

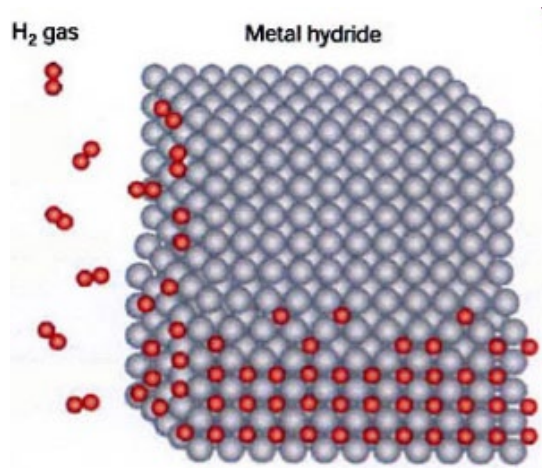
Developing Materials-based Solutions for a Hydrogen-driven Green Transition: Challenges and Opportunities with Metals hydrides

Stefano Deledda

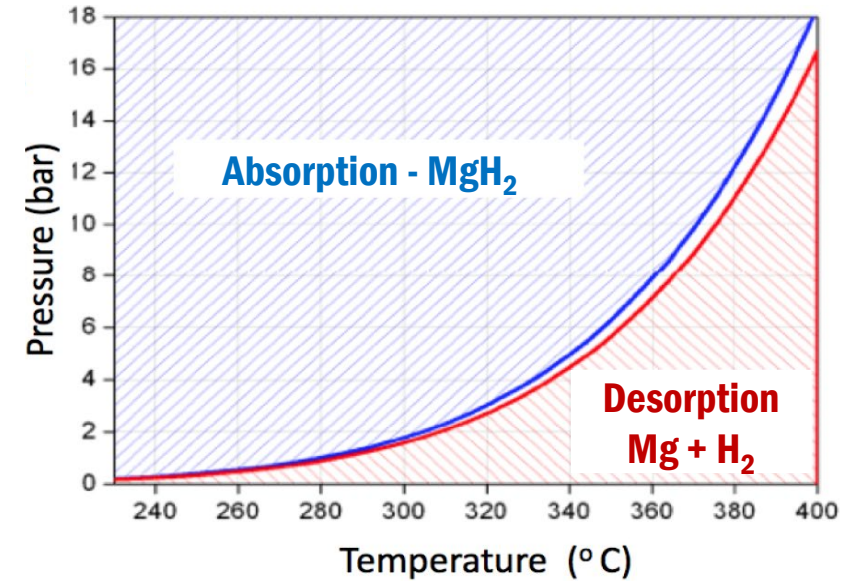
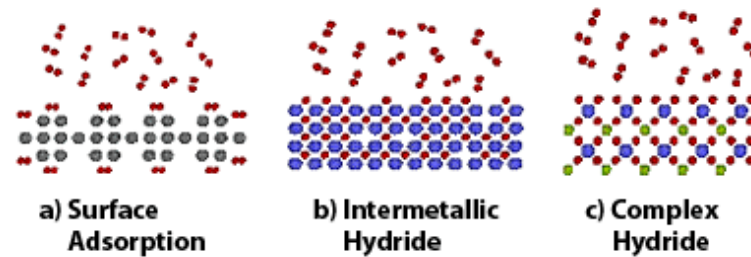
Department for Hydrogen Technology
Institute for Energy Technology
Kjeller, Norway



Hydrogen Storage in Metal Hydrides



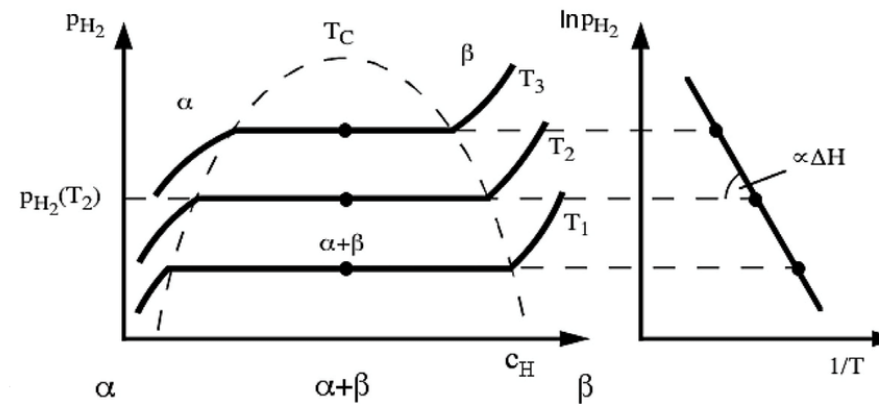
Schlapbach and Züttel, Nature 414 (2001) 353–358



Jehan and Fruchart, J. Alloys Comp. 580 (2013) S343–S348

- H₂ molecules adsorbed on surfaces
 - Metallorganic Frameworks (MOFs)
 - Carbon-based materials
- H atoms absorbed in bulk
 - Chemical M-H bonds
 - Metallic
 - Ionic
 - Covalent

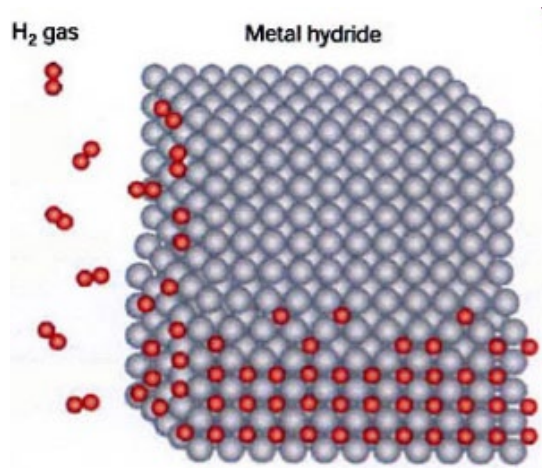
PCT diagram



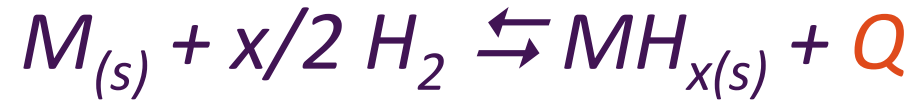
Van't Hoff equation and plot

$$\ln \frac{p_{eq}}{p_0} = \frac{\Delta H}{R} \cdot \frac{1}{T} - \frac{\Delta S}{R}$$

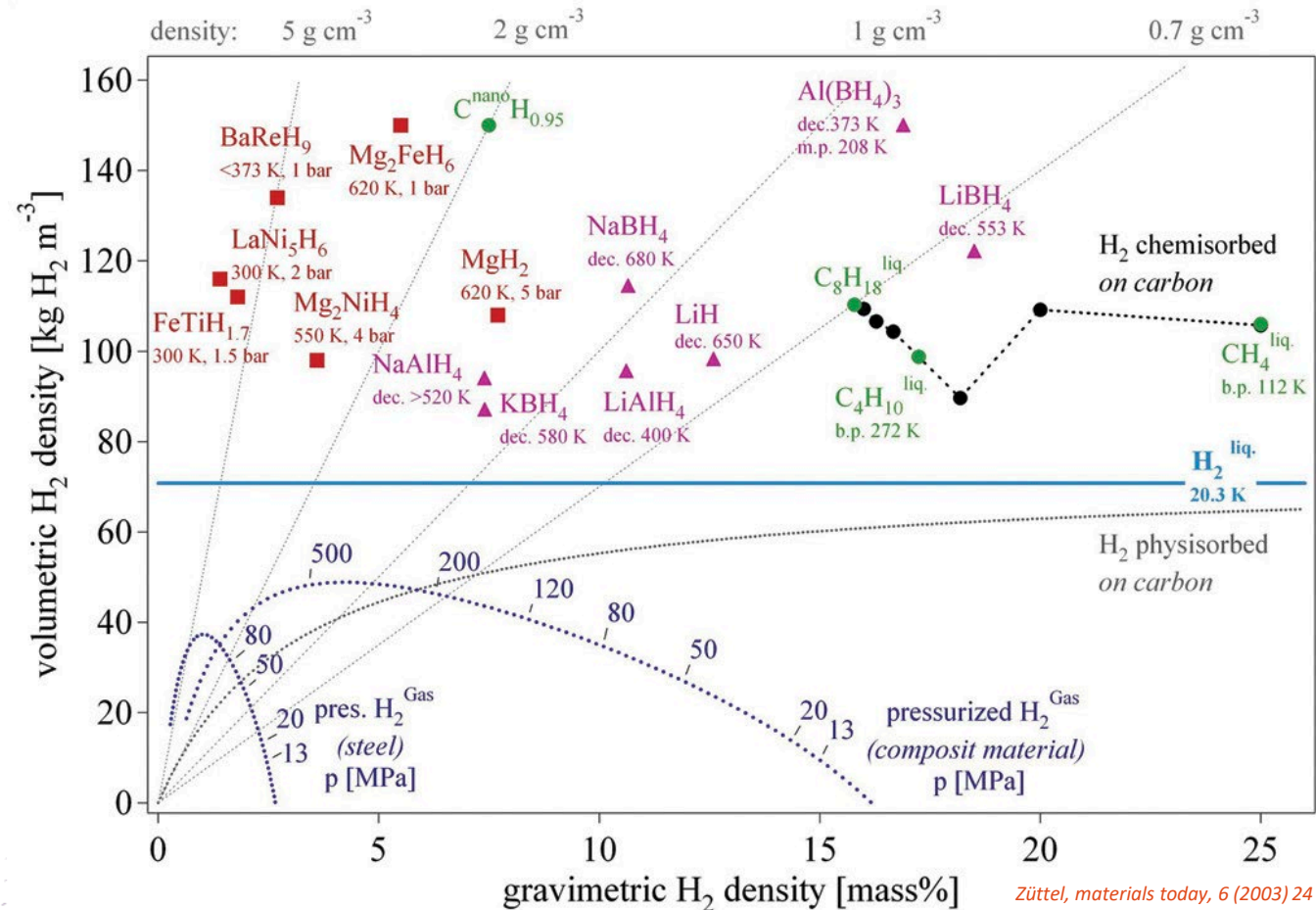
Hydrogen Storage in Metal Hydrides



Schlapbach and Züttel, Nature 414 (2001) 353–358

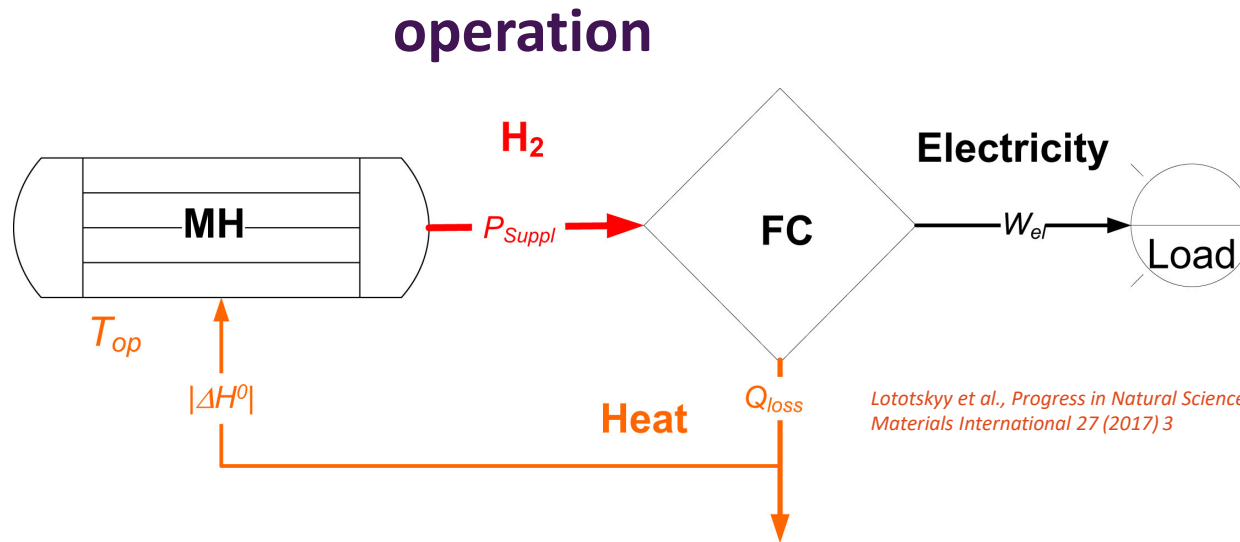
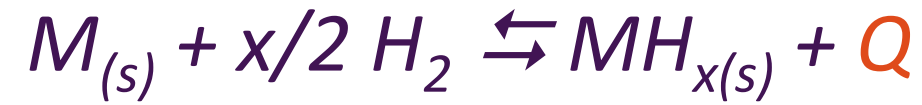


- H₂ molecules adsorbed on surfaces
 - Metallorganic Frameworks (MOFs)
 - Carbon-based materials
- H atoms absorbed in bulk
 - Chemical M-H bonds
 - Metallic
 - Ionic
 - Covalent

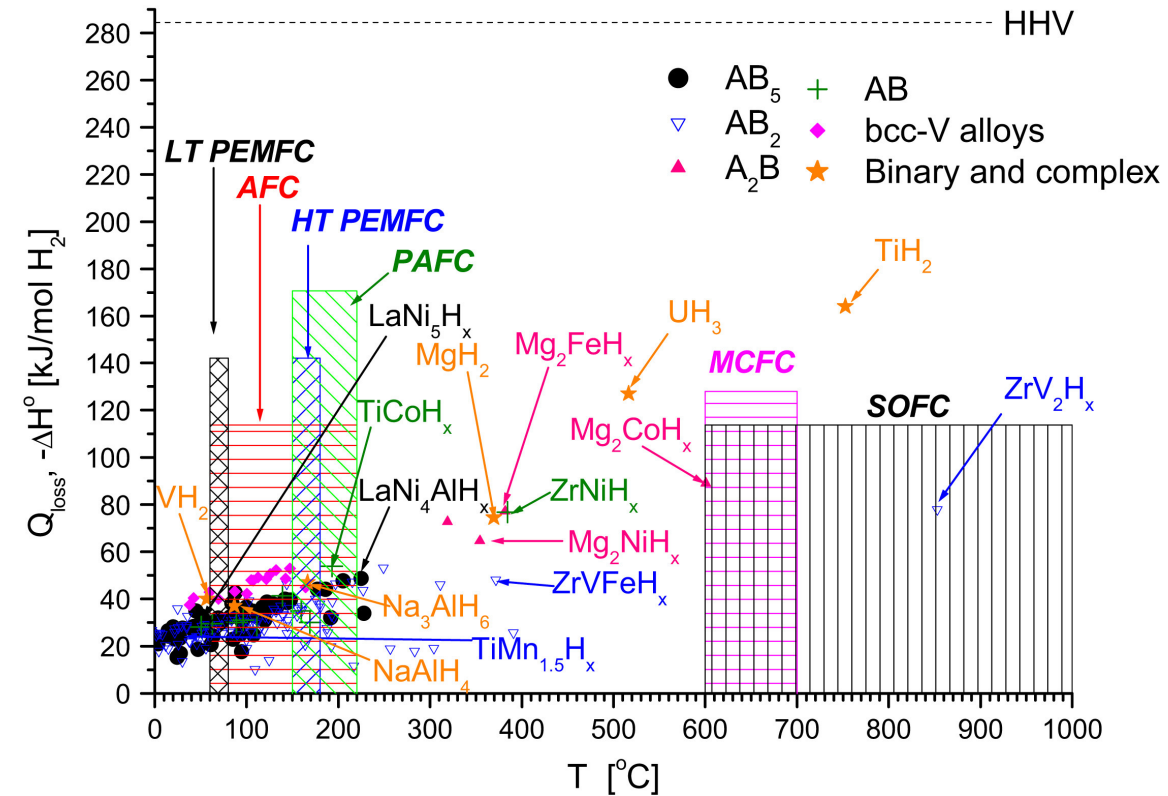


Züttel, materials today, 6 (2003) 24

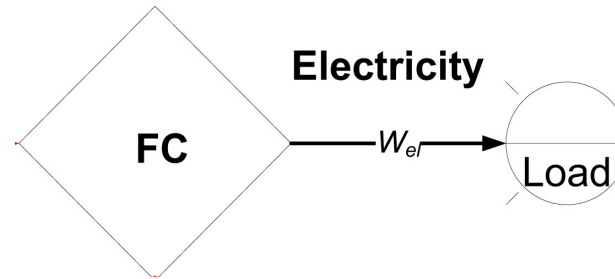
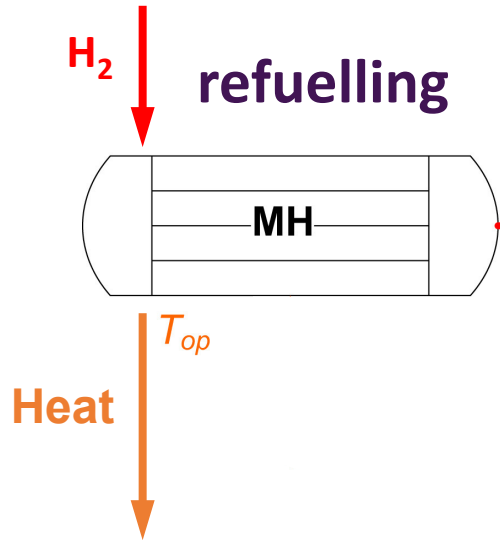
Integration with Fuel Cells



Lototskyy et al., Progress in Natural Science: Materials International 27 (2017) 3



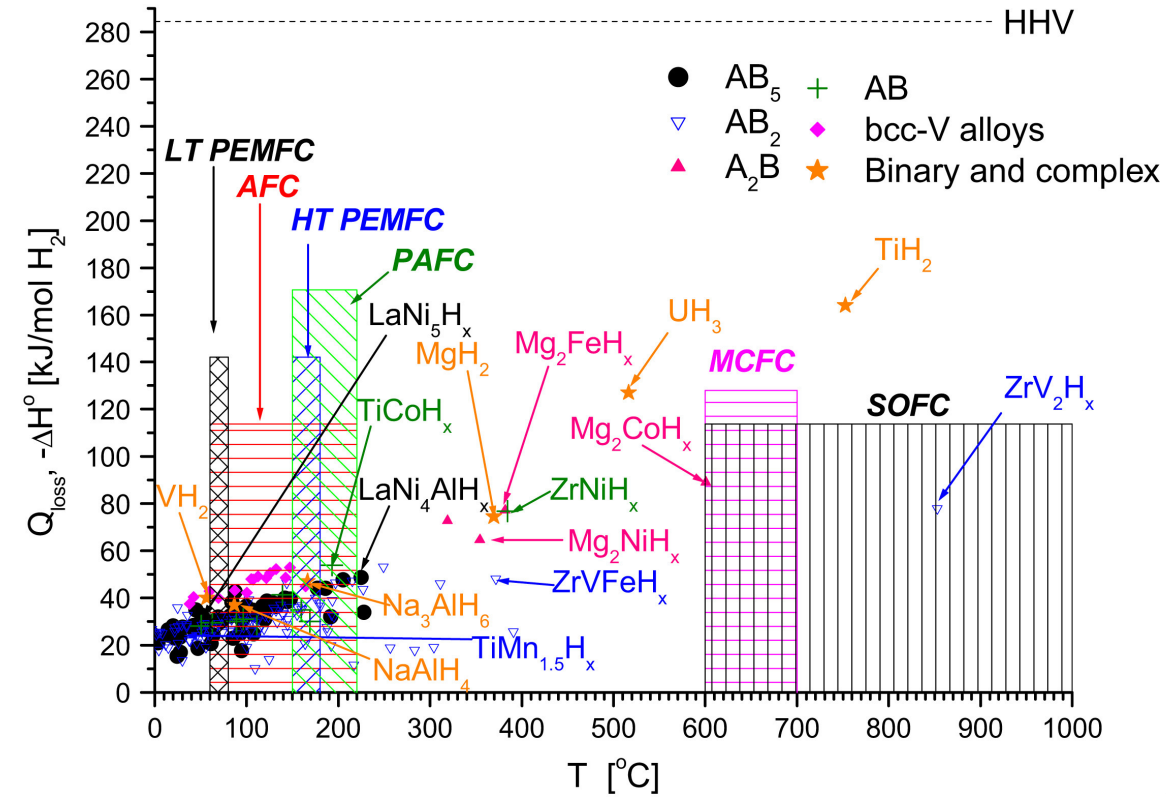
Integration with Fuel Cells



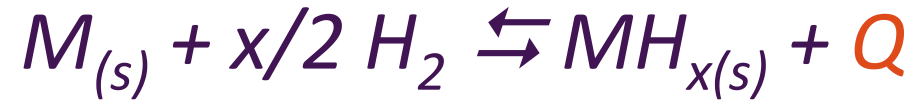
Lototskyy et al., Progress in Natural Science: Materials International 27 (2017) 3



HyCARE Project
Project time: 2019-2023



Safety Benefits



Hydrogen is bound chemically and requires heat to be desorbed

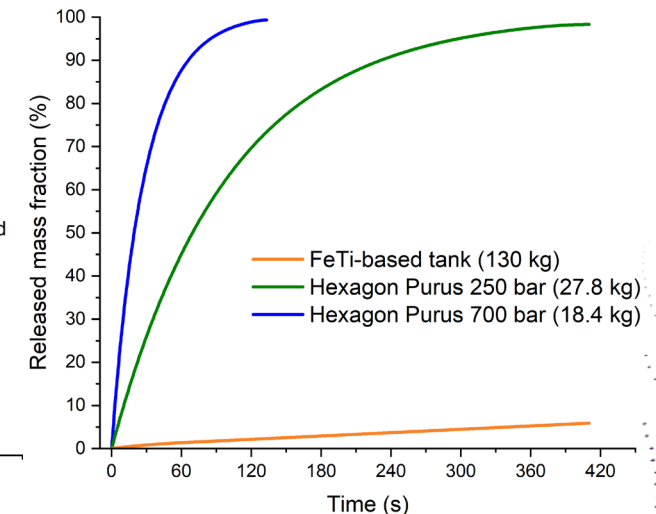
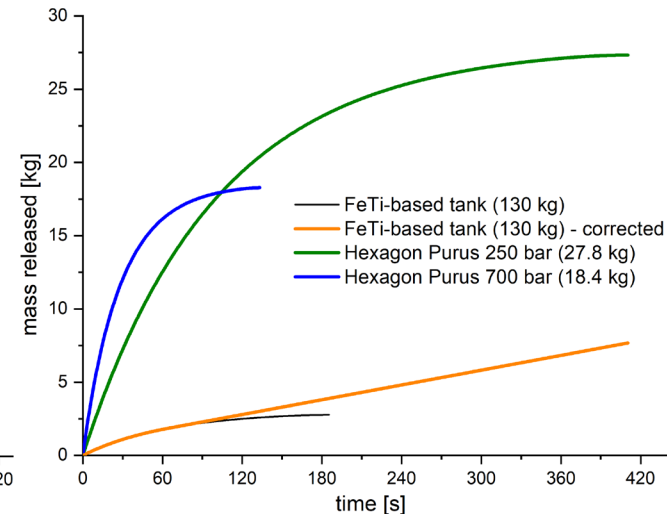
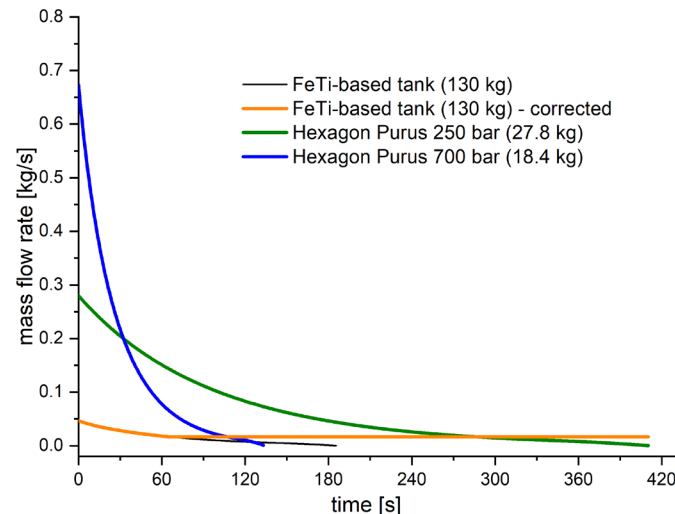
➡ risk associated with leaks in case of tank ruptures is greatly reduced

Comparing blowdown from compressed H₂ and metal hydride storage tanks

- FeTi-based tank with a capacity of 130 kg H₂ operating at **40 °C and 40 bar**
- Type 4 cylinders max pressure of **250 bar**
- Type 4 cylinders max pressure of **700 bar**



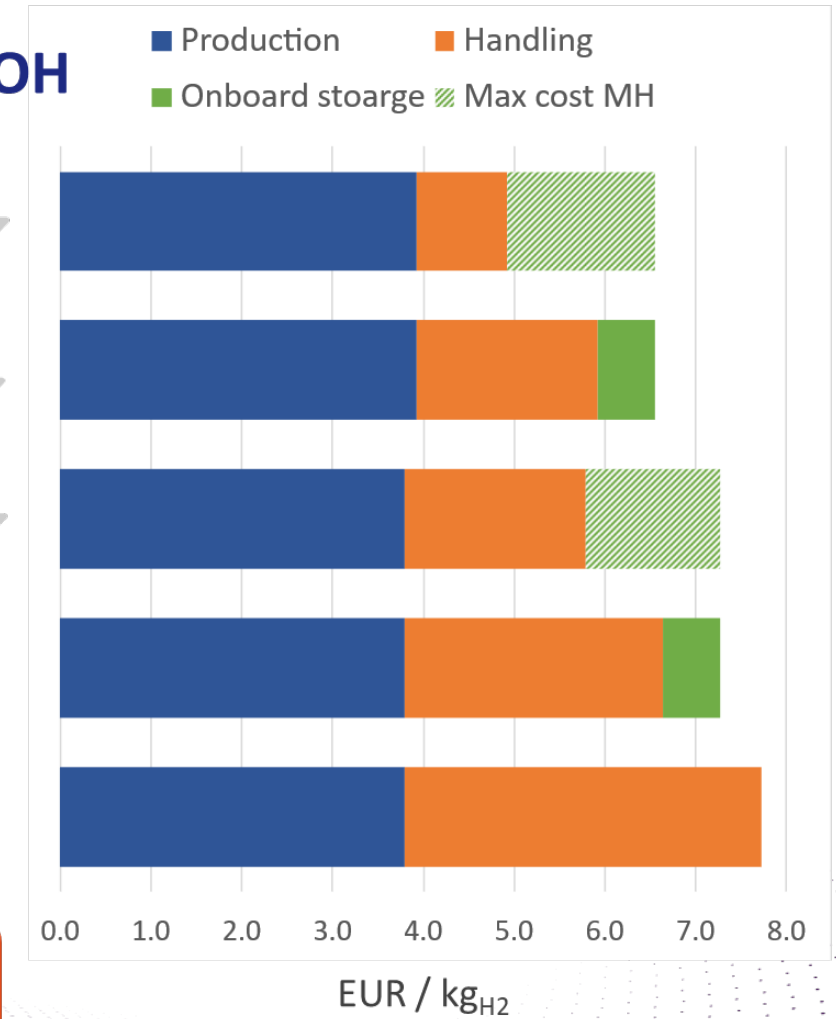
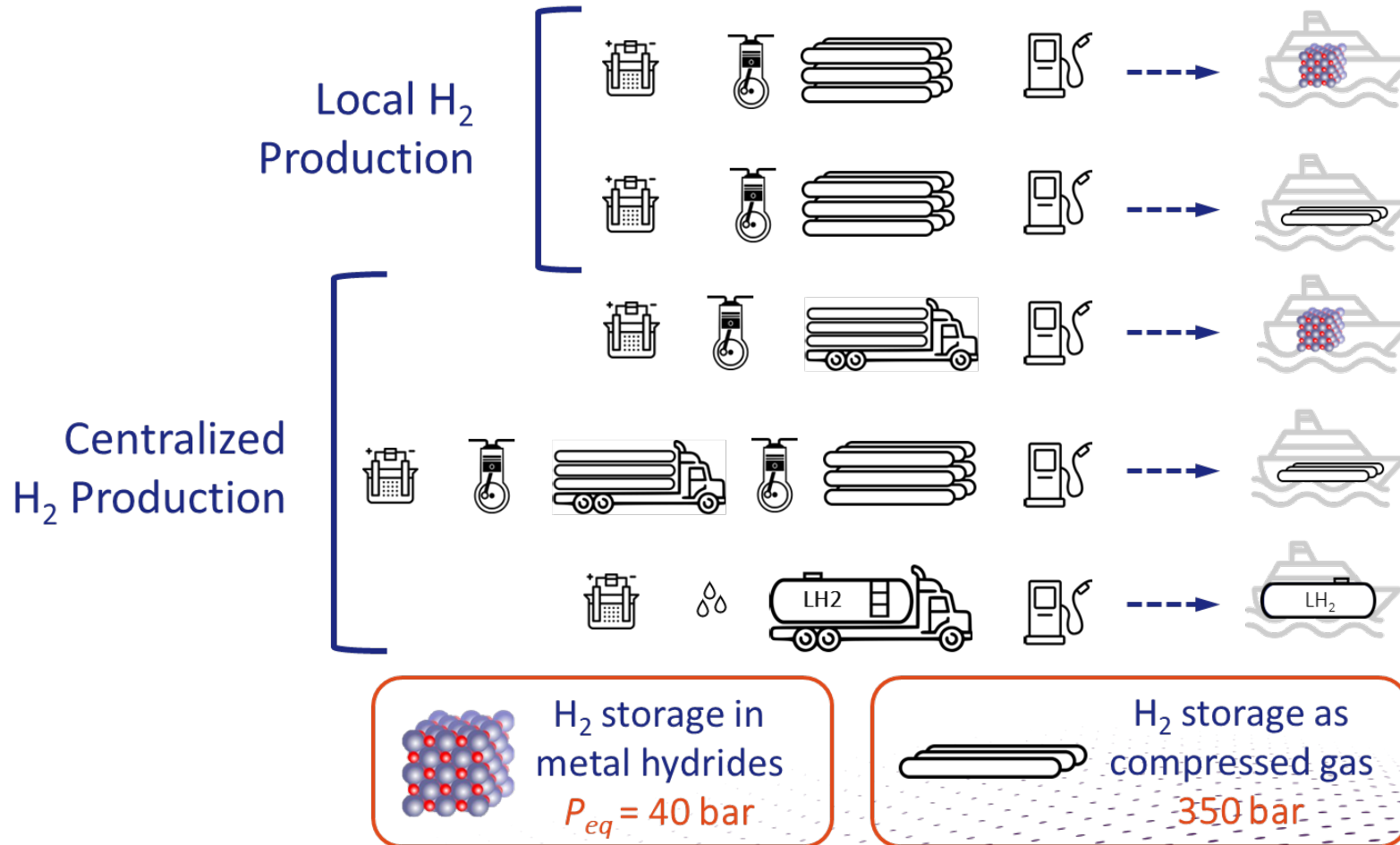
tank blowdown through a 5 mm orifice



Techno-economical benefits

Hydrogen refueling scenarios for a small maritime vessel

LCOH



J. Daneberg, S. Deledda, Int. J. Hydrog. Energy, 50 (2024) 1040-1054

Benefits vs. Costs

Solid-state hydrogen storage can

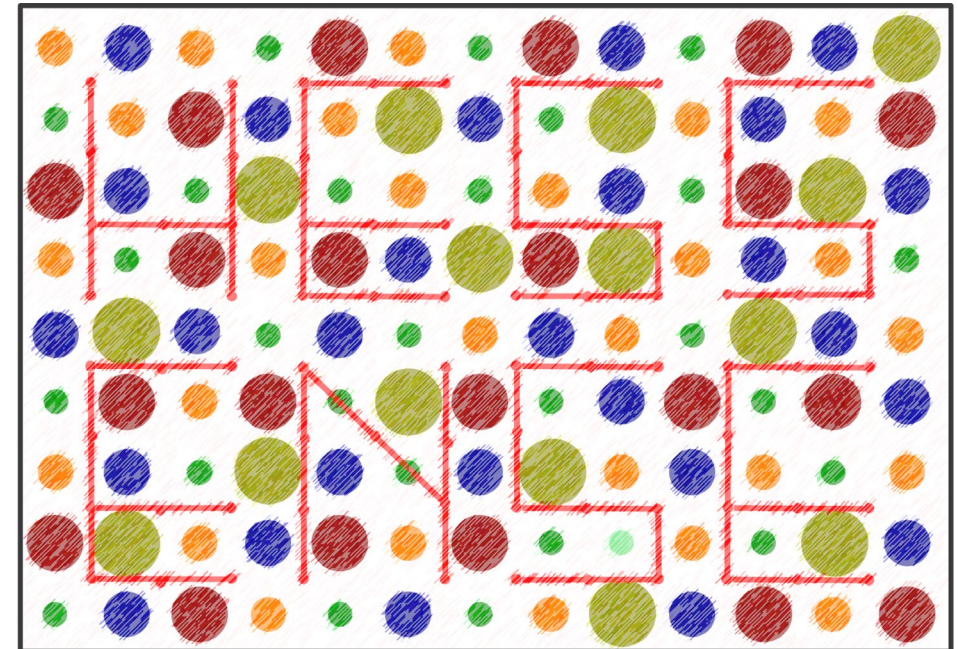
- Increase overall system efficiencies
- Decrease risk from hydrogen leaks
- Significantly simplify the refueling infrastructure

But the costs of metal hydrides (raw materials, production and processing) must be factor in the total investment costs of storage – huge drawback compared to compressed and liquid hydrogen storage

- to achieve a CAPEX comparable to compressed hydrogen storage tanks (ca. 750 €/kgH₂) the cost for a hydride-forming alloy with H₂ capacity of 1.5 wt.% should be around 7 €/kg (current market price is typically well over 20 €/kg)
 - increase gravimetric capacity – HESSENSE
 - use recycled materials to reduce raw materials costs – REMEDHYS

HESSENSE - Light Weight High Entropy Alloys for Safe and Sustainable Energy Storage

- 3-year project from 01.09.2024 to 31.08.2027
- 2 research institutes, 2 universities, and 1 SME from 4 different countries (Norway, France, Poland and Italy)



Light Weight High Entropy Alloys for Safe and Sustainable Energy Storage



UNIVERSITÀ
DI TORINO

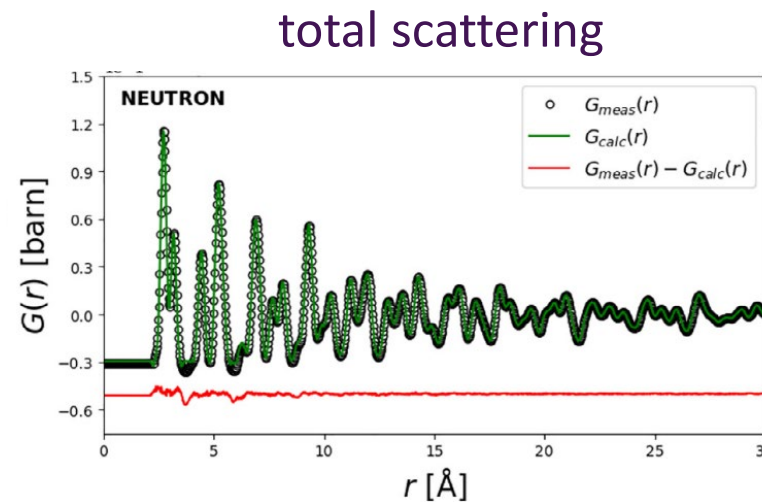
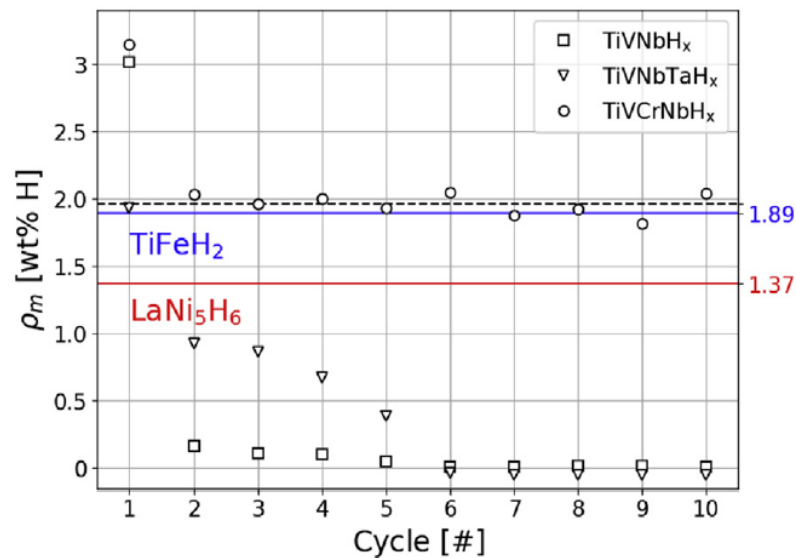
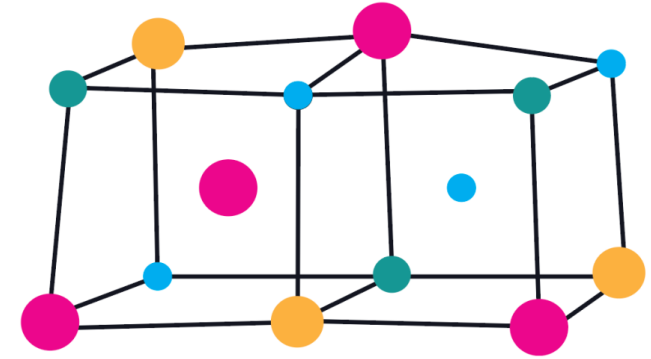


HYSTORSYS



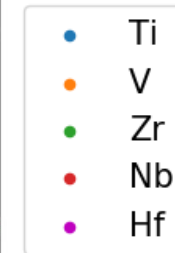
HESSENSE – background

- High Entropy Alloys as Hydrogen Storage Materials
 - single-phase solid solutions stabilized by high entropy of mixing
 - local lattice distortions allow for a variety of interstitial sites that can accommodate hydrogen atoms
- TiVCrNb was shown to reversibly absorb and desorb 2.0 wt.% H₂

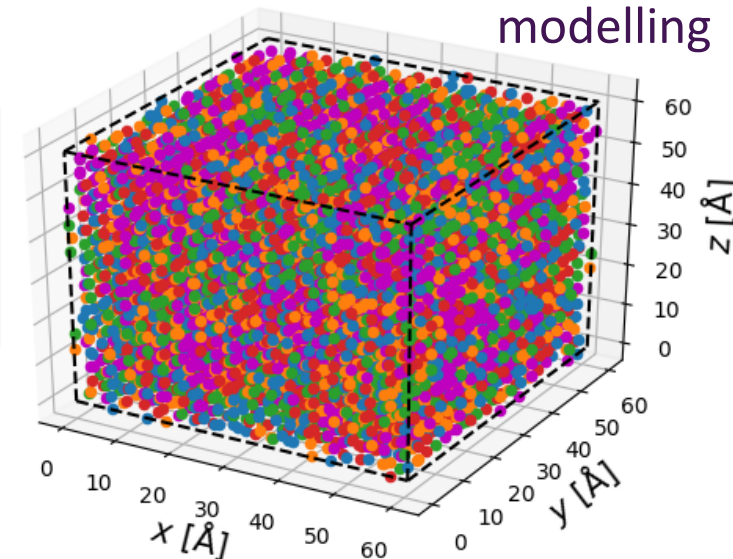


Nygård, Ek, Karlsson, Sørby, Sahlberg, Hauback, Acta Mater. (2019)

Nygård, Sørby, Sakaki, Ikeda, Nakamura, Hauback et al. Acta Mater. (2021)



Reverse Monte Carlo
modelling



HESSENSE – objectives

Main objective:

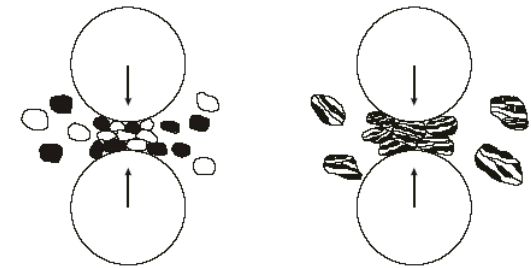
- Design, synthesis, and characterization of light-weight HEAs with properties superior to currently commercially available materials for applications as solid-state hydrogen storage media.

Specific scientific objectives:

- ***Produce selected HEAs with improved hydrogen storage capacity (more than 2.5 wt.% H₂)***
- Improve existing tools based on the Reverse Monte Carlo (RMC) method for studying the short-order in HEAs
- Build a prototype tank with a capacity of 100 gH₂



must combine arc melting with mechanical alloying

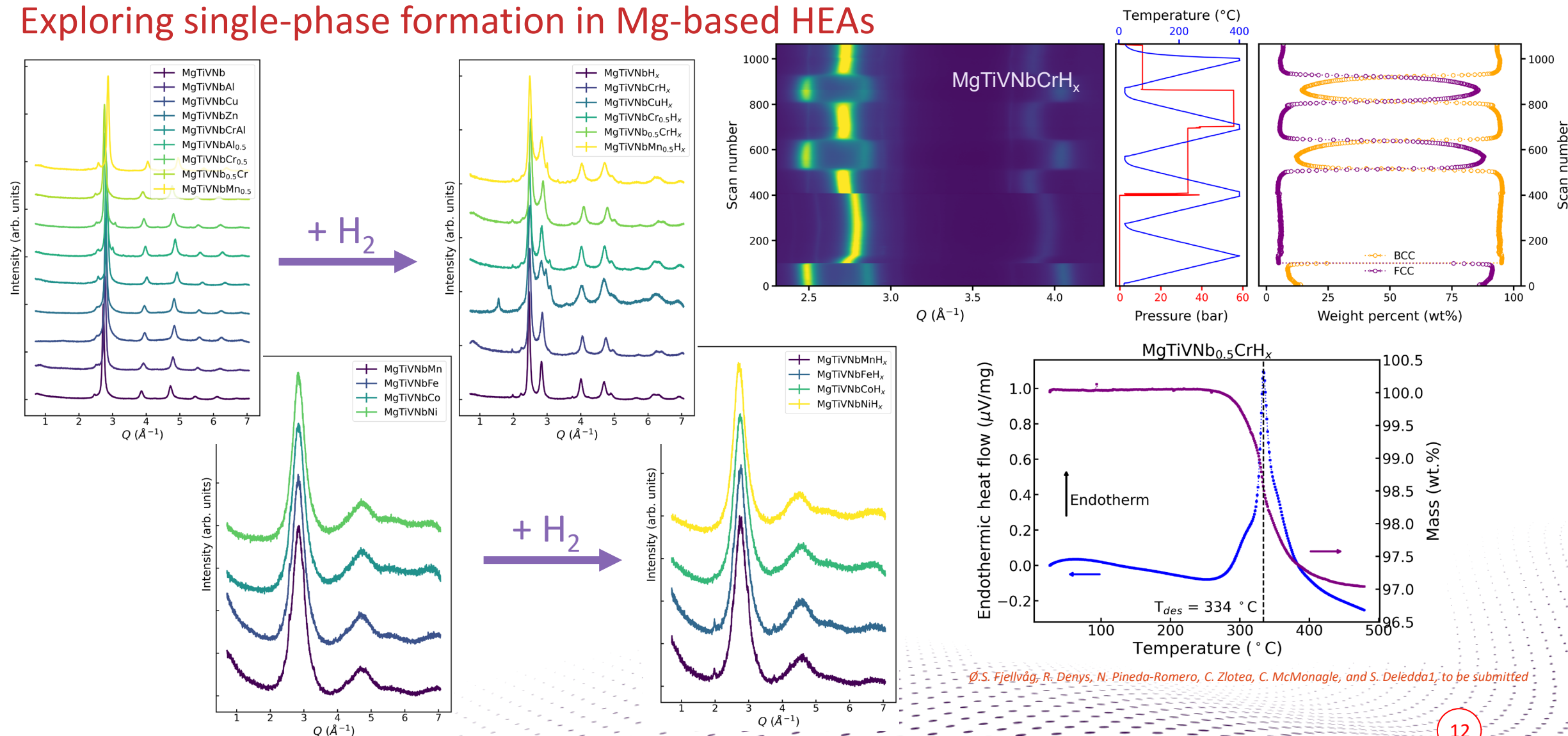


Norwegian team

- Roman Denys – HYSTORSYS
- Øystein S. Fjellvåg – IFE

HESSENSE – results

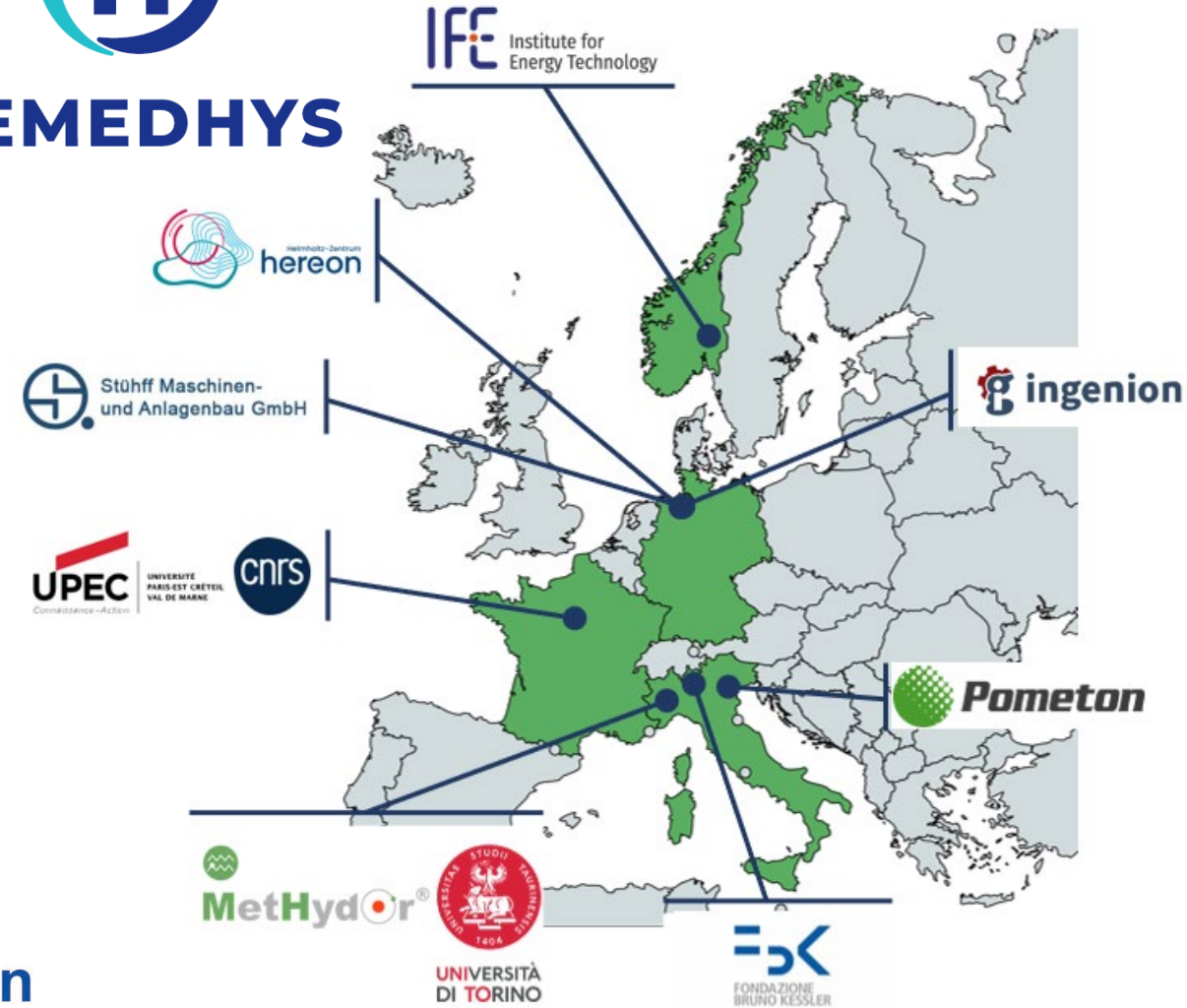
Exploring single-phase formation in Mg-based HEAs



Ø.S. Fjellvåg, R. Denys, N. Pineda-Romero, C. Zlotea, C. McMonagle, and S. Deledda¹, to be submitted

REMEDHYS - REcycled MEtals for aboveground HYdrogen Storage

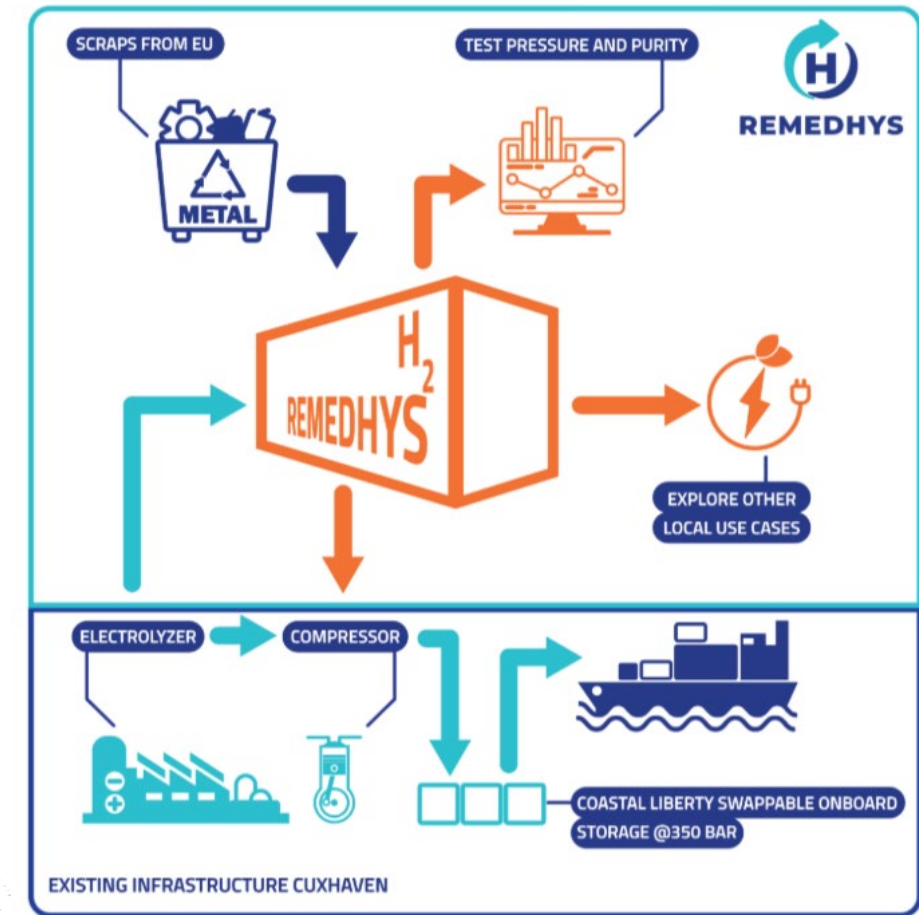
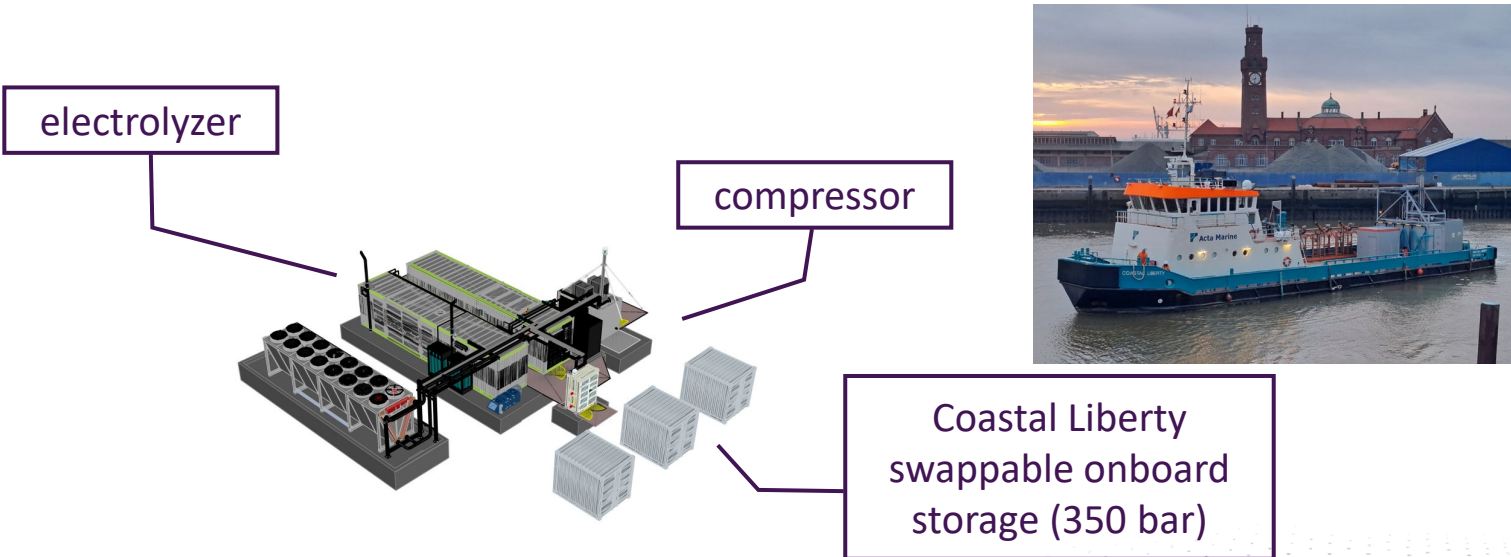
Project period: 01.01.2025 – 31.12.2028 (4 years)
Consortium: 4 research institutes, 2 university and
4 industry partners from Norway, Italy,
Germany and France



Co-funded by
the European Union

REMEDHYS – objectives

- adopt a novel approach in the production of MHs utilizing **recycled starting materials sourced in Europe**, as well as cost efficient, widely automatized production technology to achieve **CAPEX lower than 600 €/kgH₂ by 2030**
- validate in an actual end-use scenario **modular hydrogen storage system with a capacity of 100 kgH₂** and a density of at least 40 kg H₂/m³ on storage container level

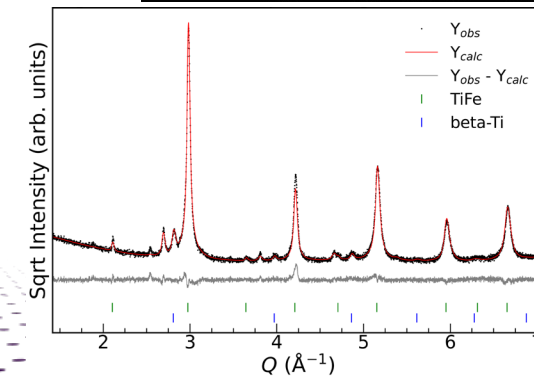
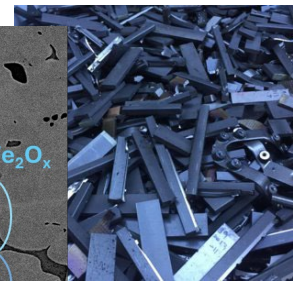
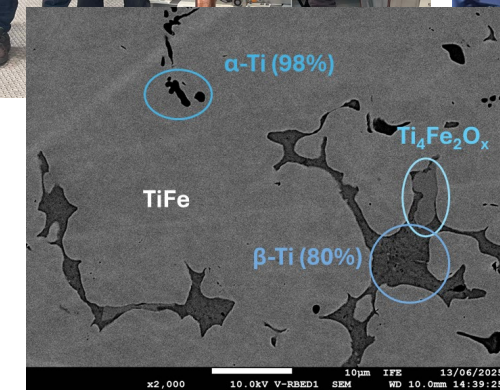


This project has received funding from the European Union's Horizon Europe research and innovation program under grant agreement No 101192503. The project is supported by the Clean Hydrogen Partnership and its members.

REMEDHYS – current activities

Selected alloy: $\text{TiFe}_{0.85}\text{Mn}_{0.05}$ (gravimetric capacity ca. 1.2 wt.%)

- Storing 100 kgH₂ requires about 10 ton of alloy
 - Production by Vacuum Induction Melting at Pometon
 - *Batches of recycled Ti and Fe from different suppliers are currently tested to ensure hydrogen storage properties are retained*
- $\text{TiFe}_{0.85}\text{Mn}_{0.05}$ powder will be mixed with a PFAS-free polymeric binder for consolidation
 - Pellets are produced to minimize volume expansion during hydrogenation and to increase thermal conductivity
 - Pellet geometry and dimension will depend on tank design
 - *Binder selection and pellet production strategies currently underway*
 - *Design of modular tank element currently being finalized*



- Despite high gravimetric capacities and high investment costs, solid-state hydrogen storage in metal hydrides can represent an attractive alternatives to compressed and liquid hydrogen storage depending on the end use.
- Materials design and processing remains crucial for advancing technological and commercial maturity of hydrogen storage in metal hydrides

Acknowledgements



- Roman Denys – HYSTORSYS
- Øystein S. Fjellvåg – IFE
- Bjørn C. Hauback – IFE



The M-ERA.NET project **HESSENSE** and funded by the Research Council of Norway (project no. 353465)



Co-funded by
the European Union

REMEDHYS has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking (now Clean Hydrogen Partnership) under Grant Agreement No 101192503. This Joint Undertaking receives support from the European Union's Horizon 2020 Research and Innovation programme, Hydrogen Europe and Hydrogen Europe Research



Thank you for your attention!

Stefano Deledda
Principal Scientist

+47 407 21 926
stefano.Deledda@ife.no