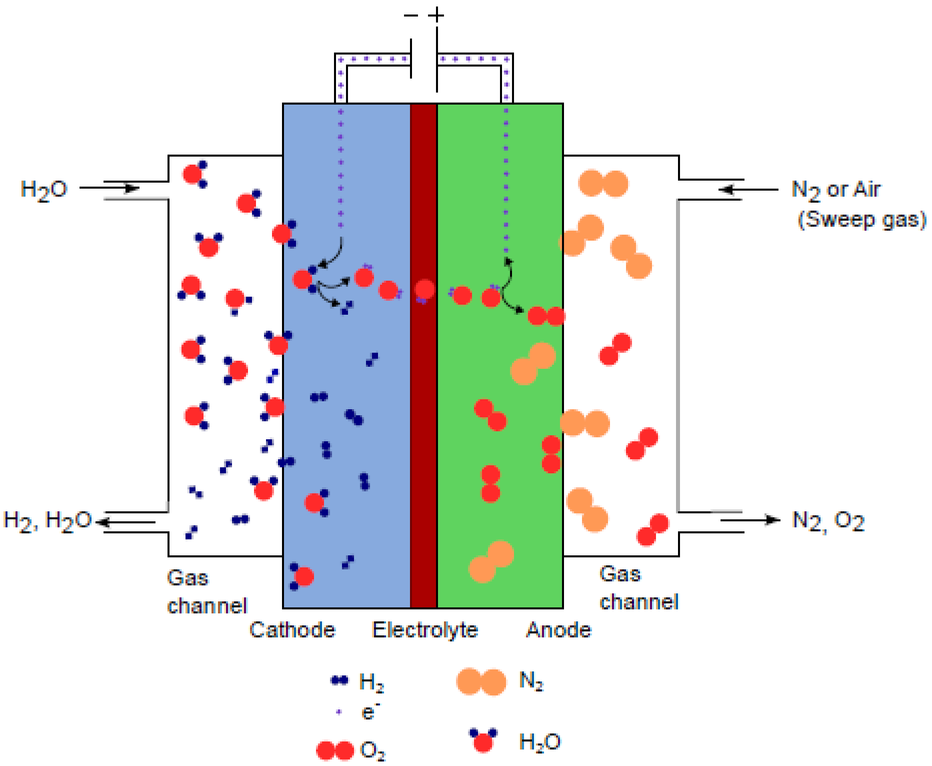

Figure 6. Sketch of the electrochemical reactions in an SOEC. [MN]

2 Significant European SOFC research projects aiming for the vehicle industry

2.1 FCH-JU (EU)

The Fuel Cells and Hydrogen Joint Undertaking (FCH JU) is a public private partnership supporting research, technological development and demonstration activities in FC and hydrogen energy technologies in Europe. The aim is to accelerate the market introduction of these technologies, realizing their potential as an instrument in achieving a carbon-lean energy system. The three members of the FCH JU are the European Commission, FC and hydrogen industries represented by Hydrogen Europe and the research community represented by the Research Grouping N.ERGHY [FCH JU].

The current phase (2014-2020, i.e., Horizon 2020), have a total budget of €1.33 billion, provided on a matched basis between the EU, represented by the European Commission, industry, and research. It is expected that the projects under FCH 2 JU will improve performance and reduce the cost of products as well as demonstrate the readiness on a large scale of the technology to enter the market in the fields of transport (cars, buses and refueling infrastructure) and energy (hydrogen production and distribution, energy storage and stationary power generation) [FCH JU].

As a part of FCH-JU, pilot deployment of buses around Europe (300-400 buses before 2020) is included, however, so far without direct Swedish participation [FCH JU 2]. It should be noted that the Volvo group also participates in FCH JU through Renault Trucks.

2.1.1 SAFARI

The aim of the SAFARI-project is to develop an SOFC APU for a truck running on LNG, to provide power, heat and cooling for the cab, in an efficient way. LNG was chosen, as the fuel, because it is increasingly used in the EU as a truck fuel and it is also economic, cleaner than diesel, and is becoming widely available. There are now 800 natural gas stations in the EU and 1000 in the US where trucks can fill their tanks with LNG. SAFARI is primarily focused on the truck platform, but the technology is transferable to other mobile end-users that use LNG, including cars, vans and boats. Project partners are Adelan (UK), Hardstaff Group (UK), Almus AG (Switzerland), University of Birmingham (UK), IREC (Spain) and ZUT (Poland). The 36 months project was finished in December 2016 [Cordis].

2.1.2 SUAV

SUAV aims to design, optimize and build a 100-200 W microscale SOFC (mSOFC) stack, and to integrate it into a hybrid power system comprising the mSOFC stack and a battery. Additional components of the system are a fuel processor to generate reformate gas from propane and other equipment for the electrical, mechanical and control balance of plant (BoP). All these components will be integrated into a mini UAV platform. SUAV is primarily aiming at the CopterCity

UAV platform from Survey Copter (France) but also considers other options (in particular fixed wing vehicles). Propane was chosen as the fuel due to its superior energy density compared to hydrogen, regardless of the storage technique used. SOFC technology was chosen because it can convert reformate (i.e., CO/H2-mixtures) to electricity, whereas other types of FC technology require very pure hydrogen. The design of the mSOFC power generator is primarily driven by the weight and volume available in the mini-UAV. The project intends to optimize the mission duration, while efficiency is of less concern. Collaborators are: HyGear Fuel Cell Systems, Adelan, Catator, CNR-ITAE, EADS, Efceco, University of Birmingham, Survey Copter and ZUT. SUAV was finished on Nov 30th 2015 [SUAV].

2.1.3 DESTA

The main objective of DESTA is the demonstration of the first European SOFC APU for trucks. The motivation for using SOFCs is the compatibility with conventional road fuels (including a reformer in the system). The project started with defining the APU requirements for the application of a SOFC APU in a Volvo heavy-duty truck for the US market. Within DESTA, Eberspächer and AVL proposed already existing SOFC APU systems which were thoroughly evaluated through a benchmark test at each of the partners at the beginning of the project and Volvo defined a test cycle for this benchmark test. The project partner Forschungszentrum Jülich had the responsibility to monitor that Eberspächer and AVL kept in line with the test cycles, to analyze the test results and to classify whether the systems were mature enough to perform well in a truck demonstration. The consortium chose the Eberspächer system, which was ready for integration after one design loop. The task of the Eberspächer technicians was then to design, build up and to pretest an APU which converts conventional US diesel into a hydrogen and carbon monoxide rich gas and finally into electricity. Volvo's role in the project comprised the development of the vehicle requirements, the design of power electronics and the control system for vehicle communication, to perform the electrical and mechanical integration into the vehicle and to conduct extensive vehicle testing. The DESTA project resulted in an APU, with an electrical net power class of 3 kW, on board a long haul truck. The project ended on June 30th 2015 [DESTA].

Figure 7. DESTA SOFC APU [www.desta-project.eu]

2.1.4 SAPIENS

Within the SAPIENS project microtubular SOFCs (mSOFCs) were designed and optimized, to systems which can recharge the leisure battery in a recreational vehicle (RV), while also providing useful heat. The project targets the RV's from Auto-Sleepers, a UK SME. Liquid petroleum gas (LPG) was chosen as the fuel because of its superior energy density compared to hydrogen and methanol, and also because it is a preferred fuel for RV appliances, with RVs having a large underslung autogas LPG tank. The mSOFC developed can utilize LPG for power and heat in a lightweight, compact unit, capable of rapid start-up, with low noise and emissions. Highlights of the SAPIENS project, which finished on October 31st 2015, include the final design of a 100 W mSOFC generator. The consortium companies are Adelan (Coordinator; UK), Auto-Sleepers (UK), CARRD (Austria), CUTEC (Germany), ZUT (Poland), JRC (Netherlands) and IREC (Spain) [SAPIENS]

2.2 NIP (GERMANY)

NIP (Nationalen Innovationsprogram Wasserstoff- und Brennstoffzellentechnologie) is a collaboration between 4 federal German ministries. NIP's first phase took place between 2006-2016. Political decisions autumn 2016 approved a continuation for a second phase between 2016 and 2026. During the second phase public funds up to EUR 1.4 billion are available and the funding from industry is expected to be more than EUR 2 billion [NIP 1].

Germany is very focused on its FC activities and as an example 192 companies were behind the last NIP call. Including subcontractors and suppliers around 500 German companies are active in the hydrogen and FC field [NOW].

3 Companies working with SOFCs for transport

3.1 DELPHI (USA)

Delphi is focusing on electronics for automotive technologies. The company has created SOFC units since 1998, focusing towards powering vehicles, military applications and stationary power. The fuel flexibility is high and the Delphi SOFC can be engineered to operate with e.g. natural gas, diesel, bio-diesel, propane, gasoline and coal-derived fuel. Delphi is the only member of the U.S. Fuel Cell Council that has developed and demonstrated a practical, operational SOFC APU for heavy duty commercial trucks. Delphi has received funding from the U.S. Department of Energy and the U.S. Department of Defense for FC development [IEA 1].

Delphi develops rectangular robust anode-supported cells. Their generation-4 (Figure 8) is the latest product in which the anode, cathode and electrolyte are based on nickel oxide yttria-stabilized zirconia, yttria-stabilized zirconia (YSZ) and Strontium-Cobalt-Lanthanum-Ferrite (LSCF) with Ceria-based interlayer, respectively. A single Delphi Gen 4 SOFC Stack can provide 9 kW of electrical power and features a modular design, which could be integrated into larger power plants. Generation-4 stacks have 403 cm^2 of active area, providing 110 VAC and/or 12 VDC, with electrical efficiencies ranging from 40 to 50% [IEA 1, Delphi].

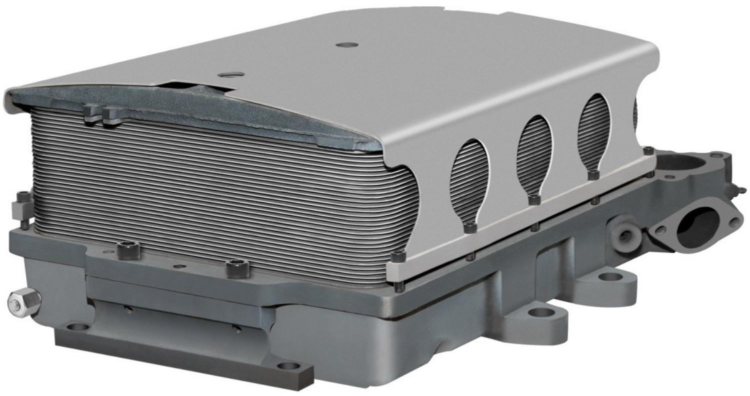

Figure 8. Delphi SOFC generation-4 stack [Source www.Delphi.com]

Delphi has in cooperation with Volvo Trucks North America (VTNA) developed a backup system suitable for heavy duty trucks and recreational vehicles, allowing main engine shut-off during long-term parking and full use of the cabin services with electricity from the fuel cell, i.e., saving up to 85% of the fuel used for main engine idling today [IEA 1].

3.2 FUELCELL ENERGY (USA)

FuelCell Energy (FCE) is originally a developer of molten carbonate fuel cell (MCFC) systems, but absorbed Canadian Versa Power, i.e., taking over and further developing the SOFC technology. In this way FCE brought their knowledge of FC system deployment, especially related to multiMW power plants, to value at smaller power scales targeted by Versa Power's SOFCs. FCE has incorporated the SOFC components into FC stacks as part of an FCE project under the U.S. Department of Energy Solid State Energy Conversion Alliance (SECA) program. The long term objective of the SECA program is to introduce low-emission, high-efficiency SOFC based systems operating on coal gas in the size range of hundreds of MW. Other members of SECA's coal based program include Gas Technology Institute (GTI), Pacific Northwest National Laboratory (PNNL), Worley Parsons Group Inc., SatCon Power Systems Inc., and Nexant Inc [IEA 1, Fuel Cell Energy 1].

The high efficiency and fuel flexibility of the SOFC technology make it attractive for selective portable power applications, an example (of an UUV (Unmanned Undersea Vehicle)) can be seen in Figure 9. FCE has contracts with the U.S. Navy and also sub-contracts with the U.S. Defense Advanced Research Projects Agency (DARPA) program. The U.S. Navy is evaluating the use of SOFC power for propulsion and ship power of unmanned submarine applications as the high efficiency, virtual lack of emissions, as well as the quiet operating nature, which is well suited for stealthy operations. The DARPA airborne system incorporates both SOFC and solar power generation. During the day, the solar power generation is used to power the aircraft and excess solar power generation is converted to hydrogen by the FCs as they operate in electrolysis (reversed) mode. At night, the FCs run in FC mode, converting the stored hydrogen to power. Notice that SOFC based energy storage systems have the potential to provide reasonable round trip energy efficiency with further development. [IEA 1, Fuel Cell Energy 2].

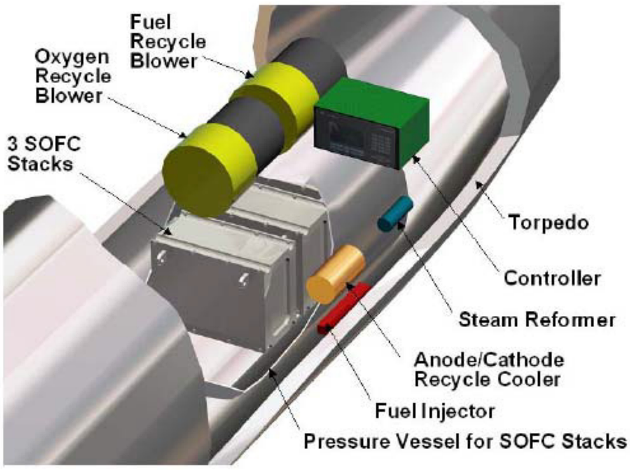

Figure 9. Close-up of the conceptual SOFC system inside the torpedo shell [www.fuelcellenergy.com]

3.3 MATERIALS AND SYSTEMS RESEARCH, INC (USA)

Materials and Systems Research, Inc. (MSRI) was founded in 1990 and has developed anode-supported planar SOFCs (Figure 10) with very high power density (W/cm^2) by optimizing the microstructure of the composite electrodes. MSRI has demonstrated 1-3kW class SOFC power modules under various projects. Their 1 kW stack consists of 33 cells and has the dimensions of 5.5″ x 5.5″ x 4.7″ (W x L x H). MSRI is also developing a 3 kW air-independent SOFC stack for U.S. Navy's UUVs [MSRI, IEA 1].

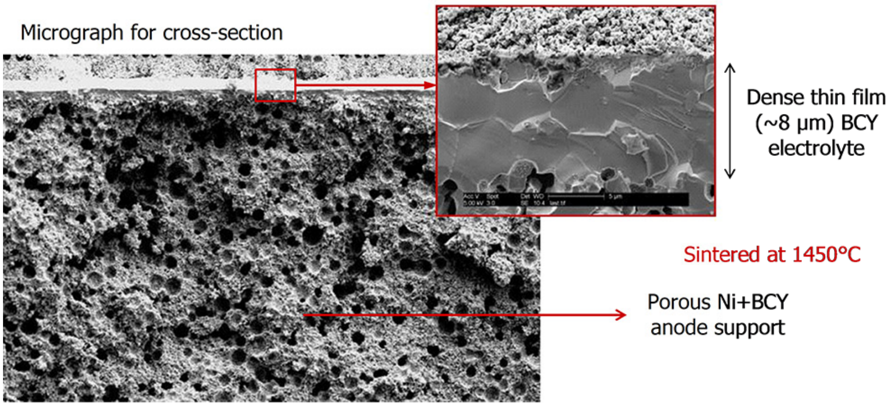

Figure 10. MSRI planar anode supported SOFC design [www.msrihome.com].

MSRI's tubular anode supported design (Figure 11) can be subjected to frequent thermal cycles and can be quickly heated (e.g., within a couple of minutes) without cracking. Also no hot seal is needed. A 36-tubes bundle for a 300 W portable power unit under an Office of Naval Research project has been developed [MSRI].

Figure 11. MSRI tubular anode supported SOFC design [www.msrihome.com].

3.4 PROTONEX (USA)

Protonex was founded in 2000 with the aim of developing and marketing PEFC units. In 2007 it acquired Mesoscopic Devices LLC, a company involved in the research and development of SOFC technology, which expanded its commercial interests to SOFC technology. In the past, Mesoscopic Devices had built 'MesoGen-75' and 'MesoGen-250' portable systems, at 75 W and 250 W, respectively, with funding from the U.S. Department of Defense and the U.S. Navy. These units were able to provide suitable power levels for radios, sensors, and small batteries, which could be fueled by propane or kerosene. MesoGen-250 models were also designed to operate as a field battery charger as well as auxiliary and emergency units on military vehicles [IEA 1].

Today Protonex develops SOFC systems based on a compact tubular-cell technology, which has the robustness required for portable and mobile applications. The SOFC product currently exhibited is the P200i (Figure 12) which outputs 20-200 W. The P200i powers remote sensors, signaling, and communications systems with a temperature range from blistering heat to arctic cold (i.e., +55°C to -30°C), for years without human contact. Protonex claims that when coupled with solar panels to minimize fuel consumption, the P200i withstands more cycles and operation hours than SOFC systems of their competitors [Protonex].

Figure 12. The Protonex P200i system [www.protonex.com].

3.5 ULTRA USSI (USA)

Ultra USSI was established in 1993 in Ann Arbor. In 2011 Ultra Electronics acquired Adaptive Materials, a developer of small SOFC systems using microtubular technology. Adaptive Materials was the first company to develop portable SOFC systems demonstrating their applicability in the field and has collaborated with U.S. Department of Defense since 2001 [USSI 1, IEA 1].

Ultra-USSI has today a portfolio of quiet, compact, and eco-friendly SOFC-based systems fed with propane to be utilized in the military (Figure 13), civilian and industrial sectors. The D300 (300W) model is suitable for applications as power support of on-field military power demand. The P250i (250W) is suitable for remote power supplies (boats or campers, to power GPS systems, radios, refrigerators) and emergency back-up power, and can also be fueled with natural gas. As an example, the P250i FC system provides 24/7 extended run back-up power for railway signals and crossings in relatively large volumes [USSI 1, USSI 2, IEA 1].

USSI delivered 45 units of the D300 adapted for unmanned aerial vehicles (UAV) to be used by the U.S military in unmanned aerial systems. The D245XR (245 W) unit provides long duration flights, i.e., more than eight hours in relatively small unmanned aerial vehicles, being much more suitable than conventional batteries. All of their devices provide 12-24 DC Voltage power supply [USSI 1, IEA 1].

Figure 13. USSI's fuel cell system [www.ultra-fuelcells.com]

3.6 AVL (AUSTRIA)

AVL is developing SOFCs as well as PEFCs. AVL has developed and operated a stationary SOFC CHP platform fueled with natural gas in the range of 5-10 kW electricity as well as APU systems for vehicle applications. The AVL APU system is operated with conventional diesel fuel and reaches a net electrical power output of 3 kW with an electrical efficiency of 35%. The system can also provide heat independent of fuel cell operation up to 10 kW. The system is intended for truck anti-idling, maritime and other mobile power generator applications. AVL participated in multiple EU funded research projects [AVL].

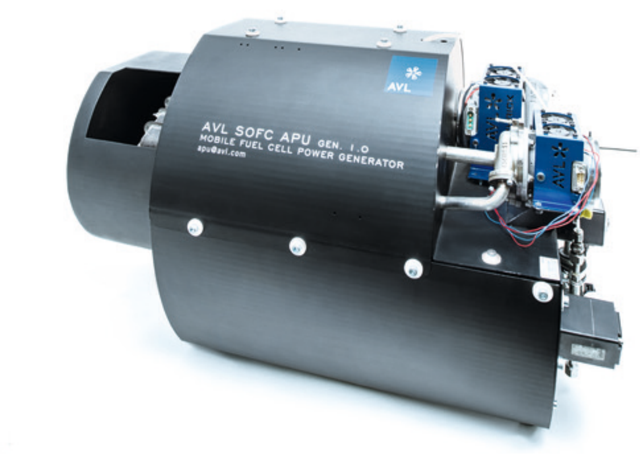

Figure 14. AVL's SOFC APU. [www.avl.com]

3.7 EBERSPRÄCHER (GERMANY)

The German automotive supplier Eberspächer has developed an FC APU that runs on diesel, to power onboard components in a truck. The APU, combines a diesel fuel reformer with an SOFC. The FC APU system operates entirely independently from the truck's main engine, i.e., the electrical loads can be taken from the generator when the vehicle is stationary, reducing consumption and emissions. These loads include the air-conditioning system or the cab's refrigerator, which require continuous power. The FC APU efficiently generates electrical power from the diesel in the truck's fuel tank. The maximum output is 3 kW, with an electrical efficiency up to 40%. The system can also be used while the vehicle is being driven, saving fuel. The Eberspächer APU features an SOFC (from an unnamed supplier) that can generate electricity from fuel gas, which is produced in a reformer, where diesel is mixed with air, then passed through a catalytic converter, to produce the fuel gas containing hydrogen and CO. Ebersprächer is planning to launch the fuel cell APU initially on the US market at the end of 2017 [FC Bulletin].

3.8 CATATOR (SWEDEN)

The Lund based company Catator participated in a few EU funded FC projects and also collaborated with the Swedish military (Figure 15). Catator developed reformer and fuel processing technology which according to themselves requires minimum amount of catalyst with maximum performance. Their fuel processor units, for generation of H_2, works with a wide range of fuels, e.g., natural gas, LPG, ethanol, methanol, diesel, kerosene and jet-fuel (JP8). Reformers are developed for SREF (Steam Reforming), CPO (Catalytic Partial Oxidation), ATR (Autothermal Reformer) and also combinations of the different reforming technologies (Multiformer). The reformers can be supplied in capacities from a few tenth of W to hundreds of kW. The fuel processor units can be used in combination with different FC stack technologies, such as the SOFCs as well as the PEFC [Catator].

Figure 15. Catator's FC system developed for the Swedish military.

4 Selected companies working with SOFCs for non-transport applications

4.1 BLOOM ENERGY (USA)

Bloom Energy was founded in 2001 with the name Ion America and is based in California (USA). Bloom Energy commercializes SOFC systems with over 50% net electrical efficiencies (the heat is not used). The core of their products is stacks of planar electrolyte-supported FCs manufactured with metals sprayed on ceramic supports. Part of the technology adopted was already developed through their work as a partner in NASA's Mars Program. The company has continuously increased the size of their systems during these last years, currently producing the servers: ES-5000, ES-5400, ES-5700 (Figure 16) and ES-5710, generating 100, 105, 200 and 250 kW_{el}, respectively. The heart of these servers is built up with 1 kW_{el} stacks, labelled as 'Bloom Boxes', which are composed of 40 cells of 25 W_{el} each, fueled with natural gas or biogas. Blooms incredible shrinking power module now delivers 250 kW_{el}, in the space that just a few years ago delivered 100 kW [IEA 1, Bloom Energy, E4tech 2].

Bloom Energy's electrons-as-a-service program was launched already in 2011. Through this program, customers buy the power from the fuel cells instead of buying the fuel cells themselves. The financing is, in the USA, a tax equity investment and the term of the deal is normally 15 years.

Figure 16. Bloom Energy's energy server [www.bloomenergy.com]

A number of renowned multinationals have chosen to install Bloom Energy's servers to power their headquarters, the vast majority of these are in California, due to the high electricity price, the unstable power grid and the environmental image. As an example, Google, Coca-Cola, Ebay, Walmart and Bank of America are amongst their customers. Each Energy Server can be connected, remotely managed and monitored by Bloom Energy. The system can be grid-connected or stand-alone configuration, ensuring continuous supply of energy, with high electrical efficiency even at part loads.

4.2 BOSCH THERMOTECHNOLOGY (GERMANY)

Bosch Thermotechnology was founded in 1886. In terms of FCs, their "energy centre" for single- and two-family houses has been launched. They use flat-tubular stack technology from the Japanese AISIN group (chapter 4.8). Their main "energy center" product is CERAPOWER, which is based on the Aisin's 700 W system and is currently tested in the frame of the European mCHP demonstration project ene.field [IEA 1].

4.3 CERES POWER (UK)

Ceres Power was founded in 2001 to commercialize the unique core materials technology developed at Imperial College during the 1990s. Today, Ceres Power develops micro-CHP SOFC systems for the residential sector and also for energy security applications. Ceres Power collaborates with industry partners such as British Gas, Calor Gas and Bord Gais (Icelandic company). The patented Ceres SOFCs are metal-supported (stainless-steel), allowing rapid start-ups and a great number of on/off cycles with little degradation. Their operating temperature range is 500-600°C, i.e., around 200°C lower than "standard SOFC" cells designed with conventional materials. This is possible due to the metal support (allowing the use of extremely thin and active catalytic components) and by using a new generation of ceramic material known as CGO (cerium gadolinium oxide), instead of the industry standard YSZ [Ceres Power 1, IEA 1].

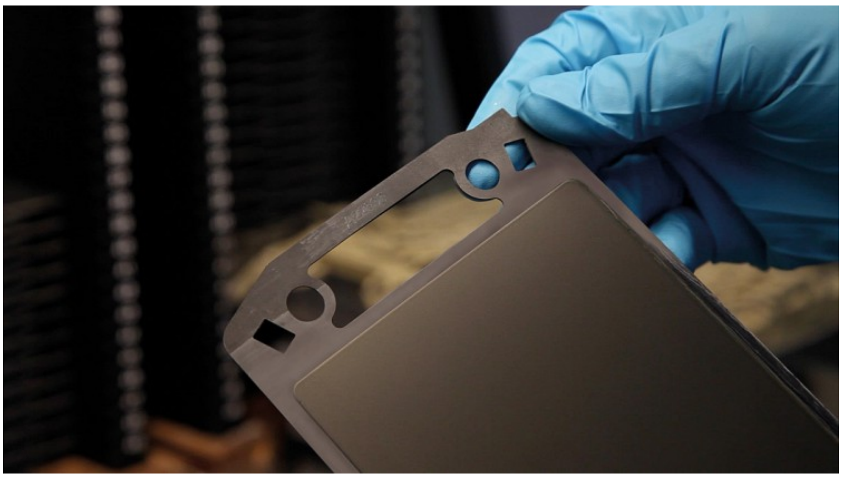

Figure 17. Ceres Power steel cell [www.cerespower.com]

The company's first pre-commercial product is an integrated wall-mounted residential FC CHP product. The compact product is designed to replace a conventional boiler, using the same natural gas, water and electrical connections and with similar installation and maintenance requirements. These mCHP units have shown degradation rates of approximately 1% per 1000 hours of operation. According to Ceres, the mCHP product has the potential to meet the overall commercial performance requirements supporting mass market deployment from 2018 [IEA 1].

Ceres' partners Itho-Daalderop (Netherlands) and British Gas (UK) are to purchase 174 mCHP units for sale, installation and trial in Dutch and UK homes starting in 2014. Feedback from these trials will be used to refine the product and validate performance and operability prior to mass volume launch in 2018. The trials are part of the *ene.field* project, a large-scale demonstration of a thousand FC micro-CHP products across Europe [IEA 1].

Ceres Power and Honda announced in January 2016 a renewed joint development agreement, to jointly develop SOFC stacks using Ceres Power's metal supported Steel Cell technology for a range of potential power equipment applications [Ceres Power 2].

4.4 CONVION (FINLAND)

Convion was established in 2012 and in 2013 the company took over Wärtsila's FC program and continued the development and commercialization of products based on SOFC technology as an independent company. Convion claims that they are committed to commercialize SOFC systems in power range of 50-300 kW for distributed power generation and fueled by natural gas or biogas. Convion shareholders include VNT Management and Wärtsila. Installations of multiple parallel modules can form an on-site power plant of power output of several hundreds of kilowatts, securing critical loads and providing continuous power and heat generation as a back-bone generator of a local microgrid. Convion is participating in the European funded DEMOSOFC project. [Convion, IEA 1].

Figure 18. Convion C50 SOFC module [www.convion.fi]

4.5 ELCOGEN (FINLAND/ESTONIA)

Elcogen was established in 2001 and focuses on commercializing anode-supported SOFC cells and stack to open markets. Its cell technology is optimized for operating at 600-700 °C and Elcogen claims that it cells provides state-of-the art cell performance both in FC and electrolysis operation modes. A lifetime expectation over 20 000 hours combined with the low-cost manufacturing methods already implemented in cell production, which enhances the cost effectiveness of stack and system structures. The development is in collaboration with the Estonian and Finnish research institutes KBFI and VTT Technical Research Centre of Finland, respectively. FC stacks of 1 kW electricity using 39 cells (Figure 19) is offered. The design is modular to enable its use in applications ranging from hundreds of Ws to hundreds of kWs. The decreased operating temperature (600–700°C) facilitates the use of cost-effective metals in the stacks. The Elcogen manufacturing process enables a production of various forms of cell, circular or rectangular up to a maximum of 20x20 cm for a cell [Elcogen, IEA 1]. It should be noted that Elcogen collaborates with Chalmers, Sandvik and Volvo developing truck APUs.

Figure 19. Elcogen E 1000, 1 kW stack [www.elcogen.com]

4.6 SOLID POWER (ITALY/SWITZERLAND/GERMANY)

SOLIDpower (SOFCpower before January 2015) is based in Trentino (Italy) and was born in 2006, by carving-out the SOFC activities started in 2002 within the Eurocoating – Turbocoating Group, active in the fields of coatings and processes for gas turbines, machinery and biotechnology. In 2007, SOLIDpower acquired 100% of HTceramix, a spin-off of the Swiss Federal Institute of Technology in Lausanne (EPFL). In 2015 it acquired, the German business and employees of Ceramic Fuel Cells (CFC) after the Australian parent company cut funds [IEA 1, Solid Power]

SOLIDpower is specialized in design, development and manufacturing of mCHP systems based on SOFC technology, with very thin (< 0.3 mm) YSZ electrolyte anode-supported cells with a porous perovskite cathode which provides high performance. The cells are produced by water-based tape-casting and screen-printing processes at an 8 MW/year capacity production plant in Mezzolombardo, Italy. SOLIDPower claims that good mechanical stability is provided by the relatively dense anode structure without any limitation on gas diffusion. SOLIDpower cells achieve high power densities (>1 W/cm²) allowing > 90 % fuel utilization and can be operated from 650 °C to 800 °C with various fuels. SOLIDPower is active partner of several European funded research projects [IEA 1, Solid Power].

SOLIDpower currently commercializes two highly efficient products for distributed cogeneration, both using natural gas from the grid:

- BlueGEN (originally from CFCL), which is the most efficient 1 kW-scale generator in the world, generates continuously electric power at 60% (LHV, lower heating value) efficiency for systems with the size of 1.5 kW. With an annual production of 13.000 kWh of electricity, BlueGEN is appropriate for small commercial applications [BlueGEN].

Figure 20. BlueGEN hotbox (opened) [www.bluegen.de]

- EnGEN 2500 is a mCHP system with a nominal electrical output of 2.5 kW and 50% electric efficiency, which targets multi-family houses and commercial applications. The wide range of modulation (30-100%) guarantees operation according to the actual electricity and heating needs. Furthermore it can be combined with other power/heat generators from renewable sources (wind, solar) or heat pumps, as well as electric storage or UPS systems [Solid Power].

4.7 HEXIS/VIESMANN (GERMANY)

Hexis/Viesmann was created in 1997 as a venture division of Swiss engineering and manufacturing firm Sulzer and became independent in 2006. In 2007 the subsidiary company in Germany, Hexis was created. In 2016, Hexis was taken over 100% by Viesmann, the multinational boiler manufacturing company. Hexis develops SOFC-based CHP units for stationary applications with electrical power requirements below 10 kW. The company develops planar SOFC technology (with a circular design). The fuel enters the anode part of the cell through the middle of the disc, flowing radially outwards. The preheated air follows the same path on the cathode side. Their latest pre-commercial product is “Galileo 1000N”, which uses a stack module made up of approximately 60 cells, and can be fed either with natural gas or bio-methane, as the system integrates a catalytic partial oxidation (CPOX) reactor. The nominal electrical power output is 1 kW (AC), and the thermal power output is 2 kW, with an electrical efficiency of up to 35% and maximum overall efficiency of 95% (LHV) [Hexis, IEA 1].

Figure 21. Hexis’ Galileo system [www.hexis.com]

4.8 AISIN SEIKI / KYOCERA (JAPAN)

Toyota Motor Corporation is the biggest shareholder in Aisin (Toyota Industries Corporation being the second) and Aisin-Seiki is one of twelve main companies in the Aisin group. Aisin Seiki is a big subcontractor for vehicle industry [Aisin Seiki].

Segmented planar, anode-supported SOFC cells which operate between 700 and 750°C are produced by Aisin Seiki. Japan has a major deployment program of micro-CHP systems ongoing, named “ENE-FARM”, based on both PEFC and SOFC technology. In 2016 over 130 000 ENE-FARMS have been installed since the start in 2009. However, approximately 90 % contain a PEFC, but the SOFC fraction is increasing. Currently Kyocera is the only company supplying stacks based on SOFC, though competitors TOTO and NGK may introduce their stacks to the market soon [IEA 1].

In close collaboration between Kyocera, Osaka Gas, Aisin Seiki, Chofu Seisakusho and Toyota, the "ENE-Farm Type S", which is fed with utility natural gas, was completed in 2011, achieving an electrical efficiency of 46.5% (LHV), and a total efficiency of 90% (LHV). The SOFC system includes a heating unit. Within the co-development agreement, Aisin produces the generation units, Kyocera the stack, Aisin the generation units with the cell stack incorporated into it and Chofu the hot-water supply and heating unit, using exhausted heat. Osaka Gas commenced sales of the system in 2012 but it is sold only to the Japanese market [Kyocera].

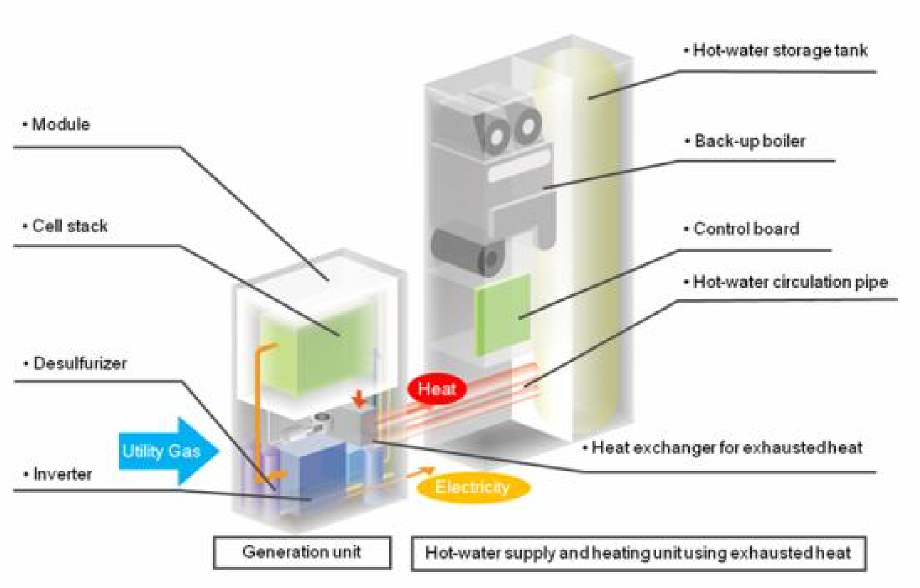

Figure 22. ENE-FARM typ-S design [www.kyocera.com]

Kyocera collaborates also with the energy company JX Nippon Oil & Energy, under the name of ENEOS Celltech Co. ENEOS was co-created in 2008 by JX NOE in partnership with Sanyo Electric, which is the system designer/manufacturer integrator and distributor. From JX NOE's background in the oil industry, the natural gas reforming technology used in the product was developed. JX NOE has announced plans to start selling its residential SOFC unit in Germany and in June 2012 a partnership was signed with the Centre for Fuel Cell Technology (ZBT) in Germany, to evaluate the suitability of the system operating under German conditions, particularly with regards to gas quality [IEA 1].

4.9 MITSUBISHI-HITACHI HEAVY INDUSTRY (JAPAN)

Mitsubishi-Hitachi Heavy Industries (MHI) was established in 1914 and has been involved in the field of high-temperature FCs since the 1990s. In 1998, in cooperation with Electric Power Development Co., a pressurized SOFC module was produced, which operated for 7000 hours and had a maximum power output of 21 kW. In 2004 MHI succeeded in the first domestic operation of a combined-cycle system combining SOFC and a micro gas turbine, with a confirmed generation of 75 kW at Mitsubishi's Nagasaki Shipyard & Machinery Works. In 2007 they scaled up the system size to 200 kW, with a maximum power output of 229 kW and an electric efficiency of 52 %. MHI has continued to increase the reliability and to further reduce the unit size. MHI recently demonstrated a 250 kW coupled SOFC-microturbine in a triple combined cycle system which also generates steam to power a steam turbine. This is currently in operation at Kyushu Ito University [IEA 1].

MHI uses a mono-block layer built (MOLB) type of cell, which is a planar cell constructed of a ceramic substrate made up of anode, electrolyte and cathode (so-called generation membrane), dimpled in three dimensions and manufactured on an uneven surface with an interconnector that connects the generation membranes in series, which acts as a gas seal at the cell end [IEA 1].

With an SOFC (pressurized) and a micro gas turbine (MGT) system, the electrical efficiency of a gas-fired 250-kilowatt-class system becomes 55 percent. In the future, the electrical efficiency of a natural gas-fired 20-MW-class system is expected to reach 60 percent. However, in a natural gas-fired 700-MW-class combined-cycle system consisting of an SOFC + gas turbine + steam turbine an electrical efficiency of 70 percent or higher can be expected [MHPS].

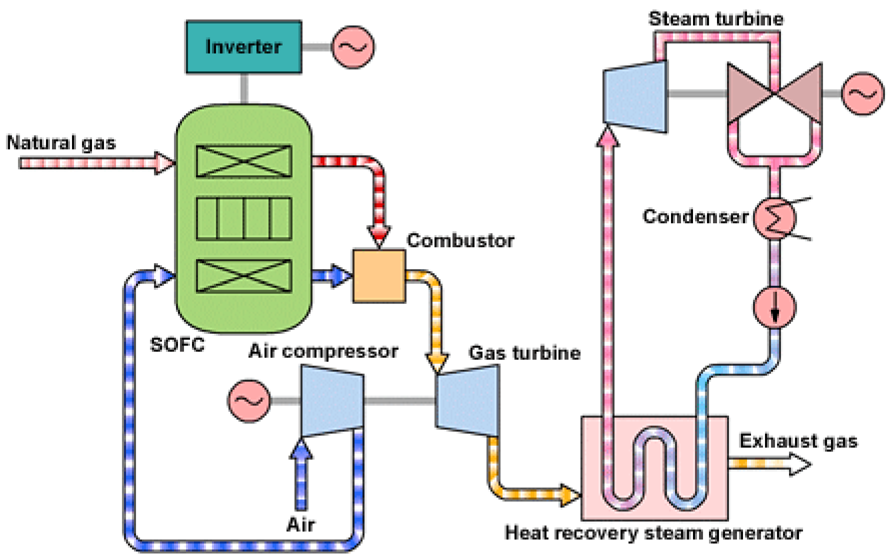

Figure 23. MHI design tri-generation system [www.mhps.com]

4.10 POSCO (SOUTH KOREA)

POSCO Energy was founded in 1969 as Kyung-In Energy Company, which joined the POSCO group in 2005. It is an energy provider engaged in four energy business areas, i.e., power generation, renewable energy, FC, and resource development. The FC division of POSCO Energy is located at Pohang City. POSCO produces stationary systems with MCFC technology and building applications with SOFC technology. It currently supplies 100 kW, 300 kW, and 2.5 MW FC systems [IEA 1, POSCO].

Figure 24. POSCO's SOFC-cells of different sizes (maximum size 1000 cm²) [www.posco.com].

4.11 SOFCMAN (CHINA)

SOFCMAN in Ningbo, China, is developing a 200 kW SOFC system with a single hot box configuration. Such a system consists of 192 stack modules, using cells in size of 14x14 cm² and with 25 cells each. Recently SOFCMAN claims that it measured a stack module having world record performance, i.e., an electrical efficiency of 72.5% (LHV) with a fuel utilization of 94.3% [SOFCMAN]. In a real system operation, one may not use such a high fuel utilization, but an electrical efficiency of almost 70 % (LHV) for a system size of some hundreds kWs should be possible.

Figure 25. SOFCMAN's 14x14 cm² stack [http://www.sofc.com.cn].

5 Analysis and Discussion (not limited to SOFC)

This chapter is based on the content of this report as well as on what the authors learned from attending conferences and IEA annex meetings (listed in chapter 7.1)

SOFC has a higher electrical efficiency compared to other types of fuel cells. It is possible to achieve an electrical efficiency of 60 % LHV for systems as small as 1.5 kW.

The FC commercialization is taking place in niche market by niche market. The APU is a good pioneering niche market for SOFC vehicle related commercialization.

The electrical efficiencies are significantly higher compared to an idling diesel engine.

The early PEFC commercialization from Toyota, Honda and Hyundai is preparing the (vehicle) market also for SOFCs at later stages.

The European research projects DESTA and ENSA have recently been finished and currently the SUAV program includes SOFCs on vehicles.

Bloom Energy, probably the biggest SOFC player (in terms of MW), but much less visible (public) information is available, compared to most other players. Their employees attend conferences but active participation in terms of presentations is rare.

The number of partnership is steadily increasing, e.g., Panasonic is a partner with Viesmann, Toshiba with BDR Thermea and Aisin with Bosch. Daimler and Ford are collaborating with their joint-venture AFCC-Auto. Honda and GM are jointly developing FCs. VW is working together with Ballard.

The number of companies selling (and developing) technology for several types of FCs increases rapidly, i.e., each type has its own advantages and disadvantages.

When writing this report, it has been easier to find information from each company's homepages, and the authors interpret this as a sign that SOFCs are coming closer to commercialization, i.e., the information is aimed for marketing.

At conferences, the military (especially the US) participation increased significantly, or at least the active participation with presentation increased. The advantage with the military market is that the customers are less price sensitive, compared to the vehicle or CHP markets.

Most public funding programs (EU, USA and Japan) require significant industrial co-funding, i.e., the research and development are following the needs of the industry.

FCs onboard trains is a new potential niche market with the first demonstrations expected during 2017.

Drivers for FC commercialization and development

- Political "push" for significantly reduced global warming emissions is expected to increase after the Paris-agreement.
  - × Hydrogen is expected to play a significant role of a future low carbon energy system.
  - × "Low" carbon today and possibility for zero carbon in the future
- Demand for an increased energy security (i.e., local production)
- Requirement of increased energy efficiency
- Development of local and regional energy markets, i.e., there will be multiple solutions and with flexible production pathways.
- Energy can be stored as hydrogen, enabling more renewable energy such as wind power.
- Air quality (significantly lower emissions compared to a combustion engine)
- Japanese government is pushing the development to make the 2020 Tokyo Olympics a showpiece for its hydrogen energy strategy, which can be compared to the Shinkansen (high speed train) development for the previous Tokyo Olympics.
- Reduced water consumption (compared to, e.g., coal based power plants)
- Electrification (for vehicles)

The benefits and opportunities with SOFCs on board vehicles were discussed in the authors' previous Energiforsk report [2015:136].

6 IEA annexes with participation from Lund University Department of Energy Sciences

6.1 IEA - SOFC ANNEX 32

Annex 32 aims for the continuation and intensification of the open information exchange, i.e., to accelerate the development of SOFC towards commercialization. Annex 32 organizes at least one annual workshop where representatives from the participating countries present the status of SOFC research, development and demonstration in their respective countries, in addition to discussing a selected topic. The workshops are generally linked to relevant conferences. The workshops lead to open discussions relating to common problems and should have realizable and achievable aims. Active partners of annex 32 are Denmark, Finland, France, Germany, Italy, Japan, Korea, Netherlands, Russia, Sweden, Switzerland and the United States. The work within Annex 32 resulted in a "The Yellow Pages of SOFC Technology 2012-2013. An updated version was published in the beginning of 2017. The next meeting is planned for Hollywood, Florida in connection with the ECS (Electrochemical Society) – SOFC conference in July 2017.

Swedish participants are: Professor Bengt Sundén and Associate Professor Martin Andersson.

6.2 IEA –FC MODELLING ANNEX 37

Annex 37 spearheads the development and application of open-source fuel cell modelling (code), as well as the knowledge base (data) to facilitate the rapid advancement of fuel cell technology. This is done through the development and application of advanced open-source computational fluid dynamics (CFD) models of fuel cells and other electrochemical processes and products in a shared environment. The present focus is directed equally at SOFC and PEFC technologies.

Key messages – Facts

- Virtual prototyping is an important component in the product cycle of fuel cells
- Open source software allows the engineer to complete technical control over the entire model
- By sharing the interface among groups (public access), development is accelerated, without compromising the specific application which remains private.
- Annex 37 is an excellent catalyst for bringing together and focusing international modelling groups in a synergistic manner.

At the 1st Annex meeting in Jülich, 2015, three stated tasks were identified:

1. Code development and application
2. Experimental validation and verification
3. Development of state-of-the art 'best practices' guide

Annex 37 intends to focus on building next generation codes in a coordinated and targeted manner, apply them to real-world designs, and validate/verify the methodologies using high fidelity empirical data. An important component of this activity is bringing together expert open-source modellers from member countries. This helps to avoid duplication of research efforts and brings a focus to distributed activities in modelling. The Annex plays a major role in coordinating this activity. Commercial code may occasionally be employed in an auxiliary role, e.g., for pre- and post-processing, and in validation and verification (V&V) exercises. It is not, however, central to the Annexes function.

Open-source software has many advantages and few drawbacks. The Annex is working on the development of multi-scale and multi-physics models on top of popular existing open source codes, such as OpenFOAM. Codes are checked into repositories for maintenance and use by multiple experts, simultaneously. The goal is to use open computer models to make a real difference in effective fuel cell design. By being able to prototype with the best possible tools, the construction of better fuel cells is facilitated. So far, the members have been able to run models with up to 1,000 cores with near linear performance, a thirty-fold increase on previous efforts. While it is likely that no single code will ever be universally adopted, and indeed several code-strands or ‘forks’ are being developed simultaneously, by different Annex members; the constant dialogue at all levels, ensures that built-in redundancy is obviated.

The latest meeting of the modeling annex was held in Beijing in November 2016 and the next meeting is scheduled for Germany in March 2017.

The following countries are members of the annex: Canada, China, Croatia, Denmark, France, Germany, Italy, Japan, United States, South Korea and Sweden.

Swedish participants are: Associate Professor Martin Andersson and Professor Bengt Sundén.

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USSI 2	http://www.ultra-fuelcells.com/News?ID=16, accessed on Nov 15, 2016.

7.1 CONFERENCES AND IEA PARTICIPATION

1. European Fuel Cell (Piero Lunghi) Conference, 2015, Naples, Italy (including IEA modeling annex meeting)

    A contribution to the "OMEV" newsletter was written

2. Fuel Cell Expo 2016 – Tokyo, Japan

    A contribution to the "OMEV" newsletter was written

3. ECS/Pacific Rim Meeting on Electrochemical and Solid-State Science, 2016, Honolulu, USA

    A contribution to the "OMEV" newsletter was written

4. IEA FC modeling annex meeting, 2015, Santorini, Greece

5. IEA SOFC annex meeting, 2016, Luzern, Switzerland
6. IEA FC modeling annex meeting 2016, Grenoble, France
7. IEA FC modeling annex meeting 2016, Beijing, China

Appendix 1 – Abbreviations

APU	auxiliary power unit
BoP	balance of plant
CFCL	Ceramic Fuel Cells Limited
CHP	combined heat and power
DOE	U.S. Department of Energy
ENE-FARM	product name for small scale CHPs on the Japanese market
FC	fuel cell
FCE	FuelCell Energy
FCEV	fuel cell electrical vehicle
FCH-JU	Fuel Cells and Hydrogen-Joint Undertaking
FZ Jülich	Forschungszentrum Jülich (in Germany)
IEA	International Energy Agency
LHV	lower heating value
MCFC	molten carbonate fuel cell
MHI	Mitsubishi-Hitachi Heavy Industries
MSRI	Materials and Systems Research, Inc.
mCHP	microscale combined heat and power
mSOFC	microscale solid oxide fuel cells
PEFC	polymer electrolyte fuel cell
SOEC	solid oxide electrolyser cell
SOFC	solid oxide fuel cell
HTE	high-temperature electrolysis
UAV	unmanned aerial vehicle
UUV	unmanned undersea vehicle
ZEV	zero emission vehicle (legislation in some US states)

Appendix 2 – Exchange rates

1 €	9.84 SEK
1 US$	9.17 SEK
1 JPY	0.085 SEK
1 CAD	6.75 SEK
1 CHF	9.19 SEK
1 DKK	1.32 SEK

Reference: Google Finance / SIX Financial Information (2016-11-14)*

* Date when the majority of the material was collected

TECHNOLOGY REVIEW – SOLID OXIDE FUEL CELL

Denna rapport beskriver nuvarande status samt nödvändig utveckling och nödvändiga genombrytningar som krävs för att SOFC (fastoxidbränslecellen) ska kunna bli relevant för fordonstillämpningar.

Antalet företag som utvecklar flera bränslecellstekniker parallellt ökat. Vidare demonstreras olika bränslecellstekniker parallellt i flera offentligt finansierade program.

Den stora fördelen med SOFC är den höga elektriska verkningsgraden, 60 % (LHV) är möjligt för ett så litet system som 1,5 kW (Solid Power), vilket kan jämföras med 72,5 % (LHV) för ett 200 kW system under utveckling hos SOFC-MAN i Kina.

Antalet samarbeten i bräncellsbranschen ökar stadigt, exempelvis samarbetar Panasonic och Viesmann, Toshiba med BDR Thermea och Aisin med Bosch. Daimler och Ford samarbetar genom deras joint-venture AFCC-Auto. Honda och GM utvecklar gemensamt bränsleceller. Honda samarbetar även med SOFC-utvecklaren Ceres Power. VW arbetar tillsammans med Ballard.

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