VTT webinar:
Tackling the material challenges in hydrogen economy

05/05/2023 **VTT – beyond the obvious**

Welcome to our webinar!

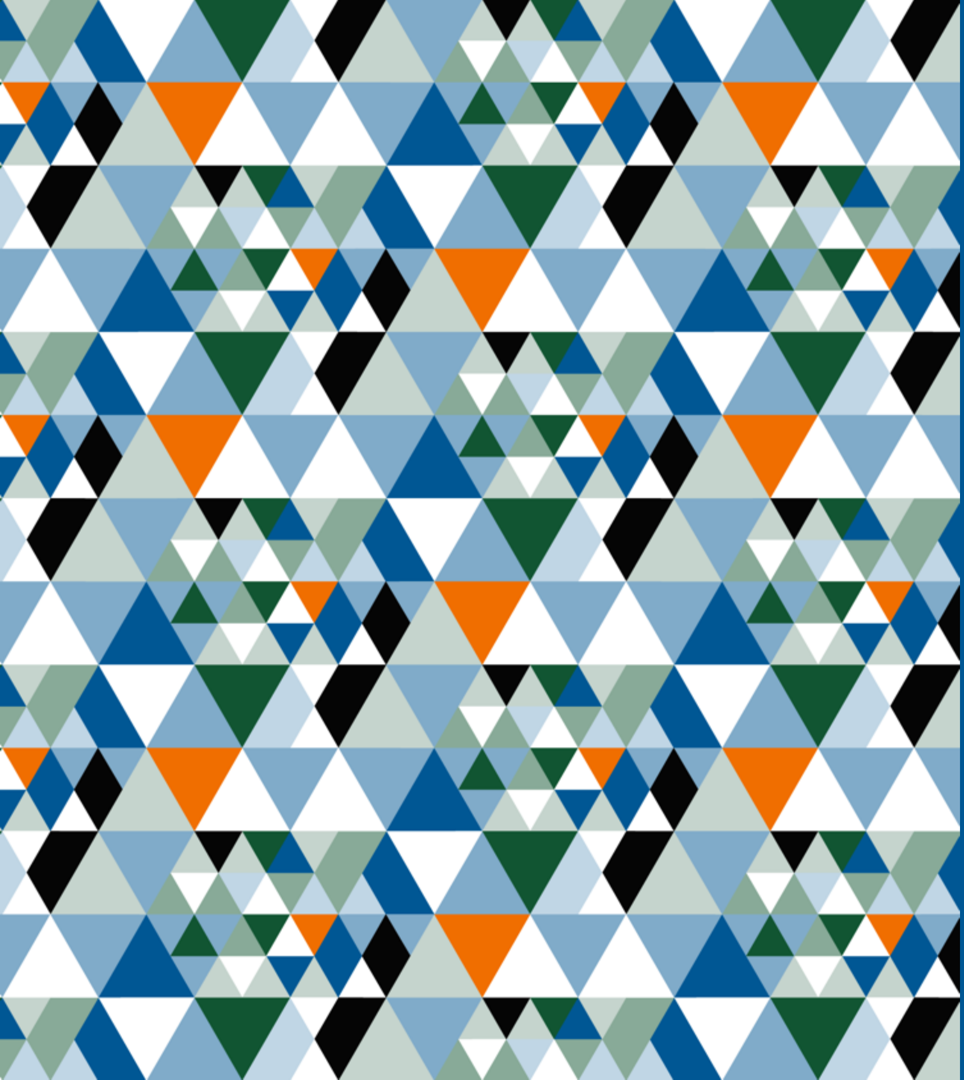
- **Duration of the webinar, including the Q&A:** 50 – 60 minutes

- **Q&A**:
    - Please submit your questions through ”Ask a question” tab
    - Please note that the tab is not visible in the full screen mode
    - We will answer questions at the end of the webinar

- **Slides**: We will provide you webinar slides and the recording about one week after the live webinar

Agenda

- **Introduction**
  Pekka Pohjanne, Lead, Materials for new energy technologies, VTT
- **Water Electrolysis for Green H2 Production – Technical Challenges, Materials and Research Activities at VTT**
  Ville Saarinen, Senior Scientist, D.Sc. (Tech.), VTT
- **Integrity of pressure vessels and pipes for H2 transportation and storage**
  Sebastian Lindqvist, Senior Scientist, D.Sc. (Tech.), VTT
- **Material challenges related to the use of hydrogen and ammonia as fuel**
  Elina Huttunen-Saarivirta, Research Professor, D.Sc. (Materials Science), VTT
- **Live Q&A**



Introduction

Pekka Pohjanne, Lead, Materials for new energy technologies

VTT – *beyond the obvious*

VTT is a visionary research, development and innovation partner for companies and society and one of the leading research organisations in Europe.

Our role is to promote the utilisation and commercialisation of research and technology in business and society. Through science and technology, we turn global challenges into sustainable solutions for business and society in a responsible way.

261 M€

turnover and other operating income

2,213

employees

43%

of the net turnover from outside Finland

32%

a doctorate or a licentiate's degree

Establishment year

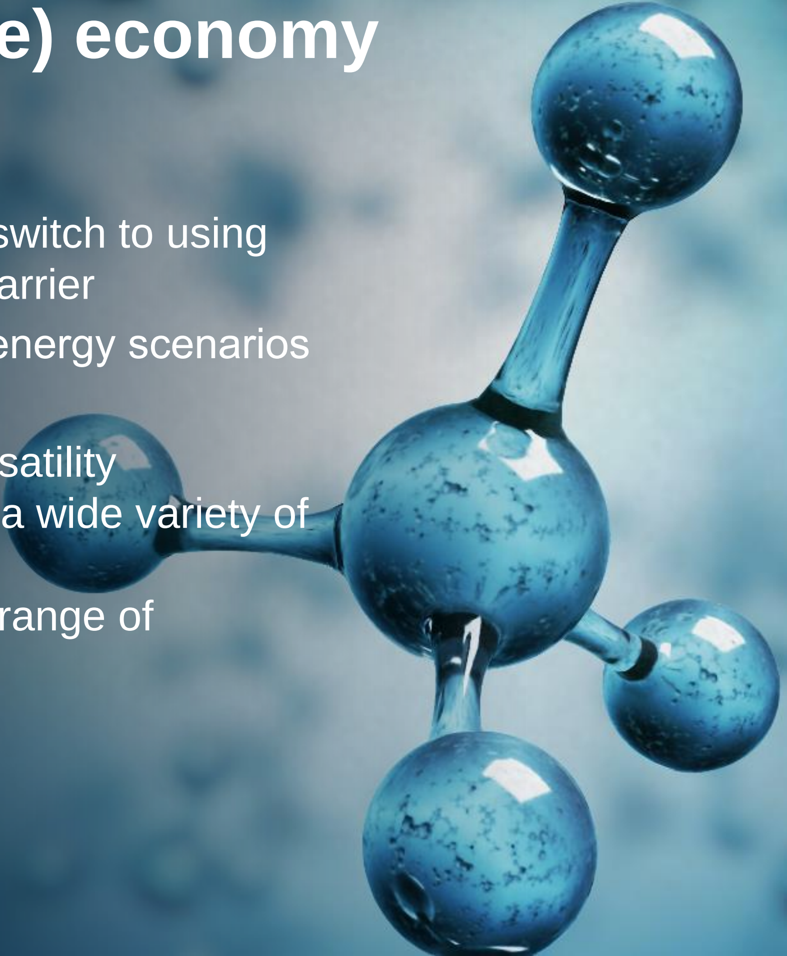
1942

Steered by Ministry of Economic Affairs and Employment of Finland

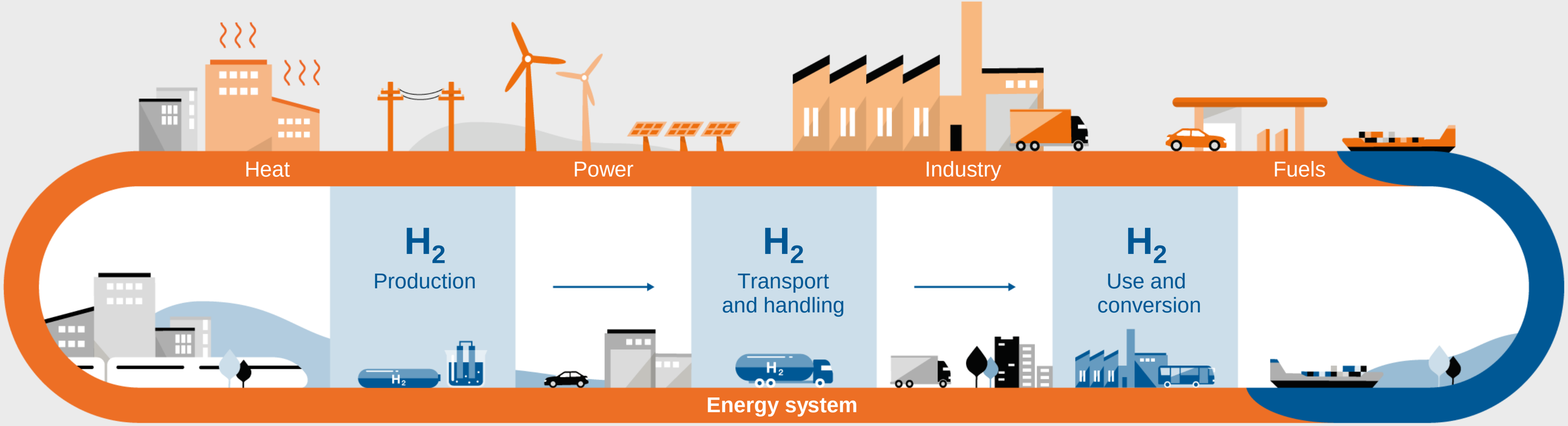
Hydrogen (in the) economy

- A vision of a large-scale switch to using hydrogen as an energy carrier
- Eternal ”magic bullet” in energy scenarios

- Main advantage is its versatility
  - Can be produced from a wide variety of resources
  - Can be used in a wide range of applications



Hydrogen is a foundation for green industrial revolution



Heat
Power
Industry
Fuels

H_2
Production

H_2
Transport and handling

H_2
Use and conversion

Energy system

- At VTT, we help companies explore the possibilities of hydrogen technology in their operations throughout the value chain.

VTT will have one of the leading clean energy transition research facilities in Europe

Clean energy pilot platform in VTT Bioruukki will be built in 2022-2025.

End-to-end research facilities for carbon neutrality in transport and industries.

Innovation platform for new solutions for hydrogen, electrification and renewable fuels.

Thank you!

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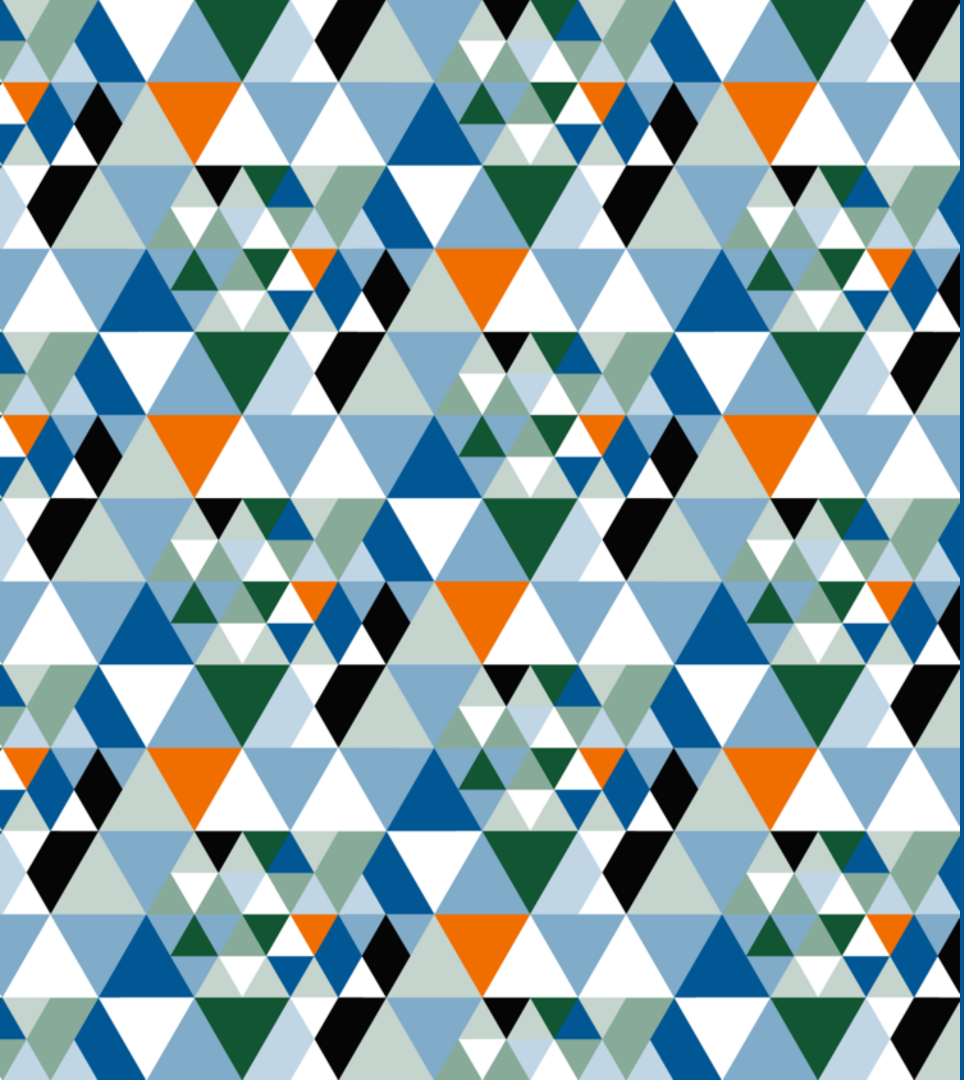


Water electrolysis for green hydrogen production

– Technical Challenges, Materials and Research Activities at VTT

Ville Saarinen, Senior Scientist

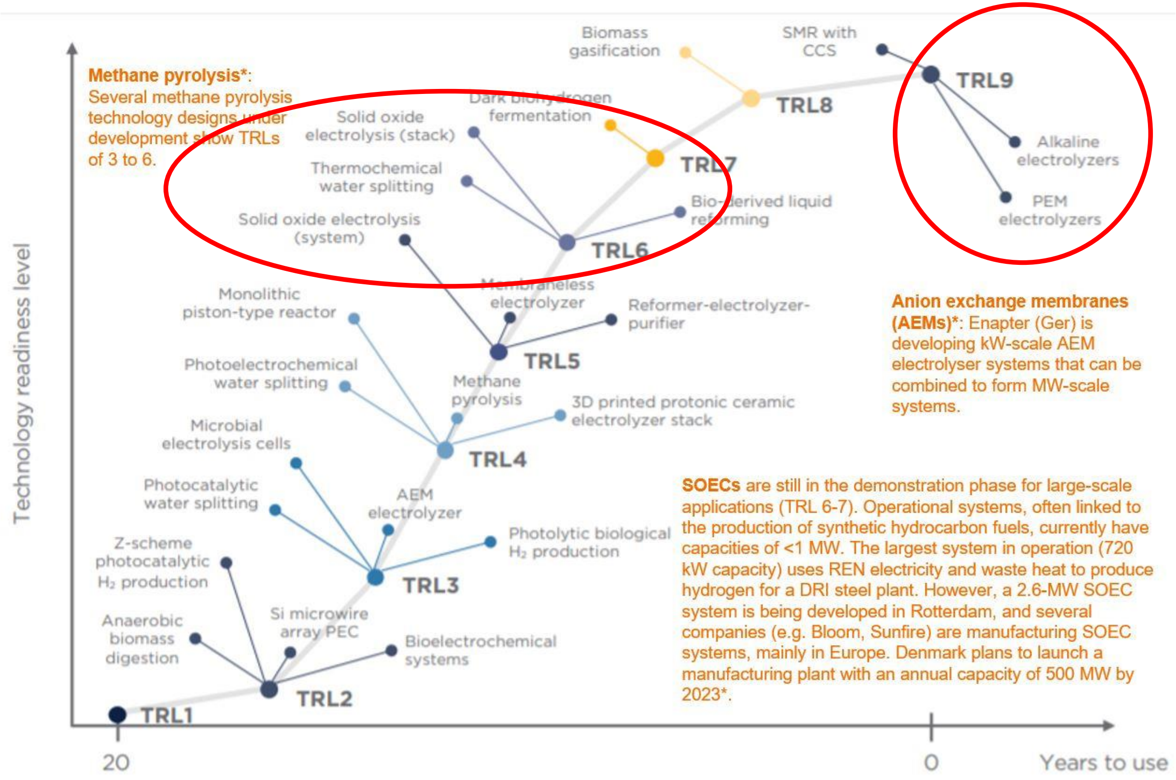
VTT Hydrogen production and applications

- 20 years of active history in PEMFC, SOFC, and electrolysis
- ~50 person involved in H_2 related activities at VTT
- Mainly working with European and Finnish companies in EU-projects and contract research, currently coordinating 7 EU-projects and participating in 17 projects
- All activities are supported by validated modeling tools (CFD, thermal, mechanical, etc.) from single components to complete systems
- Excellent know-how, research facilities, wide international partner network and long experience on high temperature electrolysis and fuel cells
- Product development for Industrial partners: sales and licensing IPR for Finnish and European companies
- https://www.vttresearch.com/en/ourservices/fuel-cells-and-hydrogen

Water electrolysis technologies

	Alkaline electrolysis (AEL)	**Proton Exchange Membrane electrolysis (PEMEL)**	**Solid Oxide Electrolysis (SOEC)**
Reactions	C: $2\ H_20 + 2\ e^- \rightarrow H_2 + 2\ OH^-$ A: $2\ OH^- \rightarrow 0.5\ O_2 + H_2O + 2e^-$	C: $2\ H^+ + 2\ e^- \rightarrow H_2$ A: $H_20 \rightarrow 2\ H^+ + 0.5\ O_2 + 2\ e^-$	C: $H_20 + 2\ e^- \rightarrow H_2 + O^{2-}$ A: $O^{2-} \rightarrow 0.5\ O_2 + 2e^-$
Electrode catalysts	C: Ni or PGM A: metal oxide(s)	C: Pt A: Iridium oxide	C: Ni A: metal oxide(s)
Electrolyte	Aqueous (KOH)	Solid (polymer membrane)	Solid oxide (YSZ)
Temperature	30-90 ^{o}C	20-100 ^{o}C	600-900 ^{o}C
Advantages	TRL 9, non-noble catalysts, long lifetime, relatively low-cost, MW range stacks	TRL 9, High current density, rapid system response, compact system design, pressurization	Highest efficiency, non-noble catalysts, co-electrolysis, CHP, reversible operation
Drawbacks	Low current densities, corrosive liquid electrolyte	Pt (high price), Iridium (low availability)	TRL 7, small module size, no pressurization

H_2 production technology readiness



Methane pyrolysis*: Several methane pyrolysis technology designs under development show TRLs of 3 to 6.

Anion exchange membranes (AEMs)*: Enapter (Ger) is developing kW-scale AEM electrolyser systems that can be combined to form MW-scale systems.

SOECs are still in the demonstration phase for large-scale applications (TRL 6-7). Operational systems, often linked to the production of synthetic hydrocarbon fuels, currently have capacities of <1 MW. The largest system in operation (720 kW capacity) uses REN electricity and waste heat to produce hydrogen for a DRI steel plant. However, a 2.6-MW SOEC system is being developed in Rotterdam, and several companies (e.g. Bloom, Sunfire) are manufacturing SOEC systems, mainly in Europe. Denmark plans to launch a manufacturing plant with an annual capacity of 500 MW by 2023*.

Source: Columbia SIPA (Aug 2021): Green hydrogen in a circular carbon economy: Opportunities and limits ; IEA (Oct 2021)*: Global Hydrogen Review 2021

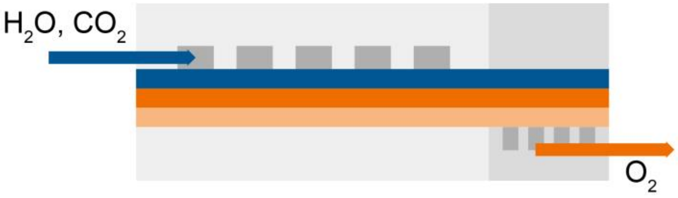
SoA Electrolyser technology comparison

	AEL	PEMEL	SOEC
Electrical energy consumption* [kWh_{el} / kg H_2]	53-60	53-65	**42-45**
Maximum module size	**~100 MW**	~20 MW	~200 kW
Cold start duration [min]	40-120	**5-10**	600+
H_2 outlet presure [bar_{abs}]	1-30	**1.5-30**	~1
Stack life time (h)	**~90 000**	~60 000	~20 000
CAPEX**(1 MW size) [€ / kWh_{el}]	**400-1500**	800-2000	1500-2500

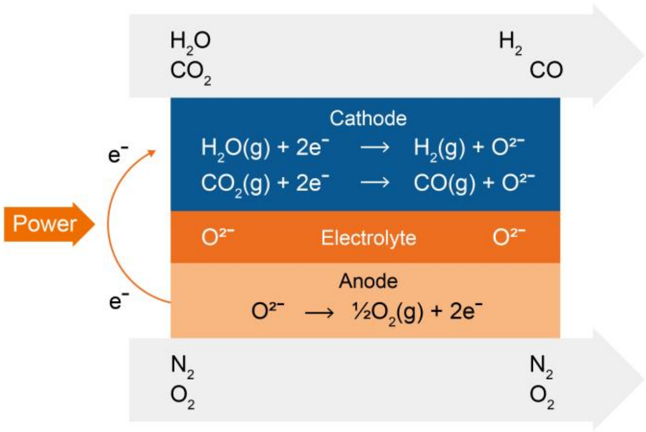
***** H_2 HHV= 39.4 kWh/kg, LHV= 33.3 kWh/kg**
****** Excl. installation, grid connection, external compression, purification and storage**

Solid oxide electrolyser (SOEC) operation principle

- Steam electrolysis $H_2O \rightarrow H_2 + \frac{1}{2}O_2$ *ΔH ≈ 250 kJ/mol*
- Co-electrolysis $H_2O + CO_2 \rightarrow H_2 + CO + O_2$ *ΔH ≈ 525 kJ/mol*

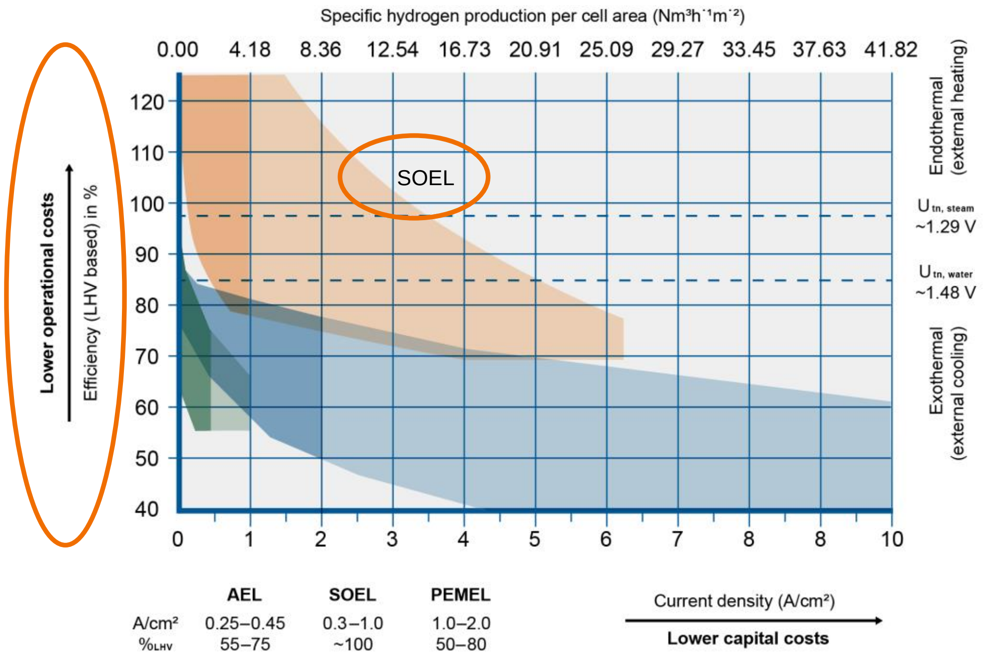


Simplified figure of SOEC cell structure



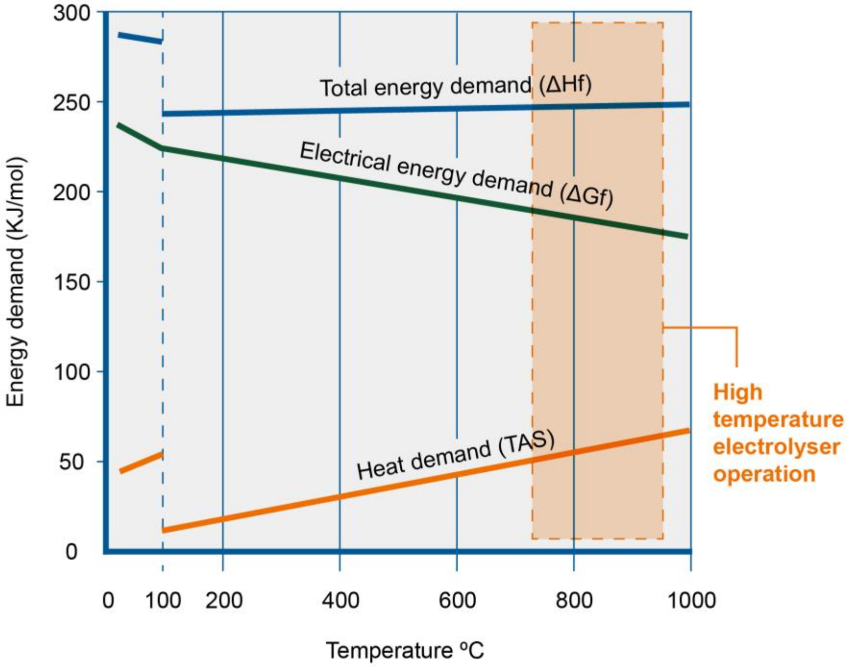
Efficiency can be improved without tradeoff

- Efficiency can be increased by
  - electrolyte and separator development (thinner, higher conductivity, better durability)
  - catalyst development (higher activity, better durability)
  - Reactant and product transport improvement (flow field, transport layer)
- Continuous field of development
- No theoretical limitation on efficiency (except energy balance)



Summary of efficiency and operational range of AEL, PEMEL and SOE cells or stacks. (Buttler & Spliethoff, 2018).

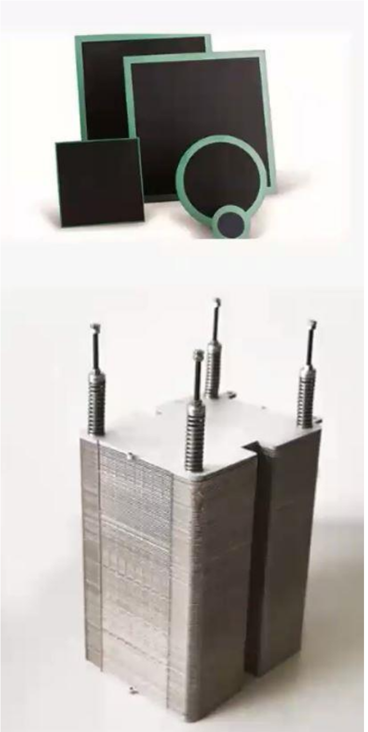
Benefit of high temperature electrolysis originates from thermodynamics



- **Lower activation losses** at lower current densities at high temperatures (700-800 ^{o}C) lead to **lower power consumption** during hydrogen production
- **No need for noble metal catalysts**
- **Solid oxide cells and stacks can be made with low cost raw materials** (suitable for mass manufacturing)

Solid oxide technology

- High operation temperature: 600-850 ^{o}C
- **SOE technology offer the potential for highest electrical efficiency in electrolysis mode (80-90%) compared to other electrolyser technologies**
- **SOEC technology is reversible**: the same system can work both as a fuel cell and an electrolyser depending on power generation and grid stabilisation needs
- **SOEC has capability also for co-electrolysis of steam and CO_2, which enables more efficient power-to-X, if integrating SOEC as part of industrial processes**
- The most commercial electrolysers are nowadays alkaline, but process has low efficiency due to needed high operation voltage. PEM based technology is more expensive than alkaline and it has also its own limiting factors like availability of iridium catalyst

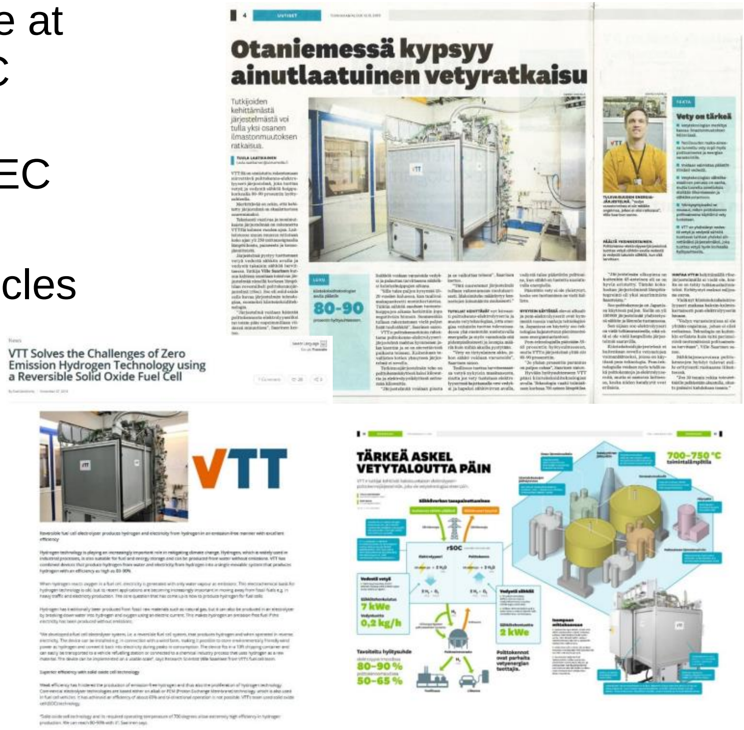


VTT SOFC/SOEC research infra

- 2 single cell test stations for SOFC/SOEC
- 5 test stations for < 3 kW SOFC/SOEC stack
- 2 test stations for < 10 kW SOFC/SOEC stack
- 1 SOFC/SOEC system for 2 x 10 kW
- Hydrogen quality and purity analysis
- All test stations designed and built by VTT
  - Reliable and flexible platform, long-term testing
- Specific test benches for materials and experimental facilities from stack materials to complete systems
- Currently we are developing and demonstrating SOFC and SOEC technology with our customers and partners

SOEC research and publications at VTT

- A lot of SOEC related research has been done at VTT during last 15 years, more specific SOEC material characterization, performance and durability analysis [1,2] and most recently SOEC system level studies [3].
- VTT press release and Tekniikka & Talous articles



Otaniemessä kypsyy ainutlaatuinen vetyratkaisu

Tutkijoiden kehittämästä järjestelmästä voi tulla yksi osanen ilmastonmuutoksen ratkaisua.

VTT Solves the Challenges of Zero Emission Hydrogen Technology using a Reversible Solid Oxide Fuel Cell

TÄRKEÄ ASKEL VETYTALOUTTA PÄIN

[1] J. Tallgren, O. Himanen, M. Noponen, Experimental Characterization of Low Temperature Solid Oxide Cell Stack, ECS Transactions 2017, 78, 3103.

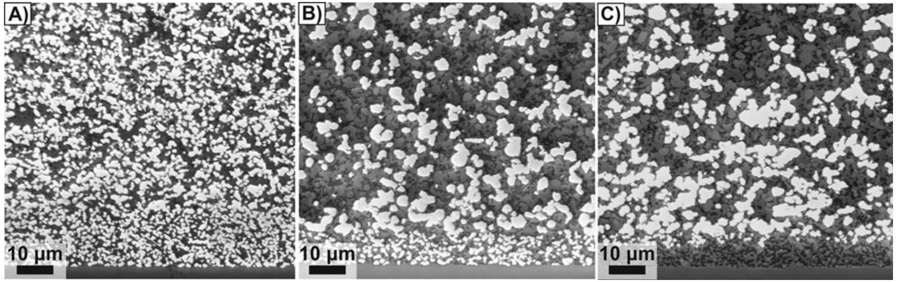
[2] M. Kotisaari, O. Thomann, D. Montinaro, J. Kiviaho, Evaluation of a SOE Stack for Hydrogen and Syngas Production: a Performance and Durability Analysis, Fuel Cells 2017, 17, 571.

[3] Saarinen, V., Pennanen, J., Kotisaari, M., Thomann, O., Himanen, O., Iorio, S. D., Hanoux, P., Aicart, J., Couturier, K., Sun, X., Chen, M., & Sudireddy, B. R. (2021). Design, manufacturing, and operation of movable 2 × 10 kW size rSOC system. Fuel Cells, 21(5), 477-487.

VTT Fuel cell and electrolyser characterization solutions

- World-class characterization facilities for fuel cell and electrolyser materials, stacks, system components, and systems
- Extensive hands-on experience of working with a very broad spectrum of fuel cell related technologies
- Tailored test campaign and recommendations for solving issues specified by the customer
- Complete, fully automated fuel cell stack and system characterization facilities.
- Very wide range of test capabilities from cold climate tests to impurity sensitiveness and detailed electrochemical characterization

Research example - SOE degradation mechanisms



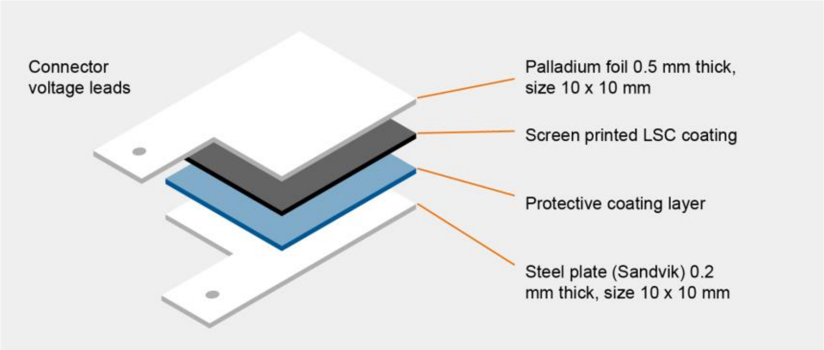
- Ni migration (function of current density, overpotential at cathode, steam content)
  - Stabilization with impregnation and formation of nanoparticle of gadolinia stabilized ceria
- Anode delamination.
  - Most critical with outdated $LaSrMnO_3$ anode, less with $LaSrCoO_3$
- Pore formation in the electrolyte
- Thermal stress, electrocatalyst poisoning (Cr, Si),

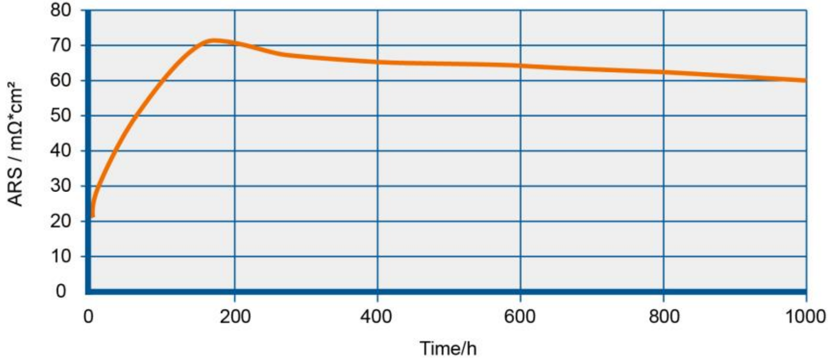
Mogensen et al. 2017
https://doi.org/10.1002/fuce.201600222

Research example - Characterisation of SOE interconnect coatings

- Coated steel sample is stacked adjacent to thin palladium foils with screen-printed cathode material (here LSC).
- The measurement setup introduces the following benefits:
  1. Realistic electric contact between coating and cathode material with same chemical interactions as in the stack
  2. Palladium spacer allows for post-test SEM/EDS analysis of Cr migration through coating into cathode material as all possible Cr in LSC originates from the sample

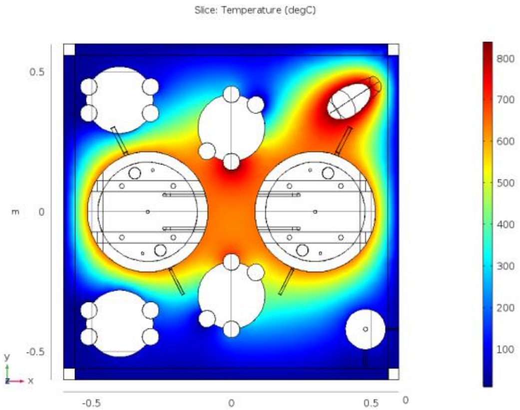
J. Tallgren et al. 2015. Evaluation of protective coatings for SOFC interconnects. ECS Transactions 68(1). 10.1149/06801.1597ecst.
J. Tallgren et al. Comparison of different manganese-cobalt-iron spinel protective coatings for SOFC interconnects. Proc. 12th European SOFC & SOE Forum 2016

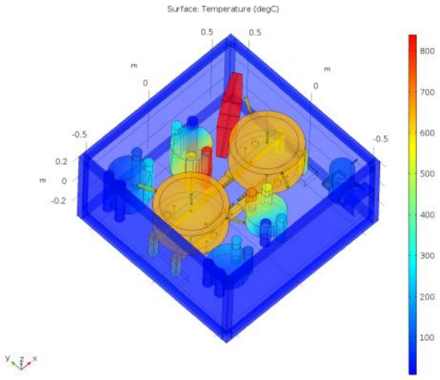




Research example – rSOC pilot system «RESSU»

- Highly instrumented **Re**versible **S**OC **S**ystem **U**nit “**RESSU”** designed and build by VTT
- High efficiency and suitable for integration with various energy sources and P2X, adaptability to local energy needs (supports grid stabilisation with high penetration of renewable electricity)
- Good technology base for green, flexible and efficient energy systems





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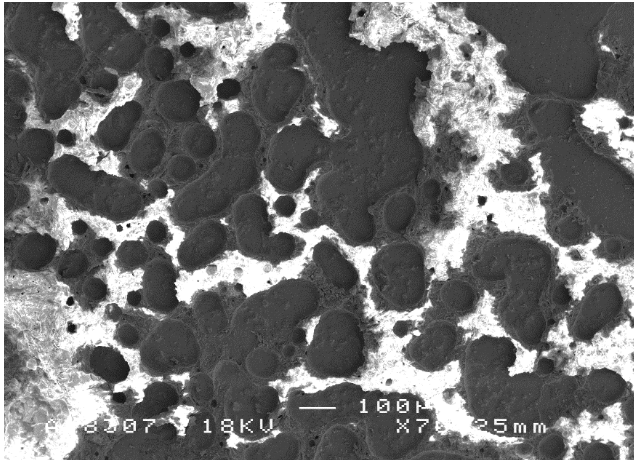
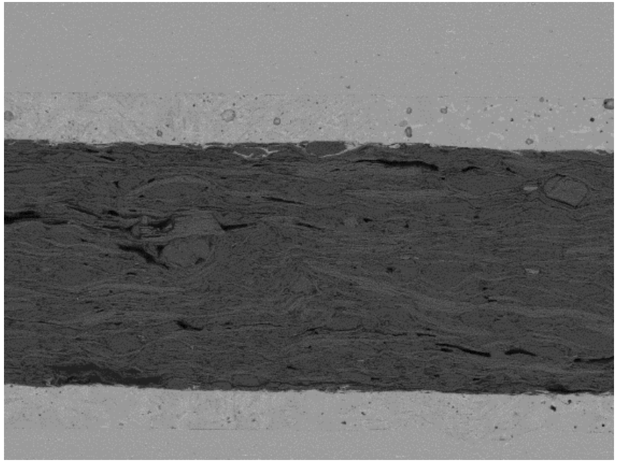
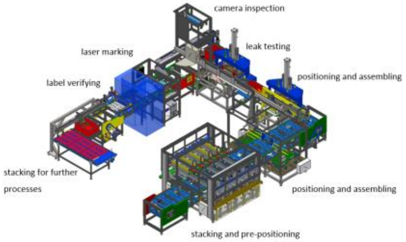
Research example: Post-mortem analysis of electrolyser system components

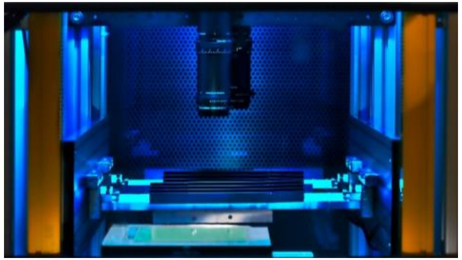
- Degradation analysis of electrolyser materials and components (cells, stacks, sealings, interconnect plates, etc)
- A wide variety of analysis services available (SEM/EDX/WDX, SIMS, etc)

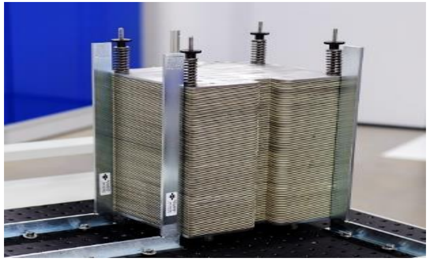




Research example – qSOFC





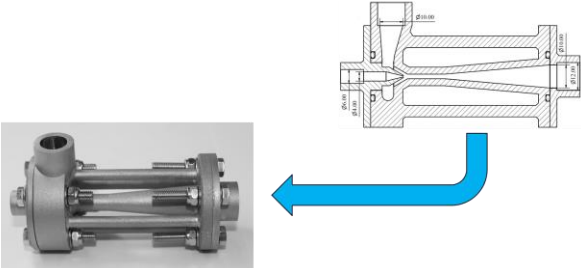


- Automated mass-manufacturing and quality assurance of SOFC stacks
- Reduction of stack production cost to 1000 €/kW at 10 MW/year volume
- Increase of production yield in all parts of stack manufacturing value chain to above 95% by automation and quality assurance

VTT
elringklinger
Fuel cell technology elcogen
HaikuTech Multilayer Ceramics
SANDVIK
MÜKO
ENEA
FCH FUEL CELLS AND HYDROGEN JOINT UNDERTAKING

PEM system and H2 quality research

- VTT has over 20 years of experience in PEMFC material, stack and system development. Participated in several PEMFC stack development projects
- Capability to characterize PEMFC stacks from up to 100 kW power range, both short term and long term measurements. Fuel cell systems up to 320 kW can be characterized at -32 ºC…+50 ºC +, also vibration, shock and drop testing.
- In system R&D, focus on contaminants from hydrogen, air and BoP components
- Cold climate issues and freeze testing at system
- At the BoP component level focus is in
  - ejector and ejector control system development,
  - air filter characterization
  - humidifier characterization



Research example – H_2 quality research at VTT

- Objective: To solve the hydrogen quality for transportation applications
  - Effects of the hydrogen supply chain derived contaminants on the fuel cell systems in automotive applications
  - Recommendations for current ISO 14687 standard
  - Technical data on fuel composition on HRS
  - Establish three European laboratories, capable of measuring all of the contaminants according to ISO 14687
- Measurements with CO and CO with CO2 (combined effect)
  - The use of 13CO for contamination studies (oxidation rate monitoring with 13CO2)
- LOHC – toluene (and benzene) impurity measurements
- 3-year EU-funded (FCH JU) project, coordinated by VTT. Six European leading FC research centres and independent European automotive stack manufacturer.

hydraite.eu

Collaboration examples with VTT

- Support in quotation requests, collaboration with electrolyser suppliers
- VTT has close dialogue with all the major electrolyser suppliers
- Networking and funding applications (>1-10 MEur bids)
- Techno-economic analysis & business case
- Demonstration activities
- Status report on the technology
- System modeling and experimental characterization

Thank you!

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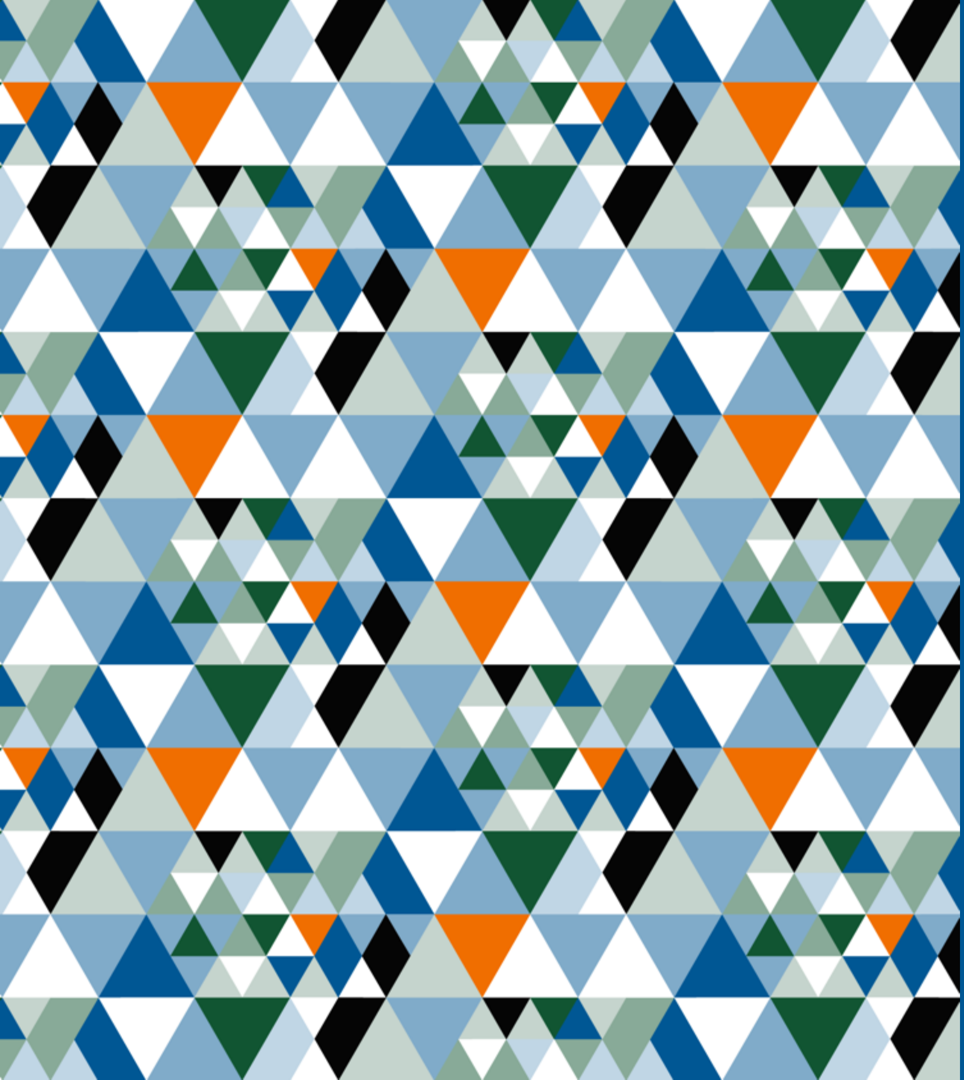

Integrity of pressure vessels and pipes for H2 transportation and storage

Sebastian Lindqvist, Senior Scientist
Siddharth Suman, Pekka Pohjanne, et. al

Hydrogen in Finland 2015:
3 Hydrogen stations (70 MPa & 35 MPa)

Arctic Driving Center, Rovaniemi, 2012

Helsinki Harbour, 2015

Control of material performance is crucial

- H2 diffuses to stress concentrations and decreases the material performance
  - H2 at crack tip → risk of embrittlement & fast growth
  - Right type of material testing is needed in relevant conditions
- Key features in materials selection
  - Hydrogen absorption, diffusion and interaction
  - Fatigue crack initiation & growth needs to be predictable
  - Fast or time dependent fracture risks controllable
- Make the right choice:
  - Material type, composition and microstructure
  - Strength level, ductility, flawlessness, purity
  - Material knowledge is needed

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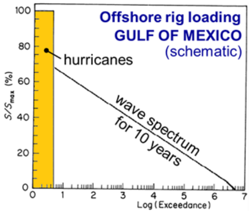
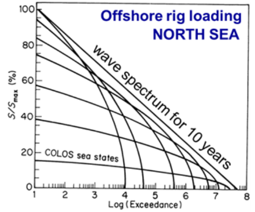
Case example: oil drilling rigs at North Sea hydrogen into the steel by cathodic protection

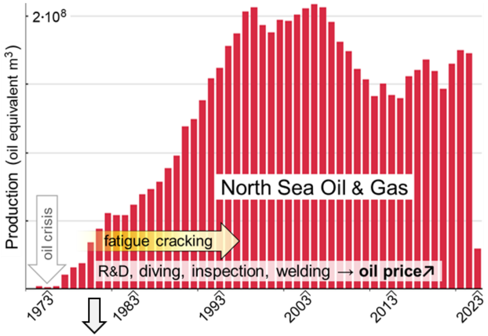
API design criteria tuned for mild sea





Round-the-year storming North Sea

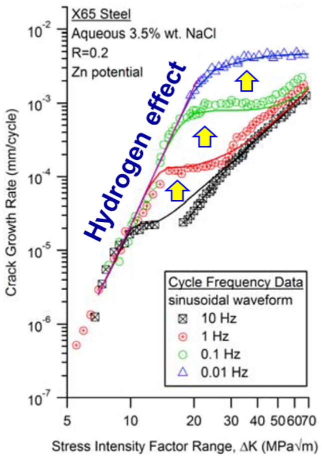
For oil & gas drilling rigs in the North Sea



Early fatigue cracking!

Oil price was affected by management of hydrogen enhanced fatigue: cracking risk, inspection and repair.

Zn anodes for cathodic protection



Cathodic potential retards corrosion & crack initiation, but charges with hydrogen and enhances crack growth

Lessons learned:

Fatigue improvement to mitigate cracking

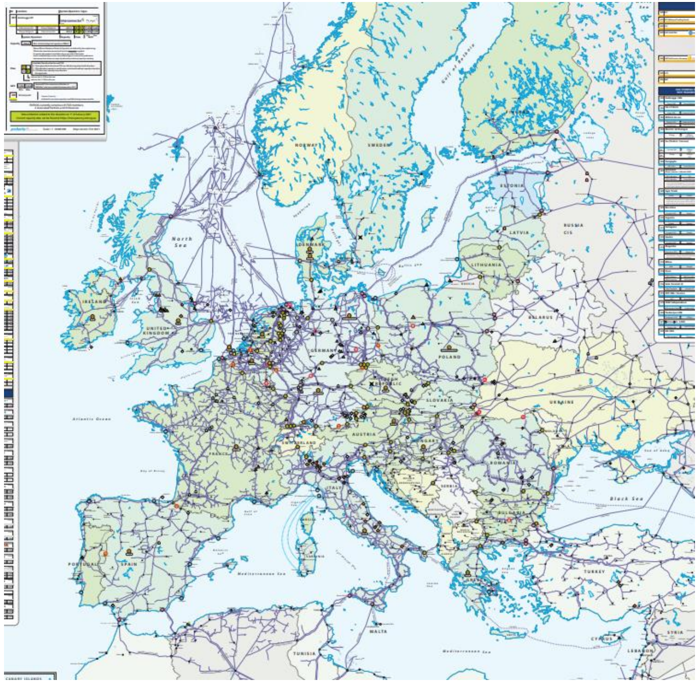
Optimized cathodic protection to reduce hydrogen absorption

Material selection for a new design

- **Low-alloy and carbon steels**
  - Risk for fast fracture depends on strength and microstructure
  - For H_2 pressure equipment fatigue design is based on crack growth
- **Austenitic steels**
  - More expensive high Ni alloys (stabile austenite) are preferred
  - Risk for fast fracture is generally lower
- **Non-metallic and composites**
  - Light weight, good corrosion resistance, low thermal conductivity
  - Development towards higher pressure and large scale
- **Materials with cladding or barriers**
  - Manufacturing and inspections a challenge

Material selection for a repurposed design

- **Major interest currently: Repurposing of the European and US natural gas grid**
  - Operation pressure: 40 – 80 bar
  - Materials: carbon steels
- **What limits repurposing?**
  - Knowledge of material performance
  - Knowledge of the existing condition
  - Applicability of standards
  - Mitigation measures



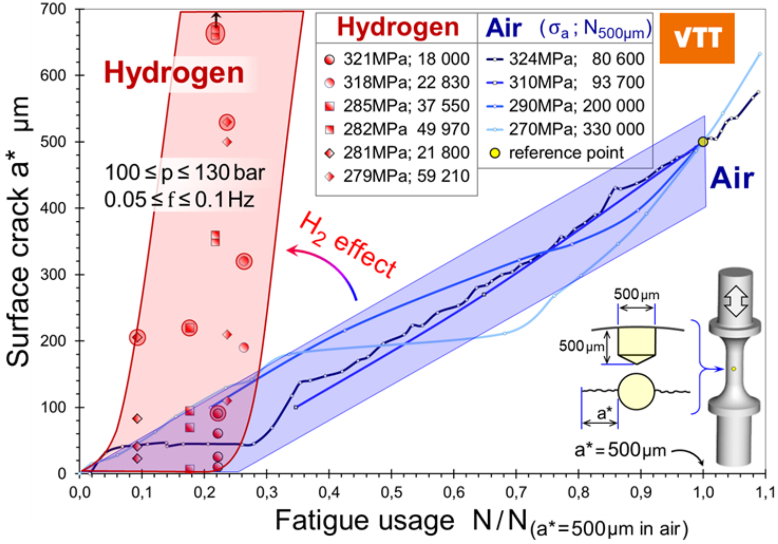
https://www.entsog.eu/

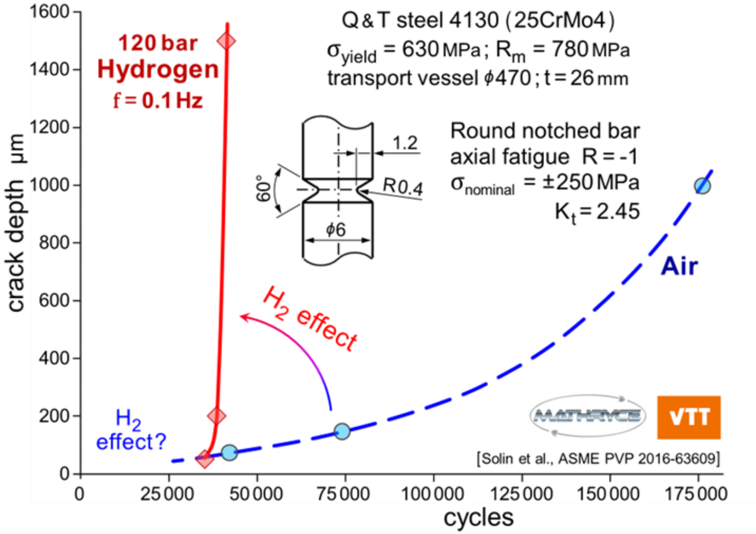
VTT's capabilities to solve material challenges of pressure vessels and pipes for H2

- **HyBello** for fatigue and fracture toughness testing in pressurized H_2
  - Operational: 2014
  - Pressure: < 200 bar
  - Hydrogen charging in the future
- Quality aspects
  - Is of high importance to us
  - ISO 9001:2015
  - ISO 17025 accredited testing
  - ISO 14001:2015
  - Continues development

- 20 years of experience on hydrogen issues and even longer for developing tailored solutions for industrial purposes
- Multidisciplinary expertise
  - design, leakage, accident simulations, etc.
- Ongoing projects:
  - MASCOT 2021, MATHIAS 2023
- Active participation inside the research community
  - ASME, ASTM, ISO, etc.

R&D collaboration EU (FCH), U.S. DOE and Japan





VTT contributed to pre-normative R&D and recommendations for ISO in 2012-2015 on design and testing criteria for safe pressure equipment in hydrogen service.

- Challenge: Conservative Fracture Mechanics → competitive design – not yet ready.

How VTT can help you to make the right choices?

- We solve your challenges related to pressure vessels and pipes for H_2 transportation and storage
  - **Right type of testing in relevant environment, under realistic loading of a real design to optimize the investment**
  - Improved design and material selection, and selection of optimal operation conditions
  - Driven to provide tailored solutions and develop methods to provide more meaningful data

Thank you!

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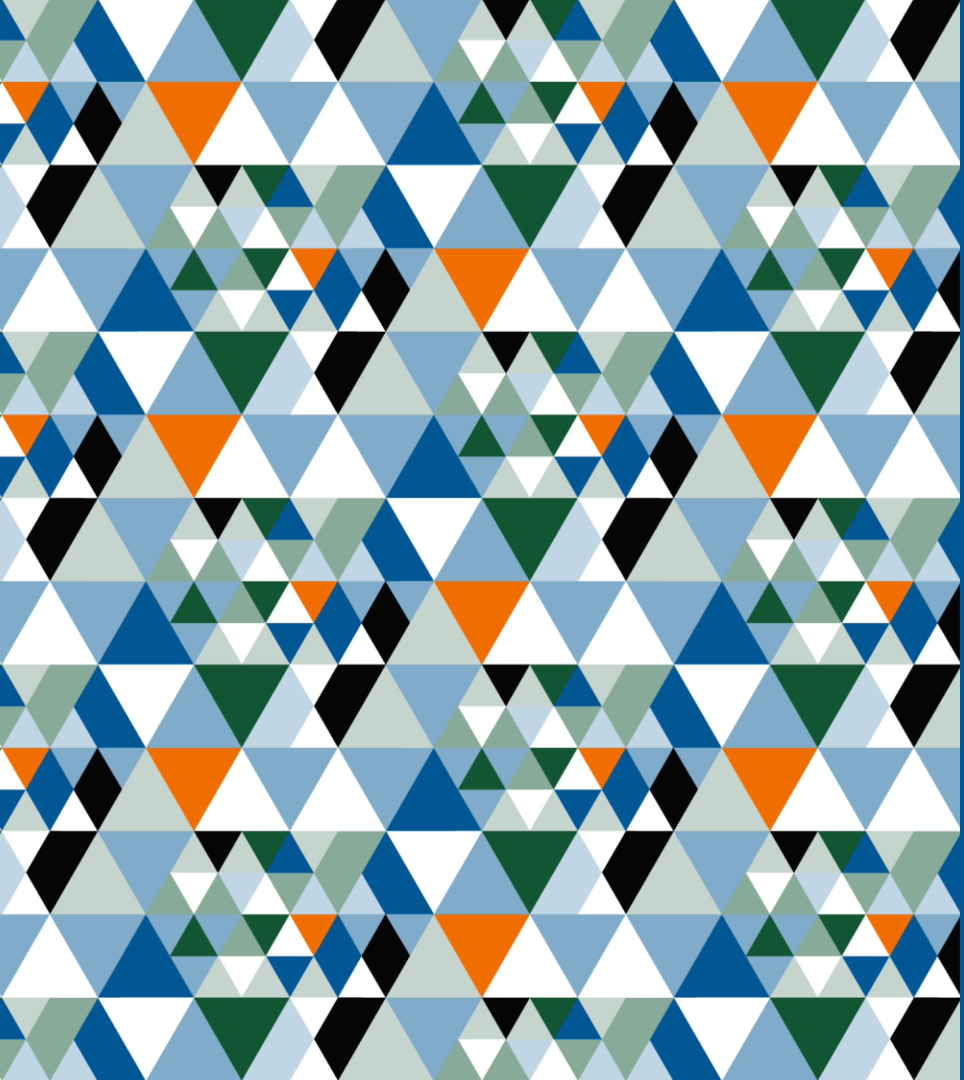
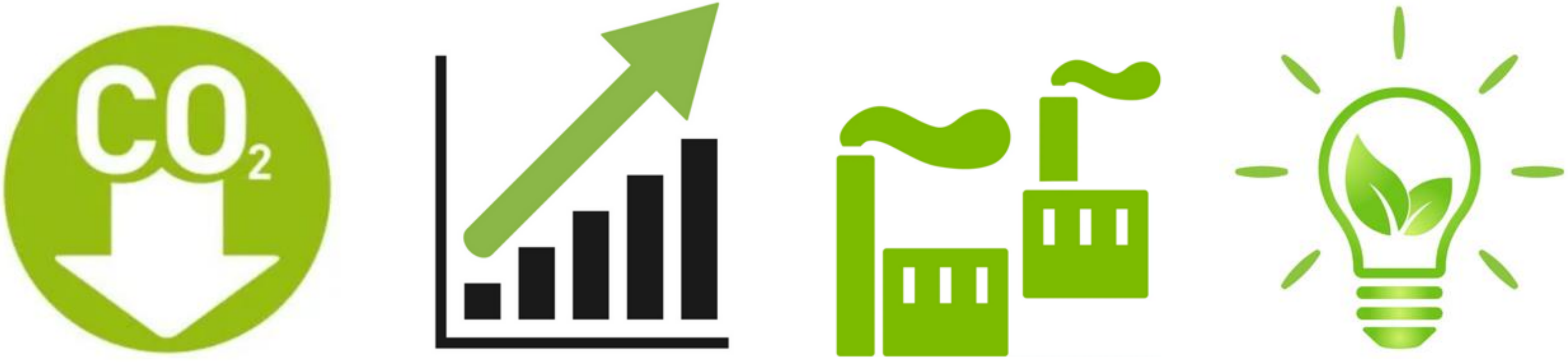
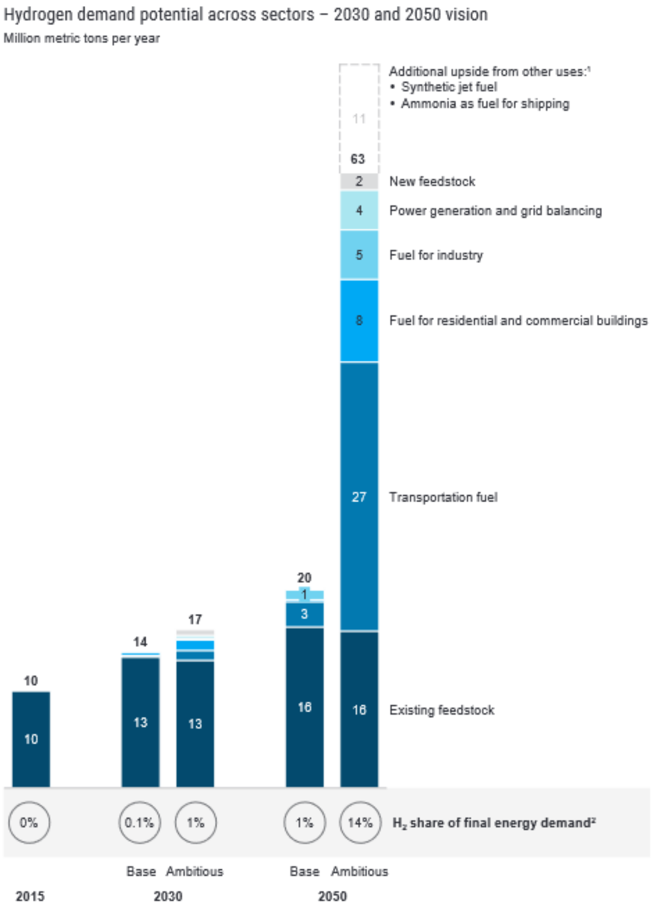


Material challenges related to the use of hydrogen and ammonia as fuel

Elina Huttunen-Saarivirta,
Research Professor

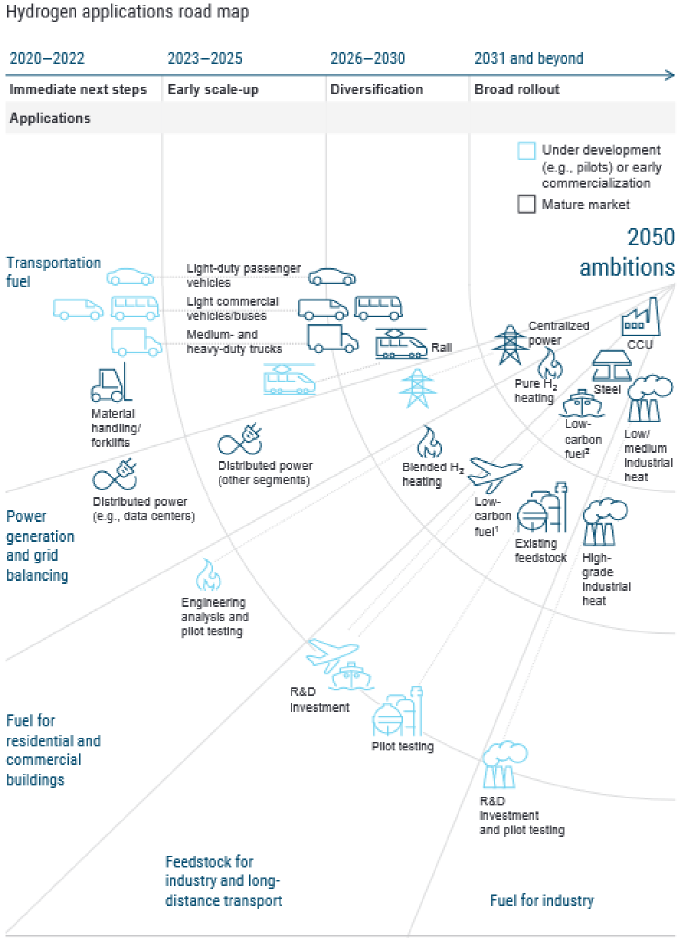
Why hydrogen?





Hydrogen demand potential across sectors – 2030 and 2050 vision

Million metric tons per year



Hydrogen applications road map

[1] Carbon capture and utilization (for chemicals production)

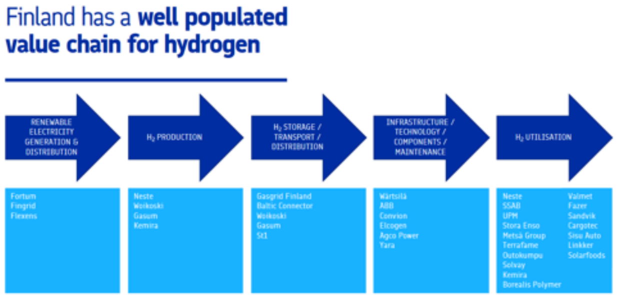
[2] Biofuel, synfuel, ammonia

From: FCHEA, Roadmap to a US Hydrogen Economy. http://www.ushydrogenstudy.org/

In Finland

Government's climate policy: climate-neutral Finland by 2035

The objective of the Programme of Prime Minister **Sanna Marin**'s Government is for Finland to be carbon-neutral and the first fossil-free welfare society by 2035. This requires even faster emissions reductions in all sectors and stronger carbon sinks.



Finland has a **well populated value chain for hydrogen**

RENEWABLE ELECTRICITY GENERATION & DISTRIBUTION	H_2 PRODUCTION	H_2 STORAGE / TRANSPORT / DISTRIBUTION	INFRASTRUCTURE / TECHNOLOGY / COMPONENTS / MAINTENANCE	H_2 UTILISATION	
Fortum Fingrid Flexens	Neste Woikoski Gasum Kemira	Gasgrid Finland Baltic Connector Woikoski Gasum St1	Wärtsilä ABB Convion Elcogen Agco Power Yara	Neste SSAB UPM Stora Enso Metsä Group Terrafame Outokumpu Solvay Kemira Borealis Polymer	Valmet Fazer Sandvik Cargotec Sisu Auto Linkker Solarfoods

Business Finland, National hydrogen roadmap for Finland, 2020.

Wärtsilä gas engines to burn 100% hydrogen

Wärtsilä Corporation, Press release, 5 May 2020 at 11:00 UTC+2

The technology group Wärtsilä continues to lead the ongoing transformation of the energy and marine sectors towards carbon-free solutions through its future fuel development work. The company is pioneering the adoption of hydrogen and ammonia as viable engine fuels through advanced testing in Wärtsilä's fuel-flexible combustion engines.

Hydrogen as a fuel

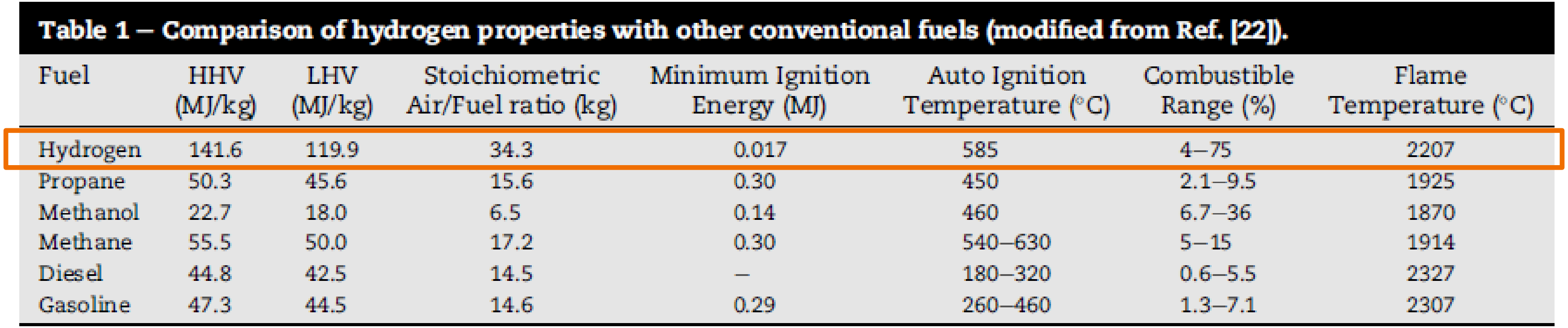


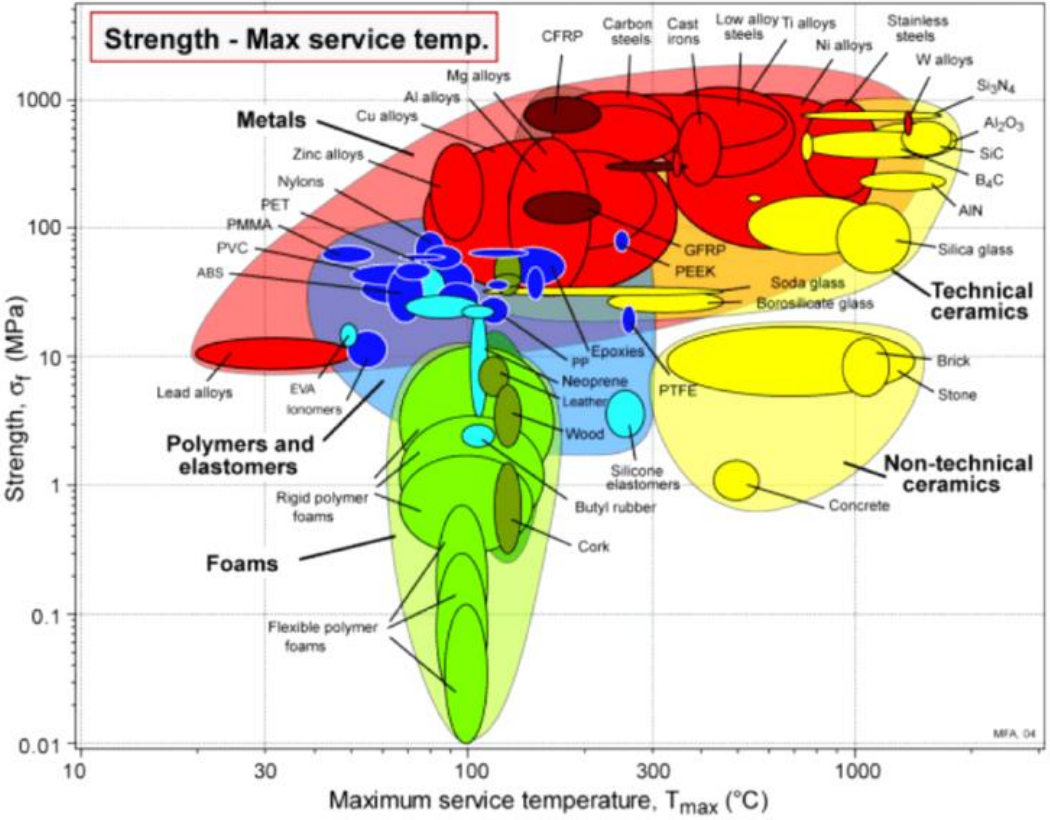
Table 1 – Comparison of hydrogen properties with other conventional fuels (modified from Ref. [22]).

Fuel	HHV (MJ/kg)	LHV (MJ/kg)	Stoichiometric Air/Fuel ratio (kg)	Minimum Ignition Energy (MJ)	Auto Ignition Temperature (°C)	Combustible Range (%)	Flame Temperature (°C)
Hydrogen	141.6	119.9	34.3	0.017	585	4–75	2207
Propane	50.3	45.6	15.6	0.30	450	2.1–9.5	1925
Methanol	22.7	18.0	6.5	0.14	460	6.7–36	1870
Methane	55.5	50.0	17.2	0.30	540–630	5–15	1914
Diesel	44.8	42.5	14.5	–	180–320	0.6–5.5	2327
Gasoline	47.3	44.5	14.6	0.29	260–460	1.3–7.1	2307

HHV: Hydrogen heating value
LHV: Lower heating value

H. Ishaq et al., Int. J. Hydrogen Energy 47, 2022, 26238-26264.

$$2H_2 + O_2 \rightarrow 2H_2O$$

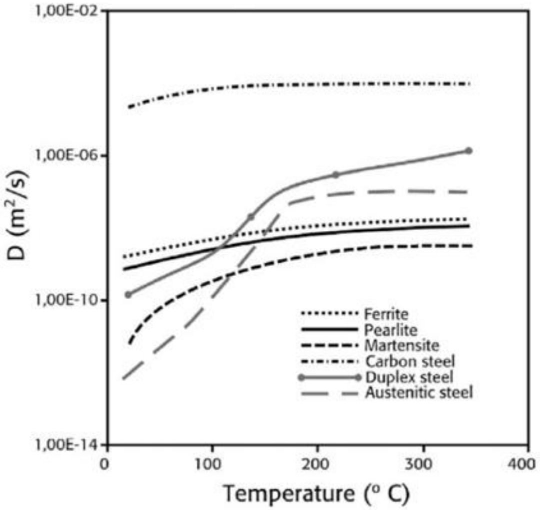


Example of materials selection chart by Ashby: strength vs. maximum service temperature.

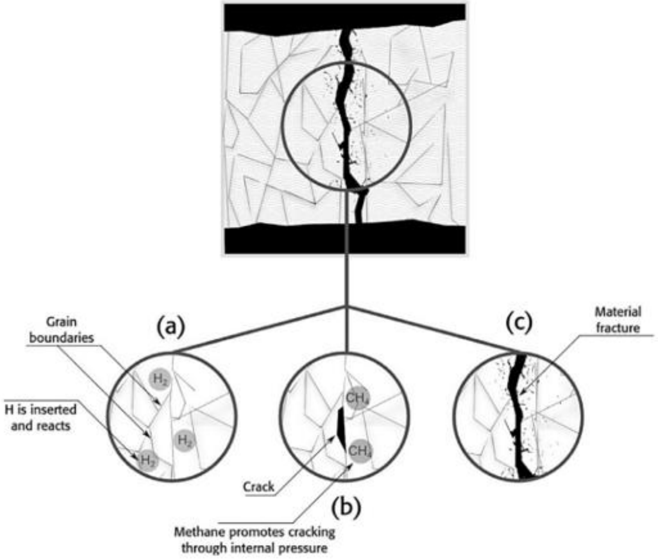
H_2 and materials at elevated temperatures

- High temperature hydrogen attack (HTHA), T>220°C
- $C + 2H_2 \rightarrow CH_4(g)$

→ Loss of ductility, i.e., embrittlement



Hydrogen diffusion coefficient as a function of temperature for steel microstructures.



M.S. Gonzáles, I.R. Hernandez, Tecnología en Marcha 31, 2018, 3-13.

Oxidation of alloys in water vapour, $H_2O(g)$

- Accelerated oxidation kinetics
- Presence of porosity & voids

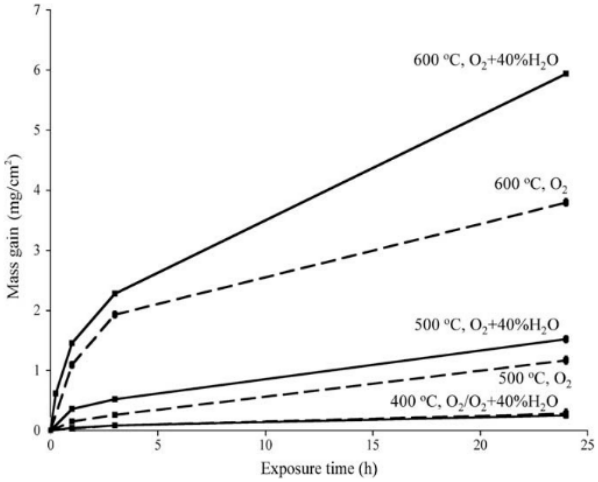


Fig. 1a. Oxidation kinetics of iron in dry O_2 and in 5%O_2 + 40%H_2O + 55%N_2 at 400–600 °C. The vertical bars (1, 3 and 24 h) show the scatter in mass gain of the triplicate samples. The lines are just guides to the eye.

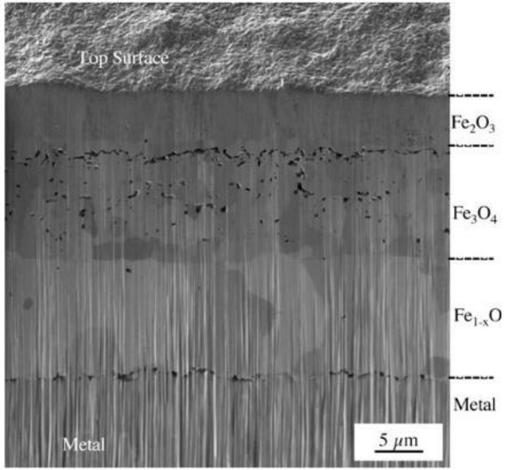
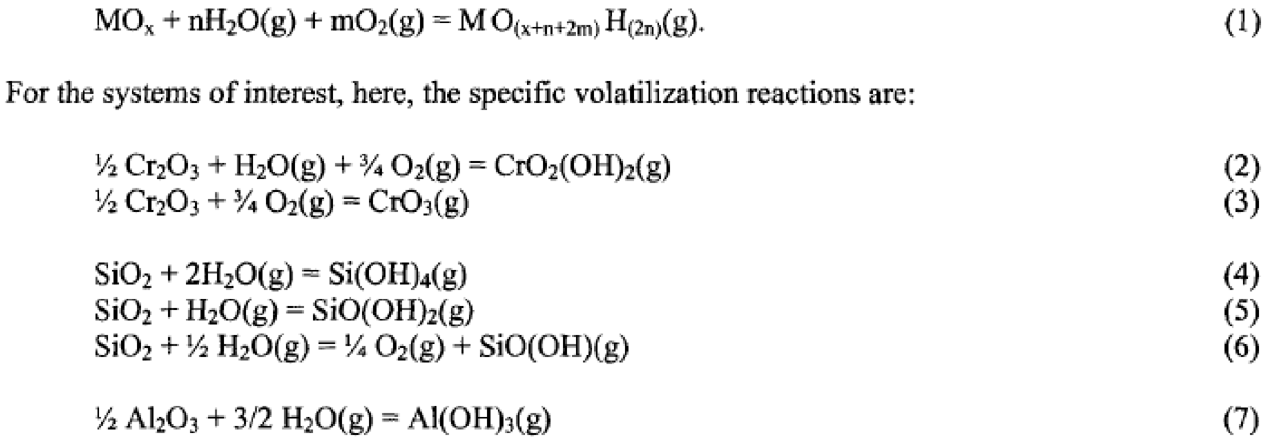


Fig. 10. FIB cross-section image after 24 h at 600 °C in wet O_2. Total oxide thickness in the image is about 40 μm. The hematite, magnetite and wüstite layers are about 6, 18 and 16 μm, respectively. The sample is tilted 42°.

B. Pujilaksono et al., Corrosion Science 52, 2010, 1560-1569.

Oxidation of alloys in water vapour, $H_2O(g)$

- Volatile oxides, hydroxides and oxyhydroxides



$$MO_x + nH_2O(g) + mO_2(g) = M\,O_{(x+n+2m)}\,H_{(2n)}(g). \tag{1}$$

For the systems of interest, here, the specific volatilization reactions are:

$$\tfrac{1}{2}\,Cr_2O_3 + H_2O(g) + \tfrac{3}{4}\,O_2(g) = CrO_2(OH)_2(g) \tag{2}$$

$$\tfrac{1}{2}\,Cr_2O_3 + \tfrac{3}{4}\,O_2(g) = CrO_3(g) \tag{3}$$

$$SiO_2 + 2H_2O(g) = Si(OH)_4(g) \tag{4}$$

$$SiO_2 + H_2O(g) = SiO(OH)_2(g) \tag{5}$$

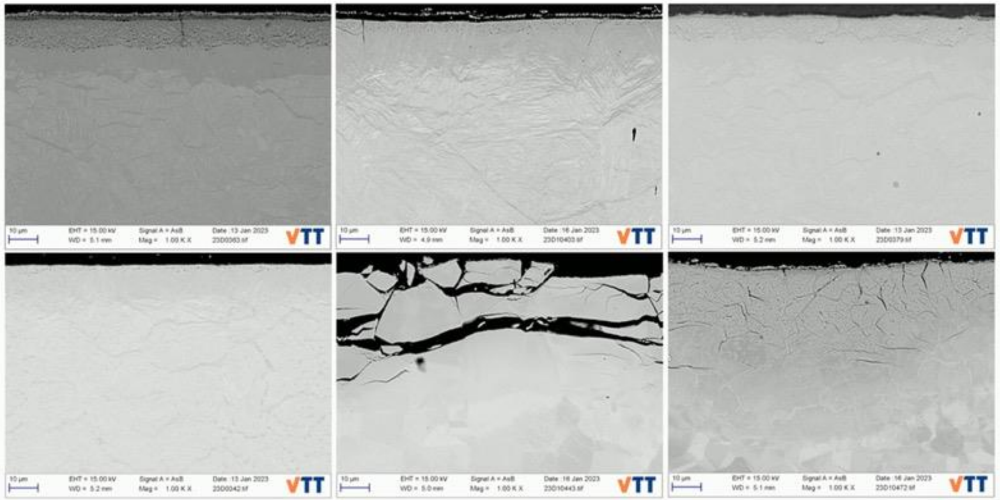
$$SiO_2 + \tfrac{1}{2}\,H_2O(g) = \tfrac{1}{4}\,O_2(g) + SiO(OH)(g) \tag{6}$$

$$\tfrac{1}{2}\,Al_2O_3 + 3/2\,H_2O(g) = Al(OH)_3(g) \tag{7}$$

E.J. Opila, Materials Science Forum 461-464, 2004, 765-774.

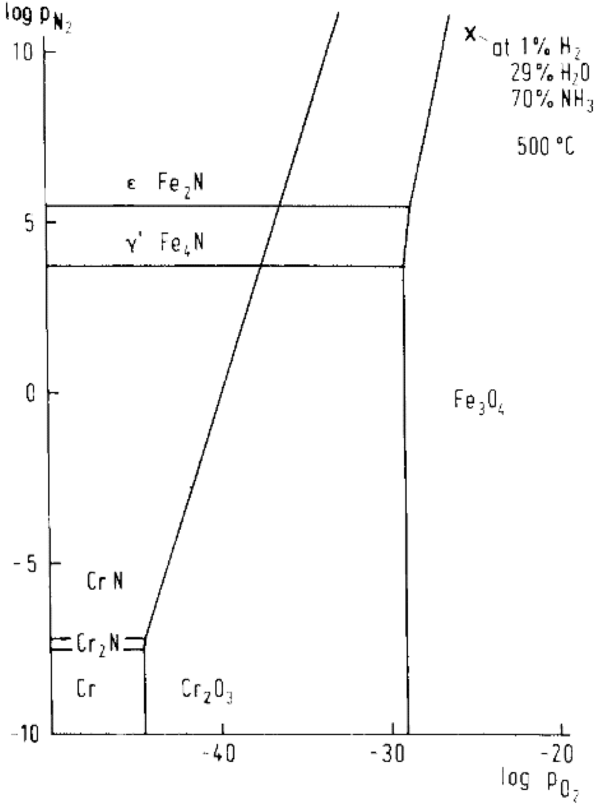
Nitridation by ammonia, NH_3 (g)

- Brittleness of the formed nitride layers



SEM micrographs of the cross-section of samples in 1000h exposure of 14%NH_3-Ar at 400 °C. 1000x magnification and AsB backscatter detector. Top left to bottom right: : 42CrMo4, 34CrAlNi7, 34CrNiMo6, X40CrSiMo10-2, 316L and 316+.

Ongoing M.Sc. Thesis at VTT (Sofia Ojasalo)



H.J. Grabke et al., Materials and Corrosion 54, 2003, 895-901.

MASCOT

MAterialS for CO_2-neuTral processes in resource-intensive industries

- Aim is to tackle the material technology related challenges raised in emerging fossil-free processes
- Business Finland partnership project with six companies and two research institutes
- 2022 – 2025
- EUR 7.2 M€ total

www.mascotproject.fi

MASCOT

Storage & transport
New material solutions and tank designs for gaseous fuels

Zero emission marine
Safe, sustainable and competitive material solutions for the H_2, NH_3 engines

Battery recycling
New hydrometallurgical processes and related safe and sustainable materials selection

Closed loop processes
Materials and equipment to valorise corrosive P&P sidestreams

Fuels and chemicals from recycled feeds
Materials performance and selection for new chemically aggressive processes

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MASCOT collaboration key for success

VTT

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NextGenerationEU

SA FIRI: Hub for Hydrogen-Materials Interaction Research Infrastructure (H2MIRI), with OU & TAU

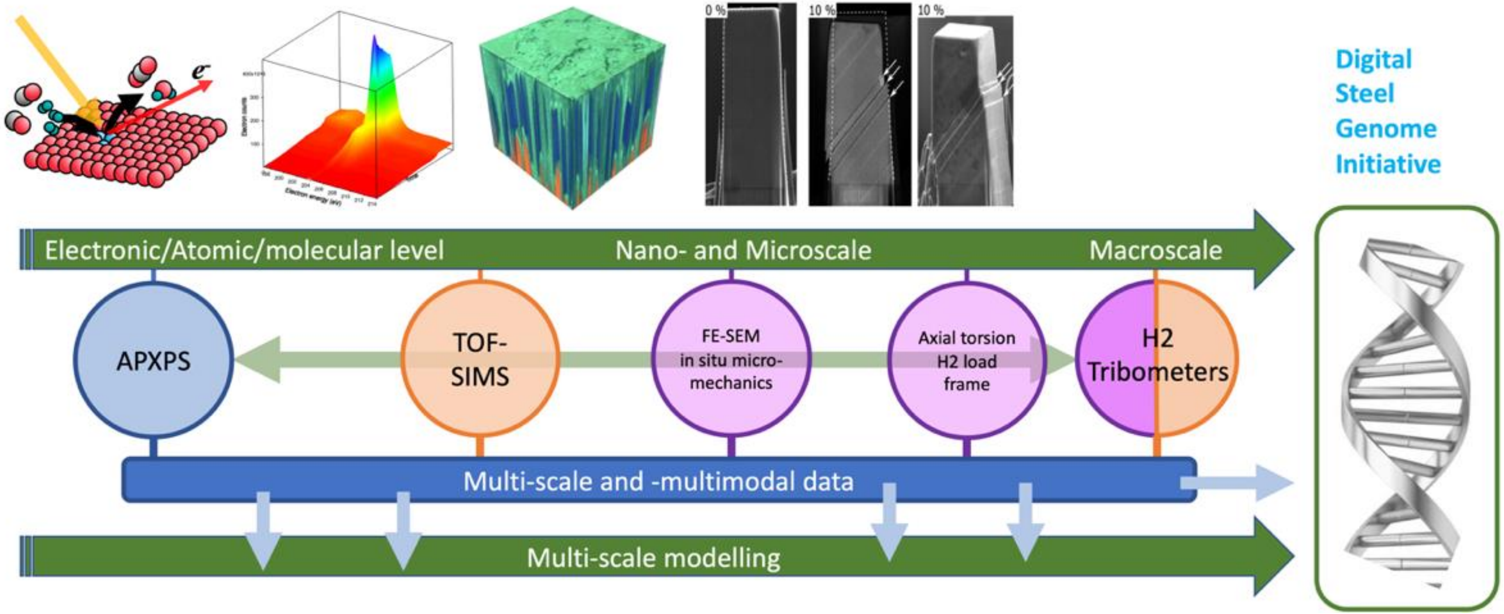

Figure 2. The multi-scale and multimodal approach of H2MIRI. The produced data is used for multi-scale modelling and as part of the Digital Steel Genome Initiative. Coordinated sample transfer systems and digital tracking allow characterization at different sites.

1.1.2023-31.12.2015

Thank you!

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Q&A

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  - Please note that the tab is not visible in the full screen mode

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beyond
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