STATUS OF SOEC AND SOFC ACTIVITIES AT SUNFIRE

Dr. Christian Walter
Head of Stack Development & Testing
H2FC Supergen Hydrogen Research Conference 2020
AGENDA

· Our vision
· Company facts
· Sunfires Products for sectoral integration
  · Update on Stack development
  · High temperature fuel cells
    · Sunfire Home
    · Sunfire Remote
  · High temperature electrolyser
    · Sunfire Hylink
  · High temperature Co-electrolyser
    · Sunfire Synlink
· Conclusion
Achieve a zero emission society in transport, industry and energy sectors via electricity based liquids and gases, making renewable energy available wherever and whenever it is needed.
A POWERFUL ORGANISATION
COMPANY FACTS

Knowhow
- ~ 150 Employees in Dresden and Neubrandenburg
- Full value chain from Ceramics, Engineering, Stack + System
  Production, up to Synthesis Processes, Service etc.

Patents
- More than 60 patent families (e.g. »process patent sunfire« WO/2008/014854)

Revenues
- Multi-million Euro Revenues in Global Markets since 2011

Investors

Sunfire Headquarters

2019 GLOBAL CLEANTECH100 COMPANY

National and international awards for innovative and pioneering technology
SUNFIRE INVESTOR PAUL WURTH / SMS GROUP

- Invested 20 M€ in Sunfire series-C round in 2018
- World leading EPC contractor in iron and steel plants
- Clear strategy to go from fossil to renewable
- In-house technology for transition readily available
- Ability to support project financing and de-risk large commercial projects in the range of > 100 MW
- Global presence to support sales and project development
SUNFIRE PRODUCTS IN ACTION WORLDWIDE

Global industry leader in solid oxide technology

- Hundreds of systems installed
- Longest operation in customer applications
- Largest SOC electrolysis installer of the world
PRODUCTS FOR SECTORAL INTEGRATION
SOLID OXIDE CELLS CONVERT...

... Electricity into **Hydrogen (or Syngas)**

- Steam (+CO₂)
- Hydrogen (Syngas*)
- Oxygen

... Fuels and Gases into **Electricity and Heat**

- Fuel
- Oxygen
- CO₂ & H₂O
- Heat
- Electricity

* Syngas (H₂ + CO) is the building block for e-Fuels
SUNFIRE’S SOLID OXIDE CELL TECHNOLOGY

**Characteristics** | **Advantages**
--- | ---
Electrolyte supported, planar cells | High robustness and durability
Sheet metal cassette used as interconnector | Low costs due to industrial production processes
Ceramic glass sealing | Gas-tight sealing
„Open cathode“ | Low pressure drop
THREE CORE USP

· Highest efficiencies leading to lowest total cost of ownership (TCO)

· Direct conversion of carbon molecules to provide clean solutions for the energy transition in all sectors

· Non-toxic, no critical and no expensive materials for easy manufacturing

“When steam can be preferably generated from waste heat sources, such as in steelmaking, high temperature electrolysis is the most efficient technology.”

Prof. Dr.-Ing. Heinz Jörg Fuhrmann, Chief Executive Officer and Chairman of the Executive Board of Salzgitter AG
## SUNFIRE PRODUCT OVERVIEW

| Electrolysers | Sunfire-HyLink | Providing green e-Hydrogen for multiple applications | Hydrogen: 40 Nm³/h · X | + Efficiency (3.7 kWh/Nm³ | 82 %AC,LHV)* | + High flexibility in operation |
|---------------|---------------|------------------------------------------------------|-------------------------|-----------------------------|-----------------------------|
|               | Sunfire-SynLink | Providing green e-Syngas as a platform molecule for e-Fuel and e-Gas production | Syngas: 40 Nm³/h · X | + Efficiency (3.9 kWh/Nm³ | 80 %AC,LHV)* | + Direct syngas production |

<table>
<thead>
<tr>
<th>Fuel Cells</th>
<th>Sunfire-Remote</th>
<th>Providing clean power for remote locations</th>
<th>Power: 400 W to 3.3 kW</th>
<th>+ Robust Design</th>
<th>+ Multiple fuel use (natural gas, LPG, etc.)</th>
<th>+ High proven durability / low maintenance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sunfire-Home</td>
<td>Providing clean power and heat for residential buildings</td>
<td>Power: 750 W Heat: 1,3 kW</td>
<td>+ High overall efficiency (88 %HHV)</td>
<td>+ Easy to integrate into home appliances</td>
<td>+ Low maintenance</td>
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</table>

*on system level
UPDATE ON STACK DEVELOPMENT
LONG TERM SOFC STACK TEST

- Long term test of LSCF cathode in Sunfire-stack
- Degradation value with $11-19 \text{ m}\Omega\text{cm}^2$ comparable/slightly lower than previously used LSM cathode
- Degradation decreasing over time
- No signs of failures (neither delamination nor cell breakages) after
- Test will continue running
- LSCF design available for customers
NEW STACK GENERATION SMK-B240

- New stack generation released in 2019
- Changes were done in cell design, protective coating and various process steps
- Degradation could be decreased from 20 mΩcm²/kh to ~13 mΩcm²/kh
- In addition, Stack costs could also be decreased by ~10 % to 15 %
  ➤ Total KPI € kW⁻¹ h⁻¹ could be decreased by ~40 %
HIGH TEMPERATURE FUEL CELL-PRODUCTS

Home & Remote
Achieve a zero emission society in transport, industry and energy sectors via electricity based liquids and gases, making renewable energy available wherever and whenever it is needed.
CHEMICAL ENERGY TO CLEAN POWER

Sunfire-Home | Sunfire-Remote

- Natural gas
- Propane / LPG

or

Electrical power

Heat optional

optional
Concentration of experience, know-how and manufacturing competence for Sunfire-Home and Sunfire Remote at Sunfire Fuel Cells GmbH from 01/2019

Unique access to knowledge and IP of 3 different system integration approaches for all fuel cell products

BUNDLED SOLID OXIDE FUEL CELL COMPETENCE

- Stack development & manufacturing competence
- System development & manufacturing competence
- System development & manufacturing competence
- System development & manufacturing competence and IP
- System rental fleet

Sunfire Fuel Cells GmbH

SOFC and µCHP knowledge and IP

Vaillant
Clean CHP

Delivering power and heat in a highly efficient way to households also without connection to the public gas grid
DEGRADATION UPDATE FROM FIELD TEST

Data from field test:

• **223 systems** in total
• 2*32 cells per system
• Previous stack technology (lower power density and higher degradation)
• Proven operation **up to 30,000 h** (one system **up to 40,000 h** extended operation at sunfires test bench)
• Average degradation of ~30 mOhmcm²/kh
• 3.6 million operation hours in total

### Operation Time and Units Run

<table>
<thead>
<tr>
<th>Operation time</th>
<th>Units run</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 h to 5,000 h</td>
<td>10</td>
</tr>
<tr>
<td>5,000 h to 10,000 h</td>
<td>16</td>
</tr>
<tr>
<td>10,000 h to 15,000 h</td>
<td>62</td>
</tr>
<tr>
<td>15,000 h to 20,000 h</td>
<td>111</td>
</tr>
<tr>
<td>20,000 h to 25,000 h</td>
<td>31</td>
</tr>
<tr>
<td>25,000 h to 30,000 h</td>
<td>3</td>
</tr>
</tbody>
</table>
Fuel Cell Heating System for European Market

- μCHP-System developed for households and two family houses
- SOFC stack technology developed by Sunfire
- Fuel: propane (LPG) or natural gas
- Dynamical operation with different levels
- Product launched in January, 29th 2020
- More information at: http://www.sunfire-home.de/
Remote power supply in remote areas without access to electricity distribution system.

- Telecommunication
- Remote monitoring & observation equipment
- Cathodic corrosion protection
- Remote block and gate valves
- Pressure-reducing and metering stations
- Large automation and SCADA systems
- Auxiliary equipment
- Shelter & equipment heating
SUNFIRE-REMOTE 400 INSTALLATIONS IN EUROPE
Sunfire-Remote 400

Sunfire-Remote+ 1200 PowerTrailer
- Outsides

Sunfire-Remote+ 1200 PowerTrailer
- Insides

PowerBox configuration
SUNFIRE-REMOTE: MARKET INTRODUCTION

- Available since 2015 (as New Enerday EN400)
- ~ 50 units sold
- Technical update in 2019
- Sunfire-Remote 400 Gen.2 available from Q2/2020
- Sunfire-Remote 750 available from Q3/2020
- Null series and demonstration devices available earlier on request
- Sales & service partnerships with System Integrators pursued
HIGH TEMPERATURE
(CO-)ELECTROLYSIS
Achieve a zero emission society in transport, industry and energy sectors via electricity based liquids and gases, making renewable energy available wherever and whenever it is needed.
Even in scenarios with large increase of direct electrification liquid and gaseous energy carriers remain necessary to cover the global energy needs in 2050.

Sources: IEA, June 2017; World Energy 2014-2050, Political economist, 2014
E-FUELS: A NECESSITY TO TACKLE CLIMATE CHANGE

Anticipated primary-energy consumption of the EU transport sector 10,000 PJ in 2050

- To achieve global CO₂ reduction targets, fossil fuels need to be phased out by 2050
- Hard-to-electrify sector (aviation, ships) will make up 50 % or 5,000 PJ in 2050 with e-Fuels being the most promising technology
- > 300 GW of e-Fuels needed in 2050 (> 10 GW/a from now)
- For e-Fuels to be available in those quantities after 2030, we must start now

Calculation based on dena/LBST

„E-Fuels – The potential of electricity based fuels for low emission transport in the EU“, 2017
POWER-TO-X PRODUCTION PATHWAYS

Renewable Power \[ \begin{align*} \rightarrow & \text{ Electrolysis} \\
\text{ + } & \text{ Renewable Power} \\
\text{ + } & \text{ Electrolysis} \end{align*} \]

Hydrogen

Methane

- Methanation*

- Fischer-Tropsch Synthesis*

- Methanol Synthesis*

- Ammonia Synthesis*

- Exothermic reaction providing steam for e.g. steam electrolysis

Source: dena, Heutige Einsatzgebiete für Power Fuels, 08/2018
e-Hydrogen

Delivering renewable e-Hydrogen for a variety of industrial processes to reduce CO₂ emissions, e.g. carbon-reduced steel via direct reduction
TECHNOLOGY COMPARISON (ELECTRICITY AC TO LHV H₂)

**PEM electrolysis**
- Hydrogen membrane
- Efficiency: 50 – 60 % or 5 - 6 kWh$_{AC}$/Nm³$_{LHV}$
- Low temperature (< 100 °C)
- Flexible operation from part load to full load (0 % - 300 %)

**Alkaline electrolysis**
- Hydroxide membrane
- Efficiency: 50 – 60 % or 5 - 6 kWh$_{AC}$/Nm³$_{LHV}$
- Low temperature (< 100 °C)

**Sunfire-HyLink / Sunfire-SynLink**
- Oxygen membrane (Solid Oxide Cell)
- Efficiency: 82 % or 3.7 kWh$_{AC}$/Nm³$_{LHV}$
- High temperature (850 °C)
- Ability to electrolyse CO₂, most promising economics
E-HYDROGEN COMPARATIVE COST ANALYSIS:

SOEC, Alkaline, PEM

Assumptions (2025 scenario):

- Electricity Costs: 60 €/MWh
- IRR 8 % @ 20 years system lifetime
- Capacity Factor:
  - 90 % (~ 7,880 full load hours)
  - 50 % (~ 4,380 full load hours)

Sunfire electrolysis (SOEC) enables lowest costs compared to legacy technologies.
GrInHy SUMMARY

- 150/30 kW RSOC system
- 40 Nm³/h hydrogen output in EL mode
- FC operation with NG or H₂ → efficiencies about 50%\textsubscript{LHV}
- Efficiency of 82 %\textsubscript{LHV} achieved in SOEC mode
- Integrated into an iron-and-steel works using existing infrastructures
- Providing green hydrogen for downstream processes
GrInHy OPERATION RESULTS

- 13,000 hours operation, about 120,000 Nm³ H₂ produced
- Load varied between 50 % (20 Nm³/h, 80 kWAC) and 113 % (45 Nm³/h, 180 kWAC)
- 20 thermo-cycles and a few hundred load cycles, no safety related incidents
- Average SOC degradation approx. 25 mΩcm²/kh ≈ 0.8 %/kh voltage degradation
Next step: GrInHy2.0 - HYLINK 200

- Focus on electrolysis only
- Up to 1 MW in one container
- Close to market readiness, small series production

In production, will be installed this year at the Salzgitter steel pant

GrInHy: 40 Nm$^3$/h production rate in 20’ container

Sunfire-HyLink 200 (GrInHy2.0): 200 Nm$^3$/h production rate in 40’ container with approx. 50% cost reduction
OUTLOOK: 100 MW SCALE ELECTROLYZERS FOR STEEL INDUSTRY AND REFINERIES

Concept study for SOEC scale up:
- Power requirements at full load = 120 MW → Direct Reduction Plant in the steel industry
- H₂ output at full load = 32,400 Nm³/h
- Cost target: <800 €/KW_{AC}
- CO₂ saving: 1.3 million tons per DRI

1.2 MW SOEC module (350 Nm³/h)
E-FUELS

Turning renewable electricity and CO₂ into e-Fuels for carbon neutral transportation, especially for transport sectors that cannot be electrified directly.
Synthetic paraffins of high quality as clean raw materials for the replacement of mineral oil in a variety of products in different industries such as Cosmetics, Clothing, Plastic processing and others.
TECHNOLOGY COMPARISON FOR E-FUELS

Water-Electrolysis + RWGS + Synthesis

- 3-step process
- Reverse Water-Gas-Shift (RWGS) necessary (900 – 1000 °C)
- Efficiency:
  \[ \eta_{\text{max, theor}} = 69 \% \]
  \[ \eta_{\text{max, real}} = 40 - 48 \% \]

Steam-Electrolysis + RWGS + Synthesis

- 3-step process with heat recuperation
- Reverse Water-Gas-Shift (RWGS) necessary (900 – 1000 °C)
- Efficiency:
  \[ \eta_{\text{max, theor}} = 81 \% \]
  \[ \eta_{\text{max, real}} = 50 - 58 \% \]

Co-Electrolysis + Synthesis

- 2-step process with heat recuperation
- No Reverse Water-Gas-Shift (RWGS) necessary
- Efficiency:
  \[ \eta_{\text{max, theor}} = 81 \% \]
  \[ \eta_{\text{max, real}} = 55 - 63 \% \]

All values refer to energy conversion necessary for the production of 1 kmol of -C_xH_y- hydrocarbons.
RENEWABLE E-FUELS & E-CHEMICALS

Sunfire-SynLink for e-Crude production

- Powered by renewable electricity, CO₂ and steam:
  - Production of more than three tons of 100% renewable e-Crude providing e-Fuels (Diesel, Gasoline) and e-Wax
  - Industrial reactor concept for quick upscaling
- Synthetic fuel with premium properties, verified by AUDI AG
  - High cetane value
  - Excellent combustion properties
- ASTM certified and drop-in capable (up to 50 %)
  - e-Jetfuel tested within Demo-SPK Project

Installation Site
SUNFIRE-SYNLINK: CO-ELECTROLYSIS TEST SYSTEM

- Development and testing within the BMBF funded project Kopernikus Power-to-X (FKZ: 03SFK2QO0)

- System design:
  - Proof of concept full co-electrolysis system
  - Electrolyser: max. 10 kW_{DC}
  - Feed: CO_{2}, H_{2}O, FTS recycle gas
  - Product: max. 4 Nm³/h syngas

- Standalone tests already conducted
- Currently operation in PtL Plant (@KIT, Karlsruhe (GER))
SUNFIRE-SYNLINK GEN.0: OPERATIONAL RESULTS

- Successful hot electrolyser system operation of > 2000 hours (1000 h SOEC, 1000 h Co-SOEC)
- Prototype efficiency at 62 %LHV** (comprising losses, using steam)
- No higher degradation compared to H₂O-SOEC
- Operation modes validated:
  - H₂/CO = 1 ... 4 (depends on synthesis process)
  - Load changes (part/nom/over)
  - Reforming of FTS recycle gas

** Upscaling potential >80 % LHV by reducing losses (+4%), optimizing power electronics (+4%) and heat recuperation (+10%)
SUNFIRE-SYNLINK GEN.0: INTEGRATION IN PTL PLANT

- World’s first integrated Power-to-Liquid (PtL) test facility to synthesize fuels from the air-captured carbon dioxide
- Container-based test facility integrating all four chemical process steps needed was used to implement a continuous process
- Partner: Climeworks, Ineratec, Sunfire and KIT
Sunfire-SynLink for e-Crude production

- Sunfire will build the first commercial e-Fuels plant by 2022 in Herøya, Norway
- Multiple off-take agreements in place for 8,000 t/a
- Unique advantages through location
  - Low electricity prices (ca. 3 ct€/kWh)
  - Continuous supply (>7,000 h)
  - Distribution shipping terminal at site
- 10 potential sites for expansion identified

Business case repetitive in other European countries (e.g. Eastern Europe)!

Installation Site in Herøya, Norway
CONCLUSION
SUNFIRE: EXECUTIVE SUMMARY

✓ Leading provider of electrolysers and fuel cells based on Solid Oxide Technology

✓ Serving the emerging gigawatt markets for renewable gases and fuels (e-Fuels, e-Gas, e-Hydrogen)

✓ Providing solutions for a variety of fuel cell market segments from micro to mini CHP

✓ Delivering game-changer products through highest process efficiency and lowest equipment costs

✓ Constantly improving Stack & System Design in terms of costs and Degradation
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