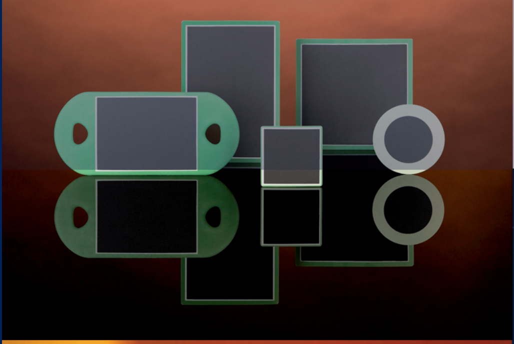

Italian National Agency for New Technologies, Energy and Sustainable Economic Development

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THE YELLOW PAGES OF SOFC TECHNOLOGY

International Status of SOFC deployment 2012-2013

Stephen J. McPhail, Luigi Leto, Carlos Boigues-Muñoz

iea Energy Technology Network

IEA

Implementing Agreement *Advanced Fuel Cells*
Annex 24 – SOFC

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THE SOFC BASIC PRINCIPLES

Solid oxide fuel cells (SOFC) are a cutting-edge technology for converting the chemical energy in hydrocarbon fuels to electrical power and heat by means of an electrochemical reaction. SOFC technology has many advantages over conventional power trains, such as combustion engines, including:

- high efficiency, including at small scale
- fuel flexibility
- insignificant NO_x, SO_x and particulate emissions, reduced CO_2 emissions
- silent and vibration-free operation.

High efficiency

The SOFC differs from conventional technologies such as combustion engines and gas turbines in that it converts the chemical energy of fuels *electrochemically*, generating electrical power directly, avoiding the inefficient steps of combustion and transformation of heat to mechanical work in order to drive the electrical generator.

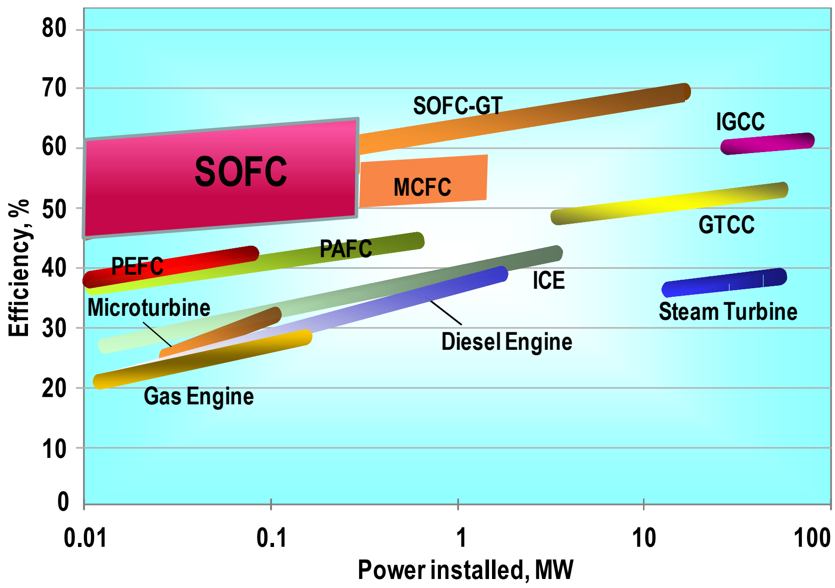

Figure 1. *Comparison of combustion-based system and fuel cell efficiencies vs. power installed (ICE = internal combustion engine, GTCC = gas-steam turbine combined cycle, IGCC = integrated gasification combined cycle, PEFC = polymer electrolyte fuel cell, PAFC = phosphoric acid fuel cell, MCFC = molten carbonate fuel cell, SOFC = solid oxide fuel cell, SOFC-GT = SOFC and gas turbine bottoming cycle).*
[source: ENEA, www.enea.it]

Ideally, the power produced in an SOFC can reach up to 70% of the inlet fuel energy; in practice, within an end-user-ready system, these efficiencies are between 40-60%, depending on the power plant configuration. Combustion-based technologies can only reach 55% electrical efficiency in very large-scale power plants (of hundreds or thousands of Megawatts). The SOFC efficiency is unique in being practically independent of scale, and systems have been demonstrated with 60% net efficiency even at one kilowatt of delivered power.

Fuel flexibility

Thanks to the SOFC's high operating temperature (600-900 °C), low molecular weight hydrocarbons can be internally reformed, without the need for an external reformer. With appropriate conditioning, in order to remove harmful contaminants and to ensure a proper balance of the specific carbon compounds, such diverse fuels can be utilized as natural gas, biogas, ethanol, methanol, propane, LPG (liquefied petroleum gas) and even diesel and jet fuel.

Alternative carbon-free liquid fuels such as ammonia and hydrazine can also be utilized in SOFCs, even though the use of the latter remains limited due to its high production cost. Ammonia, used to great extent in industry for the synthesis of fertilizers and explosives, presents the advantages of being low-cost, simple to store, containing high energy density without production of carbon dioxide.

Insignificant emissions

By avoiding a combustion process to convert fuel to electricity, the SOFC does not produce nitrous oxides (NO_x) or fine particulate matter. Furthermore, because sulphur compounds are poisonous for the fuel cell, they need to be extracted from the fuel beforehand to ensure reliable operation, therefore sulphurous oxide (SO_x) emissions are insignificant. In this way it is also guaranteed that no harmful compounds are released into the environment, shifting the onus of emission control onto the fuel supplier, where it can be handled efficiently and centrally.

Thanks to the SOFC's high efficiency, for a given amount of power produced less primary fuel is required, which means less CO_2 is emitted to the atmosphere.

If the fuel is obtained from renewable sources, such as biogas, the operation of the SOFC is effectively carbon-neutral, and ultra-clean.

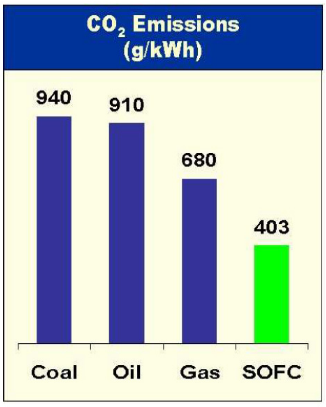

Figure 2. *Comparison of CO_2 emissions between combustion-based systems and a natural gas-fed SOFC. [source: Acumentrics, www.acumentrics.com]*

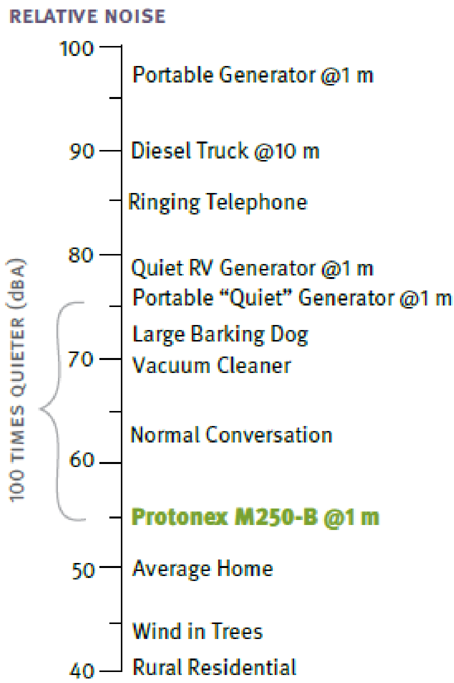

Figure 3. *Noise and vibration emissions from a small FC system may reach so low levels that you may not heard it while you talk. [source: Protonex, www.protonex.com]*

Silent operation

Electrochemical conversion of the fuel forsakes the need for moving parts for power generation, which means an SOFC system runs essentially vibration- and noise-free: a desirable characteristic both in open spaces and closed areas.

How it works

In Figure 4 below, the building block of the SOFC is shown: each of these cells – consisting of an anode, electrolyte and cathode – can be connected and stacked up to provide any requirement of power. This modular build-up is what makes it possible for the SOFC to have practically constant efficiencies from Megawatt to single watt scale.

The fuel is fed to the anode side, where the high temperature allows it to be separated into its essential constituents. In hydrocarbons, these are hydrogen (H_2) and carbon monoxide (CO). H_2 and CO react in the same way at the anode. Taking H_2 as an example, it reacts electrochemically to generate two electrons per molecule of hydrogen. This current is made to flow across the electrical load that needs to be powered, and reacts at the cathode side with the air – or the oxygen (O_2) in particular – that is fed there. Every two electrons generate an oxygen ion (O^{2-}), which migrates across the gas-tight electrolyte to the anode, where it reacts with the hydrogen to release again the two electrons that generated the O^{2-} ion, effectively closing the circuit. In the process, the only by-product formed is water. In the case of CO, the by-product is CO_2. The outlet of the SOFC therefore produces a clean and relatively pure mixture of water and carbon dioxide. Thus, if necessary, the carbon dioxide can be separated and sequestered much more easily than is the case with the by-product flows from combustion, where large quantities of nitrogen, contained in the air used for combustion, dilute the CO_2 content and make it energy- and cost-intensive to separate. Furthermore, the potential to generate clean water could make them attractive for areas and applications where water is in short supply.

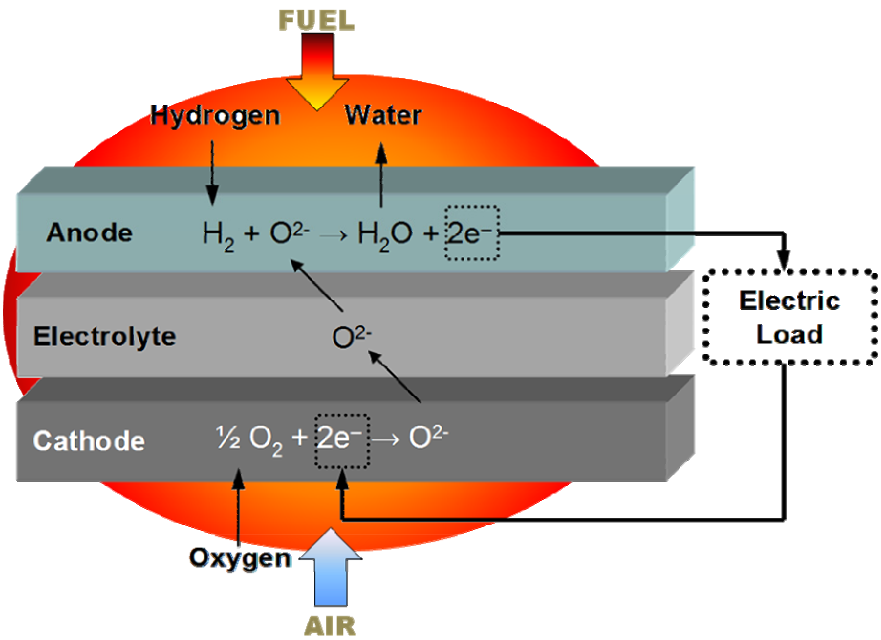

Figure 4. *How the SOFC generates high-efficiency power and heat from fuel and air.*

To turn the stack of cells to a fully functional power generating system several auxiliary components (the so-called balance-of-plant, BOP) have to be integrated, taking care of fuel pre-treatment, power management and heat exchange.

In order to preserve the high efficiency of electrochemical conversion in the SOFC, the BOP often needs to be designed and produced specifically to optimize the integration and minimize parasitic losses. This is an important part of turning the SOFC to real, viable end-products.

APPLICATION AREAS

Since SOFC systems can be built to any scale between several watts up to several hundreds of kilowatts, they can serve a large variety of applications, maintaining their properties of fuel flexibility and high electrical efficiency. In particular, the most promising areas for their immediate utilization are:

- Mobile, military and strategic (<1 kW)
- Auxiliary Power Units (APU) and back-up power (1-250 kW)
- Stationary small-scale combined heat and power (m-CHP) (1-5 kW)
- Stationary medium-large scale (0.1-10 MW).

For each of these fields of applications, there are already pioneering industrial developers attempting to enter the market, gaining valuable experience and expertise in terms of practical know-how and end-user requirements. This front-line activity is highly necessary in order to make up the lag between the SOFC and the conventional technologies utilized in these areas, especially in terms of robustness, cost and familiarity with consumers. That is why for each of the application areas mentioned, a brief overview will be given of the current suppliers of end-user-ready systems.

Mobile, military and strategic

One of today's major concerns in the energy field is to fulfil the harsh requirements for mobile applications (<1 kW), especially in the field of military defence and strategic reconnaissance. Above all reduced weight and volume with high power densities, as well as robustness, are the requested characteristics.

Figure 5. *The iRobot PackBot UGV AM is a reconnaissance unmanned system, capable of 12 hours autonomy covering about 40 miles of terrain. This System is hybridized with a standard battery for 2.5 hours (8 miles) extra autonomy. [source: Ultra-AMI, Proceeding of Fuel Cell Seminar and Exposition 2011]*

The portable electronics market represents a niche market for solid oxide fuel cell micro-systems. State of the art Li-ion and Ni-ion rechargeable batteries and the PEMFC have significantly lower energy densities than the SOFC. More powerful hand-held electronic devices such as mobile phones or laptops could be used uninterruptedly for weeks fuelling the micro-unit with with a small fuel cartridge.

Fuel consumption in military defence applications represents an enormous economic cost to Defence departments, and thus to the taxpayers. Currently, power generator sets (gensets) are the largest consumers of fuel on the battlefield, making the transport of fuel to be an army's Achilles' heel. SOFC systems not only offer up to 85% fuel savings when compared to traditional diesel electricity generators, but can run on a variety of fuels. The silent operation of the fuel cell technology is an inherent advantage for strategic operations and the generation of water as a by-product makes the unit even more valuable as it could be a source of clean water supply for soldiers.

In the civilian field there is a vast number of telecommunication systems located in isolated regions, far away from the natural gas grid or electricity network, which are powered by traditional inefficient stand-alone gensets. SOFC technology fits like a glove for supplying clean, reliable and efficient energy to the telecommunications' network. Another industry that could certainly take advantage of these characteristics is the gas & oil industry. Apart from providing more efficient power off-shore, SOFC systems can be used for cathodic protection of gas pipelines to prevent corrosion, substituting the devices used today, which have an extremely low efficiency.

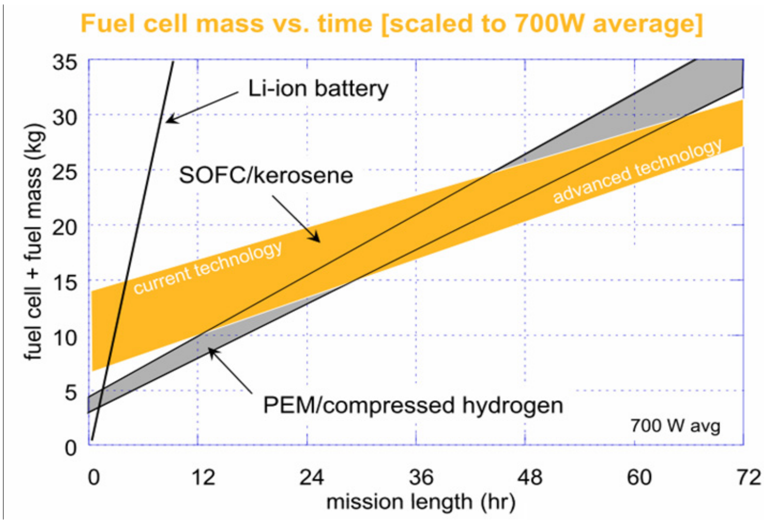

Figure 6. *Device weight as a function of autonomy for 3 portable power solutions. [source: Protonex, Proceeding of Fuel Cell Seminar 2009]*

Industrial Developers Mobile, Military & Strategic:
Ultra Electronics AMI, Lockheed Martin, Protonex

Auxiliary Power Units (APU) (1-250 kW)

SOFCs can also be employed in auxiliary power units (APU) for on-board generation of electricity on vehicles of any kind. The main scope for application is that of electricity supply while a vehicle is at a standstill, ranging from caravans stationed overnight to aircraft parked at an airport gate. An SOFC-based APU also improves electricity generation efficiency during the vehicles' journeys and can supply back-up power during emergencies.

Many large vehicles run on diesel today, and SOFCs offers the advantage of being able to operate on diesel reformate without the necessity of further gas processing steps that would be required to purify the reformate to hydrogen. It is the ideal APU unit from a size of 500 W_{el} (watts electric power) up to several tens of kW_{el} for road vehicles or even several hundreds of kW_{el} as required by aircraft and marine vessels.

Figure 7. *A demonstration model of the Delphi APU on-board of a commercial truck. [sources: Delphi, Proceedings of Fuel Cell Seminar 2011 and DoE Peer Review 2012]*

The efficiency of electricity generation on board of vehicles, using a conventional generator coupled to the engine, is in the range of 10 to 15% today. The system net efficiency of an SOFC APU could reach above 30%, which would more than double the power yield from the same amount of fuel. Additionally, on-site emission of diesel fumes, noise, and other pollutants would be reduced to near-zero. Utilization of the heat produced by the SOFC for heating or cooling (via absorption coolers, for instance) on the vehicles would further increase the overall efficiency.

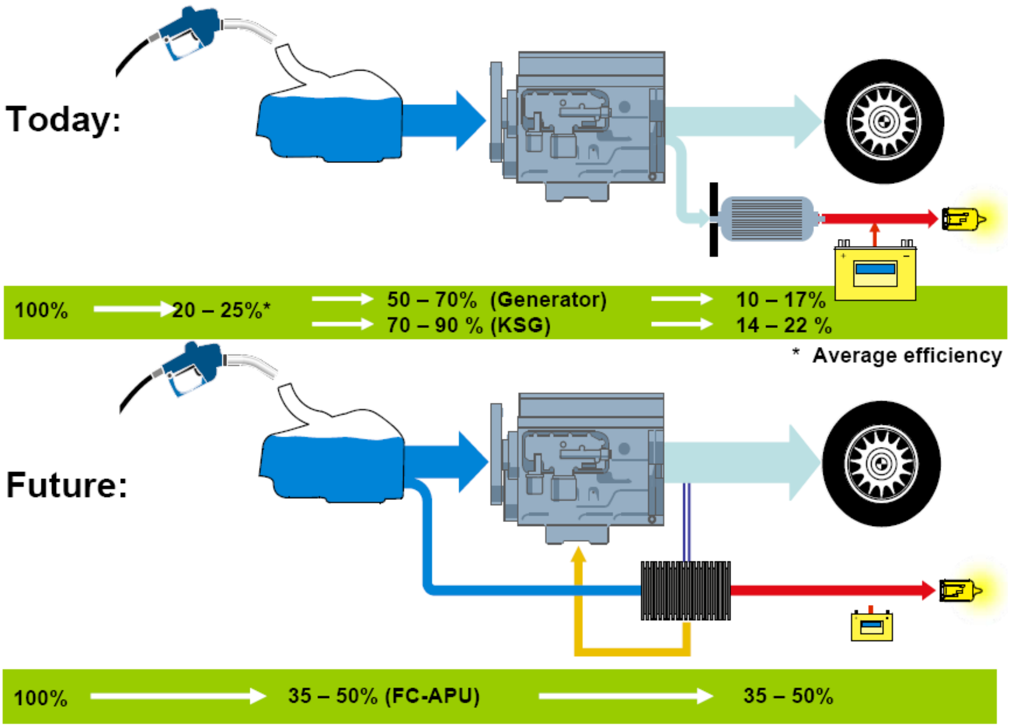

Figure 8. *Comparison of overall electric efficiency between a conventional engine-based power train (fuel-engine-generator-load) and a SOFC-based APU (fuel-SOFC-load). [Source: BMW, courtesy of Forschungs Zentrum Jülich]*

Industrial Developers Auxiliary Power Units (APU):

Delphi, Elcogen, Protonex, Ultra Electronics AMI, Topsøe Fuel Cells

Stationary small scale combined heat and power (m-CHP)

Stationary small scale power plants (1-5 kW) are usually referred to as micro-CHP, which stands for residential-scale combined heat and power.

The great potential of this application lays in the fact that both power and heat for a household can be generated on the premises, from a single primary energy carrier, such as natural gas or LPG. This obviates transportation losses and greatly enhances the utilization of these fuels, reducing waste. Each end-user thus becomes a producer as well, creating the opportunity to sell electricity when supply exceeds the household's demand. This concept is known as distributed, or decentralized, generation and is explained in the following figure.

As can be seen, considerable amounts of primary energy input can be saved by producing power on the spot and utilizing the excess heat for heating purposes, rather than relying on centralized production of power and separate heat generation.

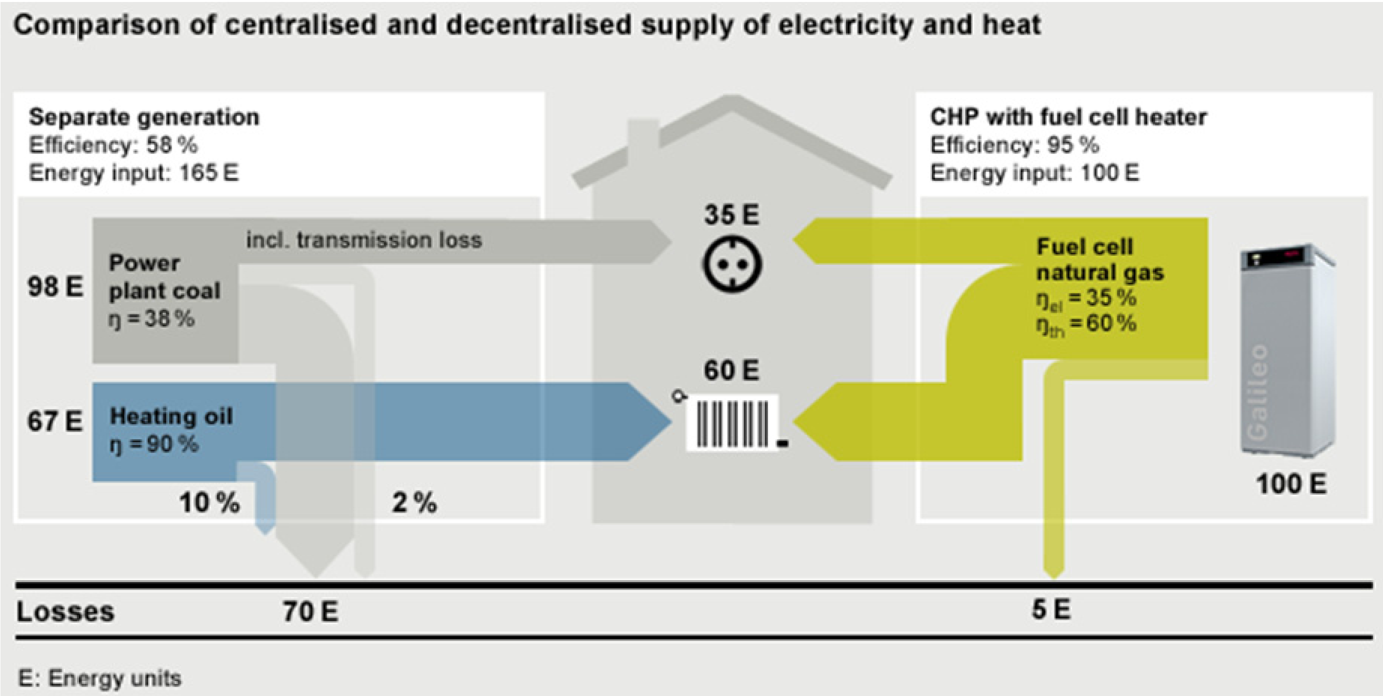

Figure 9. *Comparison of overall primary energy consumption between centralized supply or on-the-spot micro-CHP, for given household power and heat requirements. [source: Hexis AG, www.hexis.com]*

Two main modalities can be distinguished of micro-CHP systems: those that obtain the fuel from the grid (e.g. natural gas) and those that work isolated from the grid (off-grid or stand-alone) thus having to store the fuel.

Thanks to the widespread availability of natural gas through the distribution grid, the grid-connected application has the potential to become very widespread, and the potential market – aiming in particular at the replacement of old household boilers – could be of several hundreds of thousands of systems per year in Europe alone.

Industrial Developers Stationary Small-Scale CHP:
Acumentrics, Ceres Power, Ceramic Fuel Cells, Elcogen, Hexis, Kyocera, SOFCpower, Staxera-Sunfire, Topsøe Fuel Cells

Stationary medium-large scale

Electricity can be transported over long distances with little power loss, but heat cannot be piped efficiently far from the point of generation. In order to make use of the generated heat, power plants should therefore be smaller, dispersed and located nearby the end-users. However, conventional power plants cannot be down-scaled without efficiency loss, and also the negative impact of a combustion-based plant is generally not desirable in the vicinity of the end-user basin. Medium and large SOFC-based generation systems (in the range of hundreds and thousands of kilowatts) do not have these drawbacks and can efficiently combine heat and power delivery at “neighbourhood scale”, as well as to other centres that can benefit from having their own, independent power and heat supply.

Medium-scale SOFC generation can also fit the needs of the automotive industry for clean and efficient powering, either by integrating the unit inside the vehicle (see the section on Auxiliary Power Units), or by externally recharging battery electric vehicles (BEV). The transportation sector represents the fastest-growing sector in terms of energy consumption, with a vast majority of greenhouse gas emissions being produced by road-based transport. Battery-recharging stations installed strategically in areas isolated from the electricity grid could contribute to improve the infrastructure and promote the use of electric vehicles, thereby reducing local CO_2 emissions and overall fuel consumption.

Though smaller systems limit the liability of SOFC products in the early stages of market introduction, and are therefore favoured by industry today, large-scale SOFC plants certainly represent the next step in providing clean affordable energy to society at large. At multi-megawatt scale, traditional powering technologies can be integrated into fuel cell-based power plants to achieve even higher electrical efficiencies, for example by incorporating a bottoming cycle with gas and/or steam turbines working either under atmospheric or pressurized conditions. Integrated gasification fuel cell power plants (IGFC) become economically feasible with large-sizes, as the efficiency of turbines increases with their size.

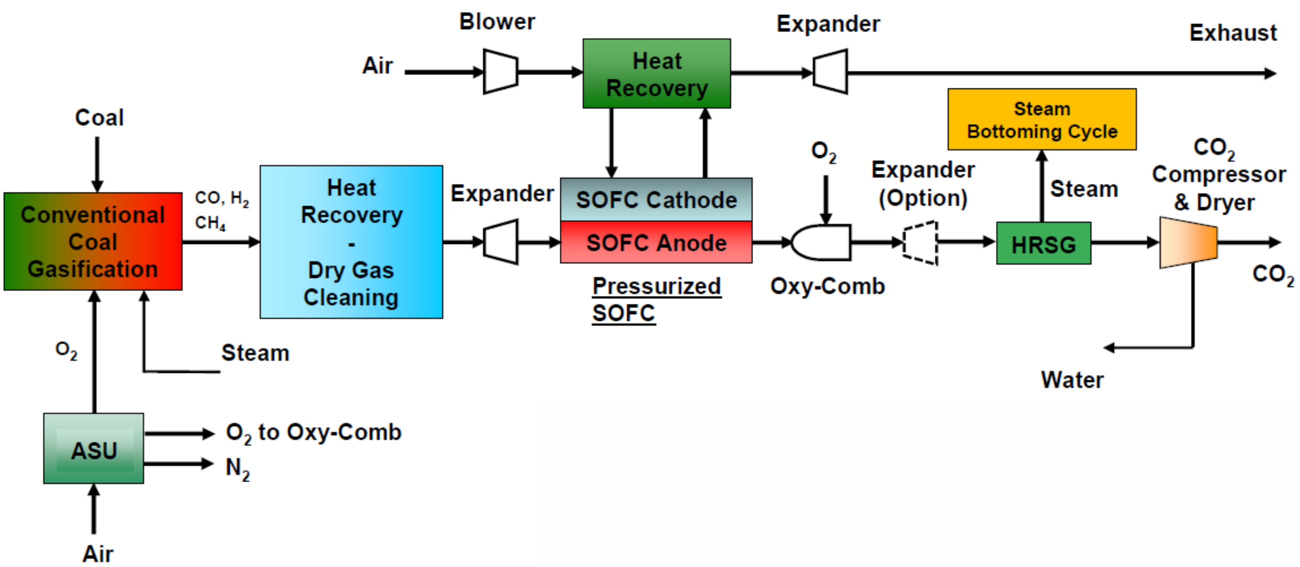

Figure 10. *SECA Coal-Based Systems Pressurized IGFC*
(conventional coal gasification, low water use, 99% carbon capture, 50% efficiency).
[source: NETL, Proceedings of International Energy Agency (IEA) 2011 - Annex 24, Solid Oxide Fuel Cells]

Industrial developers Stationary Medium-Large Scale:
Bloom Energy, Delphi, Mitsubishi Heavy Industries, LG Fuel Cell Systems, Versa Power Systems

A WORLD INDUSTRY: Overview of worldwide SOFC developers

North America

Acumentrics was established in 1994 and is headquartered in Massachusetts (USA), as a part of Acumentrics Holding Corporation. Acumentrics produces and installs remote, military and residential small cogeneration applications from 250 W to 10 kW. In order to expand its commercial activities outside the United States in 2003 Acumentrics announced the formation of Acumentrics Japan from a joint venture with Sumitomo, and in 2007 they acquired Fuel Cell Technologies forming Acumentrics Canada. The SOFC division of the company develops and manufactures micro-tubular anode-supported ceramic-based solid oxide fuel cells. Acumentrics cells' small radius improves the resistance to mechanical stress, increasing robustness towards thermal gradients during start-up and shut-down, having a direct positive effect in the life span of the fuel cells. Start and stop cycles are greatly improved by these characteristics, and consequently a number of their latest systems can be started in less than half an hour.

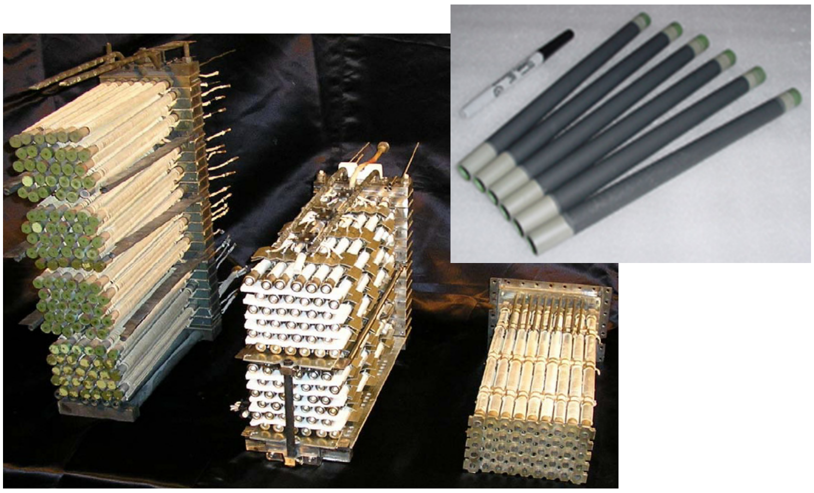

Figure 11. *Acumentrics mini-tubular cell geometry and stack size reduction (33% volume reduction was obtained in 2009-2010 and 90% weight reduction in the years 2004-2010, from 126 to 20 tubes for 1.25 kW stack). [sources: Acumentrics, www.acumentrics.com, DOE Hydrogen Program and Vehicle Technologies Program - Annual Merit Review and Peer Evaluation Meeting 2009]*

In the range of micro-CHP applications Acumentrics has produced 'Acumentrics 5000', a unit that can be fed with a variety of fuels such as natural gas and biogas, producing 3 kW_{el} and having an electrical efficiency of around 50% and overall 80%. The system package can be hooked up to fuel supplies at any inlet pressure, so that it is very flexible, easy to install and to operate. Fuels can be stored on-site and remote control is possible by an Ethernet port. 'AHEAD' is the company's residential 1 kW_{el} micro-CHP system for the home, which provides electricity for an average family's requirements and which may be connected to the electricity grid or to traditional batteries to smooth out peaks. The unit can be fed directly with natural gas or propane, and the extra electricity may be fed into the electric grid. It is coupled to a boiler which can provide up to 24 kW of thermal power for home heating using energy from the exhaust gases. It can be operated between -30 °C and 50 °C ambient temperatures at 30% electrical efficiency at nominal power load, but with an overall efficiency of 90%.

The commercially available prototype RP-20 (efficiency: 30%, start-up time; lower than 60 minutes, fuels: natural gas and propane, fuel consumption @ 500 W: 0.16 m^3/hr or 0.24 l/hr, operating temperature: from -30 to +50 °C, dimensions: 56x56x99, weight: 136 kg) is currently being tested for cathodic protection of gas pipelines and powering up telecommunication systems off-grid, as well as in the Exit Glacier Nature Centre in Kenai Fjords National Park (USA). The fuel cell unit can also provide 1 kW of power for all of the centre's electrical needs including lights, outlets, and other basic appliances.

Figure 12. *An example of remote, stand-alone power supply.*
[source: Acumentrics, North East Corrosion Conference 2012]

Bloom Energy was founded in 2001 with the name Ion America and based in California (USA). The company changed its name to Bloom Energy (BE) few years later, following major investments.

Bloom Energy develops and commercializes large reliable SOFC systems with high efficiencies. At the core of their products are stacks of planar electrolyte-supported fuel cells manufactured with noble metals sprayed on ceramic supports that require no special inks. Part of the technology adopted was already developed through their work as a partner in NASA's Mars Program.

In cooperation with the University of Tennessee (USA), BE produced a 5 kW_{el} stack which was tested in field trials starting in 2006 in places with diverse climatology, including California, Alaska and Tennessee. In the period ranging from November 2006 to December 2009, in cooperation with the U.S. Department of Energy (DoE), R&D activities were directed towards a 25 kW_{el} grid-connected system for co-production of electricity and hydrogen.

The field-tested units worked for more than 5000 hours and the availability of the plants was over 97%. The company has continued increasing the size of their systems during these last years, producing the servers: ES-5000, ES-5400 and ES-5700, generating 100, 105 and 210 kW_{el} respectively.

The heart of these servers is built up with 1kW_{el} stacks, labelled as 'Bloom Box', which are composed of 40 cells of 25W_{el} each, fuelled with natural gas or biogas and achieving over 50% net electrical efficiency.

Figure 13. *Bloom Energy's materials, anodes and cathodes.*
[source: Bloom Energy, www.nasa.gov]

A number of renowned multinationals have chosen to install Bloom Energy's servers to power their headquarters, the vast majority of these are in California. As an example, Google, Coca-Cola and Bank of America are amongst their clients. Each Energy Server can be connected, remotely managed and monitored by Bloom Energy, this way minimizing possible failures. The system can be fuelled by natural gas or biogas, in grid-connected or stand-alone configuration, ensuring continuous supply of energy, with high electrical efficiency even at part loads.

Figure 14. *Bloom Energy Server E-5700.*
[source: Bloom Energy, www.bloomenergy.com]

Figure 15. *Bloom Energy Servers at NASA and the Federal Bank of America.*
[source: Bloom Energy, www.bloomenergy.com]

Recently, the internet auction enterprise e-Bay and Bloom Energy signed an agreement for the construction of a novel 6MW CHP plant at e-Bay's data centre in Utah (USA). The brand-new installation will consist of 30 Energy Servers, each one providing 1-75 million kWh of electricity annually. The electricity grid is connected, but should act as a backup only. The plant will be fuelled by biogas from local organic waste, saving on CO_2 emissions twice over. This is not the first project with the companies working together as eBay also runs the first Bloom Energy 500 kW_{el} plant fuelled with biogas, powering their headquarters in California.
The cost of a 100-kW Bloom Energy Server is approximately $ 700,000-800,000.

Delphi is a leader in electronics for automotive technologies. The company has created solid oxide fuel cell units for over a decade, focusing their R&D towards powering vehicles, stationary power generation and military applications.
Delphi develops rectangular robust anode-supported cells. Generation-4 is their latest product in which the anode, cathode and electrolyte are based on nickel oxide yttria-stabilized zirconia, yttria-stabilized zirconia (YSZ) and Strontium-Cobalt-Lanthanum-Ferrite (LSCF) with Ceria-based interlayer respectively. Generation-4 stacks have 403 cm^2 of active area, providing high quality and reliable power (110 VAC and/or 12 VDC), with electrical efficiencies ranging from 40 to 50%. This stack is less expensive than Generation-3 thanks to improved interconnects and coatings and the pack's increased power (5 kW). The system can be run on several fuels including natural gas, diesel, bio-diesel, propane, gasoline and coal-syngas.

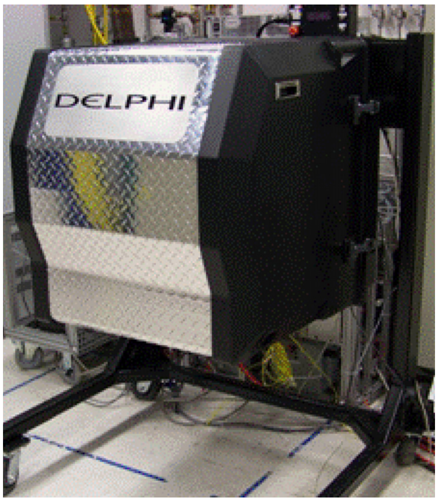

Figure 16. *The Delphi Solid Oxide Fuel Cell Auxiliary Power Unit is designed to provide up to 5 kW obtaining up to 50% of fuel efficiency (higher than current gen-set APUs) and very low noise (<60 dBA @ 3 meters distance); Gen-4 cells have demonstrated an average cell voltage of 0.7 V and power density of about 400 mW/cm² (fed by SECA coal gas blend), degradation rate less than 5 %/3000 hrs or under 60 thermal cycles (750 °C - 100 °C). [source: Delphi, www.delphi.com, Proceedings of SECA Workshop 2011]*

In cooperation with Volvo Trucks North America (VTNA) Delphi has developed a backup system suitable for heavy duty trucks and recreational vehicles. This APU allows shut-off of the main engine during long-term parking and full use of the cabin services, saving up to 85% of the fuel currently required for a main diesel engine running idle. It is the only member of the United States Fuel Cell Council that has developed and demonstrated in practice an SOFC power unit for heavy commercial vehicles.

Delphi provides the electrochemical module for the Integrated Gasification Fuel Cells Power Plant (IGFC) as developed by United Technologies Research Center (UTRC) and Battelle under the SECA program (Solid State Energy Conversion Alliance). As part of the SECA Coal-Based Systems Project the United States Department of Energy has contributed $ 22 million towards simulations where UTC has verified SOFC-ST (with a steam turbine) and SOFC-GT-ST (with a gas turbine and a steam turbine) hybrid plants, in atmospheric or pressurized operating configuration and towards the building of a 50 kW_{el} experimental facility. The goal is to develop IGFC power plants with power ratings above 100 kW at an overall electrical efficiency of at least 50%, excluding coal gasification and carbon separation processes. SECA's economical target is to achieve $ 700/kW stack cost in IGFC applications, and a preliminary analysis on the Gen-4 stack carried out by Delphi already showed costs of $ 566/kW already in 2007.

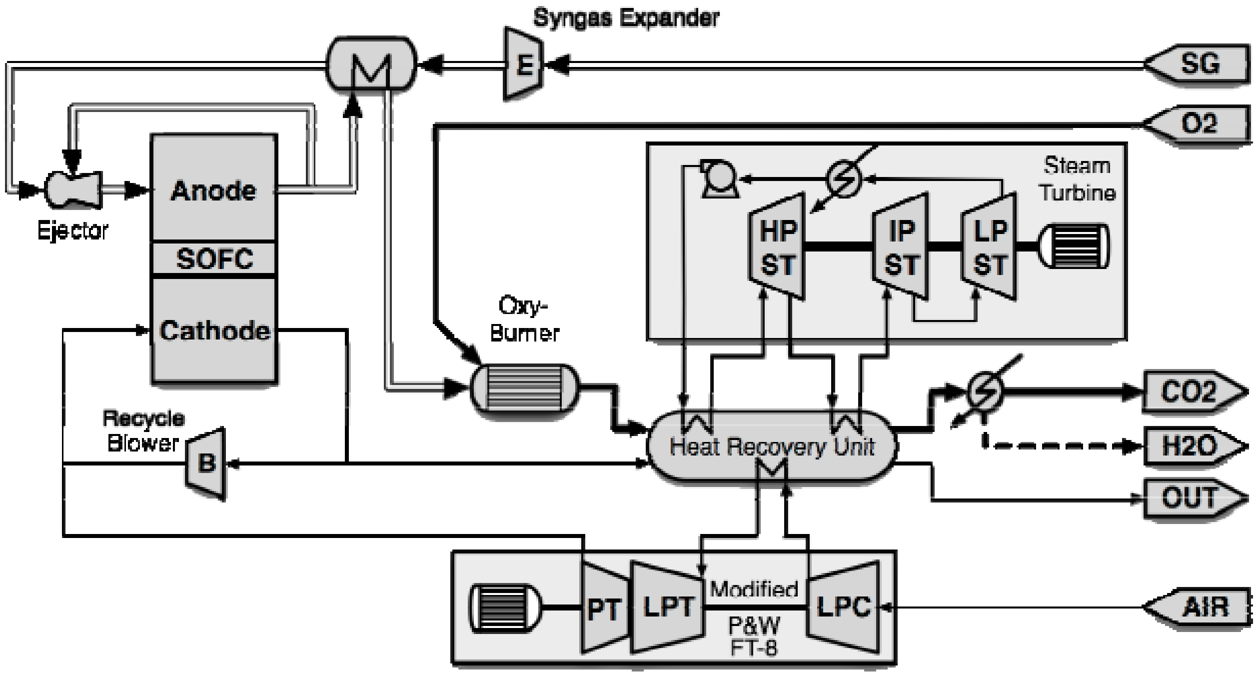

Figure 17. *A concept of an integrated atmospheric SOFC, gas turbine and steam turbine power plant, SOFC/GT/ST. [source: UTC Power, Proceedings of SECA Workshop 2009]*

LG Fuel Cell Systems (LGFCS) is part of the Korean multinational company LG. It acquired US Rolls Royce Fuel Cell Systems (RRFCS) in June 2012, investing $ 45 million for the acquisition of 51% of RRFCS stock. According to the agreement, RRFCS now takes the name LGFCS. RRFCS was created in 1992 in the United Kingdom for the development of SOFC MW-size cogeneration systems. In 2007, RRFCS had acquired SOFCo-EFS, a US company engaged in the development of SOFC systems and fuel processing. The enterprise has offices in the UK, US and Singapore, and has actively participated in European and North-American public fundamental research programs, amongst which are the *Large-SOFC* project financed by the European commission and the SECA Coal Based Systems and Coal Based SOFC Model Development Programme.

In 2008 they commenced the development of a hybrid pressurized SOFC-µGT system, where 250 kW_{el} modules would be operated simultaneously obtaining power plants with nominal power higher than 1 MW_{el}. The ultimate goal of this project is to develop the suitable SOFC technology for use in integrated coal gasification plants with sizes greater than 100 MW, achieving an overall efficiency (considering the gasification of coal and CO_2 separation) higher than 50%.

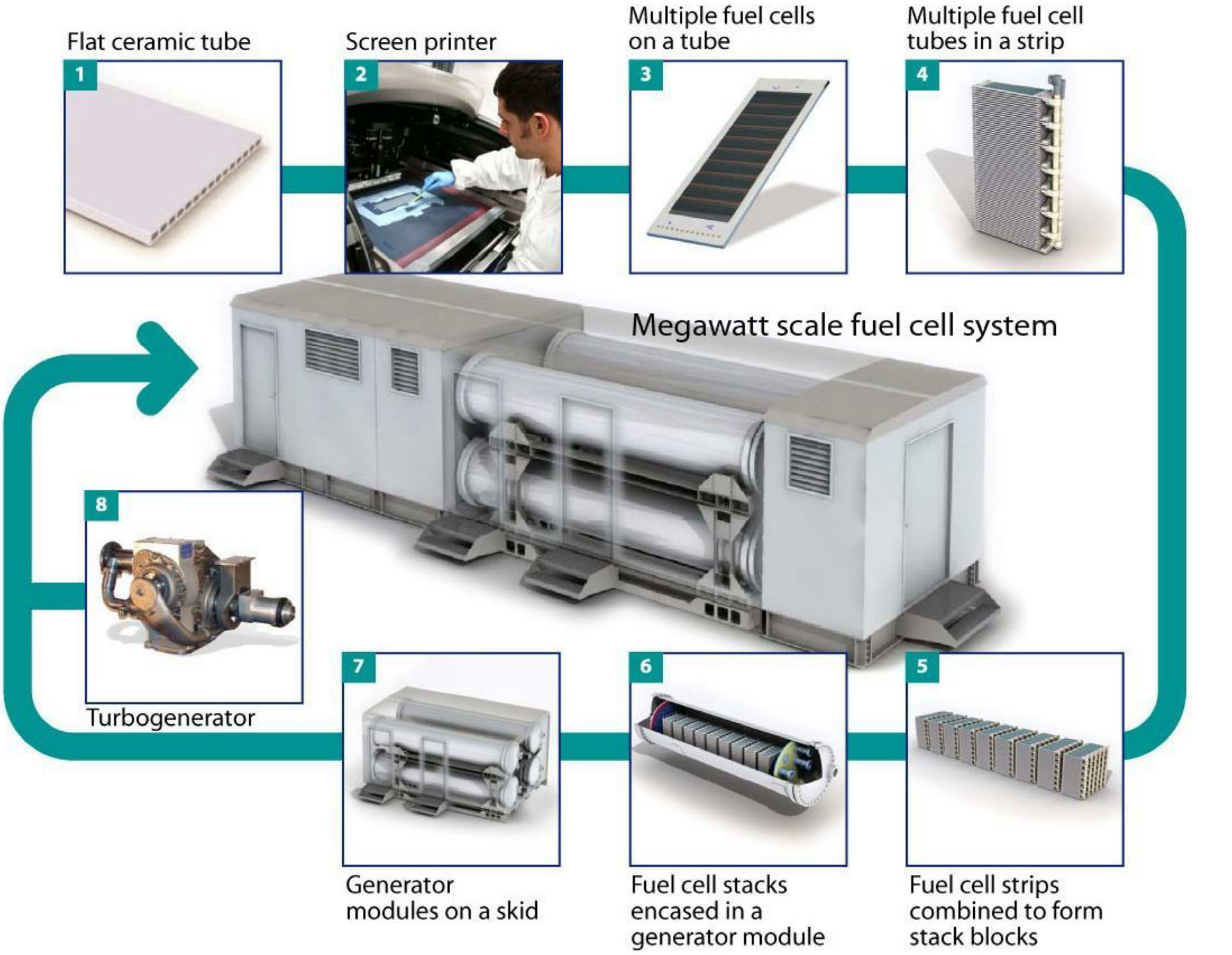

***Figure 18**. From component to final product: integration of RR-SOFC in the bundle, making up stacks, electrochemical modules and thermal units as base for multi-MW installations.*
[sources: RRFCS, Proceedings of SECA Workshop 2010 and 2011]

LGFCS uses flat tubular cells in a segmented configuration where anode, electrolyte and cathode are repeated transversely and longitudinally on a porous ceramic support which, in operation, is crossed by the fuel while the oxidant laps the cathodic surfaces from the outer side, inside of a collector.

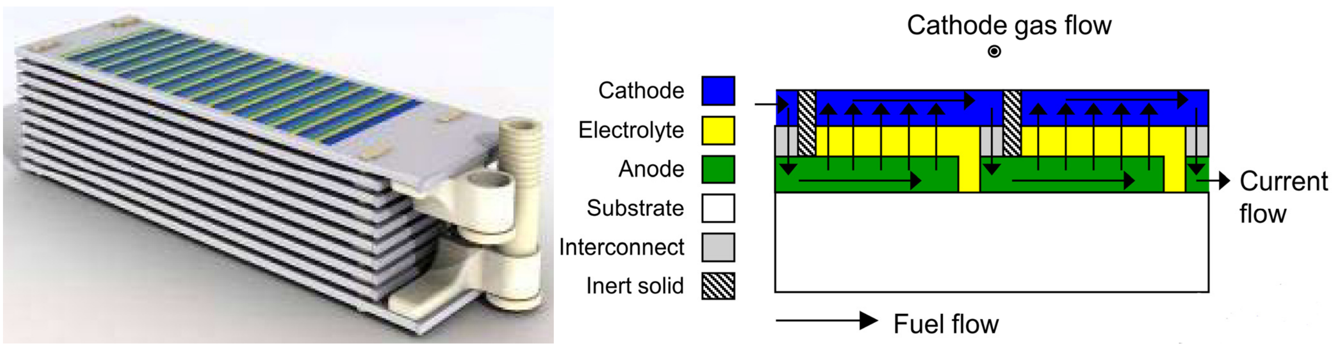

***Figure 19.** Cathode gas and fuel flows through two consecutive cells and their integration into a bundle (as elementary unit of an RRFCS SOFC Module).*
[sources: RRFCS, Proceedings of SECA Workshop 2010 and 2011]

The new generation cells have been developed with specific surface resistance of 0.29 $\Omega*cm^2$, improving power density by 73% since the beginning of the program, and exhibiting a degradation of less than 0.5%/kh in 8500 hours of operation.

With 51% of RRFCS shares, LGFCS has effectively acquired RRFCS technology, and aims to build on the technical expertise previously gained. LGFCS will focus its efforts toward efficiency increase, anodic and cathodic gas recirculation, the interaction between cathodic recirculation and the coupled microturbine and increasing the reliability of the SOFC stack to achieve lifetimes that exceed 40,000 hours.

Protonex was founded in 2000 with the aim of developing and marketing PEMFC units. In 2007 it acquired Mesoscopic Devices LLC, a company involved in the research and development of SOFC technology, fuel reforming, and desulphurization systems, which expanded its commercial interests to SOFC technology.

In the past, Mesoscopic Devices had built 'MesoGen-75' and 'MesoGen-250' portable systems, at 75 W and 250 W respectively, with funding from the Department of Defence and the U.S. Navy. These units were able to provide suitable power levels for radios, sensors, and small batteries; both versions could be fuelled by propane or kerosene. MesoGen-250 models were also designed to operate as a field battery charger, and as auxiliary and emergency units on military vehicles.

The company develops SOFC systems based on tubular-cell technology, compact and suitable to better guarantee the robustness required for portable and mobile applications. The SOFC products currently exhibited are the M250B and M250CX.

Figure 20. *Protonex M250-B (250 Watts, up to 1000 operating hours, 2 hours/litre consumption, 38 dBA @ 7 meter, 18 kg weight, operating temperature from -20 °C to 50 °C, size 56x35x30 cm) and M250-CX B (300 Watts, 2000 operating hours, 900 ml/hour consumption @ 300 W, 38 dBA @ 7 meter, 16 kg weight, from -20 °C to 50 °C operating temperature, size 30x37x23 cm). [source: Protonex, www.protonex.com]*

Protonex M250-B is easily integrated as electrical backup into existing systems, allowing automatic recharging of the batteries during periods of low electric demand, so as to guarantee the availability of the electrical power required and observing acoustic emission limits in nocturnal applications.

The M250-CX products were developed in parallel to the M250-B and were designed specifically for the U.S. Army as multi-functional on-field systems. In fact they can be used as charger, auxiliary power unit or micro-field generator.

These systems can charge multiple batteries simultaneously, so for military scenarios it would be possible to switch from rechargeable batteries to fuel cells, thus reducing the weight carried from soldiers and costs due to non-rechargeable batteries.

Ultra Electronics AMI was established in 1993 in Ann Arbor. It is a successful international defence, security, transport and energy company. In 2011 Ultra Electronics Holdings acquired Adaptive Materials, an industrial developer of small SOFC systems using microtubular technology. Adaptive Materials was the first company to develop portable SOFC systems demonstrating their applicability in the field, since 2001 in collaboration with the U.S. Department of Defence. The company has developed, demonstrated and delivered successfully since then portable, affordable and fuel flexible SOFC systems, most of them to military customers and partners.
Ultra Electronics has a portfolio of compact, quiet and eco-friendly SOFC-based generation sets fed by propane, butane and LPG thought to be utilized in the military (Defender Series), civilian (Explorer Series) and industrial sectors (Performer Series). The Defender Series,, D245RX (245W) and D300 (300W) are suitable for applications as power support of on-field military power demand. The Explorer series ROAMIO E250 (250W) has a light-weight propane fuel tank, suitable for boats or campers, to power GPS systems, radios, refrigerators, etcetera. The products of the Performer Series, P250 and P250HP are intended for industrial use, as remote power supplies without maintenance, and are capable of operating 24 hours a day. All of the devices have a 12-24V DC output and a fuel consumption of 112 gr/h of propane at peak power.
AMI recently delivered 45 units of ROAMIO D245XR (245 W) fuel cells for use by the U.S military in unmanned aerial systems. The unit provides long duration flights of more than eight hours in small unmanned aerial vehicles, being much more suitable than conventional batteries. The provision of D245XR systems is the latest in a series of orders from the U.S. Army: 30 units were delivered to the Rapid Equipping Force (REF), 15 to the U.S. Army Tank Automotive Research, Development and Engineering Center (TARDEC) and 10 to the Communications-Electronics Research, Development and Engineering Center (CERDEC). In practice, all branches of the U.S. military have tested the Ultra Electronics AMI fuel cells.

Figure 21. *ROAMIO Defender Series D245XR (245 W, dim. LxWxH 40x14x14 cm, 2.6 kg, 112 g/hr propane) and ROAMIO Explorer Series E250 (250 W, size LxWxH 40x20x36 cm, 10.9 kg, 112 g/hr propane). [source: AMI, www.ultra-ami.com]*

Ultra Electronics AMI collaborates with Lockheed Martin to manufacture the Stalker, a new unmanned air vehicle powered by a ROAMIO Defender Series D245XR fuel cell stack.

Lockheed Martin is headquartered in Maryland and is engaged in the research, design, development, manufacture, integration and sustainment of advanced technology systems, products and services.

In August 2012, the Office of Naval Research awarded Lockheed Martin a $ 3 million contract to design and develop a solid oxide fuel cell generator that can be integrated with solar panels, providing the power to perform missions while using dramatically less fuel. The goal of the program is to reduce the overall fuel usage required for tactical electrical generation by 50 percent or more. The SOFC technology is also applicable to auxiliary power units (APUs) for ground vehicles, providing clean, efficient electrical power to ground vehicle systems.

Figure 22*. The Stalker, by Lockheed Martin, has a wingspan of about 3 m (10 ft), weighs about 6.4 kg, and it can be launched by hand, flying for up to two hours at up 4600 m altitude; in 2011 Lockheed Martin announced a new version of its Stalker called eXtreme Endurance (XE) powered by Ultra Electronics' industry-leading solid oxide fuel cell. [source: Lockheed Martin, www.lockheedmartin.com]*

Versa Power Systems was founded in 2001 as a joint venture between several research institutes and the University of Utah, and currently has facilities in Colorado (USA) and Alberta (Canada). The company is focused on advanced planar anode-supported solid oxide fuel cells, stacks and power plants for stationary and mobile applications. FuelCell Energy (FCE), a leading company in molten carbonate fuel cell (MCFC) technology became a valuable shareholder of Versa in 2004, acquiring 42% of its shares. In this way FCE brought their knowledge of fuel cell development, especially related to multi-megawatt power plant with syngas from coal, to this company.

FCE and Versa Power Systems participate in the FE Program Adv. Power - Fuel Cells, Solid Oxide, relating to the SECA Coal Based Systems Program for the study and development of SOFC-GT systems. The agreement (worth almost $ 57 million) began in 2006 and will end in 2015 and it refers to the study and testing of a hybrid system powered by coal syngas. The three stages of development are the scale-up of the cell and stack base and the creation of a 16 kW and a 30 kW stack; further scale-up of the fuel cells and stack to 60 kW, followed by the making of 250 kW modules and, finally, the realization of a Proof-of-Concept multi-MW system, with integrated coal gasification, a high efficiency turbine and moreover a treatment system for CO_2 separation.

In addition to the stack development activities the first phase also included a theoretical study of a 400-500 MW system with two configurations identified as the most promising in terms of performance and cost: the first one is based on an entrained bed gasifier and commercial, cold desulphurization of the produced syngas; the second is based on an advanced catalytic fluidized bed gasifier and hot gas clean-up.

Figure 23. *11 kW stack (characteristics: 64-cells, 550 cm2 active area 0.313 W/cm^2 peak power density at design load, 61.5 fuel utilisation, from 10 to 18% air utilisation, 200 A stack current, 730-750 °C cathode outlet temperature) and 3 stack blocks of 10 kW into 30 kW stack module. [sources: Proceedings of Fuel Cell Seminar 2011, Proceedings of SECA Workshop 2012]*

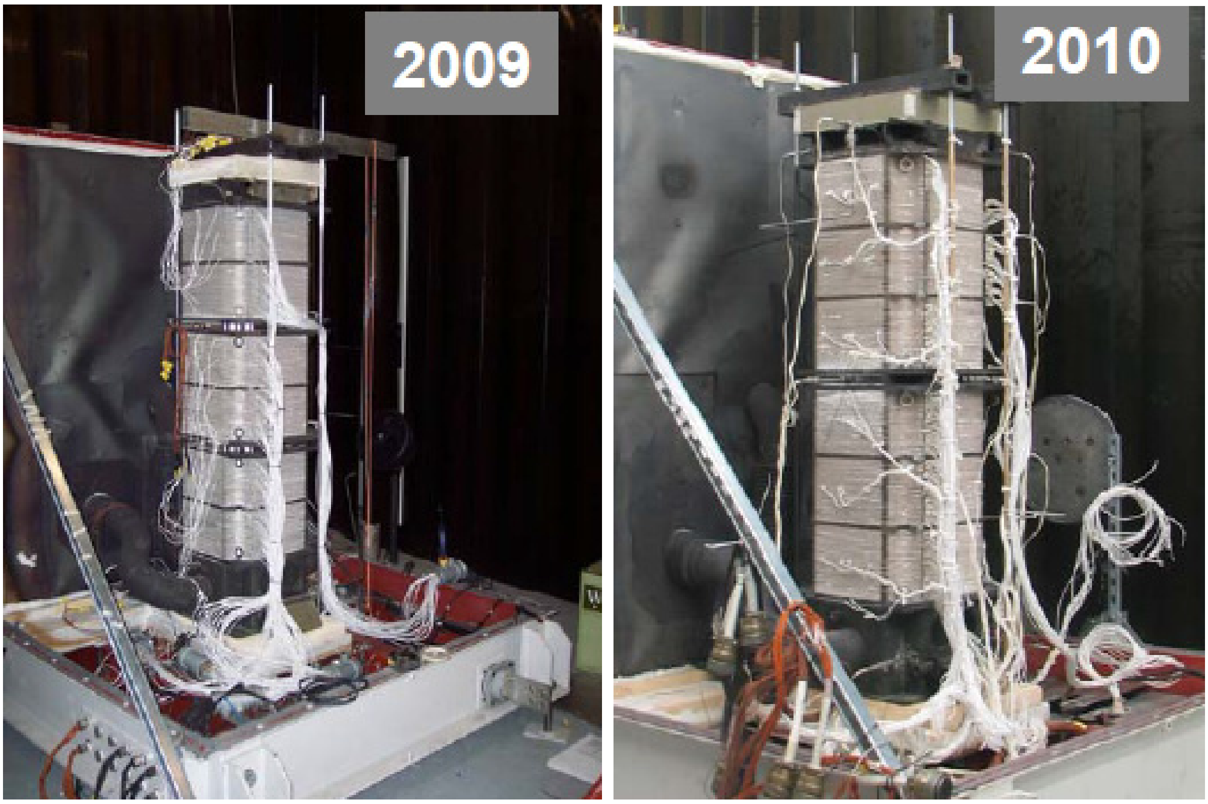

Figure 24. *Stack module evolution from 2009 to 2010 (3x64 cells stack and 2x92 cells stack. [sources: Proceedings of SECA Workshops 2010 and 2012]*

Reduction in the cost of plant (BOP and components) is necessary for the commercial success of SOFC systems with applications in generation/co-generation facilities and is one of the main keystones underpinning the success of the SECA Program.

FCE has analyzed the costs related to the main items and equipment for a plant, assuming the realization of 2 plants per year. The work revealed that the heat recovery and steam generation systems are the most expensive while the cost of the steam turbine (that increases plant efficiency) should affect plant cost by only about 6%.

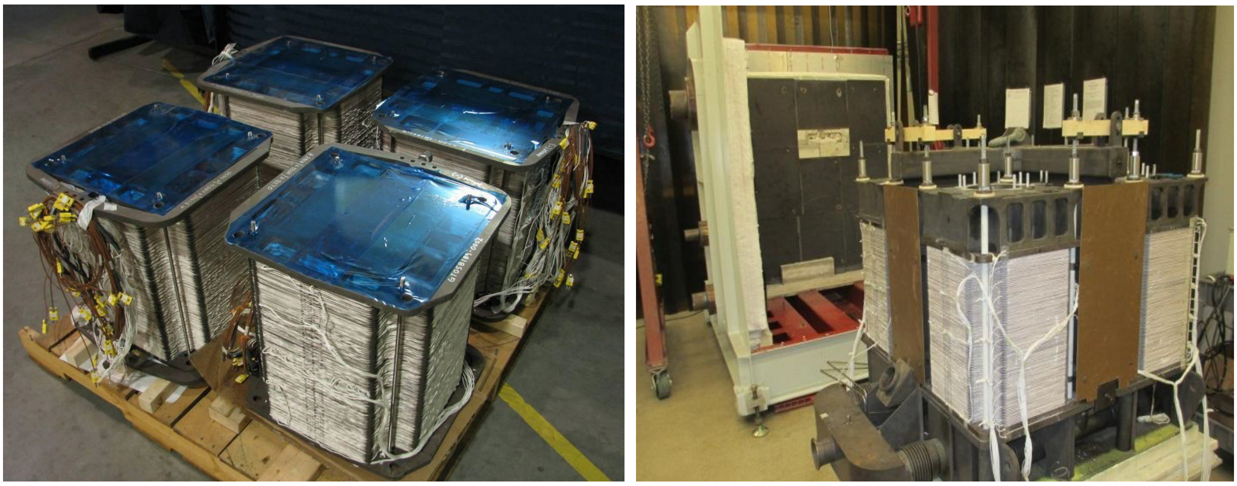

Figure 25*. 4 x 96-cell stacks integrated in a 60 kW module and module assembly for test start; modules are planned to be tested in the existing 400 kW Power Plant Facility.*
[source: Proceedings of SECA Workshop 2012]

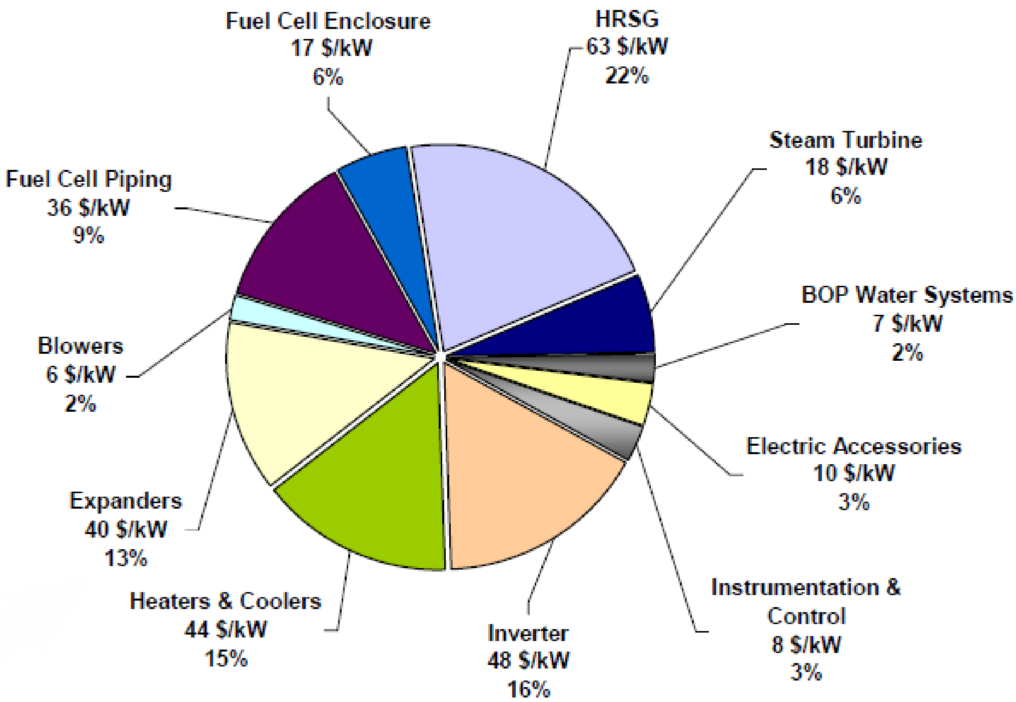

Figure 26*. Cost estimation analysis based on 2x570 MW power plant manufactured per year (costs include factory equipment).*
[sources: Proceedings of SECA Workshop 2010]

Europe

Ceres Power is located in the UK and was founded in May 2001 to commercialize the unique core materials technology developed at Imperial College during the 1990's. Today, Ceres Power develops micro-CHP SOFC systems for the residential sector and for energy security applications, basing their operations and technology centre in Crawley and fuel cell mass manufacturing facility in Horsham, Sussex. Ceres Power has built and developed relationships with key industry partners such as British Gas, Calor Gas and Bord Gáis.

The patented Ceres fuel cells are metal-supported (stainless-steel), allowing rapid start-up times and a great number of on/off cycles with little degradation. Their operating temperature range is 500-600 ^{o}C, significantly lower than the cells designed with conventional materials which typically operate at around 800 °C. This is possible thanks to the metal support (allowing the use of extremely thin and active catalytic components) and by using a new generation of ceramic materials known as CGO (cerium gadolinium oxide) instead of the industry standard YSZ (yttria stabilised zirconia).

Figure 27*. Detail of a Ceres' single fuel cell; electrolyte is sandwiched between the anode and the cathode and it is very thin.*
[source: Ceres Power, www.cerespower.com]

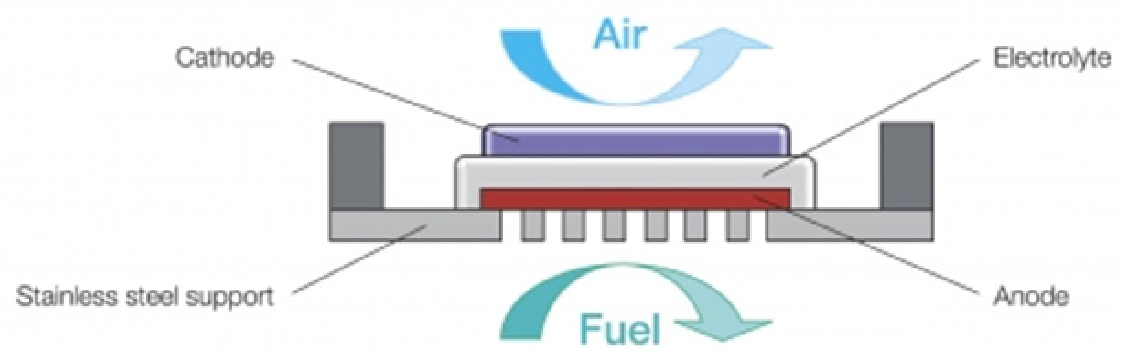

Figure 28*. Fuel passes over the anode side and air passes over the cathode while by an external circuit connecting the electrodes it provides the electric energy to power devices.*
[source: Ceres Power, www.cerespower.com]

The company's first pre-commercial product is an integrated wall-mounted residential fuel cell combined heat and power (CHP) product. The compact product is designed to replace a conventional boiler, using the same natural gas, water and electrical connections and with similar installation and maintenance requirements.

These micro-CHP units have showed degradation rates of approximately 1% per 1000 hours of operation. According to Ceres, the micro-CHP product has the potential to meet the overall commercial performance requirements supporting mass market deployment from 2016.
Under a new agreement, Ceres' partners British Gas (UK) and Itho-Daalderop (Netherlands) are to purchase 174 micro-CHP units for sale, installation and trial in UK and Dutch homes from 2014. This will be the first time the units will be available to the public and select customers will have the opportunity to purchase a Ceres micro-CHP unit with a full service and maintenance package provided by British Gas in the UK and by Itho-Daalderop in the Netherlands.
Feedback from these trials will be used by Ceres to refine the product and validate performance and operability prior to mass volume launch in 2016. The trials will be part of the new Ene-Field project, a large-scale demonstration of a thousand fuel cell micro-CHP products across Europe.

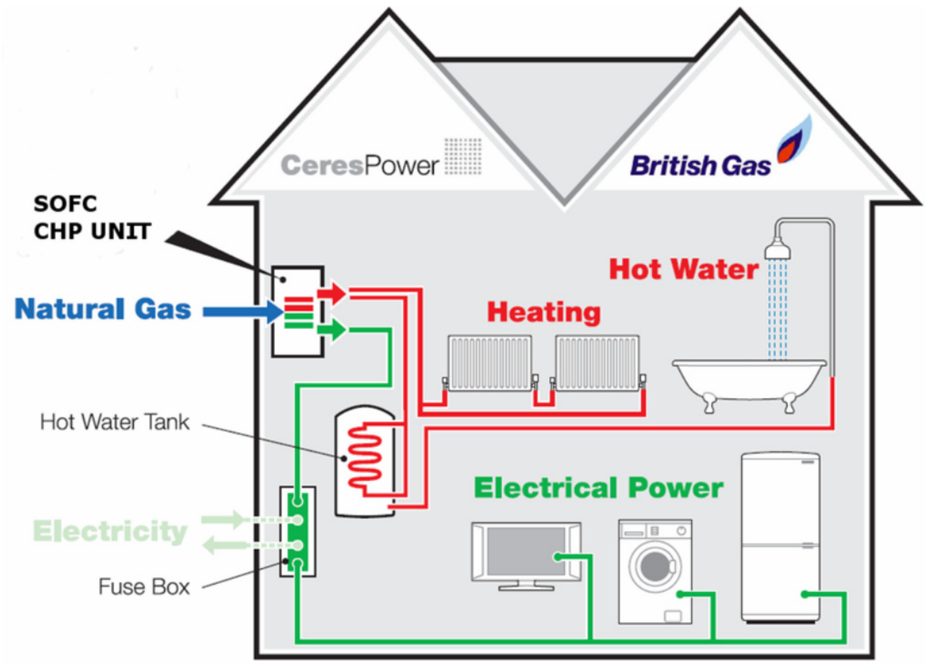

Figure 29. *Ceres Power fuel cell – existing technologies integration concept in residential.*
[source: Ceres Power, www.cerespower.com]

Elcogen is located in Estonia and Finland and was established in 2001 in Estonia. Elcogen is a privately owned company which focuses on commercializing anode-supported SOFC cells and stacks to open markets. Its cell technology is optimized for 600-700 °C operating temperature with state-of-the-art cell performance proved both in fuel cell and electrolysis operation modes. The lifetime expectation of well over 20,000 hours for the unit cells combined with the low-cost manufacturing methods already implemented in cell production enhances the cost effectiveness of stack and system structures.
Elcogen offers fuel cell stacks of 1 kW_{el} utilizing Elcogen unit cells. The low operating temperature enables the use of cost effective material design and system solutions at elevated efficiency levels. The stack structure is optimized both from the fuel and air side to ensure low pressure losses in the anode gas recirculation system, whilst still permitting high fuel utilization rates enabling fuel cell system developers to minimize parasitic losses.

Elcogen has been developing its cell and stack technologies closely with the Estonian and Finnish research institutes KBFI and VTT Technical Research Centre of Finland. Elcogen is already delivering unit cells to its global customers and its first stack deliveries to a system integrator occurred in 2012.

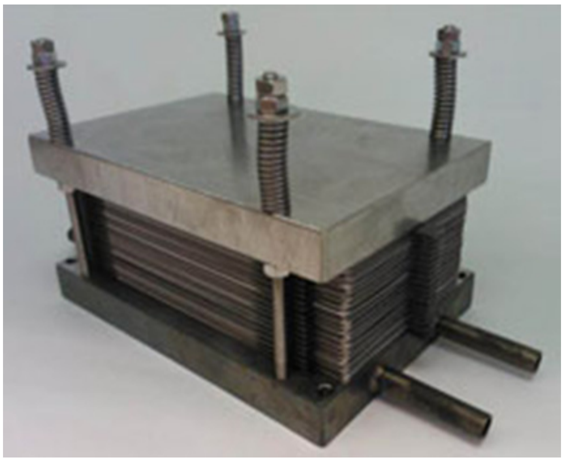

Figure 30. *1 kW stack.*
[source: Elcogen, www.elcogen.com]

The Elcogen manufacturing process enables the production of various forms of cell, circular or rectangular up to a maximum of 20x20 cm for a cell. Customers are welcome to get in touch with Elcogen in order to find the best solution.

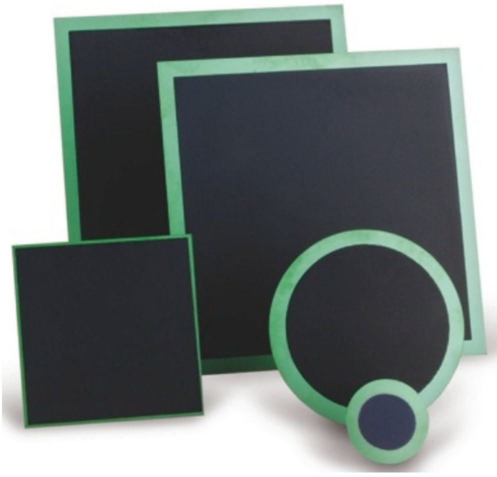

Figure 31. *Elcogen's fuel cells. Cells show 5.5% degradation after 1000 h @ 60% fuel utilisation and 650 °C operating temperature with a reformate mixture of 15% CH_4, 26% CO_2, 29% H_2, 30% H_2O.*
More detailed cell characteristics are available on the Elcogen web official site.
[source: Elcogen, www.elcogen.com]

Hexis AG was created in 1997 as a venture division of Swiss engineering and manufacturing firm Sulzer and became independent in 2006. One year later they created the subsidiary company in Germany, Hexis. Hexis develops SOFC-based CHP units for stationary applications with electrical power requirements below 10 kW.

The company develops planar SOFC technology, where the cells have a circular design. The fuel enters the anode part of the cell through the centre of the disc, flowing radially outwards. The preheated air follows the same path on the cathode side.

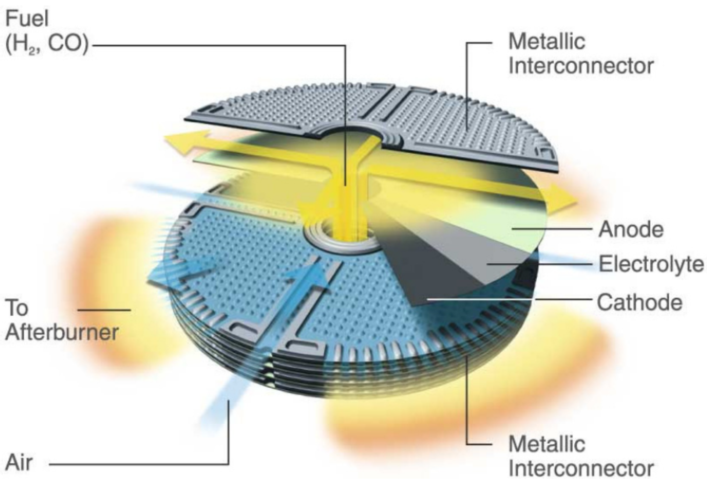

Figure 32. *Working principles of an Hexis fuel cell.*
[source: Hexis, www.fuelcellmarkets.com]

Their latest pre-commercial product is 'Galileo 1000N', which uses a stack module made up of approximately 60 cells, and can be fed either with natural gas or bio-methane, as the system integrates a catalytic partial oxidation (CPOX) reactor. The nominal electrical power output is 1 kW (AC), and the thermal power output is 2 kW, with an electrical efficiency of up to 35% and maximum overall efficiency of 95% (LHV). Galileo 1000N also incorporates a 20 kW auxiliary burner to complete the supply of thermal on-demand requirements of a house or small apartment building. The commercial unit, geared towards end-consumers, will be ready in the second half of 2013.

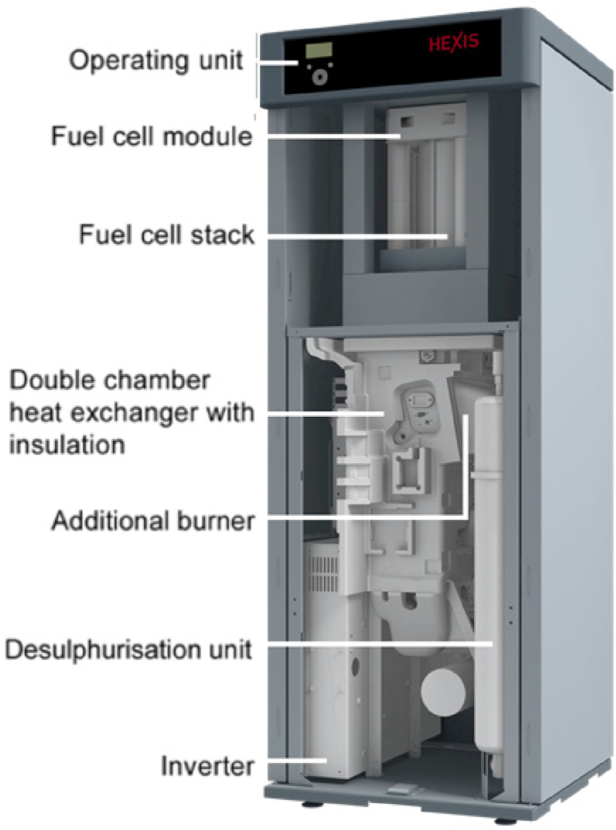

Figure 33. *Working principles of an Hexis fuel cell.*
[source: Hexis, www.hexis.com]

SOFCpower SpA is based in the Italian region of Trentino. It was created in 2006 by carving-out the SOFC activities begun in 2002 within the Eurocoating-Turbocoating Group, a privately-held group active in the fields of coatings and processes for gas turbines, machinery and biotechnology. In early 2007 they acquired 100% of HTceramix (a spin-off of the Swiss Federal Institute of Technology in Lausanne, EPFL) incorporating their patents in SOFCpower technology.

The company develops anode-supported thin-film YSZ electrolyte SOFC with a porous perovskite cathode. A Ceria barrier layer is applied between the cathode and the electrolyte to improve durability. Good mechanical stability is provided by the relatively dense anode structure without any limitation on gas diffusion. Precise wet ceramic processing enables efficient use of raw materials. SOFCpower cells achieve high power densities (>1 W/cm^2) allowing >90% fuel utilization and can be operated from 650°C to 800°C with various fuels.

Figure 34. *SOFCpower's cell components and powders.*
[source: SOFCpower, www.sofcpower.com]

Integrating all the high-temperature components of a SOFC system into a single unit, SOFCpower has developed the 'HoTbox' module which includes the SOFC stack up to 1 kW$_{el}$ with a heat exchanger, CPOX reformer for natural gas, insulation, electric heater for start-up, smart temperature control and voltage conditioning for a lead acid battery compatible output.

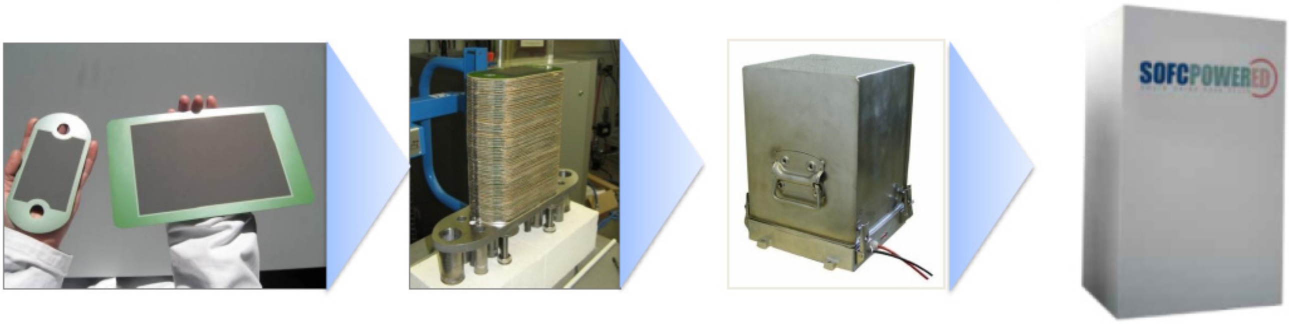

Figure 35. *Integration of individual SOFCpower cells in a stack, in a HotBox, and in the EnGen™-1000 m-CHP boiler.*
[source: SOFCpower, www.sofcpower.com].

One of SOFCpower's products is the wall-hung micro-CHP prototype EnGen™-1000, where the HoTbox™ constitutes the core of the system. It can be produced in two power ranges: up to 500 W$_{el}$ and up to 1000 W$_{el}$. The unit operates with natural gas supplied by the grid, which is pre-processed by the CPOX reactor converting the gas into a mixture of hydrogen and carbon monoxide.

The outlet exhaust gases from the SOFC are treated in a post-combustor, subsequently transferring the thermal energy through a heat exchanger to the water circuit for domestic heating. The electrical production efficiency is between 30-32%. In cogeneration the efficiency reaches the value of the more innovative condensing wall hung boilers. The EnGen™-1000 can provide up to 8750 kWh/year of electrical energy and, combining it with a standard wall hung boiler, can fulfil all thermal requirements of a domestic heating plant.

On January 2012 SOFCpower inaugurated the installation 'Isola Cogenerativa', a 3 kW_{el} and 6 kW_{heat} SOFC-based methane fuelled CHP demonstration plant in a department store in the Italian town of Roncegno Terme. The thermal power is used for heating the sanitary water and the inside of the store, whilst the generated electricity is consumed by the store itself when necessary, or fed into the electrical grid.

Figure 36. *"Isola Cogenerativa" is the first SOFC cogeneration plant in Italy; it consists of 3 modules of 1 kWe fueled by natural gas, for a total of 3 kW of electricity and 6 kW of heat for domestic hot water.*
[source: SOFCPower, www.habitech.it]

Staxera-Sunfire is a joint venture between Webasto AG and H. C. Starck GmbH and is located in Dresden, Germany. Energy-related German company Sunfire and SOFC developer Staxera merged in 2011 as equal partners creating a brand-new company, although the Staxera brand has been retained.

Staxera-Sunfire has commercialized products up to 4.5 kW, based on their Mk200 stack. The robust, cost-optimized design of the Staxera Mk200 SOFC stack makes use of ferritic bipolar plates and electrolyte-supported cells. Low pressure loss and specially optimized fuel gas distribution mean that the Staxera Mk200 stack can be used to realize top-quality systems with low parasitic losses and therefore high levels of efficiency. The stack is designed to operate in combination with a wide range of fuel gases (e.g. as part of catalytic partial oxidation (CPOX) or steam reforming (SR) systems), and is characterized by excellent reliability in terms of both thermal and redox cycles. Stack size (i.e. the number of levels or cells) can be tailored to client requirements. The stack is directly heated by anodic and cathodic gases. The gases are preheated to 400 °C. The thermal energy generated by chemical reactions within the stack further increases the temperature, up to the operating point of 850 °C.

***Figure 37**. Staxera-Sunfire's 116 x 168 x 182 mm3 cell stack, Fuel utilization 75%, rated power output 600 W, operating voltage 19.5 V, weight < 14 kg. Performance @specified fuel compositions: 1: H_2/N_2 40%/60%, process efficiency (reformer and stack, LHV) 40% power output @ operating Voltage 650W; 2: steam reformate (S/C= 2) power output @ operating Voltage 550 W, process efficiency (reformer and stack, LHV) 48% [source: Staxera-Sunfire, www.sunfire.de]*

Topsøe Fuel Cell is located in Denmark and was established in 2004 as a subsidiary owned by the major catalyst enterprise Haldor Topsøe. Topsøe Fuel Cell (TOFC) focuses on the development of residential micro-CHP and auxiliary power units with SOFC planar anode-supported technology. An extensive collaboration exists between TOFC and the research centre Risø towards the development of fuel cells.

'Topsøe PowerCore' is TOFC's micro-CHP system. It integrates the stack with fuel processing and includes all high temperature components in one compact unit, with all hot components thermally insulated. Depending on use, the manufacturer can integrate a CPOX reformer or a steam reformer, allowing the use of a wide range of fuels such as natural gas, biogas or diesel. The power range of this unit ranges from 1 kW_{el} to 5 kW_{el}.

Cell manufacture takes place in a 1400 m^2 building constructed in 2009 for the purpose, co-funded by the European Union Life Environment Program. All processes are semi-automated, modular and scalable; cells with different dimensions and geometries can be produced using the same equipment. The facility output capacity exceeds 5 MW per year, and is currently being expanded, with the inauguration of the new manufacturing line planned for December 2012.

Topsøe Fuel Cell has a strong cooperation bond with Finnish motor company Wärtsilä (Convion/Wärtsilä). Currently two projects are running with both companies working shoulder-to-shoulder. The first is at the New Energy plant in Vasa, Finland, where a SOFC unit is running on landfill gas, supplying electricity to the surrounding homes. The second project is the installation by Wartsila of a 20 kW solid oxide fuel cell on the freight ship 'Undine' which is owned by Wallenius Marine AB. The unit operates on methanol, with CO_2 and water as the only by-products of the process. Topsoe Fuel Cell developed and supplied the fuel cell stacks for the 20 kW SOFC APU and Wärtsilä was responsible for the system design. This is part of the EU funded METHAPU project to employ renewable methanol-based APUs for commercial vessels. The 20 kW SOFC unit is being demonstrated, with a longer term product power target of 250 kW.

TOFC, in collaboration with fuel cell-technology integrator Dantherm Power has developed a micro combined heat and power prototype, and the intention is to commercialize the unit in the near future.

Topsøe Fuel Cell has signed a Memorandum of Understanding with South Korean SK Holdings, which includes a very strong initiative to commercialize fuel cells in small units for private housing, as well as in large stationary units. The Memorandum gives a unique opportunity for Topsøe Fuel Cell to demonstrate and supply fuel cell technology for the fast-growing Asian economy, and it is a significant step towards the upcoming commercialization of fuel cells.

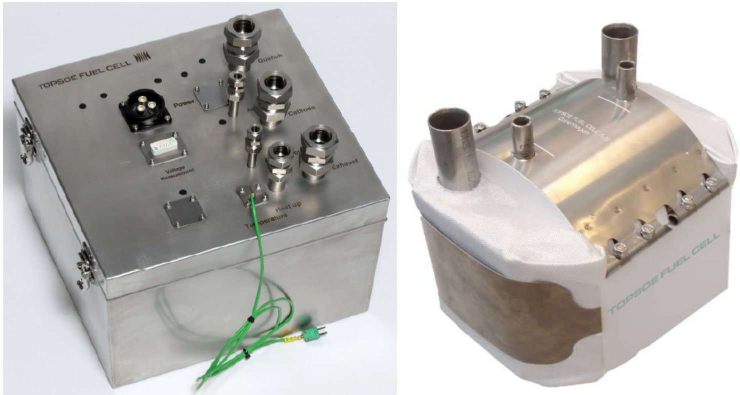

Figure 38. *a) Topsøe PowerCore. b) 3 kW light-weight stack from 2009 for APU applications. [Source: Topsøe Fuel Cell, Proceedings of Fuel Cell Seminar 2011]*

Convion/Wärtsilä are located in Finland where they carry out fuel cell development activities. The main target is to develop and commercialize 50 kW and larger SOFC products for distributed power generation markets. Wärtsilä have built and validated several 20 and 50 kW power units for natural gas, biogas and marine applications. In early 2012 Wärtsilä began restructuring the current fuel cell development program into a new company outside the Wärtsilä Corporation structure. In autumn 2012 Convion Ltd. was established as an independent company with the intention of taking over the Wärtsilä FC program and continuing the SOFC system development towards commercialization.

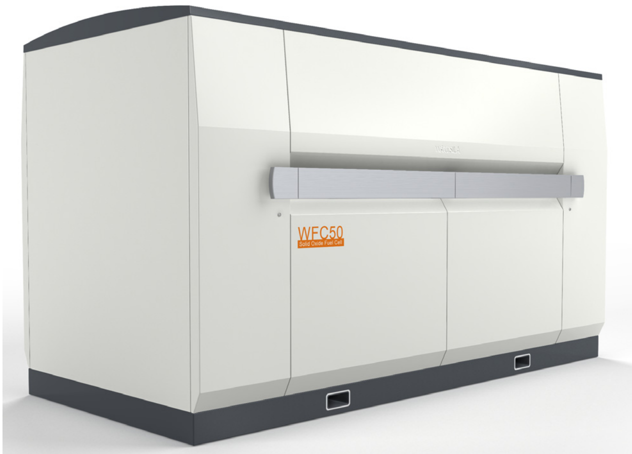

Figure 39. *Wärtsilä WFC50 mkII SOFC prototype unit; electrical efficiency (LHV) 53%, overall efficiency 69%, thermal output 17 kW, size 160 x 350 x 205 cm^3, noise level < 65 dBA, CO_2 < 0.36 g/kWh, NOx < 2 ppm. [source: Convion/Wärtsilä, Tekes Stationary Fuel Cells Espoo Workshop, 2011]*

Japan

Kyocera was established in 1959 in Kyoto as the Kyoto Ceramics Co. It produces an innovative concept of segmented planar, anode-supported SOFC cells which operate at between 700 and 750 °C.
Japan has launched a major deployment campaign of micro-CHP systems, which are named 'ENE-FARM', based on both PEFC (polymer electrolyte fuel cell) and SOFC technology. Already well over 20,000 ENE-FARMS have been installed since 2009. Currently Kyocera is the only company supplying stacks to the systems based on SOFC, though competitors TOTO and NGK may introduce their stacks to the market soon.

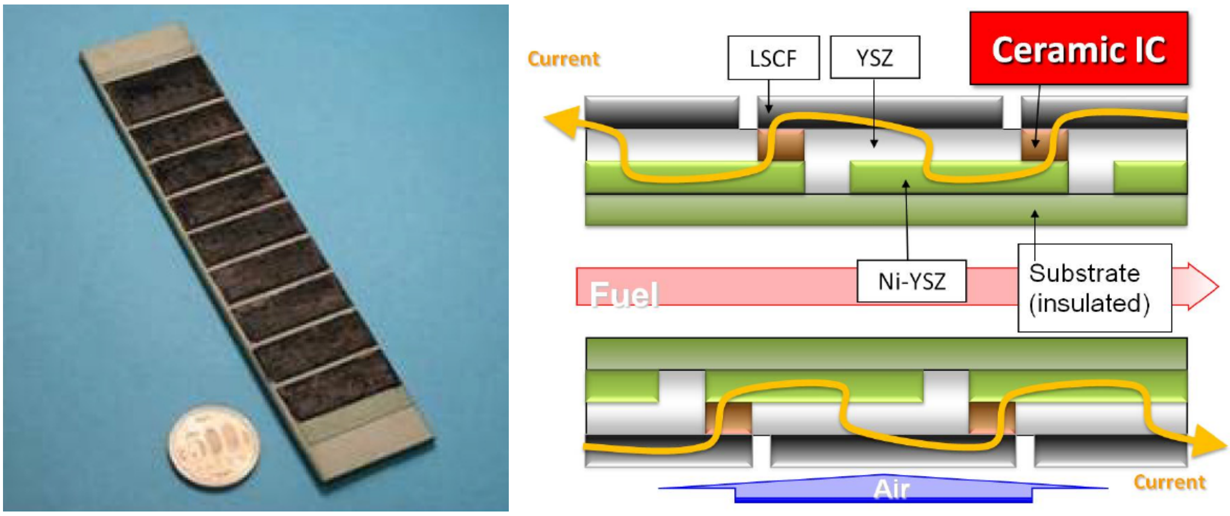

Figure 40. *Kyocera's cell design.*
[source: Kyocera, Proceedings of "Piero Lunghi" European Fuel Cell Conference 2011]

In close collaboration with Osaka Gas, Aisin Seiki, Chofu Seisakusho and Toyota, the 'ENE-Farm Type S', fed with utility natural gas, was completed in 2011, achieving a power generation efficiency of 46.5% (LHV), and an overall efficiency of 90% (LHV). The SOFC system includes a heating unit, to optimally utilize the high-temperature heat exhausted during power generation, which fills a small storage tank of 90 litres with hot water, as well as a high-efficiency latent heat recovery type unit for the back-up boiler. The micro-CHP system is environmentally and economically optimized, and avoids annual CO_2 emissions by approximately 1.9 tons while also reducing annual energy costs by about $ 909 compared to ordinary gas-powered hot-water supply and heating units. Within the co-development agreement, Kyocera produces the stack; Aisin the generation units with the cell stack incorporated into it; Chofu the hot-water supply and heating unit using exhausted heat. Osaka Gas commenced sales of the system on April 27, 2012 (only to the Japanese market) at the standard price of $ 32,926 (see Table 1).
Kyocera works shoulder-to-shoulder with the energy company JX Nippon Oil & Energy too, under the banner of ENEOS Celltech Co., Ltd. ENEOS was co-created in 2008 by JX NOE in partnership with Sanyo Electric – it is the system designer/manufacturer integrator and distributor. From JX NOE's background in the oil industry it developed the natural gas reforming technology used in the product too. Their ENE-FARM is a 700 W_{el} SOFC system which was introduced in November 2011. Around 300 units have been installed and ENEOS is anticipating further growth as SOFCs become more established in the Japanese scheme. The successful release of another SOFC-type ENE-FARM is a firm indication of an increasing interest and increasing demand for SOFC products in Japan.

JX NOE has announced plans to start selling its residential SOFC unit in Germany as from 2015. In June 2012 a partnership was signed with the Centre for Fuel Cell Technology (ZBT), an affiliate of the University of Duisberg-Essen, to evaluate the suitability of the system operating under German conditions, particularly with regard to gas quality. Alongside this activity JX NOE will explore other markets. By 2015 JX NOE hopes global production volumes will have driven the cost of the system down to a quarter of current levels, to around $ 6,150, making them competitive without subsidies.

ENE-FARM RESIDENTIAL FUEL CELL CHP		
Selling date: April 27, 2012		
Basic Function	Rated power output	700 W
	Power output range	0 ~ 700 W
	Power generation efficiency	46.5% (LHV)
	Overall efficiency	90% (LHV)
	Operation temperature range	-5 ~ 40 °C
	Start-up time	~ 130 min
	Operation time	24 hrs continuous
	Hot-water tank capacity	90 litres
	Hot-Water Temperature	~ 70 °C
	Installation	outdoor
	Voltage	100 – 200 V
Dimensions	Power Generating Unit	563 W × 900 H × 302 D (mm)
	Hot-Water Supply and Heating Unit using Exhausted Heat	740 W × 1,760 H × 310 D (mm)
Weight	Power Generating Unit	92 kg
	Hot-Water storage Unit	94kg (184 @ full capacity)
Installation Space		Approx. 1.9 m^2 (Approx. 1.6 m^2 with side exhaust gas cover)
Maintenance Service Period		10 years
Standard Price (incl. taxes and excl. installation cost)		¥2,751,000

Table 1. *ENE-Farm Type S (SOFC-based) for residential fuel cell CHP specifications.*
[Source: Kyocera, Nippon Oil & Energy, www.global.kyocera.com]

Mitsubishi Heavy Industries (MHI) was established in 1914 and is a multinational engineering, electrical equipment and electronics company headquartered in Tokyo.

MHI has been involved in the field of high temperature fuel cells since the 1990s. In 1998, in cooperation with Electric Power Development Co. they produced a pressurized SOFC module which operated for 7000 hours and had a maximum power output of 21 kW. In 2004 MHI succeeded in the first domestic operation of a combined-cycle system combining SOFC and a micro gas turbine, with a confirmed generation of 75 kW at Mitsubishi's Nagasaki Shipyard & Machinery Works. As a result of its performance, in 2007 they decided to scale up the system to 200 kW, with a maximum power output of 229 kW and an electric efficiency of 52%. In 2009, MHI achieved an operation time of 3000 hours with this system, the longest so far in Japan. From this point forward, MHI has continued to increase the reliability and to further reduce the unit size, tying these qualities to the practical development of utility-size generation systems. Indeed, MHI is demonstrating a 250 kW coupled SOFC-microturbine in a triple combined cycle system which also generates steam to power a steam turbine.

Figure 41. *Mitsubishi's 200 kW coupled SOFC-microturbine system.*
[Source: MHI, Proceedings of Fuel Cell Seminar 2011]

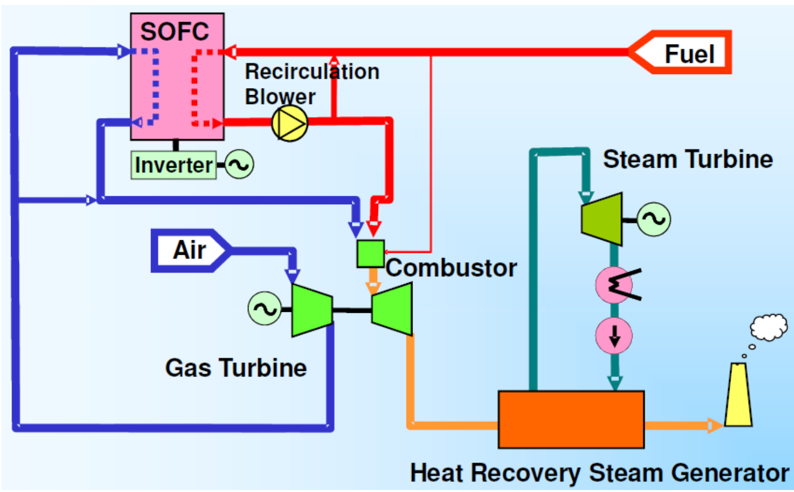

Figure 42. *Mitsubishi is developing a SOFC-turbine triple combined cycle system.*
[Source: MHI, Proceedings of Fuel Cell Seminar 2011]

Mitsubishi uses a mono-block layer built (MOLB) type of cell. This is a planar cell constructed of a ceramic substrate made up of anode, electrolyte and cathode (so-called generation membrane), dimpled in three dimensions and manufactured on an uneven surface and an interconnector that connects the generation membranes in series, and acts as a gas seal on the cell end.
MHI presented the first MOLB type SOFC cogeneration system in Japan at the World Fair held in Aichi in 2005, with a planar SOFC achieving a maximum output of 30 kilowatt through 100 percent internal reforming for the first time. Currently, the target is to further improve the fuel cell output, and research is proceeding.

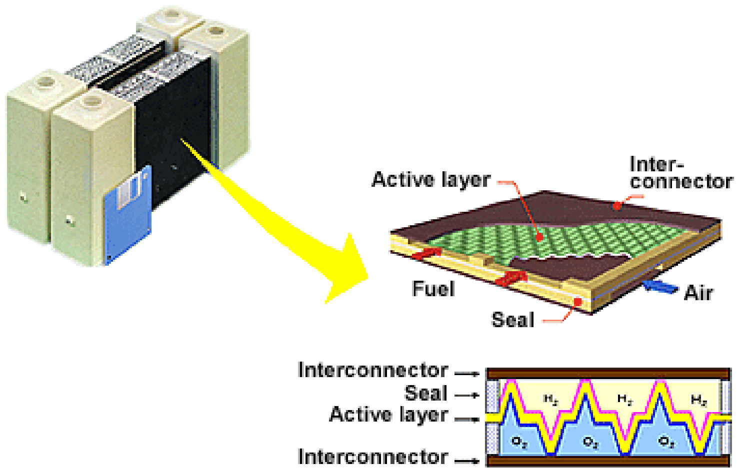

Figure 43. *MOLB Type SOFC Structural Diagram.*
[Source: MHI, www.mhi.co.jp/en]

Australia

Ceramic Fuel Cells Limited (CFCL) was formed in 1992 as a spin-off from the Australian Government Research Institute due to the fundamental research by the Australian Commonwealth Scientific and Industrial Research. CFCL is today a world leader in this technology. The company manufactures and markets planar SOFC anode-supported technology systems for small-scale cogeneration. It has its headquarters in Australia, the powder production facility in the UK and the stack manufacturing line in Germany.

In 2009 CFCL launched their star product for residential applications: 'BlueGen', a 1.5 kW_{el} planar anode supported SOFC-based cogeneration unit fed with natural gas. Since 2010 several units have been tested worldwide, with proven electrical efficiencies of up to 60% (unbeaten by any technology) and a maximum total efficiency of 85%. The electrochemical heart of the BlueGen is called Gennex. This is the high-temperature module where the main conversion of fuel to power takes place, integrating steam reforming of the natural gas, electrochemical conversion to electricity and heat, and heat management. Auxiliary condensing boilers or heat pumps can be integrated into the Bluegen, supplying enough hot water for residential purposes. BlueGen operates at ambient temperatures between 1 and 45 °C and inlet air from -20 °C to +45 °C, emits low noise and weighs about 200 kg, so that it can be placed inside the home or outside if protected from the most extreme winter colds. Start-up time is 25 hours, so that it is most suited for steady-state, base load operation. The ordinary maintenance intervals are 12 months or more, depending on conditions, for replacement of desulphuriser, air and water filters. As with the other manufacturers, CFCL monitors and can manage the operation of each BlueGen system remotely through an Ethernet connection.

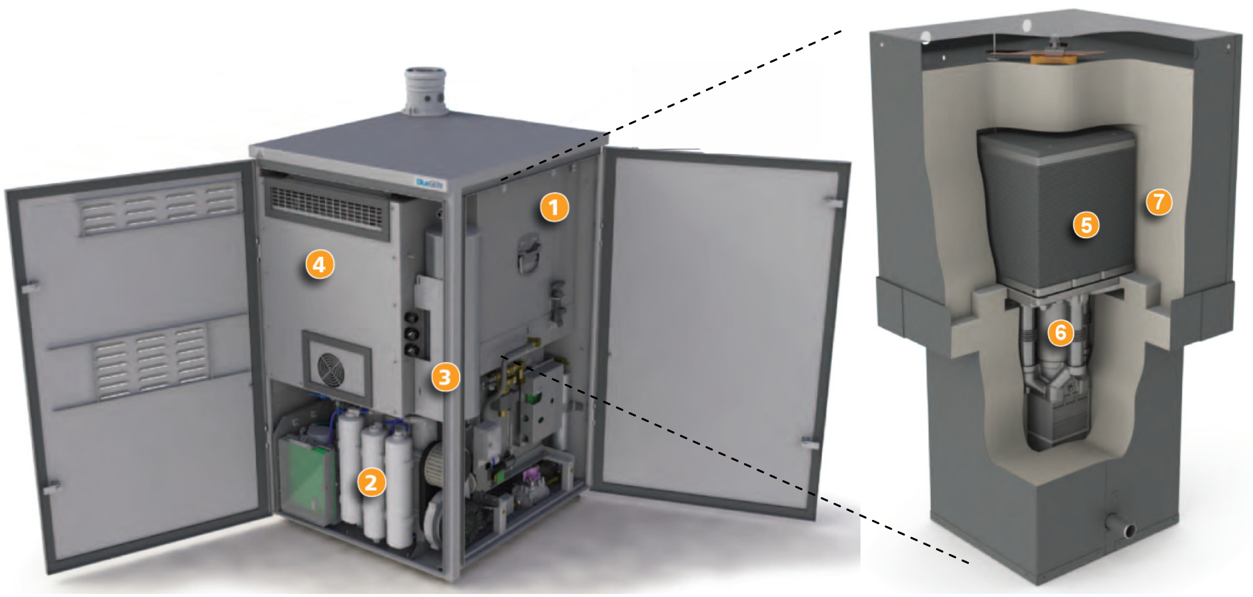

Figure 44. *a) The BlueGen microCHP generator: stack (1), water treatment and gas cleaning systems (2, 3), power conditioning system (4), and b) the Gennex SOFC module: fuel cells stack (5), steam generator, burner, fuel & air heat exchangers (6), high temperature insulation (7).*
[source: CFCL, www.cfcl.com]

CFCL received an order in November 2011 of 105 units of SOFC-CHP from UK's power and gas utility E.ON. The scope is to demonstrate domestic fuel cells in the United Kingdom. It is expected that 100.000 units will be delivered in the next 6 years as part of the post-demonstration agreement.

CFCL'S design uses low-cost widely available materials. The anode support is produced with YSZ, and the anode is nickel oxide. The electrolyte consists of a thin YSZ membrane, whilst the cathode is produced with strontium doped lanthanum manganite. The first CFCL prototypes were based on cells with circular geometry but subsequent optimization activities have led to a square shape, stacked in a 2 x 2 configuration, which has brought their system to reach exceptional performances. The planar design is better suited for high volume mass production, using existing ceramic manufacturing technology. It also allows more flexibility in stack geometry and smaller stack sizes, making it best suited for domestic applications.

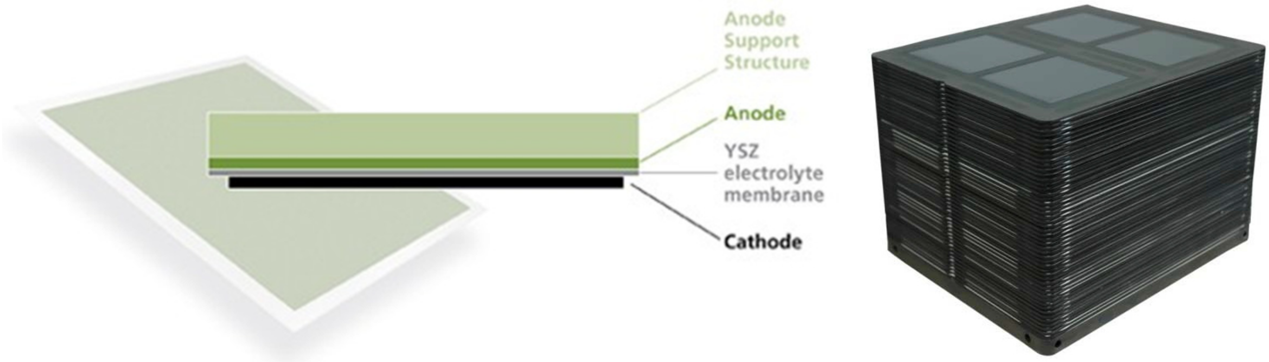

Figure 45. *Geometry of CFCL's anode-supported sofc and 2 x 2 stack.*
[sources: CFCL, www.cfcl.com, Proceedings of IEA Meeting 2011]

Among CFCL's current technological priorities are to cut costs through engineering changes and the extension of stack life span. Commercially speaking, CFCL is driving towards rapid expansion in the major markets for natural-gas fed micro-CHP in the United States, China, India, Brazil.

Figure 46. *BlueGens installed in March 2012 as retrofit of a Commercial building in Adelaide*
(over 7 tonnes of carbon saved in first 3 months).
[source: CFCL, Clean Power for Global Markets Shareholder Update 2012]

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