TECHNOLOGY REVIEW – SOLID OXIDE CELLS 2019

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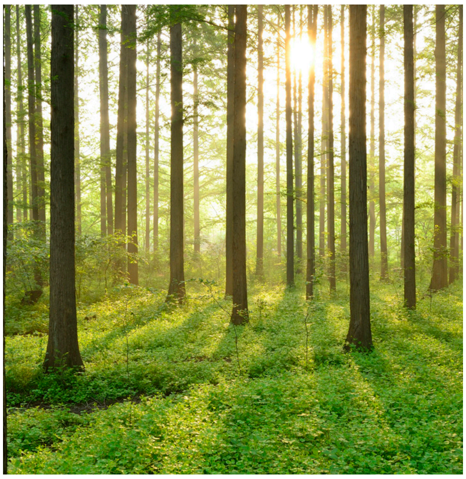

TEKNIKBEVAKNING
BRÄNSLECELLER

Swedish
Electromobility
Centre

Energiforsk

Technology review – Solid Oxide Cells 2019

MARTIN ANDERSSON AND JAN FROITZHEIM

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Energiforsk AB | Phone: 08-677 25 30 | E-mail: kontakt@energiforsk.se | www.energiforsk.se

Förord

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 och genomförs under 2016 – 2019 som ett temaområde inom kompetenscentret Swedish Electromobility Centre med Energiforsk som koordinator och projektledare.

I denna rapport, som har tagits fram inom teknikbevakningsprojektet, presenteras två projekt gemensamt som båda behandlar bevakning och genomgång av teknikstatus av fastoxidbränsleceller, SOFC. Projekten har genomförts av Martin Andersson, Lunds universitet och Jan Froitzheim, Chalmers.

Styrgruppen för teknikbevakningsprojektet har bestått av följande ledamöter: Pontus Svens/Annika Ahlberg-Tidblad, Scania, Staffan Lundgren/Mats Andersson/Johan Svenningstorp, AB Volvo, Stefan Bohatsch, Volvo Cars, Jörgen Westlinder, Sandvik Materials Technology, Andreas Bodén, Powercell, Bengt Ridell, Sweco Energuide, Göran Lindbergh, Swedish Electromobility Centre/KTH, Peter Smeds/Magnus Lindgren, Trafikverket, Elna Holmberg, Swedish 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 Swedish Electromobility Centres webbplats www.emobilitycentre.se.

Stockholm juni 2019

Bertil Wahlund Energiforsk AB

Sammanfattning

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

Fastoxidceller (SOCer) kan användas både som bränsleceller (för att producera el) och som elektrolysceller (för att producera vätgas). I ett framtida vätesamhälle måste energieffektiva produktionsprocesser för väte byggas i stor skala, till exempel med användning av SOEC, för att använda överskott av el, t ex när elproduktionen vindkraft är hög, och således låga elpriser.

Livslängdstest vid forskningscentret Jülich avslutades (februari 2019) efter 100 000 timmars livslängd. Inga liknande nya offentliga långtidstester startas idag.

En SOFC har högre elverkningsgrad jämfört med andra typer av bränsleceller. Det är möjligt att uppnå en elverkningsgrad på 60% (LHV) för system så små som 1,5 kW (Solid Power), 65 % (LHV) för ett 5kW Ceres system och 65% (LHV) för ett 200 kW system från Bloom Energy.

Bloom Energy sålde 80,9 MW av SOFC-system under 2018, vilket kan jämföras med en totalmarknad på cirka 91 MW (också för 2018).

För närvarande finns endast två ENE-FARM system (700 W kombinerat värme och kraft) tillgängliga på den japanska marknaden, ett PEFC-system från Panasonic (systemet av årsmodell 2019 har 40% (LHV) elverkninggrad och 97% totalverkningsgrad (LHV)) att jämföra med ett SOFC system från Aisin Seiki (med en elverkningsgrad på 46,5% (LHV)).

Summary

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

Solid oxide cells (SOCs) can be operated both as fuel cells and as electrolysis cells. In a future hydrogen society, energy efficient production processes for hydrogen need to be built in very large scale for example using solid oxide electrolyzer cells, to capture surplus of electricity, e.g., when wind power is high.

The life time test at research center Jülich finished (February 2019) after 100,000 hours of lifespan. No similar public long time tests are started today.

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 (Solid Power), 65 % LHV for a 5kW Ceres system and 65 % (LHV) for a 200 kW system from Bloom Energy.

Bloom Energy is clearly the main player in the SOFC commercialization, Bloom Energy sold 80.9 MW of SOFC system in 2018, which can be compared to a total market of approximately 91 MW.

Currently only two ENE-FARM (700 W combined heat and power) systems are available on the Japanese market, a PEFC system from Panasonic (system of 2019 has 40 % electrical efficiency (LHV) and 97 % total efficiency (LHV)) and the SOFC system from Aisin Seiki (with an electrical efficiency of 46.5 % (LHV)).

Funding from the European Union is rather diverse, but the general trend is that the TRL of the projects is increasing. Projects include: 1) Improved manufacturing processes, including 3D printing, 2) Demonstration and monitoring, at various scales, 3) Recycling and dismantling, 4) Validation following IEC standards, 5) Development of reversible SOFC/SOECs, 6) Defining accelerated Stress Testing protocols and 7) Research on protective coatings. The price of SOFC system is expected to be significantly decreased by mass production. Also the life length is expected to increase as result from the ongoing projects.

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1 Introduction and Development trends

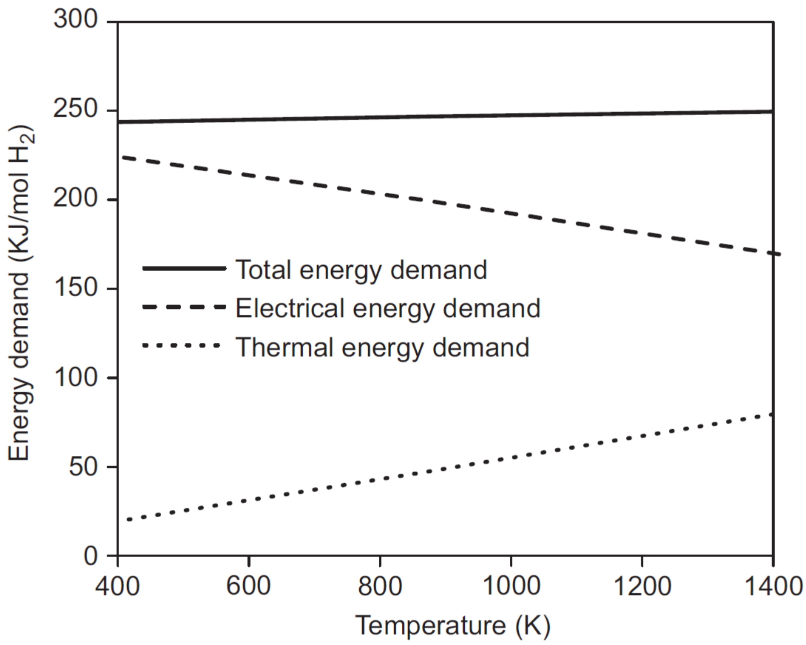
1.1 SOLID OXIDE CELL (SOC) TECHNOLOGY

Solid oxide cells can be operated both as fuel cells and as electrolysis cells. Solid oxide fuel cells (SOFCs) have been studied extensively for more than 20 years and are therefore a more mature technology than solid oxide electrolysis cells (SOECs). Current SOECs are based on SOFC design and have thus gained from the advancements made within SOFC research. Solid oxide cells (SOC) can be distinguished by their high operating temperatures which leads to a number of advantages. SOFCs are able to use many carbon-based fuels, which distinguishes them from lower temperature fuel cells which are basically limited to hydrogen as the fuel. The fuel flexibility and modular design of SOFCs makes them suitable for a wide range of power applications. SOECs can, in addition to hydrogen production, produce carbon monoxide from carbon dioxide, which allows for the production of hydrocarbon fuels. High temperatures lead gives electrode kinetics, which makes SOFCs and SOECs more efficient compared to competing technologies. [PA]

1.2 SOLID OXIDE ELECTROLYSIS CELL TECHNOLOGY

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.

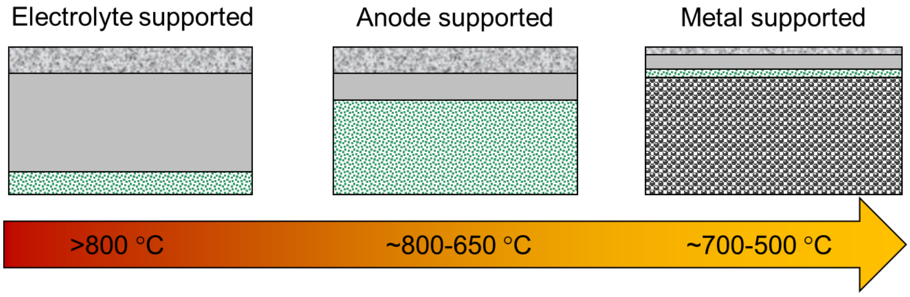
Presently water electrolysis is one of the most suitable processes for hydrogen production at large scale. Water is split into hydrogen and oxygen by applying electrical energy. An increased temperature increases the total energy required for electrolysis slightly while the required electrical energy decreases (see figure below). 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. By convention, the anode and cathode switches designation depending on if the cell is run in electrolysis or fuel cell mode. The used materials are usually the same: YSZ for the electrolyte, Ni-YSZ cermet for the steam/hydrogen electrode and LSM for the oxygen-side electrode [MN].



Calculated total energy demand ΔH, electrical energy demand Δ*G* and thermal energy demand *T*Δ*S* for steam electrolysis are plotted against temperature. [Ni et al.]

1.3 DIFFERENT TYPES OF SOLID OXIDE CELLS

Solid oxide cells can be designed and classified in different manners. One can distinguish between planar and tubular cells but currently the planar design dominates the field. Another way to distinguish different types of cells is which part of the cell acts as load baring layer (i.e. the substrate for the other layers to be deposited on). This has traditionally been the electrolyte made of YSZ. In order to achieve a sufficient transport of oxygen ions a thick electrolyte requires a higher operating temperature (~ >800 °C). The electrolyte supported design is used e.g. by Bloom Energy, Sunfire and Hexis and one of its advantages is that is fairly robust but the high operating temperature requires more expensive materials. An alternative option is to have the Ni/YSZ anode as substrate for the cell. This allows for a thin electrolyte (3µm in the case of Elcogen) which in turn allows for a lower operating temperature and the use of cheaper materials. One of the challenges with the anode supported design is that is often more sensitive to the oxidation of the anode. Anode supported cells are used e.g. by Solid Power, Elcogen, Haldor Topsoe and Fuel Cell Energy. Another option is the use of a porous metallic substrate and deposit all electrochemical active layers. This also allows for low temperatures and offers some cost saving by replacing ceramics with steel. The challenge with this technology is to limit the corrosion of the substrate. Ceres Power is best known for its use of metal supported cells.



Schematic drawing of different fuel cell designs.

1.4 LIFE TIME TEST AT RESERACH CENTER JÜLICH

For more than eleven years, i.e., 100,000 hours of lifespan, scientists at Forschungszentrum Jülich have operated a fuel cell (FC) at a temperature of 700 °C, which is as long as no other high-temperature fuel cell had operated before. Proof of such a long service life is considered an important step in the development of high-temperature FCs that has the highest levels of electrical efficiency [FZJ 1].

Ceramic high-temperature fuel cells, e.g., SOFCs, achieve high electrical efficiency and also require a low amount of maintenance. The high operating temperature put large demands on the materials used. Life lengths of 5 to 10 years, or 40,000 to 80,000 hours, make the use of SOFCs feasible. Since the start of the experiment on August 6, 2007, the cell stack consisting of two cells has been providing continuous electricity for more than 93,000 hours, totaling approximately 4,600 kWh. With the shutdown of the SOFC (February 2019) the cell will be carefully investigated. Externally, the metallic components have changed noticeably over the years. The metallic-silvery shiny surface has become much darker, almost black. But apart from this inevitable superficial oxidation, there are no negative changes from the outside [FZJ 1].

Researchers will use different methods to analyze the impact of the years of extreme thermal stress on the ceramic components, glass solder seals and metal connectors, the so-called interconnectors, has had an impact. The findings are expected to be used in the development of new materials and design approaches to further improve aging resistance [FZJ 1].

Jülich's high-temperature fuel cell after 100,000 hours of operation at 700 °C. Courtesy of Forschungszentrum Jülich.

2 Major EU-funded SOFC research projects

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 FCH (fuel cell and hydrogen) energy technologies in Europe. The aim is to accelerate the market introduction of FCH technologies, realizing their potential as an instrument in achieving a carbon-lean energy system. The members of 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].

2.1.1 Cell3Ditor

Cell3Ditor is coordinated by Catalonia Institute for Energy Research and Saan Energy participates as Swedish partner. A SOFC is a ceramic-based multilayer device that involves expensive and time-consuming multi-step manufacturing processes including tape casting, screen printing, firing, shaping and several high-temperature thermal treatments. Additionally, the cells are manually assembled into stacks resulting in extra steps for joining and sealing that makes the standardization and quality control of the final product challenging. Since current ceramics processing presents strong limitations in shape and extremely complex design for manufacturing, e.g., more than 100 steps, SOFC cells and stacks are expensive. The aim of the Cell3Ditor project is to develop a 3D printing technology for an industrial production of SOFC stacks by including inks formulation, 3D printer development, ceramics consolidation and system integration). Ceramic joint-free SOFC stacks with embedded fluidics and current collection is fabricated in a two-step process (single-step printing and sintering) to decrease the energy, materials and assembly costs while simplifying the design for manufacturing. The project is expected to finish in December 2019 [Cell3Ditor].

2.1.2 CH2P

CH2P aims at building a transition technology for early infrastructure deployment. It uses widely available carbon-lean natural gas and bio-methane to produce hydrogen and power with SOFC technology. The high quality heat from the FC is used to generate hydrogen. Hydrogen and electricity are generated with high efficiencies (up to 90%) and a reduced environmental impact compared to conventional technologies. The target cost for the hydrogen generated is below 4.5

€/kg. The overall technology concept is based on modularity. CH2P demostrates two systems, one with hydrogen generation capacity of 20 kg/day, for components validation, and another at 100 kg/day for infield testing. Industrial partners are expected to enter the market after the project end in July 2020 [CORDIS 1].

2.1.3 COMPASS

The COMPASS project is a collaborative effort of AVL, Plansee, Nissan and FZ Jülich to develop SOFC APU systems for range extender applications in passenger cars. APU systems is developed with an aim of an electrical efficiencies above 50%, a start-up time below 15 min and a small packaging size suitable for integration into electrical vehicles. Nissan will also build a prototype vehicle, where an SOFC system will be integrated into the electrical powertrain. A major focus of the project is technology validation and systematic durability/reliability development. The validation testing includes tests on stack, APU system and vehicle level. The APU system will furthermore undergo automotive testing like vibration, altitude, climate chamber and salt spray. This project is the first approach to integrate SOFC APU systems into electrical powertrains and will help to significantly improve APU systems also for other applications like heavy duty trucks, marine and leisure/camping applications [COMPASS].

2.1.4 ConSos

In the ComSos project (coordinated by VTT), SOFC manufacturers are preparing for serial manufacturing of CHP (combined heat and power) products. The aim of the ComSos project is to validate and demonstrate FC based combined heat and power solutions in the mid-sized power ranges of 10-12 kW, 20-25 kW, and 50-60 kW electricity (referred to as mini FC-CHP). The core of the consortium consists of three SOFC system manufacturers aligned with individual strategies along the value chain: Convion (two units of 60kWe each), SOLIDpower (15 units of 12kWe each) and Sunfire (6-8 units of 25kWe each). The ComSos is expected to finish in June 2021 [ConSos].

2.1.5 DEMOSOFC

DEMOSOFC is devoted to the design and installation of an SOFC plant that will generate around 175 kW electric power. The SOFC plant will be installed in the SMAT Collegno Waste Water Treatment Plant, in the Turin area, and will guarantee the supply of around 30% of the site electrical consumption, and almost 100% of the thermal requirement. The DEMOSOFC plant will be the first example in Europe of high efficiency cogeneration plant with a medium size FC fed by biogas [DEMOSOFC].

Convion FC system. Courtesy of DEMOSOFC.

2.1.6 HYTECHCYCLING

The idea in the project HYTECHCYCLING is to generate vast amounts of green hydrogen from the expected surplus of renewable energy sources to be used in transport (moving FC electric vehicles), energy (feeding stationary FCs for cogeneration, injecting hydrogen into the gas grid) and industries (hydrogen generation for chemical industries). However, the expected commercial to FCH technologies are not prepared for full deployment in what regards to recycling and dismantling stage. The main goal of this project is to deliver reference documentation and studies about existing and new recycling and dismantling technologies and strategies applied FCH technologies, paving the way for future demonstration actions and advances in legislation [HYTECHCYCLING].

2.1.7 INNO-SOFC

Within INNO-SOFC (coordinated by VTT) a next generation 50 kW SOFC system together with its key components will be developed, manufactured, and validated. This system includes improvements compared to current state-of-the-art, leading to 30000 hours operating time, 4000 €/kW system costs, 60% electrical efficiency, and 85% total efficiency, which are required for large-scale commercialization of stationary FCs. Efficiency, performance, and life-time of the system and its key components, which will be validated according to IEC standards in conditions that are relevant for end-users. Proof of reliability and durability of the system will be achieved in 3000 hours demonstration together with 10000 hours stack validation runs [INNO-SOFC].

The project is based on the products of industrial partners (Convion, EnergyMatters, Elcogen, and ElringKlinger), which are operating at different phases of the value chain and are not therefore competing against each other, which enables an efficient collaboration and knowledge sharing within the project. Within this approach, whole system and its components will be optimized comprehensively to fulfil and exceed end-users' requirements. Research centers (VTT, FZ Jülich, and ENEA) support the companies to develop, experimentally validate and demonstrate their products. INNO-SOFC is expected to finish in October 2019 [INNO-SOFC].

2.1.8 INSIGHT

The INSIGHT project (coordinated by CEA in France) aims at developing a Monitoring, Diagnostic and Lifetime Tool (MDLT) for SOFC stacks and the hardware necessary for its implementation into real SOFC systems. The effectiveness of the MDLT will be demonstrated through on-field tests on a real mCHP system (2.5 kW. The consortium will exploit monitoring approaches based on two advanced complementary techniques, i.e., Electrochemical Impedance Spectroscopy (EIS) and Total Harmonic Distortion (THD) in addition to conventional dynamic stack signals. Durability tests with faults added on purpose and accelerated tests will generate the data required to develop and validate MDL algorithms. Based on the outcome of experimental analysis and mathematical approaches, fault mitigation logics will be developed to avoid stack failures and slow down their degradation. INSIGHT aims to decrease the costs of service and SOFC stack replacement by 50%, which would correspond to a reduction of the Total Cost of Ownership (TCO) by 10%. The partnership covers: experimental testing (CEA, DTU, EPFL), algorithms developments (UNISA, IJS, AVL), hardware development (BIT), system integration and validation (VTT, SP, HTC). INSIGHT is expected to finish in December 2019 [INSIGHT].

2.1.9 OxiGEN

OxiGEN (coordinated by Saint-Gobain) aims at developing an innovative SOFC technical platform, including an all-ceramic stack design and a modular hotbox, for small stationary applications. Due to the higher durability and simpler design, this novel stack aims to fulfill the needs for long lifetime, high efficiency and low cost, in mCHP and other segments. A consortium of ICI Caldaie, R&D centers Fraunhofer-IKTS, EIFER, CEA Liten, SINTEF, the utility ENGIE and the global ceramist Saint-Gobain partners to integrate the all-ceramic stack into a hot box solution. The solution’s design is planned to be modular, starting with a 1kWe prototype (in practice, 500We to 1500We depending on preferred mCHP power specification). OxiGEN is planned to finish in December 2020 [OxiGEN].

2.1.10 PACE (PEFC and SOFC)

PACE is a project aimed at ensuring the European mCHP sector (note SOFC as well as PEFCs) makes the next move to mass market commercialization. The project will deploy a total of 2,650 new FC mCHP units with real customers and monitor them for an extended period, which will [PACE]:

- Enable fuel cell mCHP manufacturers to scale up production, using new series techniques, and increased automation. By 2018, four European manufacturers (Bosch, SOLIDpower, Vaillant and Viessmann) have installed capacity for production of over 1,000 units/year (each is expected to deliver 500 units each in PACE). These production lines will test the manufacturing techniques which will

allow for mass market scale up and the reductions in unit cost which will come from associated economies of scale.
- Allow the deployment of new innovations in FC mCHP products, which reduce unit cost by over 30%, increase stack lifetime to over 10 years (by end of the project) and improve the electrical efficiency of all units.
- Create a large dataset of the performance of the units, which will demonstrate the readiness of FC mCHP as a mass market product, which will prove that FC mCHP can be a leading contributor to reducing primary energy consumption and GHG emissions across Europe.
- Allow the units in the trial to be pooled in a large scale test of the concept of aggregating and controlling the output from mCHP to act as a virtual power plant, which will be achieved in a project run by EWE on a section of the German grid earmarked for smart grid trials.
- Act as the basis for an effort to standardize mCHP products in Europe, helping create a more efficient market for both installers and component suppliers.

PACE is expected to end in August 2021 [PACE].

2.1.11 qSOFC

The qSOFC project (coordinated by VTT) combines companies and research centers in the stack manufacturing value-chain with two companies specialized in production automation and quality assurance to optimize the current stack manufacturing processes for mass production. In 2016 (before the start of qSOFC) the state-of-the-art SOFC system capital expenditure (CAPEX) is between 7000 and 8000 €/kW of which stack is the single most expensive component. This proposal focuses on SOFC stack cost reduction and quality improvement by replacing manual labor in all key parts of the stack manufacturing process with automated manufacturing and quality control. This is expected to lead to stack cost of 1000 €/kW and create a further cost reduction potential down to 500 €/kW at mass production (2000 MW/year) [qSOFC].

The project is based on the products of its' industrial partners for stack-manufacturing (ElringKlinger, Elcogen AS, Elcogen Oy, Sandvik), that is motivated by their interest to further ready their products into mass-manufacturing market. Müko and HaikuTech that specialized in production automation and quality control participates. VTT and ENEA support with their scientific background (as research centers) and validate the produced cells, interconnects and stacks. The project is expected to end in January 2020 [qSOFC].

2.1.12 WASTE2WATTS

WASTE2WATTS (W2W), coordinated by Swiss EPFL, aims to design and engineer an integrated biogas-SOFC CHP system with minimal gas pre-processing of the biogas, focusing on low-cost biogas pollutant removal and optimal thermal system integration. Two cleaning approaches and hardware is expected to be developed:
1) small scale units (5-50 kW electricity), where a huge unutilized biogas potential resides (millions of farms, bio-wastes from municipalities) - here sulphur compounds (H_2S and organic S) are removed by an appropriate solid sorbent

matrix; 2) medium-to-large scale units (≥500 kW electricity), which is the existing scale of landfill biogas and large bio-waste collection schemes - here sulphur compounds and siloxanes are removed among others by a cooling approach. For both cases the hardware will be built and installed on real biogas-sites treating different wastes. Gas analytics will validate the approaches. A 6 kW electricity SOFC system will run on a real agro-biogas site connected to the small scale sorbents cleaning unit. Cost projections for high volume production for both the cleaning and SOFC systems will be performed. A detailed full system model will be implemented, considering the biogas feedstock, composition fluctuations (and dilution) and pollutant signatures, and optimizing thermal integration with biogas-inherent CO_2 (for dry-dominant reforming) and digester heating, with the targets to maximize net electrical efficiency and minimize cost. The project WASTE2WATTS is expected to run until December 2020 [WASTE2WATTS].

2.1.13 NewGenSOFC

New Generation Solid Oxide Fuel Cells (NewGenSOFC) is a four year EU funded (Marie Curie) project running between 2014 and 2017. Partners were a ceramic fuel cell producer SME (Adelan), a giant ceramics manufacturer OEM (Kale), and academic researchers (Gebze Higher Institute of Technology and the University of Birmingham). The overall aim was to achieve low-cost engineering solutions for the commercialization of microtubular (mSOFC) technology. mSOFCs was integrated into a mCHP system operating on natural gas, to improve the efficiency of current-day boilers [NewGenSOFC].

The strategic long-term vision for the partners was to commercialize low-cost SOFCs for household energy generation, based on patented designs, integrated systems and prototypes. The project partners envisage CHP systems will replace household boilers in a transition towards a hydrogen economy, and very early prototypes are already being installed at high cost [NewGenSOFC].

3 Major EU-funded SOEC research projects (including SOCs)

3.1 FCH-JU (EU)

3.1.1 GrInHy and GrInHy2.0

GrInHy was an EU project funded in 2016. The project was coordinated Salzgitter Mannesmann Forschung and its aim was to build and operate a reversible SOFC/SOEC stack at an industrial site. The unit has been operating successfully since December 2017 at a steel plant in Salzgitter. The unit had a nominal electrolyser capacity of 150 kW (40 Nm^3H_2/h) and a maximal power of 200 kW (50 Nm^3/h). The prototype system was set-up in June 2017 and connected to a hydrogen processing unit in order to meet the integrated iron-and-steel-works requirements in terms of H_2 purity and pressure. An efficiency of the electrolyzer of 78 % (LHV), without drying and compression, was measured. Additionally, the FC operation showed the system's fuel adaptability: Operated with natural gas in fuel cell mode, the system reached the nominal power of 25 kW and a maximum AC efficiency of 52 % (LHV) at 80 % load (20 kW). With hydrogen, the nominal power was 30 kW and a maximum AC efficiency 48 % (LHV). The reversible HTE was tested for typical dynamic cycles derived from load management and grid balancing. The prototype was operated for approximately 10,000 h in electrolysis, fuel cell or hot-standby mode. In total, about 90,000 Nm^3 of hydrogen were produced during electrolysis operation. GrInHy2.0 is the continuation of this project and started in January 2019. [GrInHy]

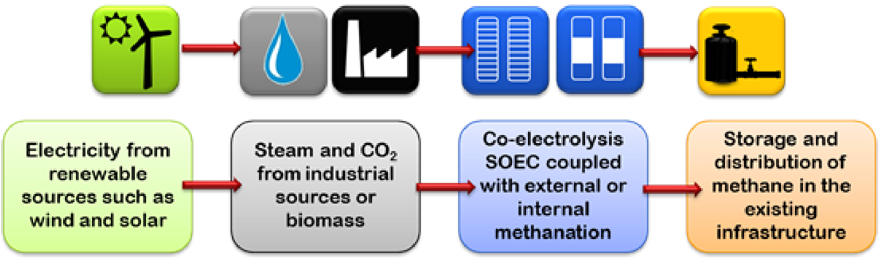
3.1.2 AD ASTRA

AD ASTRA aims to define Accelerated Stress Testing (AST) protocols deduced from a systematic understanding of degradation mechanisms of aged components in solid oxide cell (SOC) stacks, operating in both FC and electrolysis modes. In particular, fuel and oxygen electrode issues and interconnect contact loss will be tackled. The project make use of many samples taken from stacks operated in the field for thousands of hours, supplied by SOC manufacturers across the two application areas CHP and P2X (CHP generators and power-to-commodity energy storage) [AD ASTRA].

The approach to harnessing the intricate phenomena causing critical performance degradation is based on a methodical analysis of in-service performance data correlated with post-operation states, augmented by a dual-focus campaign targeting macroscopic stack testing procedures as well as specific component ageing tests. The probabilistic nature of degradation is expected to be captured by slimming down deterministic simulation models through conception and integration of stochastic correlations between (nominal/accelerated) operating conditions and degradation effects, based on statistically significant data obtained from field-tests and purposely generated experiments. Stochastic interpretation will thus serve the physical description of dominant SOFC degradation mechanisms in CHP and P2X operation, but allowing rapid estimation of remaining useful stack life. The combined results will be translated to validated test protocols that allow quantifying and predicting degradation in SOCs as a function of test aggravation, defining appropriate transfer functions between stress-accelerating and real-world conditions. The overall results are expected to be formalized for adoption by the relevant standards-developing organizations. The projected is planned to operate until December 2020 [AD ASTRA].

3.1.3 ECo

The ECo project (Efficient Co-Electrolyser for Efficient Renewable Energy Storage) focused on conversion of excess renewable electricity into distributable and storable hydrocarbons, such as methane, by the simultaneous electrolysis of steam and CO_2, using SOECs. ECo was a three-year project, involving nine partners from both academia and industry, ended in April 2019. The ECo project brought the technology from proof-of-concept to validation of the technology in a relevant environment, and made it ready for prototype demonstration. The project focused on hydrocarbon gas production as it has one great advantage over comparative storage options: it readily integrates with the existing natural gas networks and storage facilities. Approximately 50% of the total electricity produced from renewable sources could be accommodated as methane in existing underground storage facilities in Europe. Thus, no additional infrastructure is necessary, saving significant investments. The comprehensive natural gas network also makes it a system of transport for bringing power from production to consumption areas [Eco].



The project concept, courtesy of ECo. Courtesy of ECo.

The ECo partners includes industrial players from different segments in the value chain, from cells to plants and system operators: Technical University of Denmark (DTU), Commissariat à l'Energie Atomique et aux énergies alternatives (CEA), European Institute for Energy Research (EIFER), École polytechnique fédérale de Lausanne (EPFL) and Catalonia Institute for Energy Research (IREC), HTceramix (SOLIDPower), Laborelec/ENGIE, Enagas and VDZ [Eco].

3.1.4 LOWCOST-IC

The project LOWCOST-IC is running until December 2021. Coordinated by DTU and with Chalmers and Sandvik as Swedish partners. Lower costs and a better long-term stability are required to accelerate the commercialization of SOC technology. Among the enduring challenges is degradation related to the steel interconnect (IC) material and insufficient robustness of the contact between the IC and the cell. LOWCOST-IC tackles these issues by developing, fabricating and

Energiforsk

demonstrating low-cost ICs and exceptionally tough contact layers for use in SOC stacks. Novel robust contact layers, utilizing the concept of reactive oxidative bonding, will substantially improve the mechanical contact between the cell and the interconnect, while ensuring a low and stable area specific resistance [LOWCOST-IC].

The cost of SOC ICs is expected to be reduced by combining cost-effective high volume steel grades with highly protective coatings. Large-scale mass manufacturing methods will be demonstrated for application of the coating by physical vapor deposition (PVD), for subsequent shaping of the ICs by hydroforming and finally for fast printing of contact layers by a drop-on-demand process. Novel computationally efficient stack models will together with hydroforming be customized to decrease the prototyping costs and thereby accelerate IC development. The new interconnect steels, coatings and contact layers will be implemented in the SOC stacks of two commercial manufacturers and undergo extensive testing in an industrially relevant environment. Finally, the cost-effectiveness of the proposed production route is expected to be assessed and compared with existing production routes to facilitate a fast market entry of the project innovations [LOWCOST-IC].

3.1.5 REFLEX

The REFLEX project aims at developing an innovative renewable energies storage solution called the "Smart Energy Hub", which is based on rSOC technology, that is to say able to operate either in electrolysis mode (SOEC) to store excess electricity to produce H_2, or in FC mode (SOFC) when energy needs exceed local production, to produce electricity and heat again from H_2 or any other fuel locally available. The challenging issue of achieving concomitantly high efficiency, high flexibility in operation and cost optimum is addressed through improvements of rSOC components (cells, stacks, power electronics, heat exchangers) and system, and the definition of advanced operation strategies [REFLEX].

An in-field demonstration will be performed in a technological park, where the Smart Energy Hub will be coupled to local solar and mini-hydro renewable sources that provides electricity and heat to the headquarters of the park. It will demonstrate, in a real environment, the high power-to-power round-trip efficiency of this technology and its flexibility in dynamic operation. The partnership covers: cells and stacks development and testing (ELCOGEN, CEA, DTU), power electronics (USE, GPTech), system design and manufacturing (SYLFEN), system modelling (VTT), field test (Envipark), techno-economical and market analysis (ENGIE) [REFLEX].

3.1.6 SElySOs

SeIySos is coordinated by Foundation for Research and Technology Hellas. The high temperature SOEC technology has a huge potential for future mass production of hydrogen and may become commercially competitive against other electrolysis technologies (i.e., AEL and PEMEL), which are better established but more expensive and less efficient. On the downside, up to now SOECs are less mature and performance plus durability are currently the most important issues that need to be tackled, while the technological progress is still below the typically accepted standard requirements. Indicatively, the latest studies on state-of-the-art cells with Ni/YSZ and LSM as cathode and anode electrodes, respectively, show that the performance decreases about 2-5% after 1000h of operation for the H_2O electrolysis reaction, whereas for the co-electrolysis process the situation is even worse and the technology level is much more behind the commercialization thresholds. In this respect, SElySOs focuses on understanding of the degradation and lifetime fundamentals on both of the SOEC electrodes, for minimization of their degradation and improvement of their performance and stability mainly under H_2O electrolysis and in a certain extent under H_2O/CO_2 co-electrolysis conditions. SElySOs is planned to end in November 2019 [SElySOs].

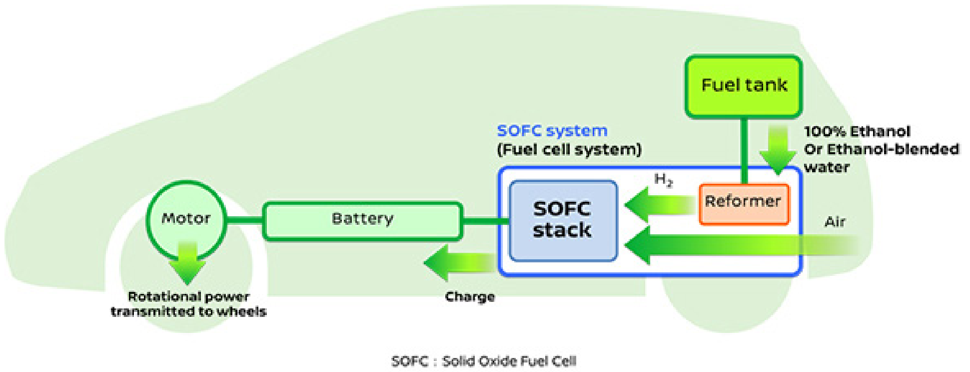
3.1.7 WASTE2GRIDS

The aim of the Waste2GridS (W2G) project (coordinated by Swiss EPFL) is to identify the most promising industrial pathways of waste gasification and SOC integrated power-balancing plants (W2G plants in short). The project aims are to perform a preliminary investigation on the long-term techno-economic feasibility of W2G plants to meet different grid-balancing needs and to identify promising business cases with necessary preconditions. The results of the project are expected to enhance the knowledge exchange and interaction among different key players (manufacturers, investors, and research institutions), providing guidelines for technology development/deployment and market positioning, increase long-term competitiveness and leadership of relevant industries, and provide knowledge for policy support on W2G plants for a circular economy and for the decarbonisation of energy systems. The project is expected to finish in June 2020 [WASTE2GRIDS].

4 Companies working with SOFC for transport

4.1 NISSAN

In 2016 Nissan announced the development of the SOFC-powered vehicle system that runs on bio-ethanol. The vehicle is a e-NV200 with a 24kWh battery and a 5kW SOFC stack. The vehicle is fueled with ethanol (30 l tank) and Nissan claims a driving range of 600+ km. In 2018 Ceres Power announced a collaboration with Nissan on electric vehicle range extenders and an ongoing collaboration so it seems likely that the above mentioned prototype is powered with a Ceres Power system. [Nissan]



Schematic of the Nissan BEV with SOFC range extender

4.2 HONDA

Honda has a joint development agreement with Ceres Power. The scope of the development is unclear and includes "a range of potential power equipment applications"[Honda].

4.3 WEICHAI

Weichai is producing 600,000 engines per year whose business covers complete vehicles, powertrains, parts and components. Weichai has invested in Ceres Power and the companies will together develop a 30kW CNG fueled SOFC range extender system for demonstration in an electric city bus application for the Chinese market in 2019 [Weichai].

4.4 AVL

AVL is developing SOFCs as well as PEFCs for various application. AVL has developed a stationary SOFC CHP platform fueled with natural gas in the range of 5-10 kW electricity (with an electrical efficiency up to 60 % and a lifetime of more than 80 000 hours) as well as APU systems for vehicle applications. AVL participated in various EU funded FC projects. 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% and a lifetime of 8000 hours. 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 [AVL1, AVL 2].

AVL APU system based on SOFC technology. Courtesy of AVL.

AVL CHP system based on SOFC technology. Courtesy of AVL.

5 Selected companies working with SOFCs for non-transport applications

5.1 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 currently up to 65 % (LHV) net electrical efficiencies. The core of their products is stacks of planar electrolyte-supported FCs manufactured with metals sprayed on ceramic supports. The company has continuously increased the size of their systems during these last years, currently producing the "Energy Server 5" giving 200-300 kW electricity, with possibility of bigger system due to its modularity. The heart of these servers is built up with 1 kW electricity stacks, labelled as 'Bloom Boxes', which are composed of 40 cells of 25 W electricity each, fueled with natural gas or biogas. Blooms power module now delivers 300 kW electricity, in the space that just a few years ago delivered 100 kW [Bloom Energy 1].

Bloom Energy Servers, Courtesy of Bloom Energy

Bloom Energy's electrons-as-a-service program was launched 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 [Bloom Energy 2].

A number of multinationals have chosen to install Bloom Energy's servers to power their activities, the vast majority of these are in California, due to the high electricity price, the unstable power grid and the environmental image. Note that BloomEnergy's customers includes 25 of the Fortune 100 companies and 42 of the Fortune 500 companies (i.e., biggest companies in the world) 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 (e.g., microgrid), ensuring continuous supply of energy, with high electrical efficiency even at part loads.

Summary of some recent fact related to the development of Bloom Energy [BloomEnergy1, BloomEnergy2, BloomEnergy3]:

- On the stock market since 2018
- Decreases customers' dependence on electrical grid
- 60 % less CO_2, compared to "US Baseload"
- May be combined with batteries to decreased the dependence on grid further
- Cost of a Bloom Energy system ($/kW) decreased with 48 % between 2015 and 2018
- Cheap natural gas on the US market
- Sold 25.7 MW (Q4 2018) and 80.9 MW for FY 2018.
- Growth rate of 30 % in kW (FY 2018 vs FY 2017)
- Current price approx. 7000 USD/kW (Q1 2019)
- Main markets USA and South Korea
- Backlog of 9-12 months
- Bloom 7.5 platform to be launched in 2019

5.2 HEXIS (GERMANY / SWITZERLAND)

Hexis which was taken over to 100% by Viesmann in 2016 has currently approximately 40 employees. 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 was the "Galileo 1000N", which uses a stack module made up of approximately 60 cells. Approximately 300 units were produced and the product is now discontinued. Instead in 2019 "Leonardo" will be launched. "Leonardo" is expected to have a 1.5 kWe output and uses the same stack as "Galileo". Hexis has also invested in its production infrastructure and claims to be able to produce >5000 CHP units/year. [Hexis]

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].

5.3 ELCOGEN (FINLAND / ESTONIA)

Elcogen was established in 2001 and focuses on commercializing anode-supported SOFC cells and stack to open markets. The Estonian/Finnish company has offers both stack and cells to customers. Cell production is located in Estonia while stacks are assembled in Finland. Elcogens cell technology is optimized for operating at 600-700 °C. It is an anode supported cell design with 3-6 μm thick electrolyte. Elcogen offers 1 kW and a 3kW stack product with 39 or 119 cells respectively.

Elcogen claims a world record in primary energy conversion efficiency to electricity of over 70%. With its low operating temperature Elcogen differs from most other SOFC companies, according to Elcogen this allows for lower production costs and Elcogen expects to be able to produce cells at less than €5 each by 2023, whether this proves true remains to be seen [Elcogen, Elcogen 2].

5.4 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 (CFCL) after the Australian parent company cut funds [Solid Power]

BlueGEN (originally from CFCL), which is the most efficient 1 kW-scale generator in the world, generates continuously electric power at 60% (LHV) 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 or for single family homes. SOLID Power collaborates since 2018 with Bosch Thermotechnology, where BlueGEN is distributed in Germany via the Bosch Thermotechnology brand Buderus [Solid Power 1, Solid Power 2].

The BlueGEN system, courtesy of Solid Power

5.5 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 SOFC systems. Ceres has traditionally have a rather narrow focus on mCHP applications for the residential sector but has recently significant broadened application range. Additionally to a 1 kW system Ceres has announces a 5 kW system e.g. for commercial CHP applications. Ceres Power has a range of industry partners such as British Gas (mCHP), Nissan (EV range extenders, see above) and Honda (various power applications) and Cummins (data centers). More recently collaborations with Weichai (electric buses, see above) and Bosch were announced.

The collaboration with Bosch includes a technology transfer and licensing agreement on 5 kW stacks. The collaboration further includes the establishment of a low-volume production at Bosch. With respect to the technology Ceres SteelCell® technology varies significantly form most competitors in the field. The use of metal-supported (stainless-steel) cells allows for rapid start-ups and a great number of on/off cycles with little degradation. The 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 an electrolyte known as CGO (cerium gadolinium oxide), instead of the industry standard YSZ. The 1 kW stack module consists of approximately 100 cells and has a volume of 5 l and weighs 11 kg. The newly developed 5 kW stack measures 14.5 l and utilizes standard cells in a metallic window frame. At the EFCF 2018 Ceres Power presented data on their V5 cells which exhibit lower degradation than the V4 cells. For the V5 cells less than 0.2%/1000h have been demonstrated for 5000+ h. Furthermore, V5 cell achieve 65 % (LHV) stack efficiency compared to 58 for V4. Ceres Power expects a stack factory cost of 650$ for a 1kW system in a 100 MW/year production scenario [Ceres].

5.6 AISIN SEIKI [TOYOTA GROUP] / KYOCERA (JAPAN)

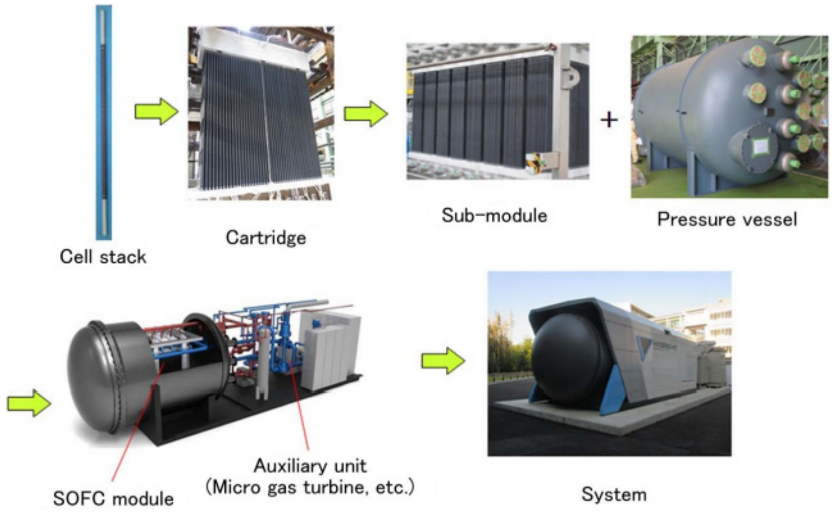
Toyota Motor Corporation is the biggest shareholder in Aisin (Toyota Industries Corporation being the second) and Aisin-Seiki is one of twelve main companies in the Aisin group. Aisin Seiki is a big subcontractor for vehicle industry.

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 mCHP systems ongoing, named "ENE-FARM", based on both PEFC and SOFC technology. In close collaboration between Kyocera, Osaka Gas, Aisin Seiki, Chofu Seisakusho and Toyota, the "ENE-Farm Type S" (700 W electricity), 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. Kyocera is, since 2007, extending the 700 W ENE-FARM system to a 3 kW system with 4 stacks for commercial customers with 52 % (LHV) electrical efficiency, which may be compared to an electrical efficiency of 46.5 % (LHV) at launch of the 700 W system in 2012. For December 2018 around 300 000 ENE-FARM systems have been installed since the start in 2009. Approximately 80-90 % is PEFC, but the SOFC fraction is increasing. Currently two ENE-FARM system is available on the market, a PEFC system from Panasonic (system of 2019 has 40 % electrical efficiency (LHV) and 97 % total efficiency (LHV)) and the SOFC system from Aisin Seiki (electrical efficiency of 46.5 % (LHV)). The average price for an ENE-FARM system (including both the PEFC and the SOFC system) was J¥ 1,140,000 (SEK 100,000) including installation in 2017, which can be compared to the governmental target price 2019/2020 of J¥ 800,000 for a PEFC system and J¥ 1,230,000 for a SOFC system. The higher price for the SOFC system may be motivated by the higher electrical efficiency. [Panasonic, AISIN, FuelCellsWorks, AISIN, Kyocera, Kyocera 2].

AISIN SEIKI SOFC mCHP system. Courtesy of Aisin Seiki.

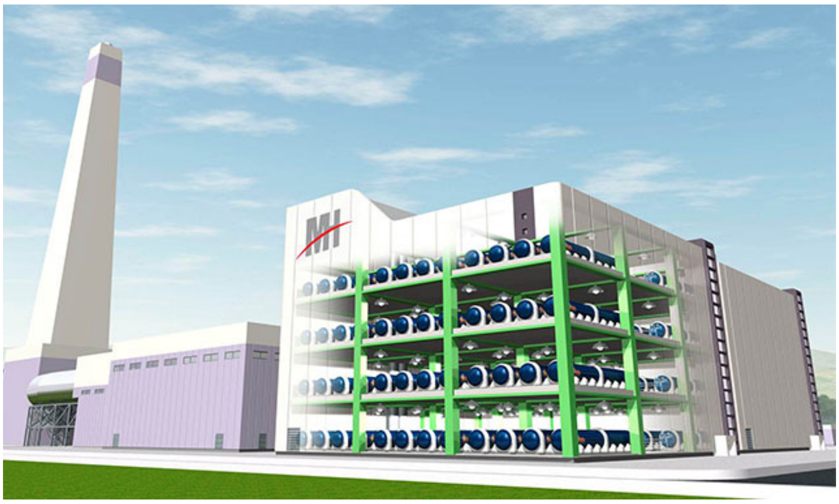
5.7 MITSUBISHI-HITACHI HEAVY INDUSTRY (JAPAN)

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 the system size was scaled up 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 demonstrated a 250 kW coupled SOFC-microturbine in a triple combined cycle system which also generates steam to power a steam turbine. With an SOFC (pressurized) and a micro gas turbine (MGT) system, the electrical efficiency of a gas-fired 250-kilowatt-class system becomes 55 % [MHPS].



Composition of MHPS pressurized 250 kW class system. Courtesy of MHPS.

Future plans includes a transmission end-power generation efficiency of more than 70 % (LHV), with a natural gas-fired 100-megawatt-class SOFC-gas turbine-steam turbine combined cycle system (gas turbine fuel cell combined cycle, or GTFC), which is positioned as a future replacement for large-scale thermal power plants [MHPS 2].



Sketch of planned MHPS Gas Turbine Fuel Cell Combined-cycle Power Plant. Courtesy of MHPS.

5.8 BOSCH

Although Bosch has been active in the field of SOFC for many years, the company's visibility has recently increased significantly. At the EFCF in Lucerne, Bosch presented a 10 kW SOFC demonstrator with a DC efficiency of 73 %. This system is, at least in parts, likely based on components from Ceres Power. The strategic collaboration between Bosch and Ceres Power was officially announced in August 2018. The agreement includes a 4% investment of Bosch in Ceres Power and seems to be based on Ceres 5 kW stack technology with the aim to build SOFC 10 kW modules for multiple applications including small power stations to be used in cities, factories, data centres and charge points for electric vehicles. The agreement also includes the establishment of a "low-volume production at Bosch". This production, with 60 employees, will be located in Bamberg and is scheduled to start by mid-2019. Apart from this collaboration, the subsidiary Bosch Thermotechnology has in 2018 also announced a collaboration with Solid Power. Through its brand Buderus, it will distribute Solid Powers Blue Gen system, which is targeting the mCHP market and thus substantially smaller (1.5 kWe). [Bosch 1-4]

5.9 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 is, for example, participating in the European funded DEMOSOFC project. Within the project a 174 kWe has been installed at a waste water treatment plant in Italy. [DEMOSOFC website]. Within the finnish LEMENE project Convion is going to install 116 kWe SOFC units (utilizing Elcogen cells) in a energy self sufficient business district.

5.10 FUEL CELL ENERGY (FORMER VERSA POWER)

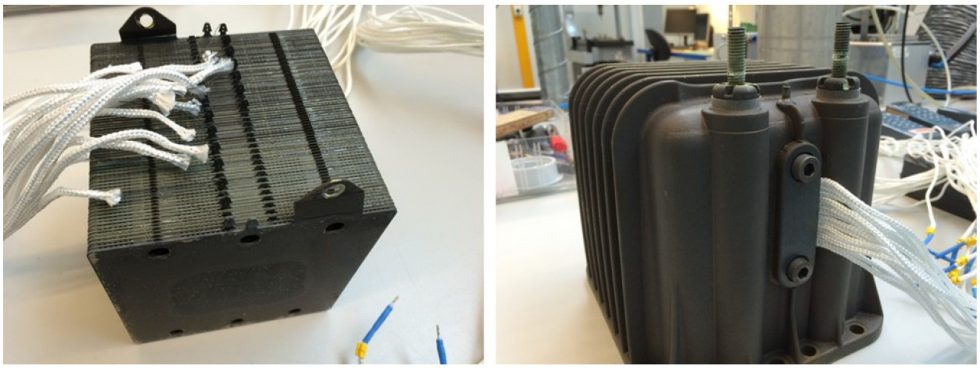
FuelCell Energy (FCE) is originally a developer of molten carbonate fuel cell (MCFC) systems, but absorbed Canadian Versa Power, and their SOFC technology. In this way FCE brought their knowledge of FC system deployment at smaller power scales targeted by Versa Power's SOFCs. FCE is currently selling MCFC systems in the range of 1.4 to 3.7 MW, to be compared to their SOFC/SOEC systems that is developed for system sizes smaller than 300 kW electricity [FCE].

6 Solid Oxide Electrolysis Cells

6.1 HALDOR TOPSOE

Haldor Topsoe has been active in solid oxide fuel cell development since 2004. After closure of its subsidiary Topsoe Fuel Cells in 2014 the mother company has Haldor Topsoe has continued the development focusing on electrolysis systems for the production of hydrogen, synthesis gas, and pure carbon monoxide. Haldor Topsoe considers electrolysis an enabling technology for de-coupling the production of industrial chemicals from the use of fossil fuels and CO_2 emissions.

The stacks in all Haldor Topsoe systems are based on the Topsoe Stack Platform (TSP) (see fig). Scale-up of SOEC systems to sizes relevant to the chemical industry places stringent requirements on stacks. In addition to cost reliably in real life situations has been a focus of the development of the stack.



A Topsoe Stack platfrom core (left) and in casing (right) [HTAS]

In a Danish project in collaboration with DTU a Topsoe stack was operated to follow the wind production of a wind farm on Bornholm assuming 100% absorption of the wind power in the stack and no additional degradation was observed compared to constant load [HTAS 3].

Haldor Topsoe has identified CO production as an attractive market for early SOEC introductions because on site production offers several advantages compared to transport in tube trailers. Its eCOs process allows for CO production from CO_2 with high purity (99.999%) on site in volumes of 10 -100 Nm^3/h. Haldor Topsoe has successfully installed a unit in for Gas Innovations in La Porte TX (3-5 Nm^3/h) and signed a contract of a full sized plant (96 Nm/h) with Gas Innovations. Furthermore, Haldor Topsoe recently announced the lease of two more units to DeLille Oxygen Co [HTAS 2]. Another process for SOEC implementation Haldor Topsoe investigates is the production of green ammonia. Ammonia production from natural gas stands for about 1% to the global CO_2 emissions and SOEC technology would allow the use electricity instead. Furthermore, Haldor Topsoe is considering the use of SOEC for biogas upgrade. Biogas contains a lot of CO_2 (~40%) and using steam electrolysis and a methanation reactor it can be upgraded to synthetic natural gas. The combination of an exothermal process (methanation) with SOEC allows for a high conversion efficiency. Topsoe has designed and build a demonstration unit (10 Nm^3/h) in Foulum [HTAS].

6.2 SUNFIRE

Sunfire develops and produces high-temperature fuel cell (SOFC) and electrolyzer (SOEC) systems. The company was founded in 2010 and is rapidly growing (~130 employees). The company merged with Staxera in 2012 and can thus build upon more than 10 years of experience in SOC stack development. Sunfire uses electrolyte supported cells and started with the production of SOFC stacks and small systems mainly for residential CHP applications (<5kW). Sunfire collaborates with Vaillant on this market. Sunfire stacks have proven 30 000+ hours of operation within the Callux/ene.field framework. A new cell with significantly lower degradation has been presented at EFCF and was scheduled to be integrated in a new stack version in 2019. Another focus of Sunfires development is cost reduction, the company expects to decrease manufacturing cost by 30-50% by 2021 (compared to 2017). At the EFCF Sunfire presented ASR data of their last 83 stacks, the average ASR was 657mOHm with a standard deviation of only 18mOhm. Sunfire has delivered stacks to the GrInHy project (see section 3.1.1) and is currently building a SOEC system with a production capacity of 40 Nm^3/h at a gas fired power plant in Mellach (Austria). The system will be able to produce hydrogen when surplus energy is available. The system will also be able to operate in SOFC mode to supply the plan with self/emergency power.

Sunfire has published collaborations with Audi, Boeing and TyssenKrupp Marine systems. One of the markets that Sunfire aims at is Power to Liquid. In 2014 Sunfire opened a Power to Liquid pilot plant in Dresden. Currently a first commercial plant is built in Norway. From 2020 it is expected to produce yearly 8000 tonnes of synthetic crude oil (Blue Crude) with in input of 20 MWe/a. Recently Sunfire has also demonstrated a 10 kW system co electrolysis system (CO_2+H_2O). Compared to steam electrolysis combined with reverse water gas shift reaction direct syngas production via co electrolysis offers higher efficiency and lower investment cost. [Sunfire 1-4]

7 Analysis and Discussion

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 9.1)

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 (Solid Power), 65 % LHV for a 5kW Ceres system and 65 % LHV for a 200 kW system from Bloom Energy.

Bloom Energy is clearly the main player in the SOFC commercialization, Bloom Energy sold 80.9 MW of SOFC system in 2018, which can be compared to a total market of 91 MW according to E4tech. It should also be noted that a customer may have to wait up to one year to get a system delivered and installed from Bloom Energy [E4tech, BloomEnergy3]. Note that the electrical efficiency is significantly improved (now 65 % LHV) compared to a 50 % (LHV) electrical efficiency for a Bloom system in 2017 [Energiforsk 2017:359]. However, at least early versions of Bloom Energies systems have relied on relatively expensive materials (95% Cr interconnects) and it is not clear whether that can be competitive in an unsubsidized market.

Currently only two ENE-FARM system is available on the market, a PEFC system from Panasonic (system of 2019 has 40 % electrical efficiency (LHV) and 97 % total efficiency (LHV)) and the SOFC system from Aisin Seiki (with an electrical efficiency of 46.5 % (LHV)). Currently the sale of PEFC and SOFC system are on a similar level (according to E4tech). The Japanese governmental goal of 1,400,000 ENE-FARM systems installed in 2020 is unlikely to be reached, however, the ENE-FARM program already deployed 100,000s of systems and has been scaled-up in many steps the last 10 years.

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.

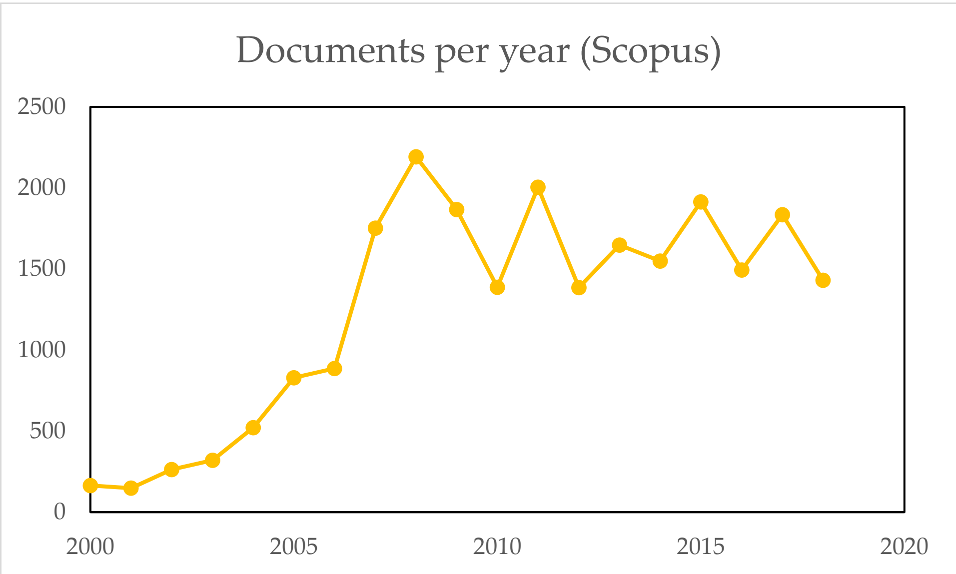
Most public funding programs (EU, USA and Japan) require significant industrial co-funding, i.e., the research and development are following the needs of the industry.

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

7.1 GENERAL TRENDS AND OBSERVATIONS

The general impression at the attended conferences was that SOFC technology is going ahead steadily albeit not at the rate promised earlier. Compared to a couple of years ago more companies are in a commercial/pre-commercial operation. Furthermore, companies now routinely show operating times >10 000 h which was not common a few years ago. Also, the presented degradation rates are in the range of 0.2%/1000 h which is commonly considered an acceptable degradation rate. Most companies seem to have thermal and redox cycles under control which was a major technological challenge few years back. Nowadays, the biggest challenges seem to be more of economic nature and in driving down cost without loss of performance. In this context a particular predicament occurs through the fact that a major cost driver is the low volume production and larger production volumes are needed, which in turn require larger demands and large investments. Nevertheless, several companies have announced or completed an upscaling of their production facilities. Ceres Power is investing 7 M£ in a new plant scheduled to be ready by end of 2019. Solid Power announced in late 2017 the investment of 19 M€ in a new production facility that would tenfold production capacity by 2020 [Solid Power 3]. Also, Hexis announced that it had upscaled its production facilities to be able to produce 5000 CHP units per year. Research on SOFC related topics seems to be stable, slightly below peak levels about 10 years ago (compare figure below).

With respect to application areas the scope seemed to have broadened. Obviously SOEC has become a lot more important and most companies pursue this track more or less actively. Also a few years back focus was very much on mCHP applications, which still seems to be one of the important markets, but other applications have gained importance. Range extenders is a new application area, data centers have been targeted by several companies and the larger scale CHP market seemed to have gained importance. As a consequence, several companies have announced larger systems in the 5 kW class often using a "window frame" concept that utilizes several standard cells next to each other to create a larger active area.



Number of publications per year with "SOFC" in title, abstract or keywords by Scopus. The biannual fluctuation is caused by the proceedings from the SOFC conference series held in odd years.

7.2 SUMMARY ON SOFC ACTIVITIES FUNDED BY EU

Funding from the European Union is rather diverse, but the general trend is that the TRL of the projects is increasing. Some observation on the collection of information in chapter 2, projects currently focus on:

- Improved manufacturing processes, including 3D printing
- Demonstration and monitoring, at various scales
    - 1000s of mCHP in PACE
    - Three 10-60 KW systems in ConSos
    - One system that run on biogas in DEMOSOFC
- Locking into recycling and dismantling
- Validation following IEC standards
- Development of reversible SOFC/SOECs
- Defining accelerated Stress Testing protocols
- Research on protective coatings

The price of SOFC system is expected to be significantly decreased from mass production. Also, the life length is expected to increase as result from the ongoing projects.

8 IEA annexes with participation from Lund University and Chalmers

8.1 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, Sweden, Switzerland, United States and Netherlands. The work within Annex 32 resulted in a "The Yellow Pages of SOFC Technology 2017 (previous edition from annex 24; 2012-2013) The next meeting is planned for Kyoto, Japan in connection with the ECS (Electrochemical Society) – SOFC conference in September 2019.

Swedish participants are: Associate Professor Jan Froitzheim (Chalmers) and Associate Professor Martin Andersson (Lund University).

8.2 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 Brunswick (Germany) in March 2019.

The following countries are members of the annex: Croatia, Denmark, France, Germany, Italy, Netherlands, Sweden, USA.

Swedish participant is: Associate Professor Martin Andersson (Lund University)

9 Cost effective IT-SOFC for mobile applications

Chalmers is coordinating the project Cost effective IT-SOFC for mobile applications within the Swedish Energy Agencies FFI program. This project attempts to mitigate interconnect degradation in SOFC stacks in a cost-effective way, using coated standard ferritic FeCr strip steel. The work is carried out in close collaboration with Elcogen (building and testing the SOFC stacks and produces coated interconnect materials). Sandvik Materials Technology provides and develops metallic nano-coated interconnect materials, and Volvo AB is responsible for system and vehicle integration aspects. The project is a successor of an earlier FFI project Improving Lifetime and Performance of SOFC for Truck APUs. The focus of both projects havehas been the metallic interconnects. The interconnect is an integral part of the stack that connectconnects the individual cells in series and simultaneously keeps the gas compartments of the different cells separated. Thus, the interconnect needs to a fuel cell stack.be electrically conductive and gastight. Ferritic stainless steels are nowadays the material of choice because they are relatively cheap. However, the steel interconnect is responsible for several degradation mechanism in the stack. The two most important are volatilization of Cr(VI), which poisons the cathode, and oxide scale formation, which increases the resistance of the stack. Within the first project at Chalmers it was shown that Co/Ce coated materials are suitable materials for SOFC applications. Lab tests showed excellent Cr retention capability, low oxidation rates and capability of the coating to self-heal in the case of damages. The coatings were also tested on stack level and performed very well. The purpose of the 2nd FFI project is to modify the coating/substrate solution to save cost. TheDespite the use of mass manufacturedferritic stainless steels like AISI 441 instead the interconnect contributes significantly to the material cost of specialthe stack. Furthermore, the cost of ferritic stainless steel varies greatly. Special grades such as Crofer 22 APU have been successfully used in SOFC systems but are more expensive than mass manufactured grades. The use of steels such as AISI 441 instead allows for major cost savings. Thus, one of the aims in the project is to investigate how such low-cost steels can be integrated into an SOFC stack without loss of performance. Furthermore, alternative coating solutions are investigated. that allow further cost reduction.

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10.1 CONFERENCES AND IEA PARTICIPATION

1. Fuel Cell Expo 2018 – Tokyo, Japan
2. Two contributions to the "OMEV" newsletter were written
3. 13th European Solid Oxide Fuel Cell & Solid Oxide Electrolyzer Forum (13th EFCF), Lucerne, Switzerland
4. A contribution to the "OMEV" newsletter was written
5. 22nd World Hydrogen Energy Conference (22nd WHEC), Rio de Janeiro, Brazil
6. A contribution to the "OMEV" newsletter was written
7. Fifteenth International Symposium on Solid Oxide Fuel Cells, Hollywood, Florida, USA
8. A contribution to the "OMEV" newsletter was written
9. 234th Meeting of The Electrochemical Society (ECS), Cancun, Mexico. Additionally, an IEA FC modeling annex meeting was held.
10. ModVal 2019 – 16th Symposium on Modeling and Experimental Validation of Electrochemical Energy Technologies, Brunswick, Germany.
11. Additionally, an IEA FC modeling annex meeting was held.
12. 7th European Fuel Cell Technology & Applications Piero Lunghi Conference - EFC17, Naples Italy
13. Additionally, an IEA FC modeling annex meeting was held.

Appendix 1 – Abbreviations

APU	auxiliary power unit
CFCL	Ceramic Fuel Cells Limited
CHP	combined heat and power
ENE-FARM	product name for small scale CHPs on the Japanese market
FC	fuel cell
FCH	fuel cell and hydorgen
FCH-JU	Fuel Cells and Hydrogen-Joint Undertaking
FZ Jülich	Forschungszentrum Jülich (in Germany)
GTFC	gas turbine fuel cell combined cycle
IEA	International Energy Agency
HTE	high-temperature electrolysis
LHV	lower heating value
MCFC	molten carbonate fuel cell
MHI	Mitsubishi-Hitachi Heavy Industries
mCHP	microscale combined heat and power
mSOFC	microscale solid oxide fuel cell
PEFC	polymer electrolyte fuel cell
SOC	solid oxide cell (both fuel cell mode as well as electrolyser mode)
SOEC	solid oxide electrolyser cell
SOFC	solid oxide fuel cell

Appendix 2 – Exchange rates

1 €	10.69 SEK
1 US$	9.54 SEK
1 JPY	0.087 SEK
1 CAD	7.10 SEK
1 CHF	9.52 SEK
1 DKK	1.43 SEK

Reference: Google Finance / SIX Financial Information (2019-05-26)

TECHNOLOGY REVIEW – SOLID OXIDE CELLS 2019

Fastoxidceller kan användas både som bränsleceller för att producera el och som elektrolysceller för att producera vätgas. I ett framtida vätesamhälle måste energieffektiva produktionsprocesser för väte byggas i stor skala, till exempel med användning av fastoxidbränsleceller, SOEC. Det innebär att det går att använda överskott av el, till exempel när elproduktion från vindkraft är hög.

Kommersialiseringen av SOFC-system sker inom specifika nischmarknader, exempelvis lokal kraftgenerering till datacenters, kontor och handel, framför allt i USA. Det görs också för småskalig kraftvärme för enskilda hushåll, exempelvis i Japan.

Den stora fördelen med den här typen av system är den höga elektriska verkningsgraden, 60 % LHV är möjligt för ett så litet system som 1,5 kW Solid Power, vilket kan jämföras med 65 % för ett 5 kW system från Ceres och även 65 % för ett 200 kW system från Bloom Energy.

Livslängdstestet för ett SOFC system vid forskningscentret Jülich avslutades i februari 2019 efter 100 000 timmars livslängd. Inga liknande nya offentliga långtidstester startas idag.

För närvarande finns endast två system tillgängliga på den japanska marknaden, ett PEFC-system från Panasonic ett SOFC system från Aisin Seiki.

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