ComSos

Co-funded by the European Commission within the H2020 Programme
the Fuel Cells and Hydrogen 2 Joint Undertaking
Grant Agreement no: 779481
2018-01-01 - 2022-06-30 (42 months)

Deliverable 2.6
Report on Large Scale Manufacturing Strategy for Solid Oxide Fuel Cells (SOFC)

Revision 1.0
Preparation date 2019-12-18 (M24)
Due date 2019-12-31 (M24)
Lead contractor.......................... Sunfire GmbH

Author:

Markus Münch .... Sunfire GmbH

This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking under the European Union's Horizon 2020 research and innovation program under grant agreement No 779481.

Dissemination level		
PU	Public	X
CO	Confidential, only for members of the consortium (including the Commission Services)	

Table of contents

1. Preface ... 3

2. Typical Applications for Solid Oxide Cells ... 5

3. General Design and Function of SOFC Systems ... 6

4. Proprietary Components ... 7
- 4.1 Fuel Cell and Stack Design ... 7
  - 4.1.1 Solid Oxide Cell Types ... 7
  - 4.1.2 Fuel Cell Stack Designs ... 8
  - 4.1.3 Macro Stack / Stack Unit Approach ... 8
- 4.2 Manufacturing and Assembly ... 10
  - 4.2.1 Solid Oxide Cells ... 10
  - 4.2.2 Repetitive Elements and Stack Formation ... 10
  - 4.2.3 Stack integration to Hotbox ... 11

5. Common Components ... 11
- 5.1 Desulphurisation ... 11
- 5.2 Exhaust Gas Heat Exchanger ... 11
- 5.3 Catalysts ... 11
- 5.4 Power Electronics ... 12
- 5.5 Water Treatment ... 12
- 5.6 Other Cold Box components ... 12

6. Life Cycle Management ... 12

7. Harmonisation of international standards ... 12

8. Summarise ... 13

9. Literature ... 13

1. PREFACE

Fuel cells convert fuels (chemical energy) into electricity and heat electro-chemically in a highly efficient way without combustion. The fuel cell principle itself was discovered in the 19th century but found its initial commercial use at NASA's Apollo and Gemini missions in the 1960ies [1].

Proton Exchange Membrane (PEM) fuel cells are most common today. Power generation systems utilizing this type of fuel cell are well known for the use as back-up power generators or power converter in fuel cell cars, forklifts and other mobile equipment. These electro-chemical converters have reached a high technological maturity with its industrialization during the last years but need a high-quality hydrogen supply and logistic infrastructure that is only available in industrialized countries.

Direct methanol fuel cells (DMFC) have occupied the niche of small portable, military and off-grid power supply applications, molten carbonate fuel cells (MCFC) are established in the multi-hundred to megawatt power generation range.

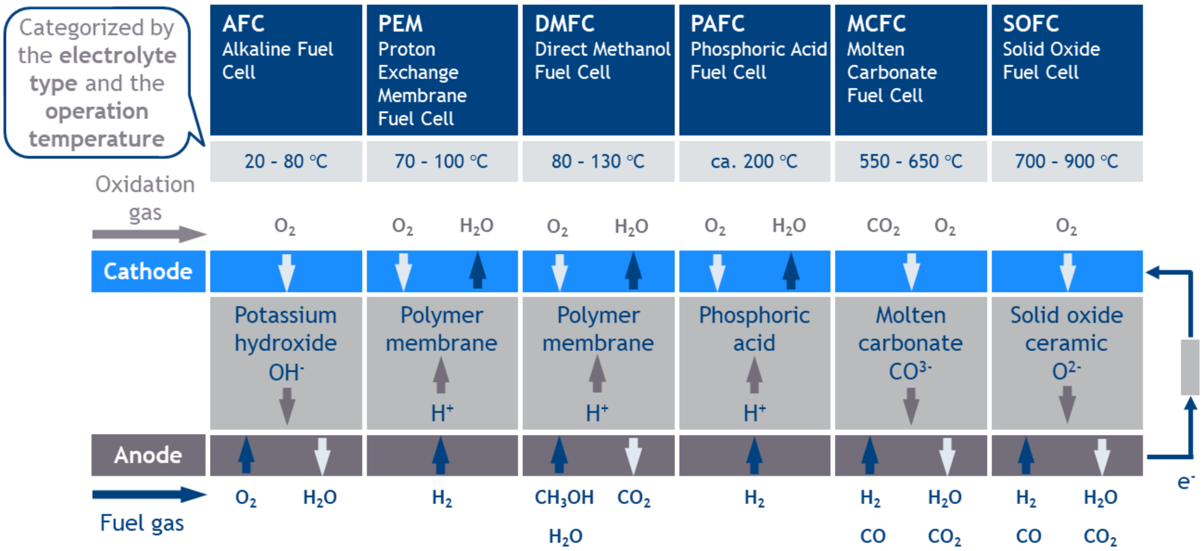

Fig. 1: Overview on different types of fuel cells

Solid Oxide fuel cells (SOFC) in particular are high temperature fuel cells, which are operated at temperatures between 700 and 900 °C. Similar to other fuel cell technologies, they are composed of an anode and a cathode separated by an electrolyte (see Figure 1). This principle is similar to batteries with the difference that fuel cells are continuously fueled. For SOFC units, this electrolyte is a solid ceramic, such as zirconium oxide stabilized with yttrium oxide. Oxygen respectively air is supplied to the cathode. The ceramic electrolyte conducts oxygen ions from the cathode to the anode whilst electrons are emitted to an external circuit in order to produce electricity. At the anode, the oxygen ions combine with the fuel to produce water and carbon dioxide in an exothermic chemical reaction that generates heat additionally. Unlike conventional PEM fuel cells, the solid oxide fuel cells run on Hydrogen AND Hydrocarbons such as natural gas or Propane, due to the Oxygen ions diffuse trough the ceramic membrane and are available for electrochemical oxidation.

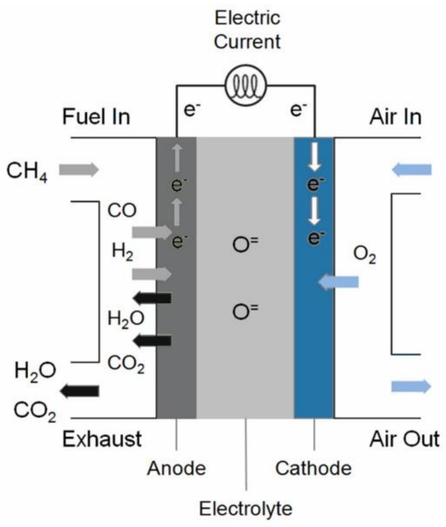

Fig. 2: Principle of Energy Conversion inside the Solid Oxide Fuel Cell

SOFC with its high electrical efficiencies between 30 and 60 % can be found in pilot and demonstration projects since 2010. In some applications like micro-CHP, industrial off-grid generation or co-generation for commercial buildings it could be established as a niche product in small quantities at relatively high cost. The development and sustainable market demonstration and introduction of SOFC technology is supported with funding of several projects within the EU Horizon 2020 program by the Fuel Cells and Hydrogen Joint Undertaking 2 (FCH-JU), e.g. in the frame of ComSos, PACE and RoRePower projects.

Industrialization and large scale manufacturing were recognised as key factor to reduce manufacturing cost and to make SOFC competitive to other, conventional technologies. The key advantage that have to be highlighted are:

- the high electrical conversion efficiencies as well as total energy utilization in combined heat-power generation
- CO_2 emission reduction, specifically related to reduced primary energy effort [2]
- availability of high temperature heat for existing building
- minimization of local emissions, with no particles, no NO_X, no CO
- capability of direct conversion of carbon
- use of non-toxic, non-critical and no expensive materials for fuel cell stacks
- capability of use of H2 blended natural gas and “Opportunity Fuels” like syngas or biogas from any other sources locally available for power generation and heat integration

It is expected, that the cost-down potential of SOFC follows the cost learning curves in a similar measure like other energy technologies during their development to maturity as e.g. batteries or photovoltaics. Here could be observed cost reductions of 18 to 25 % each time when the cumulated output was doubled [3,4].

This paper shall illustrate the ways to largescale manufacturing along the different steps of the value chain, also related to specific SOFC materials, components and technologies that are the proprietary knowledge in the different companies that own this knowledge and IP

2. Typical Applications for Solid Oxide Cells

Solid Oxide Fuel Cells were identified will find its easiest market entry as energy converter for

a) µCHP solutions in the range of 0.5…1.5 kW_{el}
b) off-grid power generation in the range of 200…3000 W_{el}
c) Mini-CHP in the range of 5…50 kW_{el}.

While the µCHP solutions with an addressed power range that is suitable for one or two family homes profit from high price levels behind the meters at end user side, the advantages in off-grid generation are the absence of lubricants and significant longer maintenance intervals compared to internal combustion engines (ICE). That predestines the use of this units in industrial applications in very remote regions, e.g. in telecommunication, security, oil & gas industry.

Mini-CHP solutions are in a range, where ICE are on a heightened cost level compared to large scale engine CHP in the Megawatt range. It must be taken into account that the cost for scaling fuel cells increases more directly proportional with the power output while their increase at ICE based generator sets is significantly disproportionately. The higher electrical efficiency of such SOFC miniCHP with more than 50 % makes it highly attractive for use cases with continuous high electricity and moderate heat demand, e.g. like hospitals, residences for retired people, hotels etc.

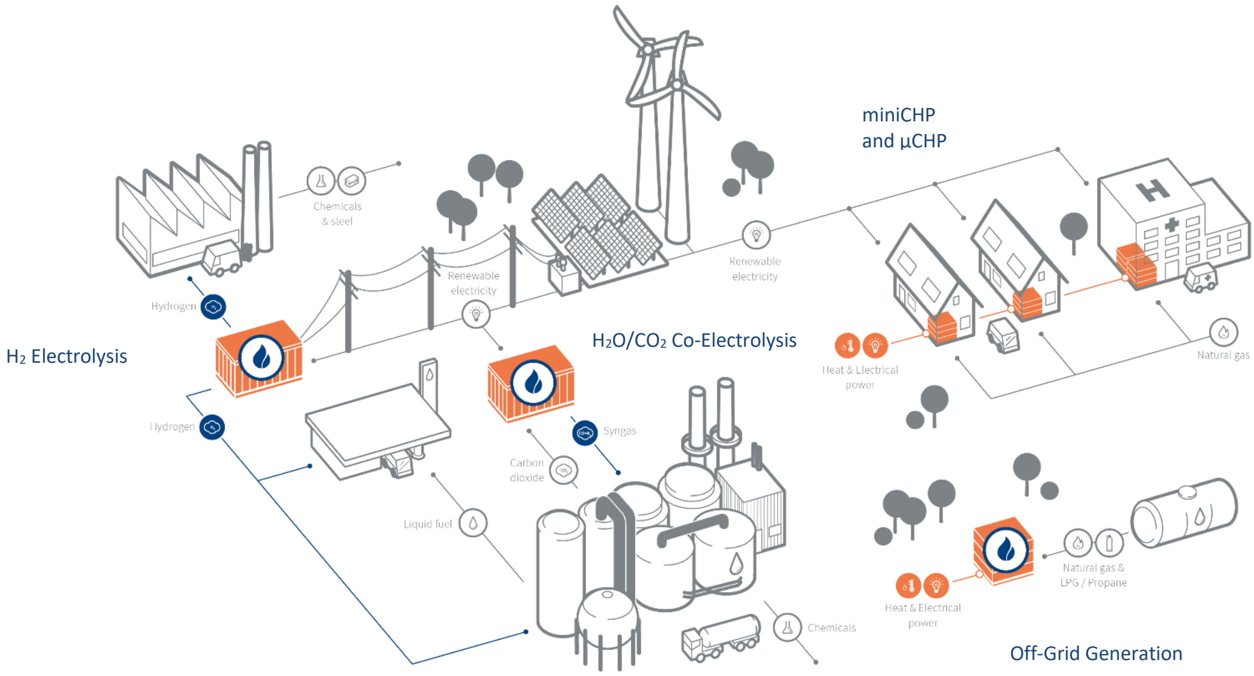

Fig. 3: Application Fields of Solid Oxide Cells (Source: Sunfire)

Besides the use as Solid Oxide Fuel Cell for the oxidation of fuel, in most cases the same cell and stack design with modified and specifically optimised integration can be used for electrolysis (chemical reduction) as well when operated in reverse mode as Solid Oxide Electrolysis Cell (SOEC). To close today's lack of technologies to convert renewable electricity to storable chemical energy in the form of Hydrogen or synthetic fuels by Solid Oxide Cells is a further strategic path with a significant influence to mass manufacturing. The SOFC technology will benefit directly by the effects of volume scaling and technological improvements of SOEC that is currently in preparation and expected within the next five years.

SOEC technology is able to reach more than 80 % efficiency in electrolysis, compared to < 70 % in conventional PEM or alkaline electrolysers, when steam can be used instead of water. This advantage promotes the use of SOEC in large industrial applications with high hydrogen demand like refineries or steel manufacturing. The capability of direct and simultaneous conversion of CO_2 and Steam to Syngas, a mixture of H_2 and CO, that can be used or fuel syntheses as needed for CO_2-neutreal operation of sea vessels or aircrafts was demonstrated by Sunfire in 2019. Both, Hydrogen and synthetic fuels are potential Gigawatt markets for Solid Oxide Cell technology that will support cost reduction by massive scaling for this separate business.

Combined units that were developed in the past and that had the capability to work bi-directional as a Reversible Solid Oxide Cell (RSOC) in fuel cell as well as in electrolyser mode, could not demonstrate the technical and commercial performance as expected due to significant differences in the power density between both modes and the peripheral components.

3. General Design and Function of SOFC Systems

The general design of a complete SOFC system is illustrated in Fig.4 and can be divided in two parts: The Hotbox includes all components that are operated on a temperature level of above 500 °C and includes a thermal insulation to enable a self-sustaining operation. The Coldbox consists of the outer enclosure, the components to control the educts and energy flow.

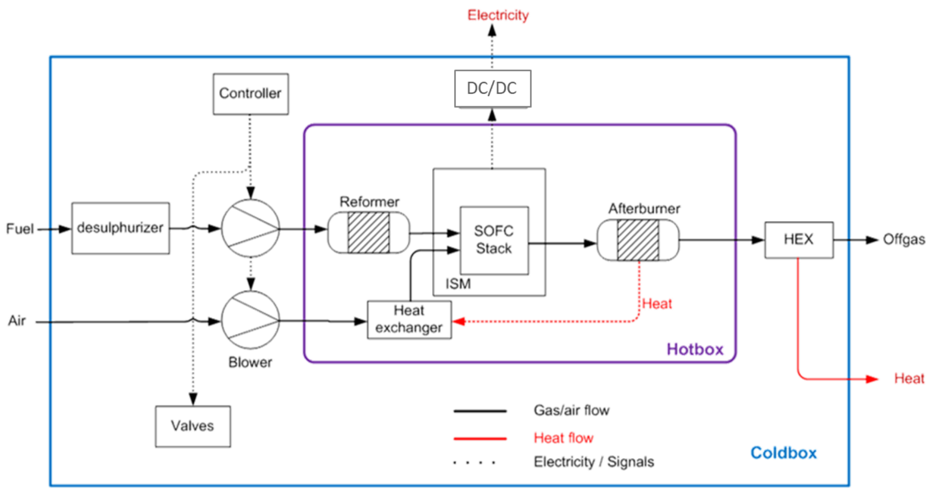

Fig. 4: Simplified layout of a Solid Oxide Fuel Cell generator, consisting of Hotbox and Coldbox (Source: Sunfire GmbH)

The fuel gas has to be desulphurised. In this stage, the natural Sulphur compounds and added odorants will be removed to avoid the poisoning of the fuel cell. The following reformer converts a large portion of fuel to H_2 and CO. A rest will remain as Hydrocarbons in the educt stream called reformate that will be led to the anode and oxidized within the fuel cell stack at a high share. In parallel, preheated air will be made available at the cathode side of the fuel cell stack. The anode and cathode off-gases will be mixed and oxidized afterwards in the afterburner. The generated heat will be recuperated for the preheating of the educts. An additional heat exchanger allows the extraction and utilization of the waste heat of the fuel cell system for external demand.

4. Proprietary Components

Solid oxide cells have a need for specific materials and specific technologies as well. It is the originary target of the manufacturers to keep these under their control. In general, there are established industrial processes that can be used for the manufacturing of components. Since the raw material cost are on a relatively low level, the specific processing has a strong impact to cycle time and throughput as well as cost. Specific investments to optimized equipment and tooling is only worthwhile in the case of larger quantities. Furthermore, a technology in a less mature development status has still a strong perspective and potential for innovations and improvements. A high grade of automation bears the risk that these can not implemented easily to mass manufacturing without significant investments and changes. Results and improvements from ongoing R&D need to be implemented into production after intensive risk assessment and approval. Finally, the industrialization of SOFC manufacturing needs to be a compromise between throughput and cost optimization as well as flexibility in regard of design and process changes.

4.1 Fuel Cell and Stack Design

4.1.1 Solid Oxide Cell Types

There are different solid oxide cell technologies established today. These are basing on different development paths. Most common are anode-supported cells (ASC) and electrolyte-supported cells (ESC), but metal supported cells (MSC) play also a role in the emerging market. Tubular cells look back on a long history, but are relegated to a niche existence in low-power systems today.

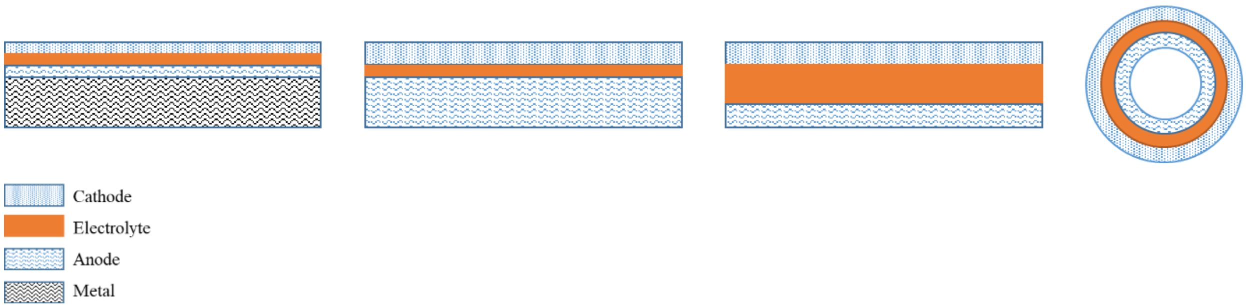

Fig. 5: The common SOFC types (left to right): metal supported cell (MSC), anode supported cell (ASC), electrolyte supported cell (ESC) and tubular cell

Typically, an increase of unit size reduces handling and assembly steps and allows higher cycle times in manufacturing. Today’s size of electrolytes are optimized to planarity, best match in regard of thermomechanical interaction to interfacing materials and components as well as minimum scrap rate. The track record related to field experience with the actual technology is not negligible, so that manufacturers are very carefully to implement changes into their products and technologies.

The planar fuel cells itselves have a low thickness and need supporting structures to be connected electrically and to enable a controlled educt flow and distribution to the cells’ surface. There are used carrier plates to meet these requirements usually.

4.1.2 Fuel Cell Stack Designs

A single fuel cell supplies only a low amount of energy, which is why a so-called fuel cell stack is used in SOFC systems. A number of fuel cells are stacked on top of each other using carrier plates and joined under the influence of heat and pressure in this way together to a suitable assembly to generate sufficient energy for use in residential and commercial buildings.

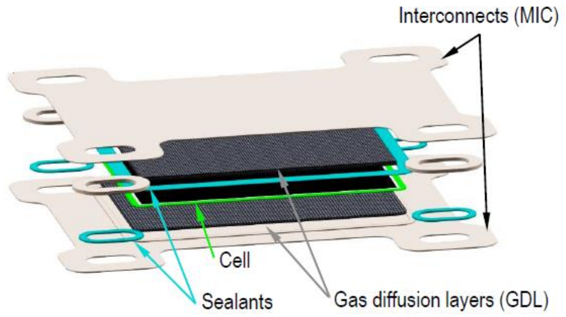

Fig. 6: Planar cells have to be integrated between carrier plates (Source: SolidPower)

The plates or so called repetitive elements can carry one or several fuel cells that lead to parallelising or a more serial scale-up according to the manufacturers decision.

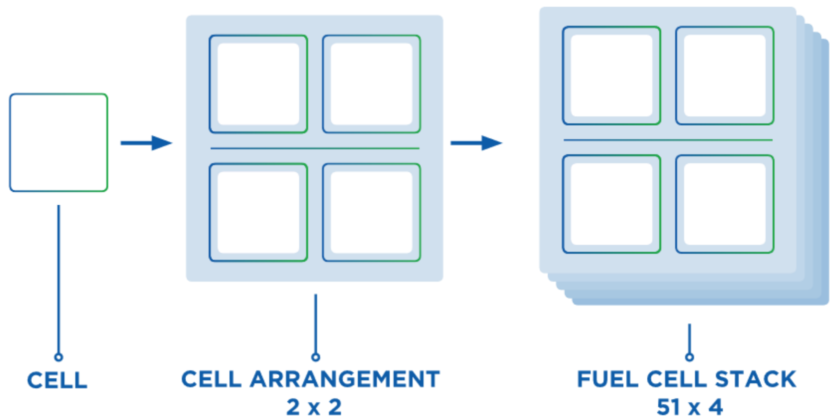

Fig. 7: Parallelising of fuel cells on carrier plates (Source: SolidPower)

Based on the variety of technologies, the manufacturing of solid oxide cells and its assemblies to repetitive units and stacks are the proprietary core knowledge of the manufacturer. The following explanations and discussions base on the technologies and materials described in [5].

4.1.3 Macro Stack / Stack Unit Approach

As fuel cell repetition units will be assembled to stacks, the most simple way to increase power output is the increase of the number of cells per stack respectively stack height. But there are given limitations by mechanical stability, flow and temperature homogeneity and manufacturing capabilities that restrict this approach in the single-digit Kilowatt range.

Higher power output requires a parallelizing of solid oxid cells accordingly. There are two approaches:

1) Parallelising on repetition unit level as exhibited in 4.1
2) Parallelising of stacks to stack units on a common mechanical carrier

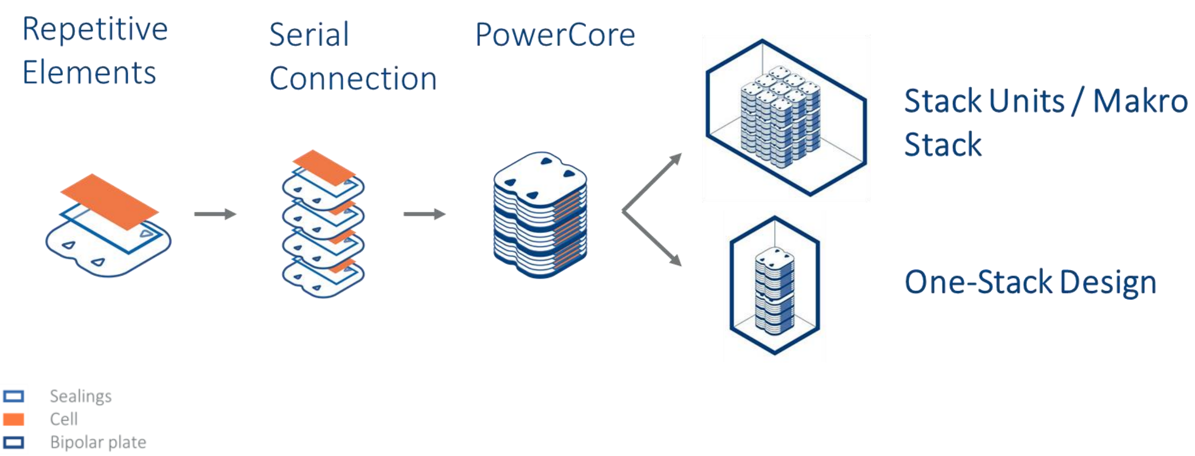

Fig. 8: From fuel cell to complete stack assemblies (Source: Sunfire)

So-called stack units can be used for further scaling to different power classes in modular approaches up to several hundred Kilowatt. That allows to use solid oxide cell technology in different scales. These macro stacks with a standardized design are an effective way to enable qualified system designers and integrators to develop and establish specific solutions according to customer demand. Early movers with high potential for increased stack demands in a mid to long-term perspective can be found in the field of clean power supply of passenger ships, specifically cruise ships and ferries that are under strong political pressure to reduce their emissions and pollutions. A further push to rise the demand of solid oxide cell based solutions is their use in industrial steam electrolysers for refineries and steel manufacturing with demands in the multi hundred Megawatt range.

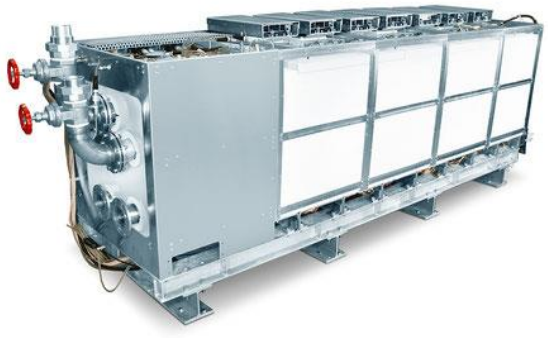

Fig. 9: Multi-Stack assembly with common media supply interfaces designed for sea vessels [6]

4.2 Manufacturing and Assembly

Large-scale manufacturing and assembly requires different levels of scaling and automation along the value chain. Table 1 demonstrates the dependency on quantity in regard of automation and specific tooling and equipment. Since an automation of cell manufacturing is a reasonable approach for quantities above 5000 pieces, it is only worth to think about manufacturing lines for complete devices from an annual assembly volume of more than 500 units per year. Automation goes along with the integration of quality measurement steps and reduction of influence of manual handling. Process oriented failure mode and effect analysis and continuous improvement processes allow to lift manufacturing quality to a significant higher level.

Quantities for 25 kW CHP units

Fuel Cell CHP units p.a.	Macro Stacks	Stacks	Solid Oxide Cells
1	1	48	1.440
10	10	480	14.400
50	50	2.400	72.000
100	100	4.800	144.000
500	500	24.000	720.000
1.000	1.000	48.000	1.440.000

Table 1: Different levels of automation along the value chain at the example of a 25 kW CHP unit: red - manual, blue - semi-automated, green - automated, orange - intermittent assembly line (Source: Sunfire)

Under these presumptions, industrialisation will focus currently on the manufacturing processes of cells and stacks as the main components with a significant cost share and in mid-term on highly optimised assembly with design-to-manufacturing for macro stacks and fuel cell units.

4.2.1 Solid Oxide Cells

The solid oxide cell electrolytes are usually tape casted with several screen or stencil-printed and sintered electrode layers. Tape casting as a continuous process can be scaled-up easily at non-proportional costs by increasing the width. Printing in step & repeat technology as well as the use of continuous furnaces allow an effective scaling but require continuous operation.

4.2.2 Repetitive Elements and Stack Formation

Besides the cells, the main material of the repetitive elements is high-temperature ferritic stainless steel. The single parts can be punched and embossed automatically in progressive dies and welded automatially with laser. Coating and sintering of protective layers are to industrialise easily with available industrial technologies and equipment. The assembly of parts and the completion with glass sealings have to be processed on specifically designed assembly automates. The stack joining processes are propriatary at manufacturers side but can be scaled by cooperations with special purpose machinery manufacturers.

4.2.3 Stack integration to Hotbox

Hotbox components have to be designed according to the specific product in regard of fuel gas, chemical input, electrical and themal power output and the type of stack and its specific interfaces. For an economical, efficient and self-sustainable operation, an individual design is required that also takes into account the changes in surface resistance and other degradation effectes of fuel cells. Similar to the technological know-how, the design of the hotbox and the knowledge about the operation strategy of solid oxide fuel cells is propriatary by the manufacturers too and will not be disclosed.

Besides the stack, a reformer, an afterburner and a recuperating heat exchanger are the main components of the hotbox that needs a high temperature insulation additionally. The components are usually made from ferritic high temperature steel and are combined in some cases to a so-called fuel processor [7].

Basic technologies are punching, cutting, bending and welding. The industrialisation of such welded assemblies that include interfaces to hot and cold educts that induce high thermo-mechanical stress is a challanging task. Special tooling and manufacturing equipment will be usually only economical if significant numbers of standardised assemblies can be manufactured.

5. Common Components

Outside the hotbox, mainly commercially available components are used that are not core technology of the fuel cell manufacturers. In some cases, specific adaption to fuel cell requirements is necessary. Otherwise, the use of commonly available components can be supported by the adaption of the fuel cell design and interfaces.

The fuel cell manufacturers will become more attractive as customers for heating appliance components manufacturers with increasing quantities. Their components are usually on an affordable cost level and come with approvals that are necessary when it has to be integrated to products.

5.1 Desulphurisation

Commercially available desulphurization solutions were developed for e.g. Biogas and petrochemical industry and adapted to fuel cell requirements. Increasing demand will enable to manufacture larger batches and reduction of costs significantly.

5.2 Exhaust Gas Heat Exchanger

Exhaust gas heat exchangers from heating appliances can be used for fuel cell based CHP units in some cases. There are different vendors with a wide range of products active in the market that offer further potential to cost reduction.

5.3 Catalysts

Catalysts are in use for steam reforming of fuel gas. These are commercially available from established manufacturers and have similar coatings and structures as used in automotive application.

5.4 Power Electronics

Power conversion equipment for fuel cells has to fulfil some specific requirements. There are no commercial products available that are specifically matched to the current-voltage characteristics of fuel cells due to the absence of markets that are able to absorb quantities of more than 10,000 units per year that is a critical number for mass production of electronic equipment. Since power conversion equipment is available for photovoltaics, battery storage and other industrial equipment, it is a potential path to adapt the fuel cells voltage level and interfaces to such existing devices.

5.5 Water Treatment

Some fuel cell device designs require water supply and de-ionisation for steam reforming. Suitable water treatment processes are reverse osmosis or the use of desalination cartridges. The preferred approach will mainly depend on fuel cell size and water demand. Both technologies are well established and available as commercial solution at different scalings.

Alternatively, vapor for steam reforming can also be made available by utilization of a share of the water-rich anode off-gas that will be recirculated to the steam reformer. In this case, a proprietary and device specific design is required and needs to be integrated.

5.6 Other Cold Box components

Valves, mass flow controller, blowers, ignition and flame monitoring components are standard industrial parts that find their applications also in fuel cells.

6. Life Cycle Management

Manufacturing of fuel cells requires a high energetic effort, mainly related to high temperature steel demand for hotbox components as exhibited for example in life cycle studies [8]. Significant advantages related to emissions and consumption of energy and resources compared to natural gas combined cycle plants were identified.

Fuel cell systems need a qualified dismantling at the end of service life. Electrical components, thermal insulation and scrap metal have to be separated. Since there is a large portion of steel available, this is a valuable part of recyclable material with high rates of reuse after processing. Steel made from scrap reduces CO_2 emissions to 50 % compared to primary steel production [9]. Noble metal catalysts can be recycled separately, in the existing value chain of automotive catalyst material recycling.

7. Harmonisation of international standards

Standards and regulations related to solid oxid fuel cell products are different related to the intended use and countries. There is the case in Europe, that if the primary purpose of fuel cell is power generation, the harmonised fuel cell standard EN 62282-3-100 has to be applied. For the use as CHP with heat generation as main property, the EN 50465 has to be selected. The both standards define different requirements and normative references for components and materials partially. That impedes the selection and design process massively with direct impact to large scale manufacturing if different regulations needs to be fulfiled. This should be on a strong focus for future normative maintenance

8. Summary

Large scale manufacturing is the common target of all solid oxide cell developing and manufacturing companies as the measure of first choice for reducing costs and to reach the level of competitiveness to competing technologies.

As automation is obviously a constructive strategy as it can be realised on cell and stack level easily, cost achievements on macro stack or fuel cell generator are mainly related to optimisation of assembly and cost-to-manufacturing design approaches that also will result to significant cost reduction. This is specifically valid for units that include large quantities of stacks. The ComSos-related SOFC will benefit from synergy effects in regard of increased stack demands, that is generated as well from Micro-CHP and off-grid fuel cell unit ramp-up as well as from solid oxide electrolyser business, for which is predicted a strong growth rate in mid-term.

Finally, the manufacturers are able to provide competitive solutions with the ComSos-related units. Use cases have to be established and markets to be developed which can adsorb manufacturing volumes of several hundreds, preferably above thousand units per year. The creation of the political framework conditions in the markets with a higher priority of co-generation has to be seen as the main political task related to the sustainable establishment of fuel cells in the national as well as in the EU markets.

9. Literature

[1] M. Warshay and P. R. Prokopius, The Fuel Cell in Space: Yesterday, Today and Tomorrow, NASA Technical Memorandum 102366, September 1989

[2] Roland Berger Strategic Consultants: Advancing Europe's Energy Systems: Stationary Fuel Cells in distributed Generation; Luxembourg 2015

[3] Cost Learning Curve Solar Solar PV module cost learning curve for crystalline silicon and thin-film; found at https://www.irena.org/costs/Charts/Solar-photovoltaic at 17.12.2019

[4] How cheap can energy storage get; found at https://energypost.eu/cheap-can-energy-storage-get-pretty-darn-cheap/ at 17.12.2019

[5] N.N.: Manufacturing Cost Analysis for 1 kW and 5 kW Solid Oxide Fuel Cell for Auxiliary Power Applications; Prepared for: U.S. Department of Energy, Golden Field Office Golden, CO, DOE Contract No. DE-EE0005250, February 7, 2014

[6] https://www.e4ships.de/deutsch/hintergrund/vorg%C3%A4ngerprojekt/

[7] WO2008021719A2: Integrated solid oxide fuel cell and fuel processor

[8] J. Nease, T. A. Adams: Life Cycle Analysis of Bulk-Scale Solid Oxide Fuel Cell Power Plants; Wiley, May 2016

[9] R. Winkelgrund: Recycling-Weltmeister Stahl; Themenpapier Infozentrum Stahl, stahl-online.de