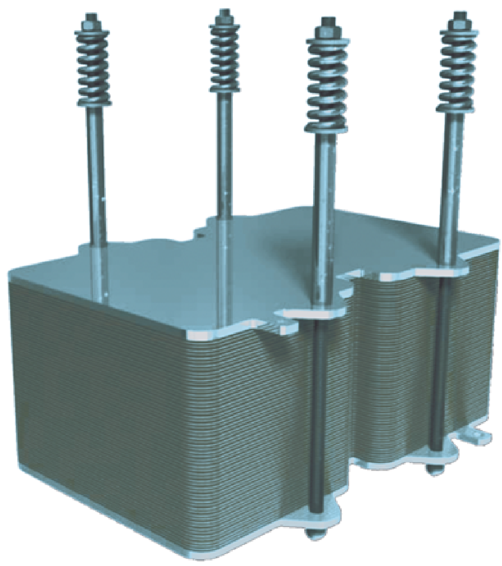
NELLHI



A new all-European technology
for clean, efficient power

Layman's Report

2017

A project supported by the Fuel Cells and Hydrogen Joint Undertaking

NELLHI: A new all-European technology for clean, efficient power

Final Layman's project report for the European project "New all-European high-performance stack: design for mass production" (NELLHI), funded under the 7th Framework Programme of the European Union, supported by the Fuel Cells and Hydrogen Joint Undertaking (FCH JU) under Grant Agreement 621227.

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THE ENERGY UNION AND THE NEED FOR EFFICIENT ENERGY

Accelerating the transition to a low-carbon, competitive economy is both an urgent necessity and a tremendous opportunity for Europe. It is a central challenge of our time. Failure may put our welfare at stake. Success would open unprecedented economic opportunities and new avenues to prosperity, welfare and growth. **Energy efficiency is the great, invisible source of energy** that drives creativity, sustainability and economic independence: it is the energy that is saved, the primary source that isn't consumed, and the trigger to smarter solutions for industry, transport and buildings. Europe's businesses are ahead in many world markets – where competition from global competitors is growing – and European scientists and innovators are pushing the frontiers of knowledge at the service of this inexhaustible energy resource.

The transition to a low-carbon, energy-efficient and climate-resilient economy will certainly require a more decentralised, open system with the involvement of all society. The energy system has traditionally been marked by the dominance of large companies, incumbents and large-scale, centralised technological projects. But in the future the consumer has to be at the centre of the energy system: demanding competitive low-carbon solutions; participating as producer and manager of decentralised energy networks; acting as an investor, through decentralised platforms; and driving change through user innovation. More involved citizens take greater responsibility for their own and the EU's energy security.

The European Union is committed to the mission described above through pursuit of the so-called **Energy Union**, foreseeing a growing integration of European Member States in terms of energy supply, exchange and utilization, embracing 5 dimensions:

- Energy security
- A comprehensive, free internal market for energy
- Energy efficiency
- Decarbonization of energy
- Pushing European competitiveness through research and innovation

What Solid Oxide Fuel Cells – SOFC – can do

Solid oxide fuel cells (SOFC) are a cutting-edge technology for converting the **chemical energy** in hydro-carbon fuels, of both fossil and renewable origin, **directly to electrical power and heat**, avoiding the inefficient and polluting stage of combustion, by means of an electrochemical reaction.

The SOFC is the most efficient device available for power generation: 60% net electrical efficiency for a small, 1 kW system fed with natural gas has already been achieved, and 70% is close at reach, which is double the efficiency of the most efficient combustion engines of the same size and with less than a tenth of the harmful emissions produced by burning any fuel.

And **what is more**, the SOFC can be reversed to work as an electrical power storage system, allowing to capture excess renewable power (for example generated by wind turbines or solar PV panels) in the form of chemical energy: in other words, regenerating a fuel for future use, **sustaining the energy cycle**.

The SOFC is a high-tech solution, integrating cutting-edge chemistry, material science, engineering, process control and manufacturing, all fields where Europe is at the forefront of development. The **NELLHI project** shows how SOFC technology can engage audacious, knowledge-based enterprises and forward-looking multinationals to **drive European competitiveness** in high value-added, strategic supply chains such as **providing clean, cost-effective and smart energy to the end users of tomorrow**.

THE SOFC BASIC PRINCIPLES

SOFC technology has these crucial advantages over conventional power trains, such as combustion engines:

- high efficiency, also at small scale
- insignificant NOx, SOx and particulate emissions, reduced CO2 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 to drive the electrical generator.

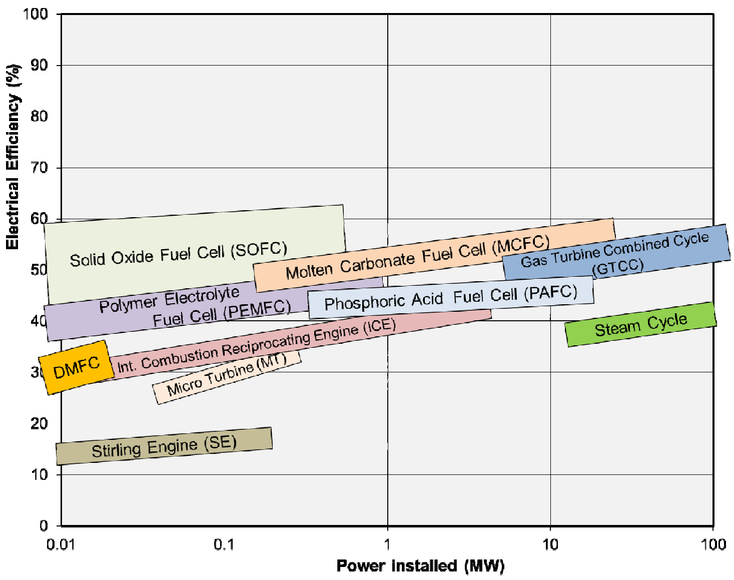


Figure 1. *Comparison of combustion-based system and fuel cell efficiencies vs. power installed (ICE = internal combustion engine, GTCC = gas-steam turbine combined cycle, IGCC = integrated gasification combined cycle, PEFC = polymer electrolyte fuel cell, PAFC = phosphoric acid fuel cell, MCFC = molten 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 currently 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). Furthermore, the SOFC efficiency is unique in being practically independent of scale, allowing to create modular or virtual power plants, where many small-scale systems – for example installed at people's homes – can be combined and considered as a flexible and highly efficient contributor to energy security and grid stability.

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 sup-plier, 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.

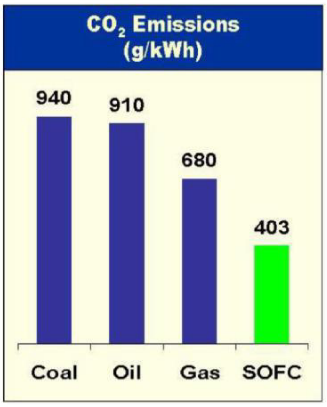


Figure 2. *Comparison of CO_2 emissions between combustion-based systems and a natural gas-fed SOFC [source: Acumentrics, www.acumentrics.com]*

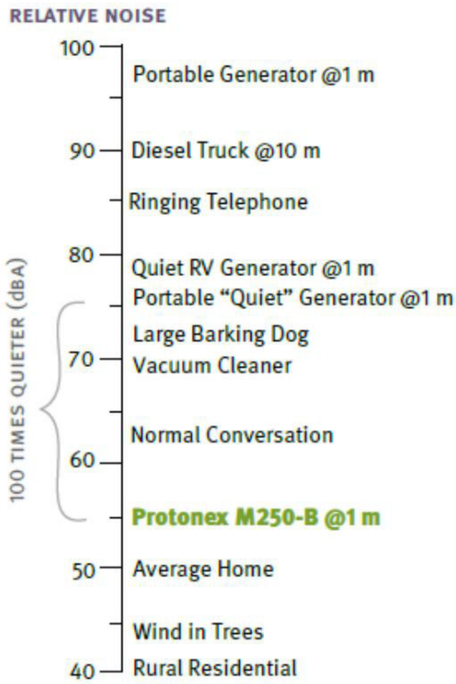


Figure 3. *Noise and vibration emissions from a small FC system allow you to hear yourself speak [source: Protonex, www.protonex.com]*

Silent operation

Electrochemical conversion of the fuel forgoes 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.

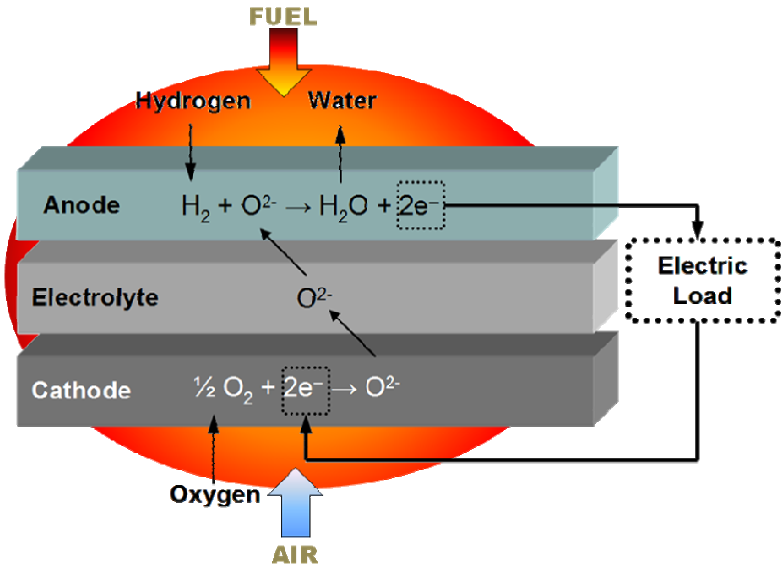


Figure 4. *How the SOFC generates high-efficiency power and heat from fuel and air*

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.

Stationary small-scale combined heat and power

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 5.

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.

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.

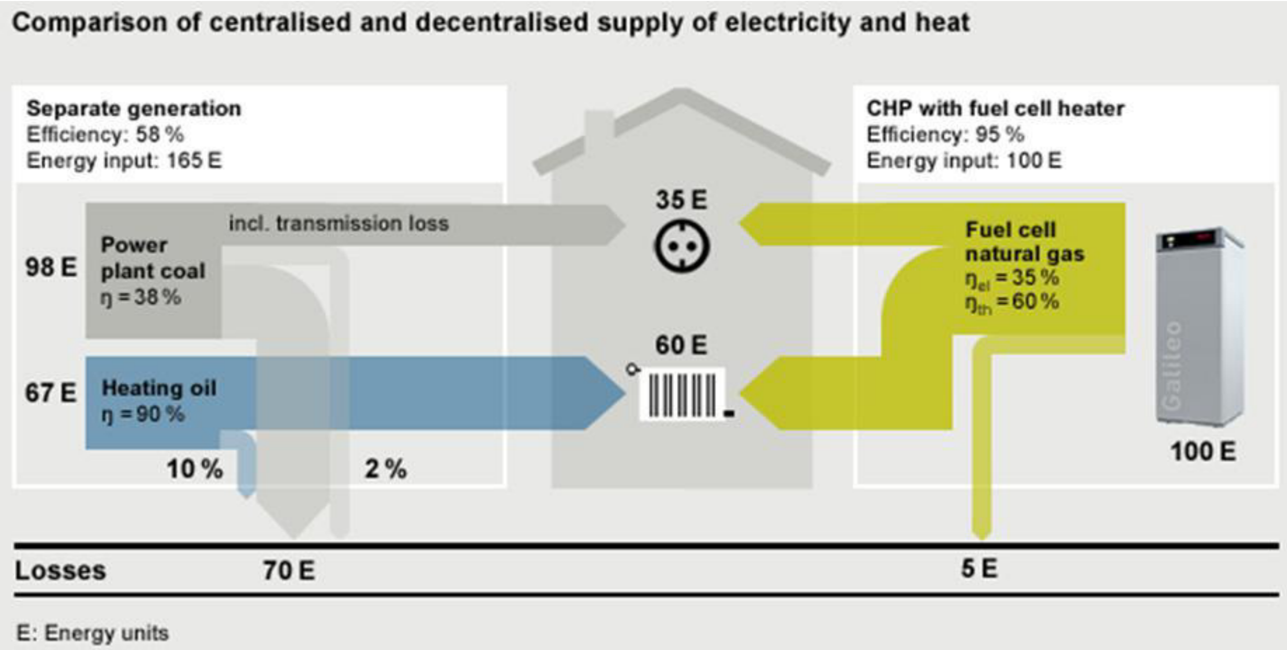


Figure 5. *Comparison of overall primary energy consumption between centralized supply or on-the-spot micro-CHP, for given household power and heat requirements [source: Hexis AG, www.hexis.com]*

Furthermore, putting together SOFC modules to power scales of around 50-100 kW, and thanks to their ability to work on biogas and other residual fuels, SOFCs can be used effectively for the recuperation of energy from waste streams in the food and agriculture industry and making municipal waste-water treatment cleaner and more efficient. In Europe alone, waste-water treatment plants serving 20.000 people (corresponding to roughly 30 kW SOFC power) have huge potential, with 2.5-7 billion m^3 per year of biogas that could generate 1-2.5 GW of power using SOFC, that can largely be used on-site, with great savings on the plant's electricity bill.

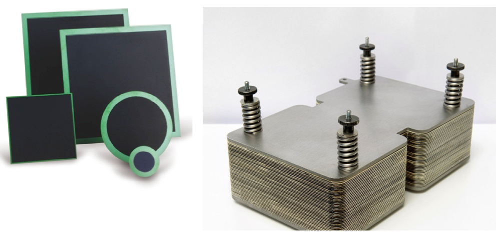
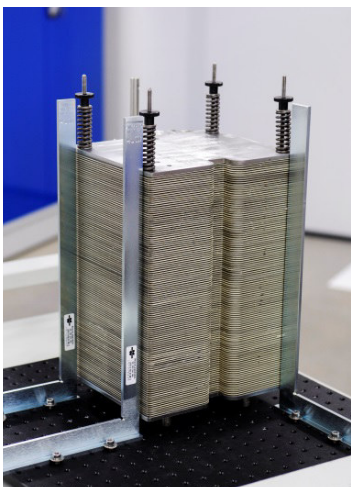
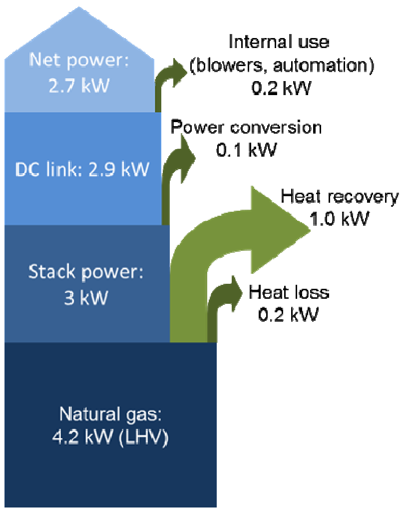


Figure 6. *Stacking single SOFC cells generates the power desired. On the far right, a diagram showing the energy flow through an Elcogen SOFC system: 64% electrical efficiency and 24% heat recovery*





THE NELLHI PROJECT

NELLHI has been a collaborative effort to produce a new, all-European, high-performance SOFC stack, designed for mass production. The project received 1.6 million euro funding from the Fuel Cells and Hydrogen Joint Undertaking (FCH JU) in support of the expected costs amounting to just under € 3 million. It started on the 1st of May 2014 and lasted until 30 April 2017.

The NELLHI Team

Putting together specialized industries focusing each on a specific, key component or aspect of the finalized stack, and supporting their development process with leading research centres across Europe, has been the results-oriented approach of the NELLHI initiative.

Elcogen AS is a developer and manufacturer of intermediate-temperature Solid Oxide Fuel Cells (SOFC) based on proprietary materials and technological solutions. Elcogen AS was established in 2001 and is located in Estonia, engaging numerous scientists and engineers. The company works closely with leading Estonian and Finnish research institutes.

The **Flexitallic** Group is the international leader in the manufacture and supply of high quality, high value, industrial static sealing solutions. Flexitallic has 37 manufacturing locations comprised of owned plants, ventures, and manufacturing licensees in 15 countries to meet worldwide demand for all kinds of gaskets and sealing solutions, leading innovation in terms of sealing materials and the design of novel gaskets.

Figure 7. *Gowning for Elcogen operators during cell production process*

Borit's core competence is their proprietary hydroforming technology, for producing complex designs of metal bipolar plates for various global manufacturers of fuel cells as well as electrolysers. As a small and flexible enterprise Borit is dedicated to support customers and partners through the complete product development cycle. Borit has also developed high-speed laser welding processes to join formed parts into interconnect assembly.

Sandvik Materials Technology is one of the world's leading producers and distributors of tube, strip, wire and bar for many advanced applications. The products are made of stainless and high-alloy steels and of special alloys, mainly intended for those industries that make high demands on reliability in operation, corrosion resistance and mechanical properties. Sandvik has 20 production plants in 13 countries all over the world apart from the main facilities in Sandviken, Sweden. It employs about 7,300 people, of which 3,500 are at the main plants in Sandviken.

Elcogen Oy, based in Finland, was established by Elcogen AS (Estonia) in 2009. The company is focusing on commercialization of solid oxide fuel cell stack technologies for stationary applications. **VTT** Technical Research Centre of Finland has been the key partner for Elcogen Oy in terms of stack development and characterization. **CUTEC**, the institute for environmental technology in Clausthal, Germany, contributed to Elcogen's stack characterization in NELLHI. **ENEA**, the Italian agency for new technologies, energy and sustainable development, provided support in the development of cells and interconnects, and coordinated the joint effort.

WHAT WE HAVE ACHIEVED

Highly performing cells

Elcogen AS has led the development of single cell manufacturing processes, improving material formulations and modernizing equipment to achieve the lowest scrap rates possible maintaining the highest standards for cell quality, performance and reliability.

Fuel cells make up the heart of the NELLHI technology. Overall system performance depends strongly on the cells' electrochemical properties. Thus, one of the crucial steps was to develop an optimal microstructure using particular materials helping to decrease the operational temperature to 650 ˚C – a more manageable temperature than the conventional 750-800°C – with remarkable electrochemical efficiency.

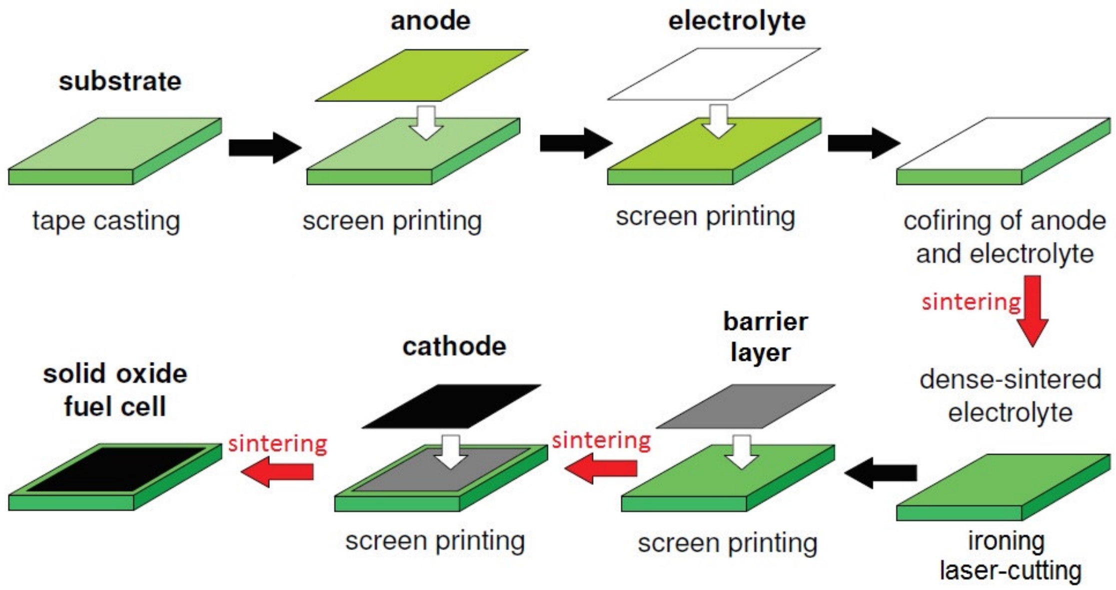


Figure 8. *Solid oxide fuel cell manufacturing process in NELLHI.*

There are a lot of different ways to produce a solid oxide fuel cell. Elcogen AS has chosen a highly reproducible route allowing to reduce final cell price and at the same time to increase manufacturing rate.

In order to increase the efficiency per cell and to decrease the final price of the SOFC stack, Elcogen's cell dimensions were increased from 100×100 mm^2 to 120×120 mm^2, which allowed to increase the effective electroactive surface by almost 50%. This was followed by overall manufacturing process optimization, raising electrochemical performance of the newly sized cells and giving less than 5% of production scrap. ENEA supported the cell development process by conceiving and realizing a highly innovative set-up for locally resolved, in-depth, in-operando electrochemical characterization of the produced cells.

Cost-effective, robust interconnects

Elcogen Oy, Sandvik and Borit worked together to improve the design of the interconnect, or bipolar plate, a crucial component for the assembly of cells to high-performance stacks and power modules. Sandvik, with support from VTT and ENEA, has gone through extensive material combinations (of substrate and coating) with in-depth analysis of their behaviour in stack-relevant environment, which has led to radical new insights (self-healing properties as well as unforeseen diffusion phenomena). Taking the pre-coated, rolled coils of interconnect material from Sandvik's manufacturing line, Borit has optimised its Hydrogate forming process for larger throughputs, achieving over 99% yield rates.

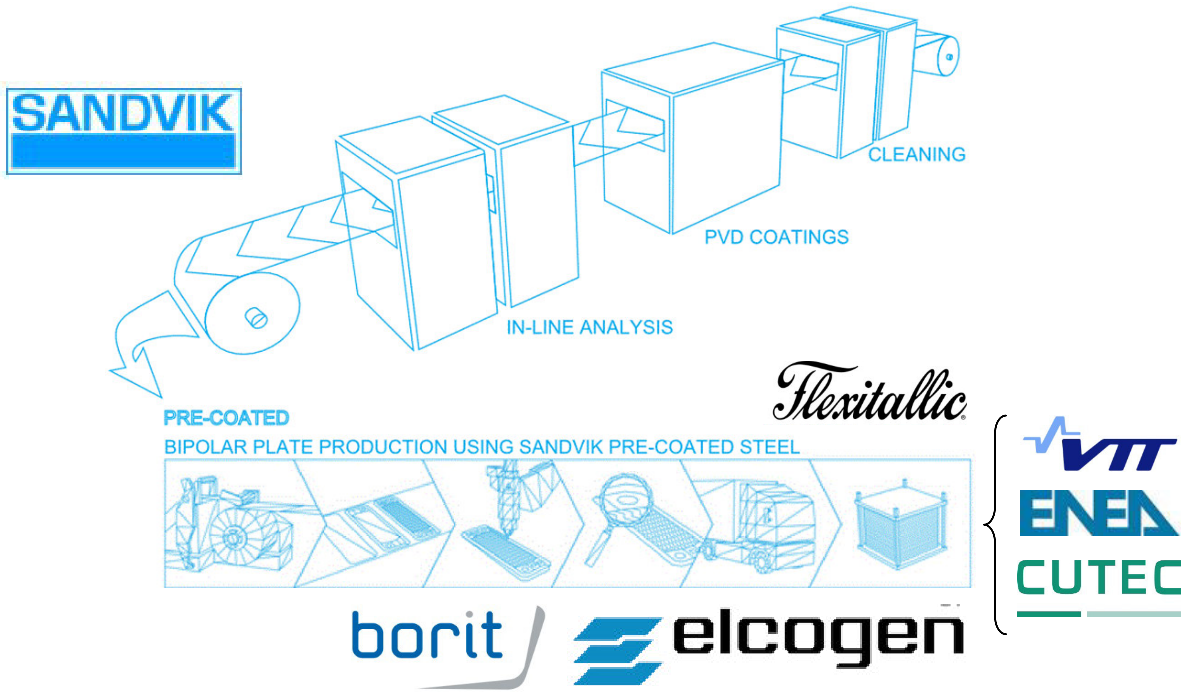


Figure 9. *The interconnect/bipolar plate manufacturing process in NELLHI: preparation and coating of the steel (SANDVIK), shaping, cutting and welding (BORIT) on ELCOGEN OY's design, assembly with cells (ELCOGEN AS) and gaskets (FLEXITALLIC). The cells and stack are continuously validated by VTT, ENEA and CUTEC.*

Game-changing seals

Between each interconnect layer in a fuel cell stack is a seal, also known as a gasket, which prevents the fuel gases (oxygen and hydrogen) and the exhaust gas (steam) leaking out. A fuel cell stack can contain between 30 to over 100 seals depending on design and power output. Whilst sealing is the primary function of the gasket it also serves as an electrical isolator to prevent an electrical short circuit between the layers; as a mechanical spacer to accommodate the variability in tolerances of other components in the stack and crucially it must be manufactured from an inert material so that the sensitive chemistry of the fuel cell is not compromised.

Due to the various competing functions of the seal there are very few materials that can be used. Very specialist glass is sometimes used, however this requires the fuel cell to have very controlled start-up and shutdown processes, and makes it unable to respond well to repeated on-off cycles. Fundamentally glass seals must have very tightly controlled gaps between the layers.

The Flexitallic design is a compression seal, therefore a small load must be applied to the stack to compress the gasket and create a seal but this overcomes the problems inherent with traditional glass sealing systems. The requirements of this project needed a gasket with improved sealing performance at a much lower compressive load and an ability to demonstrate maintained seal performance over multiple thermal cycles. It was also necessary

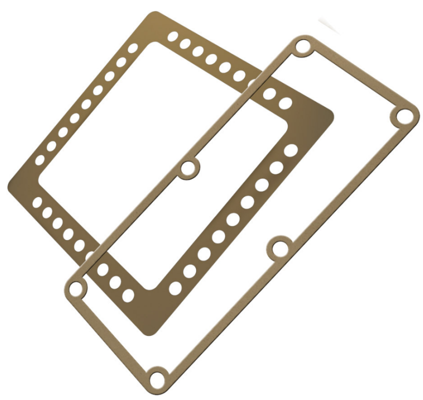


Figure 10. *Gaskets that resist to high temperatures, extreme atmospheres and are compliant to tolerances: the Flexitallic Thermiculite® 870*

for the improved material to be compatible with a surface glass treatment previously jointly developed by VTT and Flexitallic. The high compliance required by the gasket allows for tolerances in other components to be relaxed therefore helping to reduce the overall costs of the stack.

Over the course of the NELLHI project Flexitallic developed an entirely new, ultra-high compressibility seal which has met the project requirements and enabled the stack to be sealed with a low bolting force and accommodate the thermal cycle requirements. This was achieved by reformulating the Flexitallic standard SOFC gasket product, Thermiculite® 866, through optimising the particle sizes and proportions of the ingredients. The basic manufacturing method was maintained however the specific parameters have been altered to achieve the finished material. The base material is then cut to the required shape to fit the design of the stack.
This new formulation, patented during the NELLHI project under the name CL87, has been successfully tested in collaboration with VTT to assess different application means, including glass coating and design optimisation to reduce the number of manufacturing steps required as well as improve manageability of the finished, cut seals. In addition to the achievement of the technical requirements for sealing, thanks to the NELLHI project this material has now been launched as a commercially available grade of material, Thermiculite® 870.

A new, low-cost, prime power module

Elcogen Oy has put together all the developments above in the high-performance stack that gives the name to the project. This entailed much design optimisation of interconnects and seals, assembly and conditioning procedures, stack characterization protocol definitions and testing, deconvolution of the ultimate, compound stack performance into the contributions of each component. Elcogen Oy was supported by CUTEC and VTT in this evaluation, and numerous stacks were tested in several conditions, yielding comprehensive data for the assessment of the progress achieved in the successive stack generations.
This has led to some outstanding results, see figure 11, showing over 70% stack gross efficiency (methane to electricity, not counting system losses) versus the high achievable single-pass fuel utilization (a), and the excellent resilience of the stack towards load cycles, ramping the power several times a day without changes in performance (b).

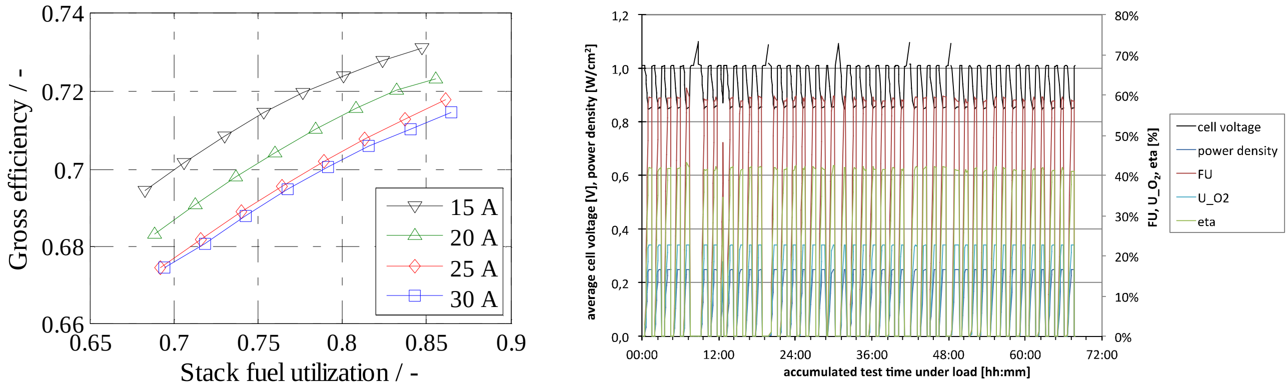


***Figure 11**. NELLHI stack testing, showing gross efficiency vs fuel utilization at different currents (a), and stack response to multiple, accelerated full load cycles*

The outcome of the project can therefore be considered fully in line with expectations, providing a stack ready for integration in any clean power-generating system and implementation in the energy market.

Consolidation of an all-European SOFC supply chain

Through the NELLHI cooperation, the project partners have been able to consolidate their positions as key component manufacturers in the European arena of SOFC technology. The focused activity in NELLHI has allowed bottlenecks in design and production processes to surface and be dealt with. Unexpected issues related to contamination through carrier belts, material diffusion and interaction mechanisms, leak testing and surface corrosion have all been identified and resolved in a plenary approach. This joint undertaking has led to a highly committed team of players that are fully aware of the interconnectedness of the development process and assembly of the highly sophisticated components that make up the NELLHI SOFC stack.

This constructive collaboration has been acknowledged and awarded through the follow-up projects that take up the knowledge built up in NELLHI to carry on the improvement, integration and scale-up of the achievements in NELLHI:

- INNOSOFC (FCH JU Grant agreement 671403, www.innosofc.eu): Adoption of NELLHI stack development for integration in a 50 kWe combined heat and power generation system
- qSOFC (FCH JU Grant agreement 735160, www.qsofc.eu): Mass-manufacturing and quality assurance of NELLHI stack components
- DEMOSOFC (FCH JU Grant agreement 671470, www.demosofc.eu) Implementation of a 50 kWe SOFC system with NELLHI-based stacks fed with biogas from a municipal waste water-treatment plant.

Thus, a healthy and thriving supply chain has been established for an all-European, high-tech product with great potential to contribute to the establishment of the Energy Union.

The NELLHI Team wishes you happy, clean power generation!

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