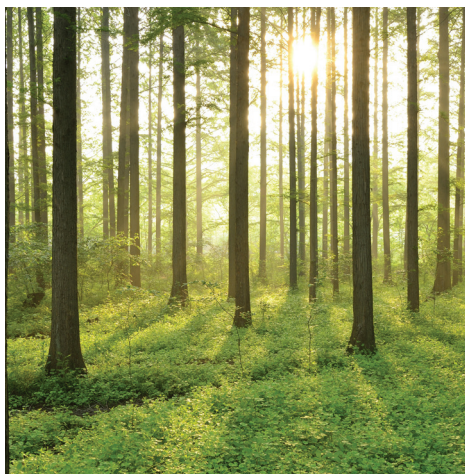


TECHNOLOGY REVIEW – SOLID OXIDE FUEL CELL

RAPPORT 2015:136



Technology review – Solid Oxide Fuel Cell

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Förord

I syfte att koordinera teknikbevakning, samt sammanställa, analysera och sprida information om utvecklingen inom bränslecellsområdet till svenska intressenter, främst fordonsindustrin, finansierar Energimyndigheten ett projekt "Teknikbevakning av bränslecellsområdet". Projektet genomförs under 2014-2016 inom ramen för Svensk Hybridfordonscentrum (SHC) med Energiforsk som koordinator och projektledare.

Denna rapport är en förstudie som har tagits fram inom teknikbevakningsprojektet. Samtliga rapporter kommer att finnas publicerade och fritt nedladdningsbara på Energiforsks webbplats för bränslecellsbevakningen www.branslecell.se och på SHC:s webbplats www.hybridfordonscentrum.se.

Styrgruppen för projektet har bestått av följande ledamöter: Anders Hedebjörn Volvo Cars, Annika Ahlberg-Tidblad Scania, Azra Selimovic AB Volvo, Bengt Ridell Grontmij AB, Göran Lindbergh SHC/KTH, Elna Holmberg SHC och Bertil Wahlund Energiforsk AB. Energiforsk framför ett stort tack till styrgruppen för värdefulla insatser.

Stockholm maj 2015

Bertil Wahlund

Energiforsk AB

Sammanfattning

Den första fastoxidbränslecellen (SOFC) utvecklades redan 1937, dock har den stora kommersialiseringen väntat. Det är främst inom specifika nischmarknader, t.ex. lokal kraftgenerering till datacenter, småskalig kraftvärme för enskilda hushåll samt för militära ändamål där SOFC-system är tillgängliga i dag. Den framtida potentialen är stor inom nämnda områden och även för t.ex. distribuerad kraftgenerering i MW-skala samt för APUer (och i vissa fall även för framdrivning) i lastbilar och andra fordon.

Två projekt inom den europeiska forskningsfinansieringen fokuserar på SOFC "ombord" fordon, d.v.s. DESTA och SAFARI projekten. Det svenska deltagandet består av Volvo, som har deltagit i DESTA. Exempel på fordonsföretag som arbetar med SOFC-utveckling är: AVL, Eberspächer och Elcogen i Europa, samt Delphi, Protonex och Ultra Electronics AMI i Nordamerika.

Det är intressant att jämföra utvecklingen av småskalig kraftvärme (särskilt i Japan) med APU marknaden, d.v.s. kommersialisering av PEMFC startade ca 5 år innan kommersialiseringen SOFC och en nischmarknad för SOFC uppstår när elverkningsgraden blir viktigare. En elverkningsgrad 10 procentenheter högre för ett SOFC-system jämfört med ett PEMFC-system kan förväntas. En elektrisk verkningsgrad på 60 % för ett SOFC-system (CFCL och ett system så litet som 1,5 kW) har uppnåtts jämfört med upp till 70 % i labb-skala. Dessa siffror för elverkningsgraden kan jämföras med dieselmotorn (för vägfordon), där en maximal verkningsgrad om 48 % (världsrekord är 54,4 %) för en optimal belastning är möjlig. Det bör noteras att både dieselmotorn och SOFC-systemet för framdrivning vinner betydande elverkningsgrad från en hybridisering, d.v.s. kan motorn eller bränslecellen arbeta på en optimal belastning och eventuellt överskott (eller brist) kan då lagras i batteriet.

Både Topsoe Fuel Cells och CFCL har nyligen avbrutit deras respektive SOFC verksamhet. Författarna ser detta som en följd av den ekonomiska "valley-of-death", d.v.s. produkten var där, men betydande ekonomiska resurser hade behövs för att få produkterna ut på marknaden.

NASAs SOFC-forskning är mycket långt ifrån någon kommersiell tillämpning. Det är dock lovande för framtida produktutveckling av SOFC-teknologin att NASA tror på tekniken. På samma sätt är det för GEs SOFC-aktiviteter, som till en början inte är ämnade för fordonsindustrin, men när en av världens största företag startar sin SOFC forskning, är det klart att de tror starkt på teknologin.

Summary

The first solid oxide fuel cell (SOFC) was developed in 1937. However, the commercialization has waited. It is mainly in specific niche markets, such as on-site power generation for datacenters, small-scale CHP for individual households and as military applications, where SOFC systems are available today. 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.

Two projects within the European research funding are focusing on SOFCs onboard vehicles, i.e., the DESTA and SAFARI projects. The Swedish participation contains Volvo, which participated in DESTA.

SOFC development for the vehicle industry includes AVL, Eberspracher and Elcogen in Europe, as well as Delphi, Protonex and Ultra Electronics AMI in North America.

It is interesting to compare the microscale CHP development (especially in Japan) with the APU market, i.e., the commercialization of PEMFC started approximately 5 years before the SOFC commercialization, and the niche market for SOFCs appear when the electrical efficiency becomes more important. An electrical efficiency 10 percentage points higher for an SOFC compared to a PEMFC system can be expected. An electrical efficiency of 60 % for SOFCs in the field (CFCL and for systems as small as 1.5 kW) is reached compared to up to 70 % in the lab. These numbers for electrical efficiencies can be compared to the Diesel engine for road vehicles, which reach at the maximum an efficiency of 48 % (world record is 54.4 %) for an optimal load. It should be noted that both the Diesel engine and SOFC for propulsion would gain electrical efficiency from the vehicle hybridization, i.e., the engine or fuel cell can operate at an optimal load and any surplus (or lacking) power is stored in (or discharged from) the battery. The suitability to run on reformed hydrogen from biogas, bio-ethanol, bio-methanol and syngas makes SOFC the natural choice for many heavy vehicle applications.

Both Topsoe Fuel Cells and CFCL recently canceled their SOFC activities. The authors see this as a consequence of the economical "valley of death", i.e., the product was there, but significant financial resources were needed to bring the product(s) out to the market.

The SOFC research at NASA is very far from any commercial application. However, it is promising for future SOFC product development that NASA believes in the technology. Similarly for the GE activities, which are initially not aimed for the vehicle industry, but when one of the world's biggest companies restart its SOFC research, it is clear that they strongly believe in the technology.

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1 News and Development trends

This chapter presents the recent and present European funded research and development SOFC projects which aimed for the vehicle industry. Some selected companies developing SOFCs aiming for the vehicle industry are also introduced. Finally, the closure of SOFC activities at Topsoe Fuel Cells and CFCL are discussed.

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

- The efficiency and electrochemistry issues of SOFC are essentially solved: the state-of-the-art SOFC show reasonable efficiencies and stable electrochemical performance.
- Lifetimes over 60,000 hours reached for stack in laboratory environment (FZ Jülich).
- Electrical efficiency over 60% achieved for residential SOFC in a 1.5 kW combined heat and power (CHP) system (CFCL).
- Cost still remains the major barrier to SOFC systems' commercialization.
- With the advent of certain additional stack related development steps, a commercially feasible system for large scale projects with an investment cost of less than EUR 2,000/kW (SEK 18,500/kW) can be achieved.
- SOFC for CHP and power only, for stationary industrial, commercial, residential and small applications are relatively mature and are at the threshold of the commercialization process, mainly in Japan but also in Germany.
- SOFCs using metallic support is one promising emerging technology for APUs with lower material costs, higher robustness during fabrication and operation.
- The Callux Programme in Germany and the ENE-FARM products in Japan, both for domestic-scale combined heat and power (CHP) provision from fuel cells, have started installing SOFC systems.
- Large-scale SOFC installations provided by Bloom Energy in the USA, have achieved significant adoption and deployment in a number of US states by large companies.

1.1 European funded bigger SOFC research projects aimed at the vehicle industry

The interested reader can find information about Europe's Fuel Cell and Hydrogen Undertaking in a recent report written by Bengt Ridell (in Swedish).

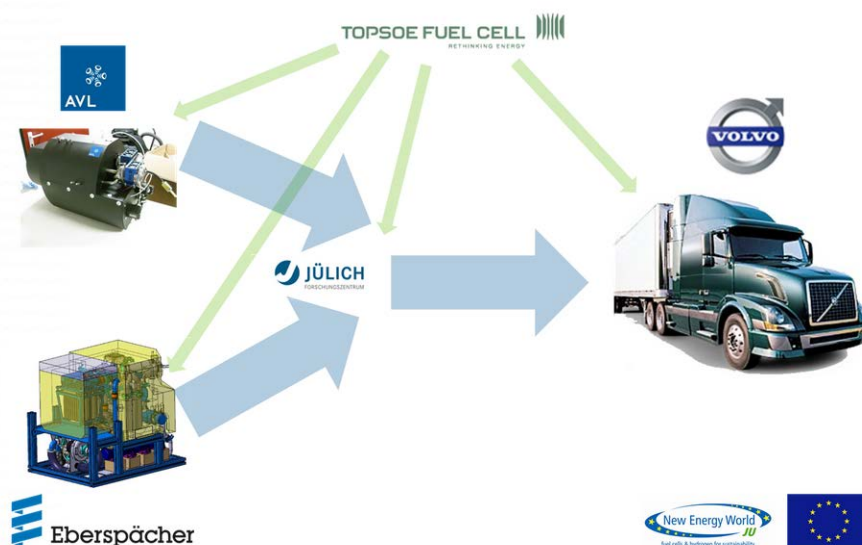
1.1.1 DESTA

The main objective of DESTA is the demonstration of the first European SOFC APU for trucks. 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. Based on test results including e.g., production costs, controllability and manufacturability of two existing systems from AVL (project coordinator) and Eberspächer Climate Control Systems, a benchmark will be performed by the independent research institute FZ Jülich, leading to an optimized DESTA SOFC APU. Totalt six APU systems (three from AVL, three from Eberspächer) have been thoroughly tested and compared. The final unit will combine the superior features of the individual systems. In parallel, Topsoe Fuel Cells worked on the SOFC stack optimization [DESTA a].

The research has received funding from the European Union's Seventh Framework Programme (FP7/2007-2013) for the Fuel Cells and Hydrogen Joint Technology Initiative under grant agreement n° 278899 [DESTA a]. The DESTA program ends by the end of June 2015 and the total budget was 9,8 M EUR (91 M SEK) [DESTA c].

The APU stack test standards developed within the DESTA program is freely available online:

http://www.esta-project.eu/fileadmin/downloads/Deliverables/DESTA_20130717_D1.3_APUStackTestStandards.pdf



1.1.2 SAFARI

SAFARI (SOFC APU for auxiliary road-truck/installations) aims to design an SOFC APU for trucks, using liquid methane (LNG), to provide power, heat and cooling for the cab, in an efficient way. The project partners are Adelan (Coordinator; UK), Hardstaff Group (UK), Almus AG (Switzerland), University of Birmingham (UK), IREC (Spain) and ZUT (Poland). Methane was chosen because it is increasingly used in the EU as the fuel supply for trucks and because it is economic, cleaner than diesel, and is becoming widely available [Adelan a].

SAFARI is funded under the FCH JU for 36 months starting January 1, 2014: Grant Agreement n° 325323 [Adelan a].

1.1.3 ENSA (German national project)

The SOFC-APU, which is developed within the project “ENSA” by the consortium of the companies Eberspächer Climate Control Systems, ElringKlinger and Behr, contains all technical components that are necessary for mobile power generation. A reformer, which has been developed with the support of OWI (part of RWTH Aachen University), transforms diesel fuel out of the vehicle's tank and out of ambient air into a synthesis gas by means of catalytic partial oxidation. This synthesis gas, which mainly consists of hydrogen and carbon monoxide, reacts in the SOFC with the fed atmospheric oxygen [RWTH Aachen a].

The latest project (ENSA III) ran from April 2012 to March 2015 and was supported by Ministry of Economy and Technology.

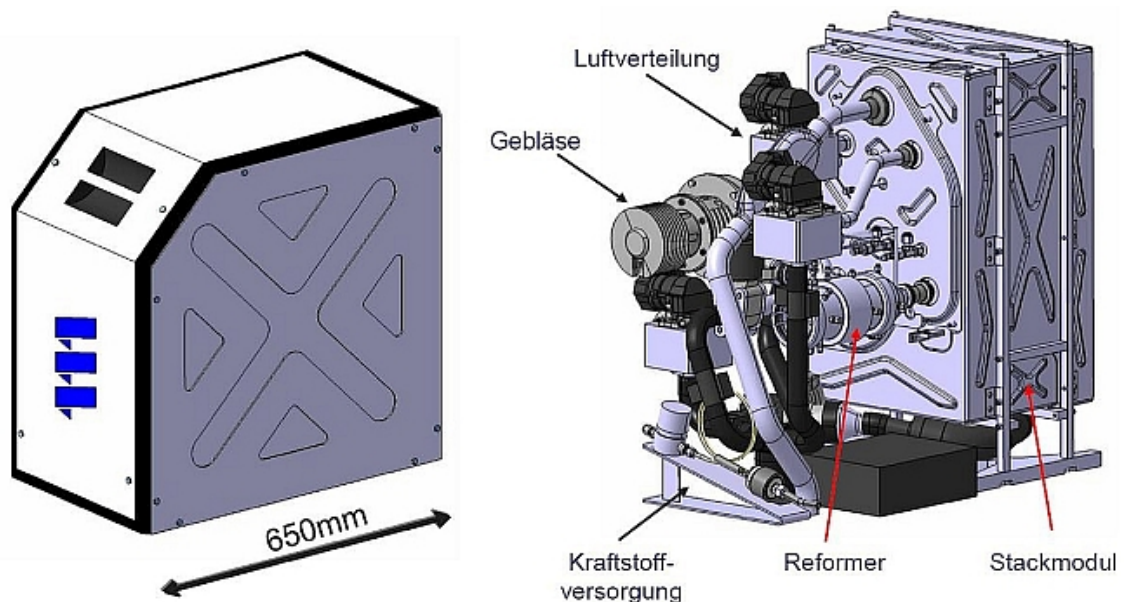


Illustration: Eberspächer

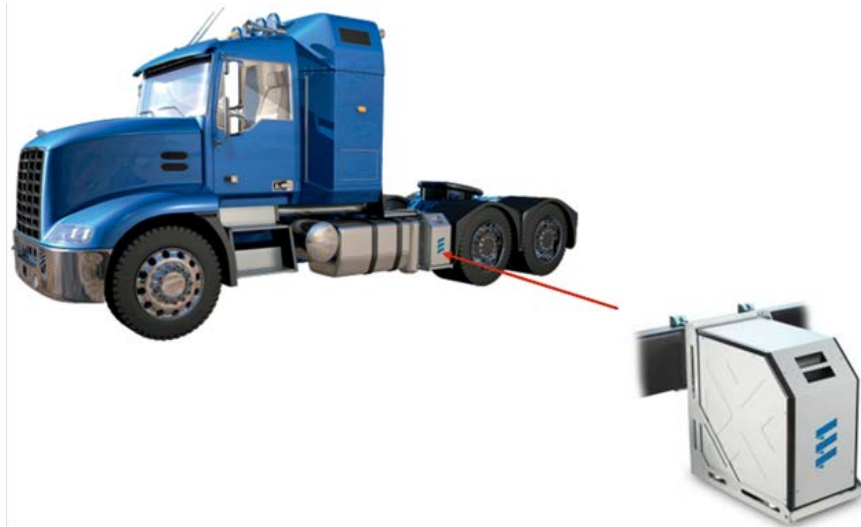
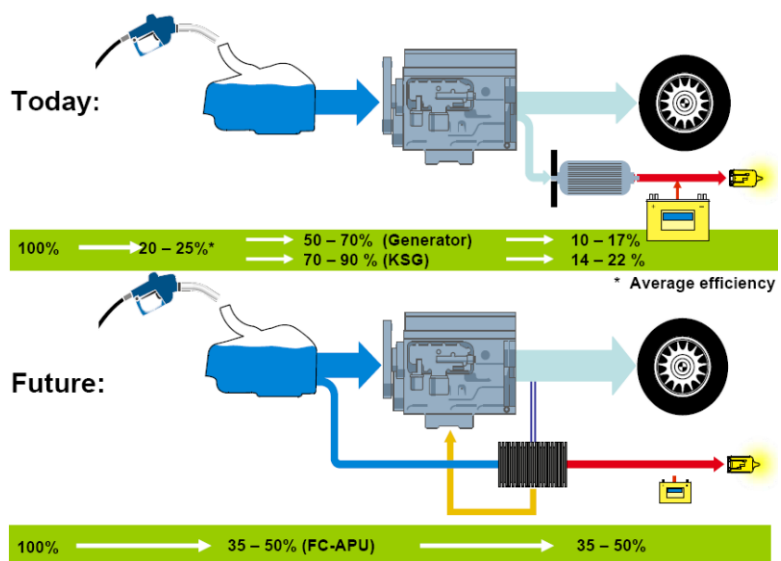


Illustration: Eberspächer

1.2 SOFC development aiming at the vehicle industry

SOFCs can be employed in APUs for on-board electricity generation on vehicles of any kind. The key for this application is the electricity supply at standstill. An SOFC-based APU significantly improves the electrical efficiency and can also supply back-up power during emergencies. Diesel is today the most common heavy duty fuel, and SOFCs offers the advantage of being able to operate on diesel reformat without the requirement of further gas processing steps. The APU size can range from 500 W up to tens of kW [IEA Annex 24].



Courtesy of FZ Jülich.

Comparison of overall electrical efficiencies between a conventional engine based power train and a SOFC-based APU.

The SOFC research and development aimed for vehicles for a selected amount of companies are listed in this chapter. A more comprehensive list of companies developing SOFCs are given in Appendix 2.

1.2.1 Delphi

Delphi (based in Michigan, US) worked with SOFC APU development for over a decade and participated in many US-governmental programs. The main challenge with Delphis APU solution has been related to the desulfurizer [IEA Annex 24 & Marketwire].

On October 28 it was released that Delphi sign an MOU on SOFC technology with Dominovas Energy (an energy-solutions company based in Georgia, US) to jointly develop new power generation technology using SOFC technology [Marketwire].



Courtesy of Delphi

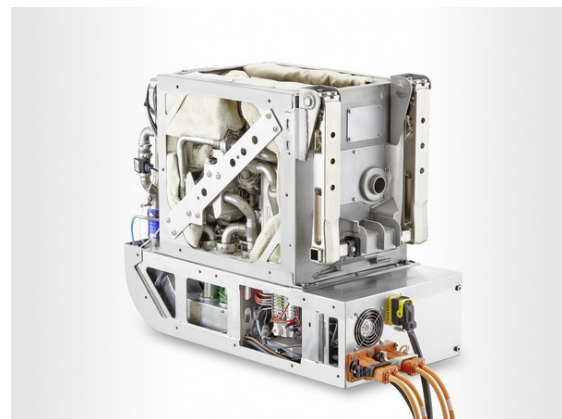
Delphi presented the current status of their APU development for many years at the annual Fuel Cell Seminar, however, no presentation was on the schedule for the November 2014 conference.

1.2.2 Eberspächer

The German automotive supplier Eberspächer has unveiled a fuel cell APU running on diesel. The maximum output is 3 kW and Eberspächer claims the future efficiency to be up to 40% [Fuel Cells Bulletin], compared of an efficiency of around 30%, for the Eberspächer APU-system in the DESTA project [DESTA d]. The Eberspächer APU features an SOFC (from an unnamed supplier) that can generate electricity from fossil fuel gas. A reformer is used, where diesel is mixed with air, then passing through a catalytic converter, to produce fuel gas containing hydrogen and CO. Eberspächer (as of October 2014) are planning to launch the fuel cell APU initially on the US market at the end of 2017 [Fuel Cells Bulletin].



from [DESTA b]



from [DESTA b]

1.2.3 AVL

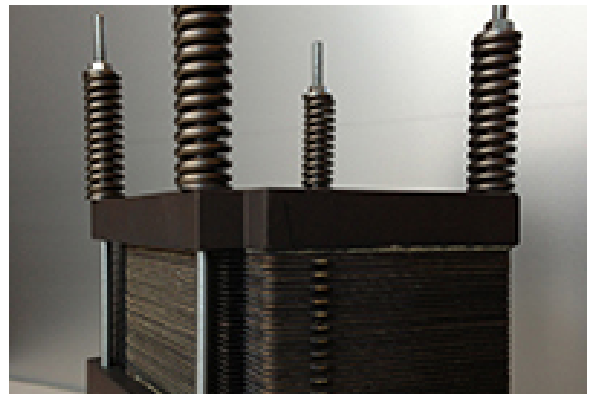
AVL (with headquarter in Austria) has developed APU technology based on SOFCs since 2002. Diesel is used as fuel and AVL claims an electrical efficiency of 35% for its 3 kW system. The system is intended for truck anti-idling, maritime and other mobile power generator applications. AVL also claims that their system is the most compact package in the industry and the lifetime to be 8000 hours [AVL a].



Courtesy of AVL

1.2.4 Elcogen

Elcogen is a manufacturer and developer of high-performance anode-supported intermediate temperature (IT) SOFCs and stacks based on proprietary materials and technological solutions. Elcogen was established in 2001 and we have offices in Tallinn, Estonia and Espoo, Finland. The company works closely with leading Estonian and Finnish research institutions. Elcogen has been financed by Estonian private investors and the government agency Enterprise Estonia and TEKES, Finland.



Courtesy of Elcogen

1.2.5 Protonex

Protonex (based in Massachusetts, US) is developing SOFC portable power sources. These systems rely on a very tightly integrated hot zone, incorporating all of the elements in the system that operated at elevated temperatures. This tight integration serves several purposes:

- Compact system for portability
- Minimizes insulation requirements, but still keeps the case cool to the touch

Protonex' SOFC systems are based on tubular fuel cells. While SOFCs can use planar or tubular cells, tubular cells have several advantages for portable systems. The most important feature is that tubular cells are inherently stronger and more robust than most planar approaches. The tubular cells, when properly integrated into a bundle and hot zone, tolerate mechanical stresses well, a critical feature for portable systems. In addition, the tubular cells are tolerant of thermal stresses, supporting rapid startup of the systems.

1.2.6 Ultra Electronics AMI

Ultra Electronics AMI (based in Michigan, US) designs, tests and manufactures SOFC technology aiming for military, leisure and emergency applications [Ultra AMI].



1.3 Markets outside the vehicle industry

The authors see the SOFC small scale CHP development in Japan as inspiring for the further development of SOFCs for the vehicle industry.

1.3.1 Small scale CHP (Japan)

The niche market aiming at small scale CHP in Japan can be compared to the FC for vehicles in terms of the different niches for SOFCs and PEMFCs.

- PEMFC was commercialized first in the ENE-FARM project (approx. 5 years before SOFC)
- SOFC is introduced when the importance of electrical efficiency increases
- Fuel flexibility is increasing with SOFCs
- SOFCs has relatively high pollution tolerance (except for sulfur)

It should be noted that AISIN SEIKI is a subcontractor for vehicle industry, however, they also developed SOFC small scale CHP system. Toyota is AISIN SEIKI's biggest shareholder. AISIN SEIKI cooperates with Bosch in the European EneField program.

1.4 “Valley of Death”

The commercialization Valley of Death exists between the pilot/demonstration and commercialization phases of the technological development cycle. Significant financial resources are required to introduce fuel cell products on the market. Recently both Topsoe Fuel Cells (in Denmark) and CFCL (in Australia and Germany) announced to cancel their SOFC related activities.

1.4.1 Topsoe Fuel Cells

Haldor Topsoe A/S announced August 12th 2014 to close its SOFC development and commercialization activities. However Haldor Topsoe remained its SOEC (solid oxide electrolyser cell) development. Haldor Topsoe invested close to 1.5 billion DKK (1.9 billion SEK), until August 2014, in its SOFC technology and estimated the investment needed to reach fully commercial cells to be more than 1.2 billion DKK (1.5 billion SEK) additionally [TOPSOE & ing.dk]. Haldor Topsoe stated *“the route to market has proven far more challenging and time-consuming than anticipated. As the sole owner of Topsoe Fuel Cell, we can no longer justify the investments and risk needed to move the company forward. SOFC remains a challenging technology and significant additional investments are needed. In addition, future success is highly dependent on the evolution of regulation, energy costs and markets”* [TOPSOE].

1.4.2 CFCL (Ceramic Fuel Cells)

On March 2nd 2015 it was announced that CFCL was insolvent [CFCL]. Currently (as of April 20, 2015) there is a message on the company homepage that the companies (in Germany and Australia, respectively) is for sale. It should be noted that CFCL's SOFC system has one of the best electrical system efficiencies (60 % LHV) for a 1-1.5 kW range. However, significant financial resources are required for bigger scale commercialization.



Courtesy of CFCL

1.5 Non vehicle related SOFC news

1.5.1 General Electric

General Electric (GE), the world's 10th largest publicly-traded company, restarted its SOFC activities in 2014. The fuel cell activities are organized as a start-up company (with GE as owner). A new pilot fuel cell manufacturing and development facility is constructed in upstate New York. GE claims its 1-10 MW-system to reach an electrical system efficiency of 65 % and a total efficiency of 95 %, when combining electricity generation with a heat demand. The GE fuel cells can be build off-grid, but requires connection to natural gas [GE].

The GE cell has no moving parts and GE claims that *“icing is the core of the breakthrough that makes the solid oxide fuel cell work. It contains three layers made from special ceramic materials: the cathode on top, the anode on the bottom, and a dense layer of solid oxide electrolyte in the middle.”* A Jenbacher engine are generating electricity of the remaining gas after the fuel cell [GE].

1.5.2 NASA

NASA previously used AFCs for Gemini, Apollo and Space Shuttle as main power source for vehicle and as water source for life support. New missions that requires long-duration stays in orbit or at a habitat cannot rely on the availability of pure reactants and should aim to be sun-independent, i.e., the SOFC might be the answer. The main advantage of an SOFC system according to NASA is the ability to tolerate “dirty” reactants with not too much reforming. A SOFC system trade well (in terms of system weight) for continues load of multiple kilowatts for a few days and longer. NASA believes that it is possible to decrease the overall system complexity using FC systems for manned-spacecrafts [NASA].

1.5.3 Solid Power

Solid Power (based in Italy) has developed a microscale CHP SOFC system (2.5 kW) with a net AC electrical efficiency of 50 % and a total efficiency (including heat) of 90 %. The system is designed for on-grid operation and with natural gas as fuel [Solid Power a]. They participated, since 2012, in the EneField Program (with financial support for installation at private homes) [Solid Power b]. Solid Power are relatively close to commercializing their SOFC system with an equity investment program of €30 million (280 million SEK) with a group of European investors advised by London based Kew Capital, and US based Leveraged Green Energy [Solid Power c]. They are also developing SOECs, and collaborate with others in the FCH-JU project ADEL (ADvanced ELectrolysers) [Solid Power d].

2 Analysis and Discussion

The main advantage for the SOFC (compared to for example the PEMFC) is the outstanding high electrical efficiency. It is possible to archive an electrical efficiency of 60 % LHV for systems as small as 1 kW.

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. It should be noted that due to different legislation in different jurisdictions the American market is expected to be pioneering.

Vehicle hybridization prepares vehicles for SOFCs, i.e., the authors does not see batteries as a competing technology to SOFCs. A system including batteries can be used while the SOFC are starting up, but also to enable the SOFC to work on an optimal load, which also means that the size of the SOFC can be decreased.

The PEMFC commercialization is preparing the (vehicle) market also for SOFCs in later stages. Of special interest is the sale of FC vehicles from Toyota, Honda and Hyundai in California and Japan (and later also in EU). As an example, GM claims to have spend USD 2.5 billion (SEK 22 billion) on the FC technology. For further development GM partnered with Honda. Renault partnered with Nissan and Toyota with BMW. The 2014 version of "The Fuel Cell Industry Review" estimates 18,500 FC vehicles by 2020, which is significantly down from the 2011 estimate of 53,000 FC vehicles by 2015-2017 [E4tech]. One should not forget that the transport sector is very diverse, and FC may be suitable also for material handling trucks, utility vehicles, buses, vans, go-karts etc. If the sector emerges successfully, it may mirror the conventional vehicle sector, i.e., some companies will produce their own FCs, which they will share with others, and other will buy FCs from proven suppliers.

The SOFC research at NASA is very far from any commercial application. However, it is promising for future SOFC product development that NASA believes in the technology. Similarly for the GE activities, which are initially not aimed for the vehicle industry, but when one of the world's biggest companies restart its SOFC research, it is clear that they strongly believe in the technology.

Both Topsoe Fuel Cells and CFCL recently canceled their SOFC activities. The authors see this as a consequence of the economical "valley of death", i.e., the product was there, but significant financial resources were needed to bring the product(s) out to the market. Note that the CFCLs BlueGen archived an outstanding electrical efficiency of 60 % for a system not bigger than 1 kW.

One can compare the introduction of FC for vehicles with FC for small scale CHP in Japan, i.e., the PEMFC was introduced approximately 5 years before the SOFC and SOFC founds its niche as the electrical efficiency becomes more important. Note that Toyota is the biggest share holder in AISIN SEIKI

(subcontractor for vehicle industry). AISIN SEIKI is also producing SOFCs for small scale CHP in Japan.

The research programs DESTA and ENSA recently finished. However, it is still required public support for the implementation of SOFC for vehicles. The authors are not aware if there are any plans for continuation of the cooperative research between the partners in DESTA and ENSA.

Legislation is a critical factor determining the speed of FC commercialization. One example of relevant legislation is the objectives regarding CO₂ emissions from legislators around the world, as the driving force hybridized cars. Within the EU emissions requirements 130g/km by 2015 and 95 g/km in 2021, according to the NEDC driving cycle, compared with 173 g/km in 2016 in Mexico, 146 g/km in 2017 in Brazil, 153 g/km in 2015 in South Korea , 117 g/km by 2020 in China , 105 g /km in 2020 in Japan , 113 g/km by 2021 in India and 93 g/km by 2025 in the USA and Canada (all values are converted to European NEDC) [EU, icct a, icct b] . An illustrative diagram can be found at The International Council on Clean Transportation (icct) [icct b]. Note that it is in discussions within the EU regarding the requirements for 2025, which are indicated to 68-78 g/km [EU, icct a]. The emission requirement just mentioned are all valid for cars, but there also legislations (at least in EU) for CO₂ emissions for other types of vehicles as well.

2.1 Benefits and possibilities with SOFCs on-board vehicles

The research focus has mostly been on the PEM fuel cell technology. This was an obvious choice in the late 90s when a lot of different technology solutions, like reformers and hydride storage were tested and benchmarked to each other. The PEM technology was the most mature of realistic choices and it had a fast start up time, which was necessary before hybrid cars showed up and allowed battery drive before the fuel cells deliver power. Today, the advantages with the SOFC are being expressed more frequently. A lot of technical achievements have made this possible:

- SOFC starts to be technically mature. SOFC based micro-CHP units are available on the market and 200 kW SOFC CHP units from Bloom Energy has been on the stationary market for some years.

- Metal supported SOFC has:

- 1) Reduced costs
- 2) Made the technology mechanically robust and suited for mobile applications

- Low temperature SOFC has:

- 1) Reduced start up time
- 2) Reduced the thermal-mechanical stress associated with SOFC, which opens up for the possibility to match SOFC thermal cycling capabilities to the need of vehicle driving cycles.
- 3) Cheaper materials in cells as well as interconnect and BOP and thus lower cost

Hydrogen as fuel might be realistic for passenger cars, however, for many heavy vehicles the hydrogen tank would be too big and too heavy to be realistic. The hydrogen tank is also the most expensive part of the FCEV (fuel cell electrical vehicle), why also cost makes hydrogen less suitable for heavy

vehicles. The driving cycle of a heavy vehicle is also much different from that of a passenger car. This implies that high efficiency becomes even more critical, e.g., for transient response. The traditional advantages with SOFC are high efficiency and a high tolerance for fuel impurities allowing for reformed fuels. As comparison, Diesel engines for road vehicle reach at the maximum (best engines, the single point of most efficient revs and load) an efficiency of 48 % (world record is 54.4 %). Already today at the infant maturity of SOFC CFCL had a commercially available micro-CHP with 60 % electrical efficiency from natural gas and efficiencies above 70 % are demonstrated in lab. Also compared to the PEM technology SOFC shows at least 10 percentage points higher electrical efficiency.

The suitability to run on reformed hydrogen from biogas, bio-ethanol, bio-methanol and syngas makes SOFC the natural choice for many heavy vehicle applications. PEMFC can be driven on reformed hydrogen, but is also less suitable because of the low tolerance for fuel impurities and the complicated reformers and gas cleaners needed, resulting in heavy, large and expensive solutions already deselected in the very late 90s. SOFC can run on CO as a fuel, while CO is a poison to the PEMFC, which makes SOFC suitable for syngas and biofuels.

Among the experts believing in SOFCs, one finds Toyota who has lately applied for many SOFC patents.

3 IEA Annexes with participation from LU department of Energy Sciences

3.1 IEA SOFC annex 32 (previously annex 24)

The overall objective of Annex 32 is the continuation and intensification of the open information exchange to accelerate the development of SOFC towards commercialization. Annex 32 holds series of annual workshops 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. Where possible, these workshops will be linked to other 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 and the United States.

The next meeting is planned for Glasgow, Scotland in connection to the ECS – SOFC conference July 2015.

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

3.2 IEA modeling annex (annex 37)

The modelling annex aims at developing, maintaining, and applying a suite(s) of open source computational fluid dynamics (CFD) software for application to FCs, electrolyzers and other electrochemical applications (hydrogen storage, batteries, etc.) including validation and verification (V&V) by comparison with other CFD codes, physical experiments, development of “benchmark problems”, and round-robin tests.

This annex is a task shared activity with a focus on information sharing and learning from members. Two web sites is maintained, a public web site accessible by anyone in the world, and a private web site, accessible only by participating members. Members can be either users or developers (or both). Indeed the bringing together of these two groups is an important contribution of the annex. Arising software will be maintained and documented online. Members will meet face-to-face at least once a year to discuss both the science (chemistry and physics) and also the technology (programming languages, software best practices etc.). This could be colocated with some suitable external conference. In addition quarterly video-conferences will be held.

The primary goal is to develop state-of-the art multi-scale models of FCs using open source software. The models are then to be used to advance the science and engineering of modern fuel cells to gain a competitive advantage over competing technologies. The models are to be validated with

experimental data and refined as a result of the validation, improved and further refined. Software best practices are to be followed including maintaining versions on a repository e.g., GIT, use of shared integrated environment (IDE), and ongoing documentation of the work by the participants.

The first meeting of the modeling annex was organized at FZ Jülich in January 2015 and the next meeting is planned for Naples in December 2015. Also working group meetings are organized between the annex meetings, with the latest one in Grenoble (March 2015).

The following countries (in alphabetical order) have indicated an interest in participating: Canada, Croatia, Denmark, France, Germany, Italy, United Kingdom, United States and Sweden.

Swedish participates are: Docent Martin Andersson and Professor Bengt Sundén.

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4.1 Conference participation

1. 11th European Fuel Cell Forum Luzern, Switzerland, July 2014
(including informal IEA Annex 24 meeting).
2. SAE 2014 New Energy Vehicle Forum, Shanghai, China, September 2014.
A contribution to the "OMEV" newsletter was written.
3. Fuel Cell Seminar, Los Angeles, USA, November 2014.
A contribution to the "OMEV" newsletter was written.
4. IEA Modeling Annex start-up meeting Jülich, Germany, January 2015.

Appendix 1 - Technology overview

Early fuel cell development and future potential

The principle behind fuel cells (FCs) dates back to 1838 when the Swiss-German scientist Christian Friedrich Schönbein (professor at Basel University) tried to prove that currents were not a result of two substances coming into "mere contact" with each other, instead the current were caused by a "chemical action". This finding was submitted on February 18th, 1838 and published in "*The London and Edinburgh Philosophical Magazine and Journal of Science*", 1838. In 1839 he published a conclusion based on experiments on platinum wire, and how it could become polarized or depolarized depending on the surroundings. Fluids, separated by a membrane, were tested, with different gases dissolved in each compartment. No current was obtained when gold or silver wires were used. It was concluded that "*the chemical combination of oxygen and hydrogen in acidulated (or common) water is brought about by the presence of platina in the same manner as that metal determines the chemical union of gaseous oxygen and hydrogen*". Not only Schönbein worked on the principle behind fuel cells, Sir William Robert Grove (Royal Institution of Great Britain) performed experiments with a set-up, where two platinum electrodes were halfway submerged into a beaker of aqueous sulfuric acid and tubes were inverted over each of the electrodes, one containing oxygen gas and one containing hydrogen. The description of the experiments was submitted on December 14th, 1838 and published in the "*Philosophical Magazine and Journal of Science*", 1839. The solid oxide fuel cell (SOFC) was developed in 1937 by Baur and Preis for a need of more manageable electrolytes.

The International Energy Agency (IEA), based in Paris, has concluded in many reports that fuel cells will be a key component in a future sustainable energy system. Fuel cell systems including niche applications or a market where fuel cells bring an added value are already competitive, compared to other energy systems. A high energy content per weight was the key point in the American space program and the low noise is the key factor for the fuel cell development related to military applications. About 80 percent of the energy resources traded today is of fossil origin (coal, oil and natural gas). These resources are limited. Many of the energy conversion technologies used today are energy inefficient, compared to fuel cells.

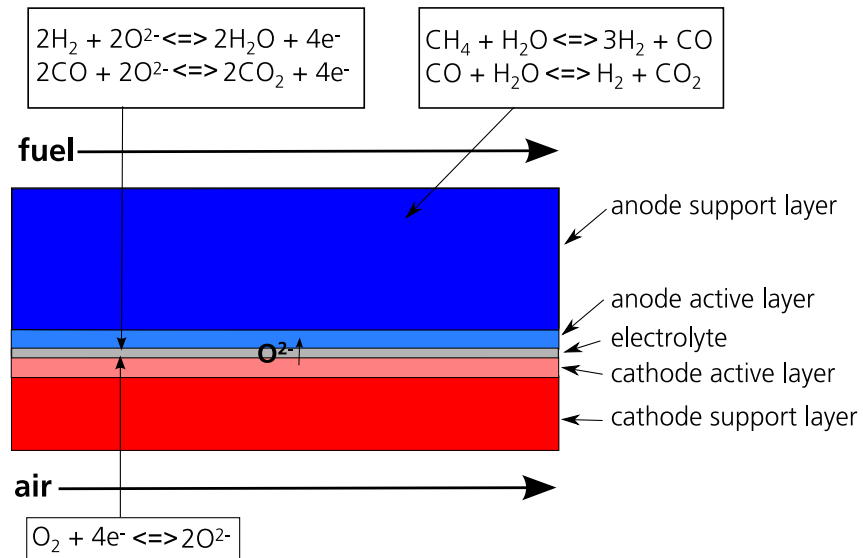
A new technology, such as the fuel cell, is usually introduced into the market in niches where the new and non-traditional characteristic of the technology provides sufficient added value to compensate for the high (capital) cost. During recent years, there have been increasing interests to use fuel cells as auxiliary power units (APUs) in on-board applications, for example in luxury passenger vehicles, police vehicles, contractor trucks, specialized utility trucks, recreational vehicles, refrigeration vehicles, and heavy trucks, military vehicles, tourist- and leisure boats, mainly due to a higher energy efficiency compared to existing technologies. In the short term, on-board hydrogen

production makes it possible to use current fuel refilling system. Gasoline, kerosene or diesel can still be used as fuel and only one fuel storage system is then needed on-board the vehicle. In these cases the hydrocarbon fuel will then be reformed in an on-board pre-reformer to hydrogen. FC APUs can be considered as a good transition state to reach the aim of hydrogen economy in vehicle applications.

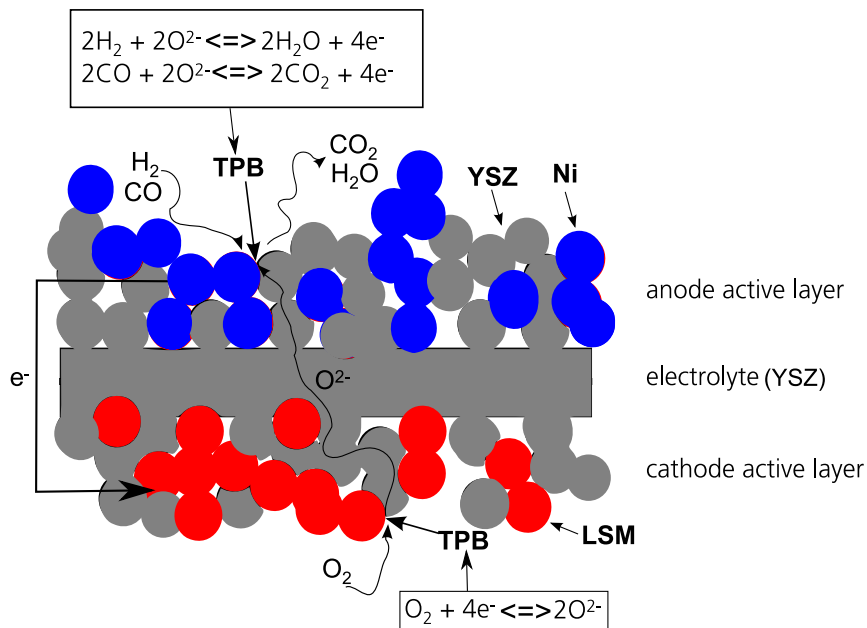
Working principle of a fuel cell

The simplest form of a fuel cell is based on the reaction between oxygen and hydrogen that forms water. A fuel cell consists of an anode, a cathode, and an electrolyte (see Figures 1-2). The anode is connected to the power source positive pole and the cathode with its negative pole. The electrolyte can be compared with a membrane. The gaseous fuel is transported to the anode where it reacts in electrochemical reactions with oxygen ions. The oxygen ions are produced in the cathode where oxygen reacts with electrons. The oxygen ions are transported through the electrolyte to reach the fuel in the anode. The electrons are blocked from being transported through the electrolyte, enabling a voltage. The description given applies to what happens in a SOFC, but also other types of fuel cells are constructed according to the same principles. SOFCs have a high operating temperature, the electrolyte, consisting of a solid oxide, is designed to allow only oxygen ions to pass. The difference between the various types of fuel cells is primarily the type of electrolyte being used and the fuel cell operating temperature.

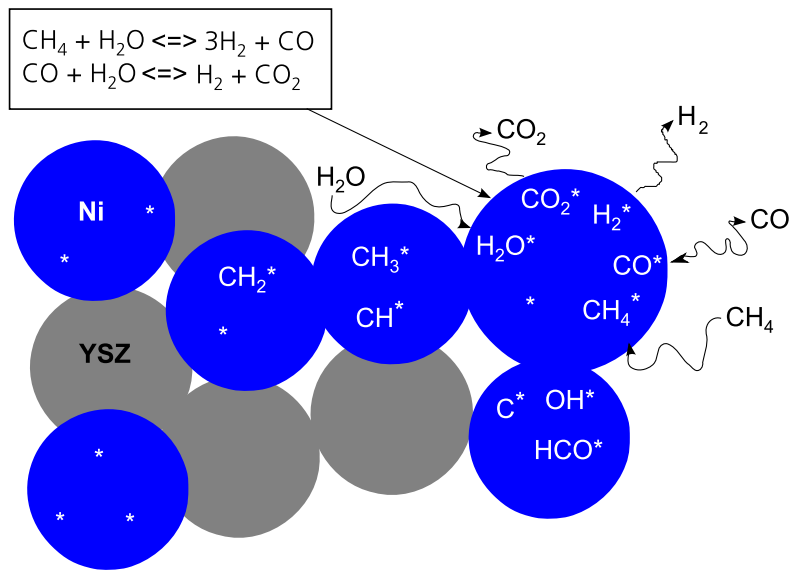
Fuel cells produce electricity and heat directly from chemical reactions between fuel and air (oxygen). When pure hydrogen or biogas is used there will be no net emissions of carbon dioxide, harmful particles and nitrogen oxides if the production process of fuel is clean. The process is thus completely environmentally friendly and carbon neutral. An advantage of SOFCs is that it is possible to use hydrocarbons, e.g., methane. With methane as fuel, the fuel reforming occurs inside the anode (see Figure 3), i.e., the products are hydrogen and carbon monoxide which can be used in the electrochemical reactions (see Figure 2). Even "heavier hydrocarbons" with longer carbon chains can be used as fuels in a SOFC systems, however, then a pre-reformer is needed, where the fuel reacts with oxygen and/or water vapor before it is directed into the fuel cell stack.



Figur 1. Schematic figure describing an SOFC in the cell scale.



Figur 2. Schematic figure describing the electrochemical reactions within a SOFC.



Figur 3. Schematic figure describing the internal reforming reactions within a SOFC anode.

In a fuel cell stack, many individual cells are stacked to a cell packet, where the electrical current is connected in series. Each individual cell is operating a cell voltage of about 0.7 V and a current density of 0.5-2 A/cm², i.e., a power density of 1 W/cm². The number of cells (per cell packet) determines the cell voltage and the catalytically active surface (m²/m³) affects the current per cell. Various cell packages can be connected either in series or parallel. A SOFC (of the second generation) are usually working at 700-800 °C. A higher temperature leads to a higher current density or voltage, however, the life-length is reduced and the manufacturing costs increases. An electrical efficiency (LHV) of 60% is possible, and even higher when combined with gas- or steam turbines. Furthermore, often the heat is utilized, i.e., the overall efficiency can be up-to 90-95%. The use of high-grade waste heat for reforming hydrocarbons can increase the system efficiency.

Appendix 2 - Currently Active SOFC Companies

North America

Acumentrics
AMI / Brentronics
Bloom Energy
Delphi
DDI
GE
LG Fuel Cell Systems
TMI
Nextech Materials
Materials & System Research
Redox Power
Protonex
Ultra Electronics AMI
Versa Power / FuelCell Energy
Watt Fuel Cell

Europe

Adelan
AVL List
Ceres Power
CFCL (expected to cancel their SOFC activities during 2015)
Convion
Dantherm Power
Eberspächer
Elcogen
EBZ
eZelleron
FuelCon
Hexis
new enerday
Plansee
Saint Gobain Corporation
Sunfire
SOFCPower
Solid Power
Topsoe Fuel Cells (canceled their SOFC activities during 2014)
Valliant

Asia & Pacific's

Aisin Seiki
Cera
Kyocera
Honda motor (initially for stationary applications)

Iwantani
JX Nippon Oil
Mico
Miura
Mitsubishi Heavy Industries (MHI)
Murata Manufacturing
Ningbo Materials Institute of Technology and Engineering (NIMTE)
NGK Insulators
NGK Spark Plug
POSCO
Sumitomo Precision Products
TOTO

References: 4th Energy Wave & IEA

Appendix 3 - Abbreviations

AFC	alkaline fuel cell
CFD	computational fluid dynamics
CHP	combined heat and power
APU	auxiliary power unit
CFCL	Ceramic Fuel Cells Limited
ENE-FARM	product name for small scale CHPs on the Japanese market
FC	fuel cell
FCEV	fuel cell electrical vehicle
FCH-JU	Fuel Cells and Hydrogen-Joint Undertaking
FZ Jülich	research center Jülich (in Germany)
GE	General Electric
icct	The International Council on Clean Transportation
IDE	integrated environment
IEA	International Energy Agency
LHV	lower heating value
LT	low temperature
IT	intermediate temperature
PEMFC	Polymer electrolyte membrane fuel cell
SAFARI	SOFC APU for auxiliary road-truck/installations
SOEC	solid oxide electrolyser cell
SOFC	solid oxide fuel cell
V&V	validation and verification

Appendix 4 - Exchange rates

1 €	9.29 SEK
1 US\$	8.67 SEK
1 DKK	1.24 SEK

Reference: Google/Citibank N.A (2015-04-21)

TECHNOLOGY REVIEW – SOLID OXIDE FUEL CELL

Denna rapport fokuserar på beskrivning och analyser av nuvarande status samt nödvändig utveckling och nödvändiga genombrytningar som krävs för att SOFC (fastoxidbränslecellen) ska kunna bli kommersiell för fordonstillämpningar. Målgruppen är främst svensk industri och akademi.

Kommersialiseringen av PEMFC (polymerelktrolytbränslecellen) startade cirka 5 år innan kommersialiseringen av SOFC och en nischmarknad för SOFC uppstår när elverkningsgraden blir viktigare. En elverkningsgrad 10 procentenheter högre för ett SOFC-system jämfört med ett PEMFC-system kan förväntas. En elverkningsgrad på 60 % är möjligt för ett system så litet som 1 kW.

NASAs SOFC-forskning är mycket långt ifrån någon kommersiell tillämpning. Det är dock lovande för framtida produktutveckling av SOFC-teknologin att NASA tror på tekniken. På samma sätt är det för GEs (General Electrics) SOFC-aktiviteter, som till en början inte är ämnade för fordonsindustrin. Både Topsoe Fuel Cells och CFCL (Ceramic Fuel Cells Limited) har nyligen avbrutit sina respektive SOFC-verksamheter. Författarna ser detta som en följd av den ekonomiska "valley-of-death", det vill säga produkten var där, men betydande ekonomiska resurser behövs för att få produkterna ut på marknaden.

Ett nytt steg i energiforskningen

Energiforsk är en forsknings- och kunskapsorganisation som samlar stora delar av svensk forskning och utveckling om energi. Målet är att öka effektivitet och nyttiggörande av resultat inför framtida utmaningar inom energiområdet. Vi verkar inom ett antal forskningsområden, och tar fram kunskap om resurseffektiv energi i ett helhetsperspektiv – från källan, via omvandling och överföring till användning av energin. www.energiforsk.se



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