Solid Oxide Fuel Cell Industry and Technology in Europe, Japan and the USA

Fuel cells stand for future energy conversion technology with the highest efficiency. Different fuel cell concepts are currently considered for portable, mobile and stationary applications. Solid Oxide Fuel Cells (SOFCs) are very important for distributed stationary power generation.

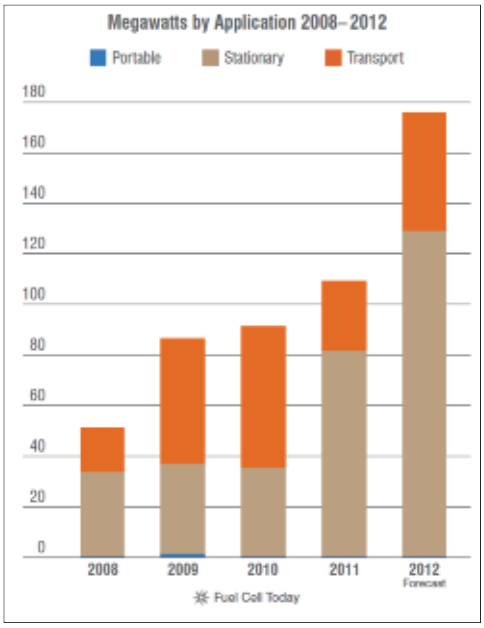

Fig. 1
Growing markets for fuel cells from 2008 to 2012 in MW/a using data from [1]

Fuel cell markets: drivers and competitors

Fuel cells stand for future energy conversion technology with the highest efficiency. Different fuel cell concepts are currently considered for portable, mobile and stationary applications. The markets for fuel cells have grown steadily from 2007 (Fig. 1). Especially small units on the basis of low-temperature proton conducting electrolyte membrane (PEMFC) are dominating the world fuel cell market today [1], however, the high-temperature fuel cell is more successful in terms of installed power. For distributed stationary power generation, high-temperature fuel cells such as molten carbonate fuel cells (MCFC, manufactured by *Fuel Cell Energy Inc.*) and Solid Oxide Fuel Cells (SOFC, biggest installations made by *Bloom Energy Inc.*) hold a leading position and a large market share (Fig. 2).

The main competitors of fuel cell technology in terms of costs and performance in nearly all markets are gas and Diesel engines. Thanks to a well-established technological value chain and low production costs, the engines hold strong positions in the power generation markets ≥10 kW_{el}. The efficiency of engines depends strongly on output power range [2] and varies between 17 – 47 % (Fig. 3). However, during the last five years, fuel cell technology has made significant progress, allowing it to compete with engines in selected markets (from 5 W up to 3 MW_{el}) in terms of costs per kWh and to create new products for highly efficient power generation below 10 kW_{el}.

Of all fuel cells, solid oxide fuel cells offer the simplest system architecture for conversion of the chemical energy of hydrocarbon fuels into electric power and heat. This makes SOFCs attractive for numerous markets. The analysis of power generation by fuel cells in different markets conducted by *Fuji Kenzai* (Fig. 4, [3]) shows a big demand in the fields of stationary and micro-CHP applications where SOFCs will play an important role in the near future.

SOFC as an opportunity

SOFC technology has the potential for broad market penetration because of the possibility of using the existing fuel infrastructure as well as new hydrocarbon biofuels such as biogas, bio-ethanol or biomethanol. The reason for that is a high operating temperature and tolerance of SOFC systems to CO as well as to fuel contaminants such as H_2S which is similar to that of combustion engines. It has been shown that for any fuel, SOFCs can reach very high electrical efficiency especially if anode off-gas recycling is used (Fig. 5) [4] and in this way the high power-to-heat ratio on the system level can be achieved. Nowadays solid-oxide-fuel-cell-based systems are under development for micro-CHP (0,3–5 kW_{el}), distributed stationary (10–500 kW_{el}), portable (25–300 W) and auxiliary power (0,3–5 kW_{el}) generation.

Keywords
Solid Oxide Fuel Cell (SOFC), cell concepts, stack performance, degradation, market overview

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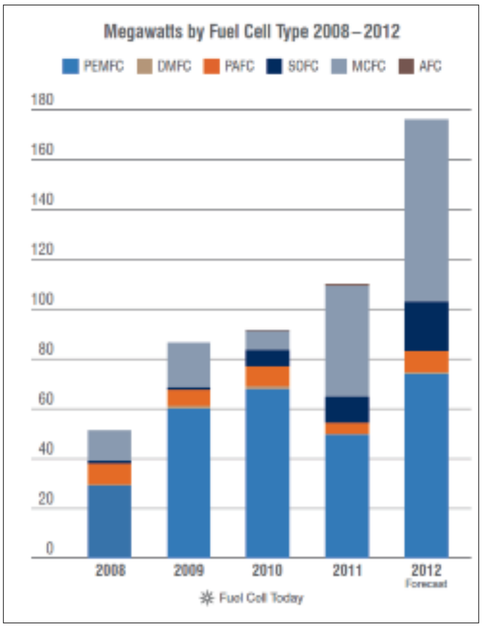


Fig. 2
High temperature fuel cells in stationary power generation in MW/a using data from [1]

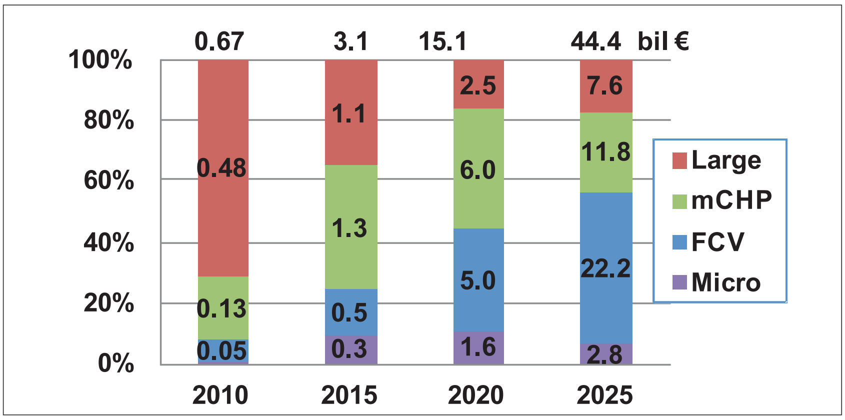


Fig. 4
Forecast for demand for fuel cell power in different markets in billion EUR [3]

First SOFC units have already passed field testing and are under commercialization in Germany (*Vaillant, Hexis, CFCL*), Japan (*JX Nippon Oil and Energy, Tokyo Gas* etc.) and the USA (*Bloom Energy*) primarily for natural gas as a fuel. The R&D priorities for fuel cell systems depend strongly on the selected application, resulting in specific challenges for individual system design. General requirements for SOFC systems depending on the potential application area are summarized in Tab. 1. These demands can be satisfied using different approaches for stack and system development.

SOFC: cell and stack concepts

The technical roots of solid oxide fuel cells go back to the late 1930s when Swiss scientists *E. Bauer* and *H. Preis* experimented with zirconium, yttrium, cerium, lanthanum, and tungsten as electrolytes [5]. In the late 1950s, *Westinghouse* began work on doped zirconia electrolyte-supported tubular cells. Parallel to this, small-scale research was also performed by researchers in the Netherlands, the *Consolidation Coal Company* in Pennsylvania, and *General Electric* in New York. *Westinghouse Electric Corporation* has continued up to today with the development of tubular solid oxide fuel cells and had a great impact on SOFC progress over the last 50 years. Since 1960s different companies have entered and exited SOFC development and different cell and stack concepts have been considered. The following classification in Tab. 2 helps to compare different types of SOFC cells in terms of the main material constituent (electrolyte, cathode, anode or metal) and design. Depending on the support material used, the cell can be realized on the basis of an

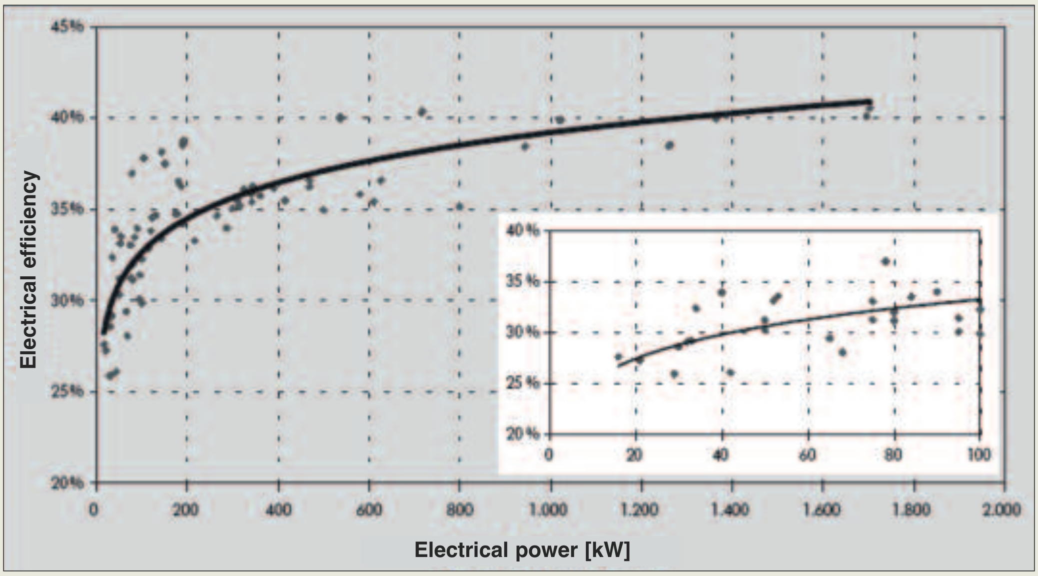


Fig. 3
Efficiency of conventional engines for distributed power generation [2]

Tab. 1
General requirements on SOFC stacks for different applications

	Portable	Remote Power / APU	Micro-CHP	Distributed Stationary (CHP)
Power range	10–200 W_{el}	0,2–5 kW_{el}	0,5–5 kW_{el}	10–500 kW_{el}
Stack service time	1–5 kh	3–10 kh	40–100 kh	40–100 kh
Start/stop cycles*	300–3000	300–3000	100–500	30–100
Stack sulfur tolerance	2–10 ppm	1–2 ppm	0,1–1 ppm	0,1–1 ppm
Vibrations	required	required	not required	not required
Start up time	10–60 min	15–60 min	1–5 h	1–7 days
Fuels	LPG, Diesel, Ethanol	NG, LPG, Diesel, Ethanol	NG	NG, biogas

* combined thermal and redox cycle for system shut down and start up

electrolyte, cathode, anode or metal support structure. The cost of ceramic materials is normally higher than that of the metallic components. Especially La-containing cathode powders have higher material costs in comparison to doped zirconia and NiO. Considering these facts, it is clear that the thin planar electrolyte-supported and metal-supported cell with the lowest ceramic material content would have the lowest material costs, and competitor cell concepts must compensate for the cost difference with a better weight-specific performance of the fuel cell unit.

Nowadays the anode support is the most commonly used concept for tubular (ASC-T), planar (ASC-P) and honeycomb (ASC-Hc) cell types, while electrolyte, anode and metal compete to be used as support for planar SOFCs. Fig. 6 shows a generalized comparison of different cell and stack concepts and challenges for their use in portable, stationary and auxiliary power units. The differences in cell concepts result in different stack potentials regarding power density, sulfur tolerance and redox stability. Planar cells with thin electrolyte have a potential advantage over honeycomb and tubular concepts in terms of power density owing to lower ohmic losses for current transport inside the cell (no lateral current paths). Metal- and electrolyte-supported cells have potential advantages over anode-supported cells in terms of redox stability and sulfur tolerance in so far as more sulfur-tolerant anodes can be applied. However, especially potential advantages regarding power density and degradation on the cell level can be easily lost by combining the cells in big stacks. By using selected stack technology for clearly defined application, the critical stack issues can often be addressed with additional system features that compensate for the disadvantages of stack technology overall.

On account of the lower robustness requirements for stationary applications, there is strong competition between planar and honeycomb as well as electrolyte- and anode-supported concepts. Metal-supported cells, which are most suitable for portable and APU markets, are still under development.

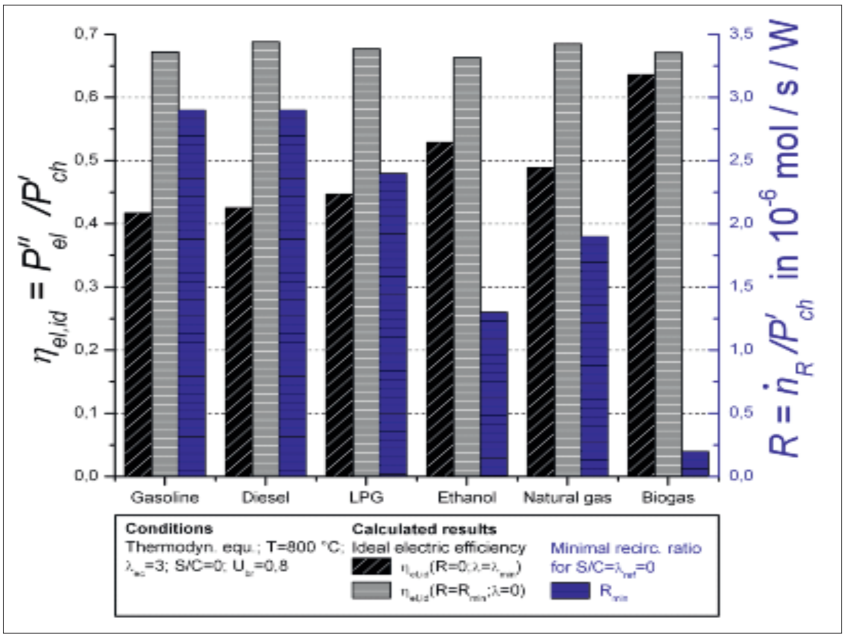


Fig. 5
Possible efficiency of SOFC based systems for different fuels without (black)/with (grey) anode off-gas recirculation [4] (R – recirculation ratio (blue); S/C – steam to carbon ratio; U_{br} – fuel utilization; λ_{ec} – air supplied/air needed for electrochemical reaction ratio)

SOFC activities in Europe/USA/Japan

The main activities concerning SOFC commercialization are currently underway in Europe, the USA and Japan. South Korea has recently started a SOFC technology initiative too. The following sections provide a general overview of industrial networks and activities in the regional European, American and Japanese markets.

SOFC activities in Europe

Three applications are at the focus of current SOFC activities in Europe: micro-CHP (with system manufacturers such as *Vaillant, Hexis/Viessmann, Ceramic Fuel Cells Ltd., Ceres Power, SOFCPower, DanTherm*), portable/residential power (with system manufacturers such as *NewEnerday, eZelleron*) and auxiliary power generation for vehicles (with system manufacturer *Eberspaecher*). All systems except the portable power unit from eZelleron utilize planar stack technology. The progress of different SOFC systems is continuously updated with the publication of corresponding data on performance and

degradation rates for stack and system prototypes during field or laboratory testing. However, owing to the absence of comprehensive information on operating conditions in the published data as well as continuous development of stack technology, only a rough and momentary comparison of the stack performance given by different manufacturers can be made (see Tab. 3). However, it is not possible to compare the performance of different stacks on the basis of data from Tab. 3 on account of the different operating conditions used by manufacturers for stack testing.
System performance degradation, observed during unit operation, often results from the superposition of different factors: stack degradation, reformer or catalyst degradation, reliability of cold balance of plant components. Especially stack and reformer degradation are addressed by com-

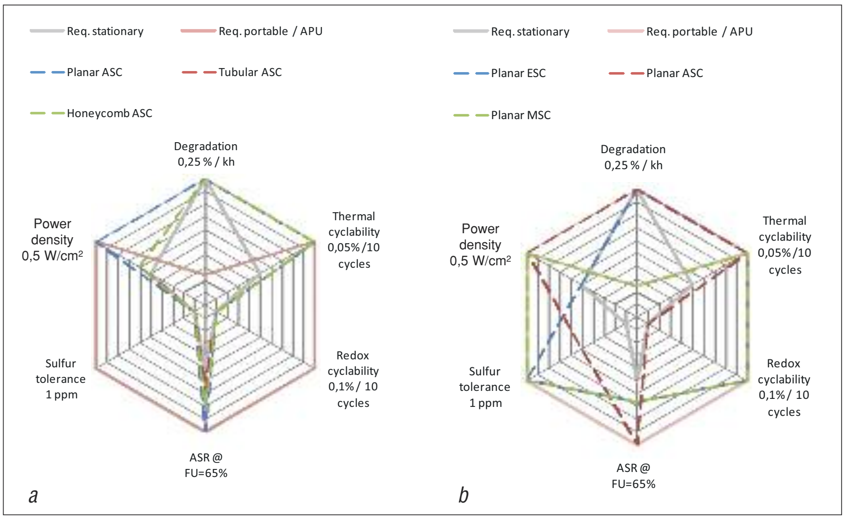
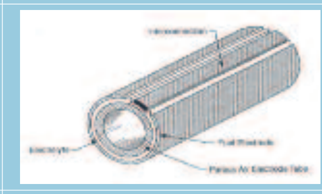
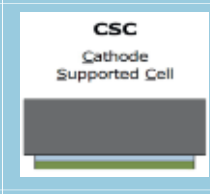
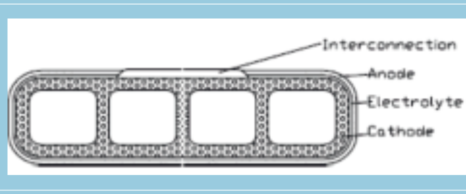
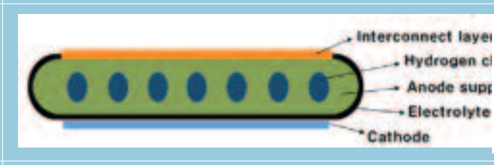
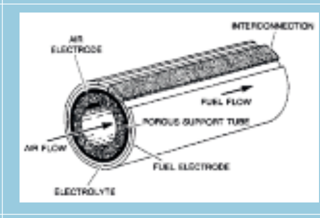
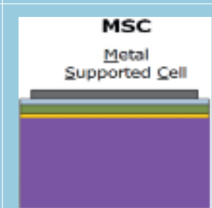


Fig. 6
Comparison of estimated potentials for different cell concepts in stack environment in corresponding long-term stable operating conditions:
(a) comparison of planar, tubular and honeycomb concepts realized in anode supported technology;
(b) comparison of metal, anode and electrolyte supported concepts realized in planar technology

Tab. 2
Simplified classification of general cell and stack concepts for SOFC

	Tubular (T)	Planar (P)	Honeycomb (Hc)
Electrolyte supported (ESC)			
Cathode supported (CSC)			
Anode supported (ASC)			
Ceramic supported (CS)		no activity	
Metal supported (MSC)			no activity

Tab. 3
Comparison of full-scale stack operation data in $H_2/H_2O/N_2$ fuel published by different stack vendors

	CFCL	Hexis	IKTS / Plansee	Kyocera	SOFC Power	Sunfire	TOFC	Versa Power
Initial power	2 kW	1,2 kW	850 W	700 W	1 kW	650 W	1,5 kW	15 kW
No. cells	4 × 51	60	30	n/a	72	30	75	96
Operating temperature	750 °C	850 °C	810 °C	750 °C	800 °C	860 °C	725 °C	700 °C
Cell type	ASC-P	ESC-P	ESC10-P	ASC-HC	ASC-P	ESC2-P	ASC-P	ASC-P
Active cell area	49 cm²	100 cm²	127 cm²	n/a	50 cm²	128 cm²	144 cm²	550 cm²
Power/electrode area	0,2 W/cm²	0,22 W/cm²	0,24 W/cm²	n/a	0,28 W/cm²	0,17 W/cm²	0,16 W/cm²	0,31 W/cm²
Initial voltage/cell	0,85 V	0,78 V	0,8 V	n/a	0,8 V	0,72 V	0,88 V	0,85 V
FU in stack	65–80 %	85 %	60–85 %	n/a	60–75 %	65–85 %	60–75 %	60–75 %
Power degradation	1,5 %/kh*	0,4 %/kh	0,6 %/kh	<0,4 %/ kh	1,5 %/kh	0,4 %/kh	0,9 %/kh	1,3 %/kh
Service time demonstrated	4–8 kh	3–30 kh	3–8 kh	3–15 kh	3–10 kh	3–20 kh	3–14 kh	3–15 kh
Power loss by thermal cycling (10 cycles)	0,4 %	<0,05 %	<0,05 %	<0,05 %	<0,05 %	<0,05 %	n/a	n/a
Published in	2012 [5,6]	2012 [7,8]	2012 [9]	2012 [10]	2012 [11]	2012 [12]	2012 [13,14]	2012 [15]

*reported value for efficiency degradation

ponent and material development to suppress ageing effects such as interconnect oxidation, chromium poisoning of the cathode, nickel agglomeration in the anode and catalyst deactivation in the reformer. Uniform temperature distribution in stack, afterburner and reformer is often a challenge addressed by component and system design, simulation and material optimization. Detailed scientific work is conducted to separate the influence of different factors on the degradation rate and to predict component durability [16–19].

The most frequently reported performance degradation merit is a power/voltage degradation rate at constant current. The comparison of power density, durability and cyclability of different stacks gives a good insight into the state of the art of specific SOFC technology (Tab. 3).

Temporary the power density of 170–240 mW/cm² and 200–310 mW/cm² with power degradation rates at constant current mode between 0,4–0,6 %/kh and 0,9–1,5 %/kh are achieved for stacks with planar electrolyte- and anode-supported cells respectively (Tab. 3).

SOFC production in Europe is realized based on “hand-in-hand” cooperation between different companies specialized in the production of key components. SOFC stack development and production for system integration are often outsourced to the stack/stack module suppliers such as *Sunfire, ElringKlinger* and *TOFC* or to R&D institutes such as *Fraunhofer IKTS, VTT* or *Research Center Julich*. Several companies such as *Hexis, SOFCPower* and *CFCL* produce the stacks for their units in-house. The activities of stack manufacturers are supported by component suppliers for cells (*HC Starck, Ceramtec, Kerafol, Elcogen*), sealants (*Schott, Kerafol*), interconnects (*Plansee, ThyssenKrupp*), testing equipment (*FuelCon, EBZ*), balance of plant components (*EBZ, FuelCon, Behr, Prototech, Bosal*) as well as powder and paste manufacturers (*HC Starck, Treibacher, Heraeus, Clariant, BASF*).

Many European R&D centers provide services and facilities for high-quality research in the field of SOFC. Among the R&D institutes, *Fraunhofer IKTS, Research Center Jülich, Riso DTU, VTT, Imperial College* and *AVL* have the greatest impact on the development of SOFC technology in Europe.

SOFC activities in Japan

The development of SOFC technology in Japan is boosted by the fuel cell micro-CHP market where the fuel cell technology on basis of PEMFC is already in business via installations from *Panasonic, Eneos* and *Toshiba*. Tab. 4 shows SOFC technology movers in Japan as well as reported product goals and properties. Only very restricted technical information on stack data for different concepts and their progress in recent years is available in the literature. Most of the technical data on stacks and cells were publically presented last time in 2009 at the SOFC XI in Vienna. For this reason it is difficult to make any comparison between the current status of SOFC stack development in Japan and that in Europe and USA where good annual updates exist.

Micro-CHP fuel cell systems developed for the Japanese market differ widely from that of the European competitors. The difference in operating strategy (power-driven operation in Japan vs. heat-driven operation in Europe) and system constraints (outdoor installation in Japan and indoor installation in Europe) makes it difficult to export technology from Japan to Europe and vice versa. Although the planar (*Nippon Sokubai, Hitachi Metals*) and tubular (*Toto*, cathode-supported cells) component developments are available on Japanese market, the most popular cell concept is the honeycomb-type, anode-supported cell developed and produced by *Kyocera*. Comparison of reported stack data from different manufacturers shows that in Japan the degradation rate reduction for long-term operation and for start/stop cycling are the main drivers for stack development. According to the data from field testing, all systems with a honeycomb anode-supported stack from Kyocera show degradation rates in the range of 0,4 %/kh or below that. Extensive studies were conducted by Japanese R&D institutes in 2009–2012 under the umbrella of and with the support of *NEDO* to investigate and understand the reasons for stack degradation (influence of contaminants in air and fuel, cell materials interaction, chromium poisoning, etc.), resulting in optimized stack and system performance and a significant (two-fold) reduction in the degradation rate from 2008 to 2012 at moderate power density. A Micro-CHP system on the basis of a Kyocera SOFC stack is now commercially available on the Japanese market and further work on stack and system cost reduction is ongoing.

The SOFC system activities of system integrators such as *Tokyo Gas, Osaka Gas, JX Nippon Oil and Energy Co., KEPCO* and *Toho Gas* in Japan are supported by strong network of component suppliers for stacks (*Kyocera, NGK Spark Plug, Toto*), cells (*Nippon Shokubai, Kyocera, Toto*), interconnects (*Hitachi Metals*) and powders (*Tosoh, Daiichi, Dowa* etc.). Many R&D centers provide services for SOFC testing and material development. The largest R&D institute in the field of SOFC is *AIST* (with its two branches in Nagoya and Tsukuba) followed by *Kyushu University, CRIEPI* and *Tohoku University*. Most of balance of plant components for SOFC systems in Japan can be adapted or used directly from PEMFC development. This fact is the strong advantage of Japanese industry, allowing relatively rapid system prototype manufacturing, test and pilot production.

Tab. 4
Overview of SOFC technology movers in Japan
[MHI – Mitsubishi Heavy Industries, MMC – Mitsubishi Materials Corporation]

	NGK Spark Plug	MHI	TOTO	Kyocera	MMC
Power	1 kW	>100 kW	700 W/9 kW	700 W	1–3 kW
Operating temperature	700 °C	900 °C	900 °C	750 °C	750 °C
Cell type	ASC-P	HC	CSC-T	ASC-HC	ESC-P
Power d	n/a	0,8 %/kh	1 %/kh	0,31 %/kh	1 %/kh
Service time demonstrated	3 kh	8 kh	n/a	15 kh	>3 kh
System el. efficiency	49 %	n/a	n/a	45 %	40 %
Published in	2010 [20]	2011 [21]	2011	2011 [10]	2009 [22]

Tab. 5
Comparison of full-scale stack operation data in $H_2/H_2O/N_2$ fuel published by US vendors/manufacturers (LG has a goal to build MW-class power plants under pressurized operation and a bundle of six cells has been selected as the repetitive unit)

	Delphi / Gen3	Acumentrics	LG	Versa Power
Initial Power	850 W	1,25 kW	300 W @ 6,4 bar	15 kW
No. cells	30	20	6	96
Operating temperature	750 °C	800 °C	860 °C	700 °C
Cell type	ASC-P	ASC-T	Ceramic supported	ASC-P
Active cell area	105 cm²	85 cm²	140 cm²	550 cm²
Power / electrode area	0,27 W/cm²	0,3 W/cm²	0,35 W/cm²	0,31 W/cm²
Initial voltage / cell	0,82 V	0,76 V	n/a	0,85 V
FU in stack	60–75 %	n/a	n/a	60–75 %
Power degradation	2,2 %/kh	1,3 %/kh	0,93 %/kh	1,3 %/kh
Service time demonstrated	10 kh	3–10 kh	4–16 kh	3–15 kh
Power loss by thermal cycling (10 cycles)	0,2 %	65–75 %	n/a	n/a
Published in	2012 [23]	2011 [24]	2012 [25]	2012 [15]

SOFC activities in the USA

Contrary to SOFC development in Germany and Japan, the main drivers for the American market are units for distributed power generation in the range of 100–1000 kW_{el}. Four big companies are active in this area: *Versa Power Systems* owned by *Fuel Cell Energy* (planar anode-supported concept), *Bloom Energy* (planar electrolyte-supported concept), *UTC/Delphi* (planar anode-supported cell) and *LG Fuel Cell Systems* (honeycomb concept for pressurized operation previously developed by *Rolls Royce*). Almost the complete value chain starting with component production (often excluding powder manufacturing) and ending with system manufacturing and maintenance services is covered within many American companies. Bloom Energy is even in the early market introduction phase with its products utilizing natural gas as a fuel, while Versa Power and LG are involved in a continuous R&D process supported by the *Department of Energy (DOE)* for the development of SOFC hybrid power stations for coal as a common fuel as well as for special markets.

Adaptive Materials Inc. (AMI) and *Delphi* are active players for the introduction of SOFC into portable and APU markets. Especially Delphi system development based on the planar ASC concept is strongly supported by the DOE and network of universities and R&D institutes within the scope of the SECA program. AMI already provides portable SOFC units on the basis of micro-tubular cells with rapid start-up capability for special applications.

The technological progress reported by *Versa Power, LG, Acumentrics* and *Delphi* is summarized in Tab. 5. Unfortunately, there are no published data on the characteristics of Bloom Energy stacks, making it impossible to make a real comparison between ASC and ESC technological platforms.

Stack manufacturers in USA rely mainly on materials available on the market such as ferritic interconnects based on Crofer 22 APU from *ThyssenKrupp*, CFY from *Plansee* or low-cost commercial SS441 steel, powders for electrodes, protective coatings and current collectors (*Praxair, NexTech Materials,* etc.) and try to develop their proprietary cells (material combination and design), sealants and joining technology and bipolar plates for in-house component and stack production. Hot balance of plant components are also often made in-house. A group of R&D teams with strong participation of *PNNL, Alfred University, Pennsylvania State University, University of Connecticut* and others is working on novel solutions for interconnect coatings, electrodes, sealants with the goal of adapting existing cheap interconnect materials for low-cost and low-degradation stack manufacturing. At the same time, suppliers such as *NexTech Materials, ThyssenKrupp, Saint Gobain, Schott Inc., Coors, Heraeus, ENrG* and *ESL* are trying to get into the supplier chain of growing OEMs (*Bloom Energy, FCE, Delphi*) with common and reliable solutions.

Although the US market is the most dynamic one, the tough cost goals set by DOE and agreed/reported by SECA teams, strong cut-off for DOE funding for SOFC research in last two years as well as shift of funding focus to very challenging big stationary co-generation systems with coal as fuel instead of natural gas hinders the progress of SOFC technology on the way to accelerated commercialization in domestic markets.

Concluding remarks

In Europe, Japan and the USA, a network of companies for SOFC pilot production is already established, although the SOFC market is still developing and the SOFC systems are undergoing permanent optimization regarding cost and durability issues. SOFC technology is very attractive for many applications and has huge market potential. The main markets for SOFC units are portable, micro CHP, residential and distributed power generation. Especially European and Japanese companies are in a good position to enter the portable, small residential and micro-CHP markets. In the USA the SOFC technology for distributed power generation as well as for supporting the big coal power station is favored and companies such as Bloom Energy and FCE have already taken the lead in this field. The main concerns for commercialization of SOFC technology independently from application are production costs, cyclability and durability.

Joint efforts should be undertaken in the next five years to bring the technology forward and promote broad penetration of SOFC in the different markets and to maintain the leadership of industrial countries in this key future technology.

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