

WORLDWIDE SOFC OVERVIEW FROM A SCANDINAVIAN AND A EUROPEAN PERSPECTIVE

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ABSTRACT

Solid oxide fuel cells are being developed by several consortia worldwide for different applications and systems. The designs, size of stack and system, and the operating temperature differ significantly, although many of the material choices are similar. An overview of status worldwide is given, with special emphasis on the developments in Scandinavia and in Europe.

INTRODUCTION

Compared to other fuel cell types, solid oxide fuel cells (SOFCs) have a number of attractive features: fuel flexibility (in particular CO tolerance), components that are all solid state (no liquid electrolytes), no water management issues, and high quality surplus heat for either combined heat and power (CHP) or for use in hybrid systems with gas turbines. Recent years have witnessed substantial improvements in performance and durability, mainly through advances in manufacturing technology. The typical cell area specific resistance has been reduced significantly thereby allowing the operation temperature to be decreased from 1000 °C to 750 °C. This, in turn, has made it possible to use cheaper materials. Although somewhat less mature technologically than, e.g., molten carbonate fuel cells, SOFC is today widely considered to be one of the two most promising fuel cell types (together with polymer electrolyte fuel cells, PEMFCs). Present-day fuel cell R&D is predominantly focused on these two cell types.

In the USA the major SOFC research program is the Solid State Energy Conversion Alliance (SECA) which brings together government, industry and research institutions. There are six industry teams with the goal of developing 3-10 kW_e SOFC system prototypes by 2010. SECA is managed by the National Energy Technology Laboratory and Pacific Northwestern National Laboratory with an annual budget of approx. 60 M\$. The ambitious development goals have been influential in setting standards for R&D in other parts of the world. Europe has been somewhat behind the US in formulating an overarching SOFC strategy. However, it is expected that the coming Framework Programme 7 will feature SOFC prominently as part of the European strategy for hydrogen and fuel cells. Nationally, a number of strategies have been implemented, in particular in Denmark, Germany and the UK. The primary focus areas are PEMFC and SOFC.

While SOFC fabrication methods have seen dramatic improvement leading to better cell performance, the developments of materials and fundamental concepts have been more incremental. To a large extent this is due to the still incomplete understanding of the cell processes at the most fundamental level. The cell nanostructure plays a crucial role and even minute quantities of impurities may affect the performance dramatically. These facts indicate the need for an increased focus on the fundamental materials issues involved.

This overview is organized as follows: The status of SOFC R&D is described at the cell level, at the level of cell components, at the level of manufacturing processes, and at the level of

materials. In addition, we briefly sketch some recent interesting research directions at the more fundamental level. Finally, systems design and demonstrations, with particular emphasis on Scandinavian efforts, are briefly summarized.

CELL GEOMETRY

Any fuel cell assembly must allow the individual cells to be connected electrically, while keeping fuel gas and air separate. How this is done is mostly determined by the choice of cell geometry. Here, solid oxide fuel cells offer a somewhat wider range of choices than other cell types due to the ready availability of standard ceramic forming technologies. Generally speaking, one may distinguish between two main classes: the tubular and the planar geometry. Both designs have their advantages and disadvantages with respect to, e.g., power density, manufacturing techniques, mechanical issues, thermal cycling, and integration with other power generating technologies. The choice of cell geometry is therefore to a large part dependent on the particular applications in mind, including the operating temperature, the size of stack and systems, the fuel and where and how the system is to be operated.

Tubular Cells

Tubular cells have internal cavities where air or fuel gas may flow, thus simplifying the sealing issues. In addition, thermo-mechanical issues may prove easier to control. However, because cells cannot be connected electrically along their entire curved surface, a substantial part of the current path will be in-plane in the cell, leading to relatively high internal resistances. In addition, mechanical limits to the lower diameter and thickness of the cells makes it harder to achieve high volumetric power densities.

The first to pursue tubular cells were Westinghouse in the USA who built both planar and tubular “fuel batteries” in 1962-63. Due to difficulties with sealing the flat cells, Westinghouse decided to go with tubes. In 1980 a “seal less” tubular design was introduced which has formed the basis for Westinghouse’s (now: Siemens’) development since. The emphasis has been on larger systems (>100 kW_e). Around 2000 it was realised that the original design would not be able to meet the SECA objectives with respect to power density. As a result Siemens has developed a number of alternative designs: Their *high power density* (HPD) cell consist of a flattened tube (length 75 cm) with integral ribs dividing the interior cavity into 5 (HPD-5) or 10 (HPD-10) air flow channels. This serves to decrease the current paths and to increase the contact area of the interconnectors. Siemens’ next-generation HPD cell, Delta-9, can be considered as a tubular-planar intermediate design. It has integrated, triangular fuel and air channels and an integrated ceramic interconnector.

The American company Acumentrics is developing small tubular cells for 5-10 kW modular stacks. Keeping the cells small (diameter 15 mm, length 42 cm) serves to minimize thermal gradients in startup and shutdown conditions.

A number of Japanese companies are developing tubular designs, including Kyocera (flat tube cells, so called *Horizontal-Stripe Cells*), Mitsubishi Heavy industries (hybrids with micro gas turbines), and Toto Ltd. The latter has been developing a tubular design similar to the original Siemens design. In 2006 Toto announced the successful development of a fuel cell stack with small tubes (length 50 mm, diameter 5 mm) operating at 500 °C for portable power generation in the power range 50 W-1 kW. The startup time from room temperature is claimed to be as short as 5 min.

In Europe the most prominent developer of tubular cells is Rolls Royce Fuel Cell Systems Ltd. (RRFCS) in the UK. They are pursuing a flat, tubular design with many cells in series. Sealing is necessary to avoid cross over of gases. The design may therefore be seen as an intermediate tubular/planar design. Each module consists of about 20-40 cells in series, giving a reasonable voltage, and the modules are easily bundled to make a stack. Recently, promising load cycle behaviour for such stacks has been reported.¹ RRFCS has presented ambitious plans for the demonstration of larger systems. The aim is for the integration of the SOFC with gas turbines to achieve higher electrical efficiencies, in the range of 70%. RRFCS has linked with the Singapore company Enertek for the manufacture of stacks and systems.

Planar cells

Planar cells (including topologically equivalent geometries such as corrugated plates) have the major advantage that the current path in a stack is predominantly perpendicular to the cells, thus minimizing the in-plane losses. In addition, the design can be made more compact than a tubular cell assembly. This results in higher obtainable power densities. The Danish company Topsoe Fuel Cell have demonstrated a stack with a volumetric power density of 2.4 kW/liter, using planar cells from Risø National Laboratory.²

A wider range of manufacturing processes may be used for planar cells than for tubular cells, thereby providing more freedom to optimize the different components of the cells. However, the mechanical and thermo-mechanical properties are generally poorer than for tubular cells, due to edge effects. Start-up and thermal cycling can induce much higher mechanical stresses in a flat cell. This can in part be circumvented by using a circular cell design. Such designs are pursued by, e.g., Hexis in Switzerland, General Electric in the USA and Ceramic Fuel Cell Ltd. (CFCL) in Australia.

Planar cell developers in Europe include Topsoe Fuel Cell/Risø National Laboratory, Research Centre Jülich (Germany), Ceres Power (UK), ECN (Energy research Centre of the Netherlands), Staxera (a joint venture between H.C. Starck and the German automobile supplier Webasto), Hexis (Switzerland) and HTCeramix (Switzerland).

In the USA most of the consortia in the SECA programme focus on planar cells. This includes General Electric, Cummins Power Generation/SOFCo-EFS Holdings, Fuel Cell Energy and Delphi/Batelle.

In Japan most of the major players are working on planar cells, including Chubu, Mitsubishi Heavy Industries, NGK Insulators, and Mitsubishi Materials.

STACKING DESIGN

The choice of stacking design is intimately connected to the choice of cell and gas flow geometries. For both tubular and planar cells the interconnects serve to connect the cells electrically. For planar cells the interconnect also play a role as gas separator, i.e. the interconnect must be gas tight and the cross over of ions minimal. To ensure gas tightness of a planar cell stack, sealing is required at places which depend on the specific stack design. For true tubular systems interconnects need not be gas tight. Then the separation of the gases may be assured by the electrolyte (e.g. in the Siemens design). In the Rolls-Royce design sealing around each cell unit is done to minimize gas cross over. In all cases, sealing at gas inlets is required.

Tubular cells are typically connected both in series and in parallel, and may be collected in bundles. Planar cells are stacked in series, but may also be a combination. The latter was used

in a design of Siemens, where each interconnect plate contacted, e.g., four cells in parallel electrically. The main reason for this design is to avoid complete failure if a single cell in a stack fails.

The manifolding may be internal or external for the planar design. External manifolding is conceptually the simplest, but the manifolds add to the cost of stacking and sealing becomes more complicated; in addition flow is restricted to being cross-flow (i.e. fuel and air flows at right angles to each other). Internal manifolding offers simpler sealing and is more flexible with regard to flow geometry which may be cross-, counter- or co-flow or even spiral-type. A disadvantage is that active cell area is lost when gas flow holes are cut. This, however, is offset by cost savings in stacking. Many developers now use the internal scheme, e.g. Topsoe Fuel Cell and HTCeramix. The internal manifolding may also be introduced in a metal skirt to which the cell then is being attached, as is being pursued by, e.g., Delphi in the USA. Flow distribution is most often effected by having channels or corrugations in the interconnect (having them in the cell means longer in-cell current paths).

The comparative advantages of different flow geometries depend on both stack design and cell performance. Topsoe Fuel Cell has performed detailed modelling of a stack for three different flow geometries. The results show that both co- and counter-flow give rise to smaller temperature gradients across the cell plane than the cross-flow configuration. This in turn means higher average operating temperatures (other conditions being equal) which then allow higher power densities. The highest power density in the study is found for the counter-flow configuration which is approx. 80% higher than the cross-flow configuration.³ This indicates that Topsoe's demonstrated stack power density of up to 2.4 kW/liter, obtained using cross-flow and internal manifolding, may be increased substantially by optimizing the flow geometry.

CELL SUPPORT

To give the cell sufficient mechanical strength to be handled, one of the cell components have typically been made thicker than the others. This component then acts as cell support. However, recently a number of proposals for so-called unsupported cells have appeared. Here, all cell layers are of comparable thickness and contribute equally to the mechanical strength.

Electrolyte supported

The first generation planar SOFCs (1980s and 1990s) were electrolyte supported. In order to make the electrolyte gas tight with the then available ceramic forming methods, it was necessary to have a relatively thick electrolyte (~200 μm) which was then acting as the mechanically supporting layer at the same time. An electrolyte with this thickness has a rather low ionic conductivity which necessitates elevated operation temperatures (950-1000 $^{\circ}\text{C}$). Zirconia-based electrolyte supported cells are still being pursued by, e.g. CFCL, Staxera and Hexis. The zirconia is typically with 3 or 8 mol% Y_2O_3 doping, giving rise to tetragonal and cubic majority structures, respectively. The cells can be made rather robust with respect to redox cycling, and for μ -CHP applications this may be more important than maximising the power density.

Anode supported

Most planar cell developers switched to anode supported cells in the second half of the 1990s. In an anode supported cell the support is made of a 250-500 μm layer of anode material

(typically a Ni-YSZ cermet) which may or may not have an active anode layer with a different structure on top of it. The advantage of this configuration is that a very thin electrolyte (~10 μm) may be introduced which reduces the cell resistance substantially. The anode support is, however, less durable under redox cycling. The metallic nickel particles in the reduced support grow when they are oxidized, giving rise to internal stresses which break the cell. This may to some extent be helped by control of the composition and by systems design (using valves and back-up gases). Tubular designs may also be anode supported, e.g. that of Acumentrics.

Cathode supported

An advantage of a cathode supported cell compared to an anode supported is that the anode layer can be much thinner, making it easier to obtain a redox stable cell. However, cathode materials tend to react with the electrolyte material at elevated temperatures, causing the electrolyte performance to diminish. This makes it difficult to manufacture dense electrolytes on a cathode support using powder methods, because of the high sintering temperatures necessary to densify the electrolyte. To circumvent this, physical or chemical deposition methods for the electrolyte may be used. Both the tubular designs of, e.g., Siemens and Toto are cathode-supported, based on extruded LSM tubes as the mechanical entity. Siemens is using plasma spraying as a deposition technique for the Delta-9 cells.

Metal supported

As the operation temperature is reduced, it becomes feasible to use FeCr steels as the cell support. Current metal supported cell designs envisage an operation temperature below 650 $^{\circ}\text{C}$. The main advantages of the metal supported cells are low price and high robustness; most of the cell material consists of relatively low-cost steel, and the ductile metal support increases mechanical strength and redox stability. In addition, thermal stresses due to thermal gradients along the cell plane are reduced due to the high thermal conductivity of the support. Metal supported cells are not yet as mature as, e.g., electrolyte or anode supported cells. However, their promising properties make them an attractive research topic for a number of cell developers. Ceres Power is using 200-300 μm thick metal foils, made porous by laser drilling 10-30 μm holes in them, as supports for a thin SOFC based on a ceria electrolyte.⁴ The use of ceria as an electrolyte limits the operation temperature to below about 500 $^{\circ}\text{C}$ because at higher temperatures ceria becomes an electronic conductor with a sizeable conductivity, thereby partly short circuiting the cell. The design of Ceres Power may be very suitable for rapid start-ups and thermal cycling, e.g. for use in the transport sector. National laboratories at Argonne, Lawrence Berkeley, and Risø are among others that are developing metal supported cells based on powder metallurgy similar to the processes used for anode and electrolyte supported cells.

MANUFACTURING TECHNOLOGIES

Due to the complexity of the many materials and processing parameters entering into the manufacture of SOFCs, going from lab-scale methods to series production is highly non-trivial. As a result a substantial amount of SOFC R&D is focused on manufacturing processes. A key challenge is to use cheap, up-scaleable technologies for producing the rather delicate and thin multi-layered structures where some layers must be porous and others gas tight. This is being pursued through several different routes. They may be roughly divided into two groups: Ceramic methods and chemical and physical methods.

Ceramic methods

Several standard ceramic forming methods may be used to manufacture the cells and stacks. The cells consist of several ceramic or cermet layers which must provide different properties when the manufacture is completed, e.g. some layers must be gas tight and ionically conducting, others electronically conducting and porous. Because the ceramic processing methods imply high degrees of shrinkage during the sintering procedures it is challenging to obtain cells with the proper dimensions and specific properties. Ceramic processing skills are hence an integral part of the development of high performance and durable cells. The sintering process by nature implies reactions, to a smaller or larger degree, between the constituents. These reactions are advantageous when they for example helps the adhesion, but may also be a problem when causing the development of species with unwanted properties, e.g. Sr-zirconates at cathode-electrolyte interfaces, or the development of glasses formed by mobile impurities during the manufacture.

For tubular cells a standard method is extrusion, where a thick paste, consisting of ceramic powder with various binders and plasticizers added, is forced through a die of the required shape. This is a cheap and mature technology. However, the need for structural integrity of the green (unfired) tubes place lower limits to their thickness.

For planar cells tape casting of the support is a common manufacturing technique. A slurry is drawn past a doctor blade which determines the thickness of the cast layer. The layer is dried and cut or punched into the required shape before additional layers are deposited. The loss of material when punching or cutting may be significant, depending on the design (round or square). An alternative method for producing planar supports is warm pressing of ceramic powders. This is one method used at, e.g., Research Centre Jülich. An advantage of this method is the avoidance of loss of material since the shape of the support is made directly. However, on an industrial scale, continuous processes like extrusion and tape casting are expected to be cheaper in the long run.

To manufacture the additional layers of an SOFC, several processes are being used. Tape cast anode and electrolyte layers may be laminated or calendared together, as done by, e.g., General Electric. Alternatively, additional layers may be cast on top of a previously cast layer; such co-casting is used by HTCeramix. Dip coating of one or more layers may be a part of the manufacture of tubular cells like the ones produced by Acumentrics. Wet spraying has been used for many years to deposit thin films of electrode or electrolyte materials. This is a widespread and cheap deposition technique. However, one of the challenges using this method is to control the thickness over the whole cell area, and the waste and environmental impact are issues of concern. Screen printing is a well-known process, where waste and thickness control is quite well established. This method is used in several places, like InDec (now part of H.C. Starck) and Risø National Laboratory. In general, the introduction of a new process necessitates an intensive development program to adjust slurry or paste properties optimally.

Chemical and physical methods

Sintering may be avoided by using various chemical or physical methods like chemical vapour deposition, sputtering, pulsed-laser deposition, plasma deposition and more. Such methods make it possible to control structure, thickness and reactions on a finer level. A major drawback of these methods is the cost at an industrial production level. This was experienced by Siemens following the procedures chosen by the Westinghouse concept, where electrochemical

vapour deposition (EVD) has been replaced by cheaper plasma spraying methods. However, plasma spraying is also problematic with respect to waste of material, whereas other physical or chemical methods may utilize the materials more efficiently.

Although many of the chemical and physical methods are being pursued actively as manufacturing processes for SOFCs it remains to be seen if they can be made cost-efficient in direct competition with the ceramic processes. However, these methods may be suitable for the manufacturing of model materials and model components.

MATERIALS

Most of the materials currently in widespread use in SOFCs have been known and used for several years. This reflects the fact that the strenuous demands made on SOFC materials are hard to meet, as regards, e.g., performance, lack of degradation, compatibility with other cell components, and suitability for large-scale production processes. A lack of precise theoretical understanding also means that much materials development takes place as a time-consuming trial-and-error process.

Electrolyte

For several years the electrolyte of choice has been yttria-stabilized zirconia, YSZ. This compound has a number of attractive properties, most notably a sizable ionic conductivity in combination with chemical and mechanical stability at elevated temperatures. In electrolyte supported cells the major part of the internal losses in the cell is associated with the YSZ electrolyte. This is no longer true for an anode supported cell operated at, e.g., 750 °C. However, when the operation temperature is lowered further the electrolyte resistance again becomes dominant. This motivates the search for new electrolyte materials for intermediate temperature SOFCs, such as the metal supported cells.

Lanthanum gallate (LnGaO_3) doped with strontium and magnesium are being investigated as a possible electrolyte. Such compounds have a higher ionic conductivity and have been shown to be stable in a range of oxygen partial pressures. As a consequence they are pursued by a number of developers, e.g. by Ceramtec.⁵ However, these materials have so far shown unsatisfactory long-term durability, and their compatibility with other cell components and standard cell manufacturing processes has not been demonstrated.

Ceria is a mixed conductor at elevated temperatures. For this reason it can not be used in anode supported cells which typically operate at 750-850 °C. However, at lower temperatures (below approx. 550 °C) the electronic conductivity becomes negligible. Ceres Power is using a ceria electrolyte in their metal-supported cell.

Scandia doped YSZ (Sc-YSZ) can exhibit a higher ionic conductivity than YSZ and is for this reason being pursued as a possible electrolyte material by several researchers. Again, the long-term performance and durability remains largely uninvestigated.

Anode

The anode in most SOFCs is a Ni-YSZ cermet. Ni is the electrochemically active material, while the YSZ acts as a backbone, keeping the Ni-particles from agglomerating and giving good adherence to the YSZ electrolyte. It is usually made by mixing NiO and YSZ particles. Upon initial reduction the NiO particles are reduced to metallic Ni, shrinking in the process, and thus creating the porous Ni-YSZ structure. The major problem with the Ni-YSZ

anode concerns redox stability: Upon re-oxidation the Ni particles grow, creating internal stresses which ultimately tends to break the cell. Even if the stresses are contained, the growth and subsequent agglomeration of the Ni particles under re-reduction reduces the activity of the anode.

A large effort is made in trying to find a metal-free anode, since this would presumably increase redox stability markedly. Among the materials investigated are doped titanates.⁶ So far, none has been reported to show comparable performance to that of the Ni-YSZ cermet anode.

Cathode

For cathodes the standard material is strontium-doped lanthanum manganite (LSM), often mixed with YSZ to increase the triple phase boundary and to ensure good adherence to the electrolyte. Since the cathode accounts for the major part of the internal losses in high-performance cells, many new materials have been investigated. Lanthanum strontium cobaltite ferrite (LSCF) is a promising candidate.⁷ It has demonstrated performances that allow the cell temperature to be lowered towards 500-600 °C. However, LSCF tends to react detrimentally with zirconia-based electrolytes due to transport of Sr from the cathode to the YSZ. Instead ceria-based electrolytes could be used, as done by Ceres Power. Alternatively, by using doped ceria as a buffer layer between an LSCF type cathode and a zirconia based electrolyte unwanted reactions may be avoided.

Interconnects and metal supports

The function of an interconnect puts stringent demands on its properties: It must be gas tight, electrically conducting, and stable both in reducing and oxidizing conditions at high temperatures. For operation temperatures around 1000 °C this means that interconnects should be made of ceramics because of the high corrosion rate of metallic alloys at these temperatures. The high costs of the ceramic interconnects and the limited possibilities of composition to obtain the required high electronic conductivity, limited ionic conductivity, thermal expansion coefficient, mechanical properties and expansion upon reduction on one side of the interconnect, have pointed towards metallic alloys for better interconnects.

To meet the severe materials requirements for metallic interconnects a number of specialty ferritic stainless steels have been developed. One such material which now has become widely used is the Crofer22APU from Krupp Thyssen, developed by Research Centre Jülich. When coated with suitable coatings such steels perform sufficiently well in corrosion resistance and electrical tests to indicate that lifetimes of 40,000 hours are within reach using cheap metal interconnector plates.⁸

For metal supports, FeCr steels are often used, primarily due to the potentially lower cell costs and due to improved mechanical properties. Corrosion aspects will probably dictate the operating stack temperature to be below, say 650 °C. If the metal is supporting the cell on the anode side, corrosion may be less of an issue than if supporting the cathode side. In any case, corrosion is probably of most concern with respect to the long term stability of the cell.

FUNDAMENTAL ISSUES

From a theoretical viewpoint a solid oxide fuel cell is a very complex system. Reliable predictions of the electrochemical activity of a typical electrode material upon doping is beyond present day capabilities. Even in well-established anode materials the exact electrochemical

reaction paths and rate-limiting steps are not fully understood. Materials development is, hence, still by large through trial-and-error, guided by heuristic understanding.

As an illustration of the complexities involved, we may take the electrodes. High-performing electrodes often consist of two interpenetrating phases forming a porous network, and electrode performance depends on the interplay of a large number of factors, including the properties of the constituent phases, the ratio between them, the porosity and percolation of the network, the adherence of the electrodes to the electrolyte, and the level of impurities present. In the best SOFC cells an unexpectedly high polarization resistance from the electrodes is often found. This may be attributed to the presence of impurities which block reaction sites. Thus, even minute traces of silica, on the order of 10 ppm, may form monolayers on the electrode materials and in this way impede ion transfer.⁹ Indeed, surface impurities may change the reaction rates by an order of magnitude or more. This points to the need for a better understanding of impurities and for developing ways of mitigating their impact.

Advances in characterization and the application of first-principles approaches, such as Density Functional Theory, may hold the promise of leading to more fundamental understanding. Systematic use of high-resolution electron microscopy, including using focused ion beam-techniques to generate tomographies of the components, will lead the way to correlating nanostructure with performance. In-situ-methods, e.g. high-temperature scanning tunnel microscopy, will hopefully add to our understanding of the cell processes during actual operation. Density Functional Theory, combined with improved modelling, is beginning to come to grips with the complexities of the surface reactions on the electrodes. Increased use of methods such as these may be necessary to achieve a substantial breakthrough in materials selection.

SYSTEMS DESIGN AND DEMONSTRATIONS

Systems design is as large a challenge as that of developing high-performing, durable cells and stacks. The work is mostly done in industrial labs, and for this reason details can be hard to find in the open literature. Among the problems to be solved are fuel reforming and treatment, grid connection, integration of the stack with the balance of plant and finding optimal control strategies, including start up and shut down. These questions are all very dependent on the specific application in mind. It may, e.g., be acceptable for large systems to have cells with limited redox stability, instead relying on backup systems with auxiliary gases creating a protective atmosphere upon loss of fuel or other unforeseen events. In such systems it may also be an option to change operating conditions over time to counteract a decrease in cell performance.¹⁰ On the other hand, use in automotive systems most likely precludes the use of backup systems and at the same time puts stringent demands on startup-time and number of thermal cycles.

Systems are being designed for power outputs ranging over many orders of magnitude. Systems of a few watts to 100 watts, μ -SOFC, are being developed for, e.g., military applications. Much military equipment needs supply of electricity, and μ -SOFCs may be a fuel flexible and silent generator of electricity for this purpose. Systems in the 1-5 kW_e range are aimed for use in, e.g., μ -CHP in single houses and for recreational applications, such as luxury yachts and camping. 5-10 kW_e units are seen as a size for implementation in trucks as APUs. In Europe, BMW, AVL (Austria), and Staxera are among the companies pursuing this track. About the same size of stacks could be suitable for hybrid cars, i.e. cars equipped with a battery and an

SOFC system and an electrical motor. Imperial College London is designing such systems together with commercial partners.¹¹ Larger systems, in the 50-250 kW_e range, are being designed by e.g. the Finnish marine power company Wärtsilä in cooperation with Topsoe Fuel Cells.¹² These systems are meant for marine applications and for larger buildings, e.g. hospitals and apartment buildings. They may also be used as back-up systems for banks and hospitals, rather than be designed to be running constantly on a base load. Much larger systems, and preferably integrated with gas turbines, have for many years been pursued by Siemens (Westinghouse), and more recently also by, e.g., Rolls Royce Fuel Cell Systems and General Electric.

Demonstrations

Compared to other fuel cell types SOFC has had limited deployment experience so far, with one or two notable exceptions, e.g. the extensive demonstrations of systems in the 100 kW-class by Siemens. However, SOFC technology has now reached a level where more widespread demonstration projects become relevant. In Europe, Hexis has since 2001 been deploying a number of 1 kW units for μ -CHP among consumers in Germany, Austria and Switzerland, gaining valuable operational experience. Other μ -CHP projects include the Danish Cluster project led by Danfoss A/S with the participation of Topsoe Fuel Cell and others. In this project 100 units (both SOFC and PEMFC) will be deployed in private households over the next few years. Ceres Power is also involved in CHP-demonstrations for domestic use, participating in a major program with Centrica (British Gas) to develop a wall-mounted system.

Wärtsilä has in 2006 operated a 4 kW prototype with stacks from Topsoe Fuel Cell, fed on pre-reformed, desulphurized Russian natural gas and connected to the grid. In 2007, 50 kW prototypes from Wärtsilä and Topsoe Fuel Cell are expected, as a stepping stone to a 125-250 kW system for marine power and decentralized landbased systems operated on e.g. bio-methanol.

The increasing maturity of SOFC development leads one to expect a substantial increase in the number of demonstrations in the coming years. Both nationally and at the EU level the funding for SOFC demonstrations are set to increase markedly.

CONCLUSION

SOFC technology has seen steady progress over recent years. Although further advances in fundamental understanding have not kept up to the same extent, a number of SOFC manufacturers now have cells of sufficient quality that large-scale demonstration projects become meaningful. On the other hand, it seems that we are still some way from any theoretical materials limitations on cell performance, suggesting a fertile area for further research. European and Scandinavian research institutes and small and large companies are well established players in aiming at a (necessary) commercial breakthrough within the coming few years.

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