TU Graz
SCIENCE
PASSION
TECHNOLOGY

F&E chemischer Speicher für erneuerbare Energien

Energy Lunch | 23 Sep 2026

Prof. Viktor Hacker
Head of the Institute of Chemical Engineering and Environmental Technology

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Institute of Chemical Engineering and Environmental Technology

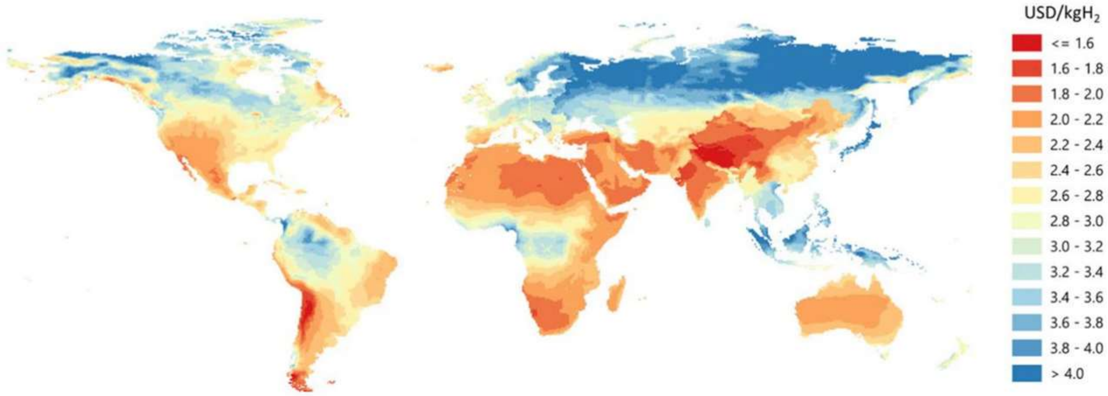
Research & Innovation in Sustainable Process Engineering

Advanced chemical process engineering
Environmental technologies and circular economy
Sustainable energy and resource efficiency
Industrial-scale innovation and applied research

tugraz.at/institute/ceet/news

Economics of hydrogen production methods

Hydrogen costs from hybrid solar PV and onshore wind systems in the long term



Transportation of Oil

million barrels per day

Location	2020	2021	2022	2023	2024	1H25
Strait of Malacca	22.8	22.1	23.0	24.0	22.5	23.2
Strait of Hormuz	19.2	19.7	21.9	21.8	20.7	20.9
Suez Canal and SUMED Pipeline	5.4	5.2	7.3	8.8	4.8	4.9
Bab el-Mandeb	5.7	6.0	8.0	9.3	4.1	4.2
Danish Straits[a]	3.1	3.1	4.2	5.0	4.9	4.9
Turkish Straits (Dardanelles)	3.2	3.3	3.2	3.5	3.6	3.7
Panama Canal[b]	1.7	1.8	2.2	2.2	2.0	2.3
Cape of Good Hope	7.9	7.2	6.1	6.2	9.3	9.1
World maritime oil trade	**74.1**	**75.9**	**78.6**	**80.2**	**79.7**	**79.8**
World total oil supply	**94.1**	**95.8**	**100.6**	**102.6**	**103.3**	**104.4**

U.S. Energy Information Administration (EIA), Short-Term Energy Outlook, 2026.
IEA (2019), The Future of Hydrogen, IEA, Paris https://www.iea.org/reports/the-future-of-hydrogen

Limitations of Current H_2 Storage Methods

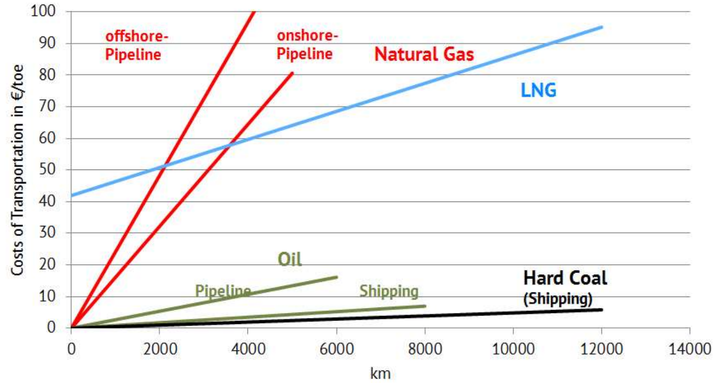
Method	Pressure	Temperature	Energy Density	Safety	Toxicity
Compressed H_2	700 bar	Ambient	Low	✗	☑
Liquid H_2	1 atm	−253°C	High	⚠	☑
LOHCs	1–10 bar	~150–200°C	Medium	☑	⚠
NH_3 Ammonia	10 bar	−33°C	High	⚠	✗
Metal Hydrides	Low	100–300°C	High (volum.)	⚠	⚠

☑ Good / Acceptable ⚠ Caution / Moderate ✗ Poor / Unfavorable

"So… is there a method that avoids all of these trade-offs?"

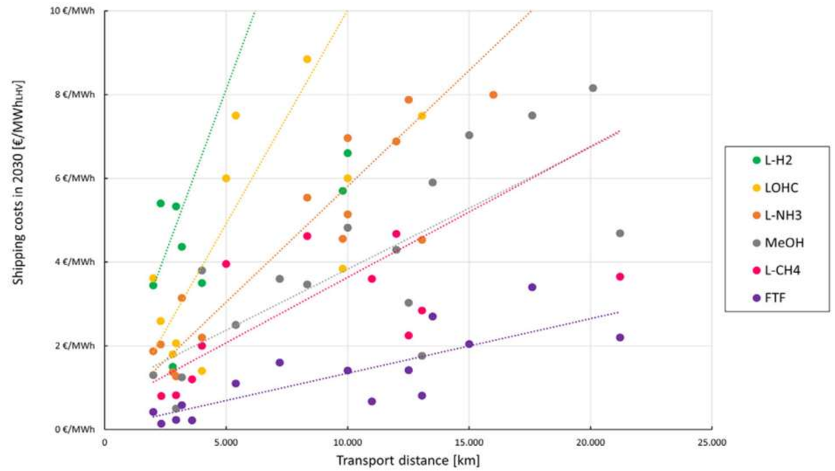
The Urgency of Hydrogen Storage in a Renewable Energy Future

"In some regions, up to 10-30% of renewable energy is curtailed , not because we can't generate it, but because we can't store or move it." (Source: IEA, Ren 2024, FT 2025)



Why is storage critical?

- Renewables are intermittent
  (→ Unmatched generation vs demand)
- Hydrogen is a scalable storage medium
  (→ Especially for long-term and intercontinental transport)
- Compression & liquefaction are expensive
  (→ +\$5.0/MWh for pipelines, \$13–\$20/MWh for liquefaction)
  IEA (2021), Global Hydrogen Review
- No global H_2 infrastructure yet
  (→ Unlike oil & gas)
- Fossil fuels remain cheaper to move
  (→ Oil: ~\$0.77/MWh/1000 miles | HV-DC: ~\$41.5/MWh) Schuler et al., Int. J. Hydrogen Energy (2024)



VDKI (Verein Deutscher Kohleimporteure) (1999),J. Petrol. Techn.
Schuler, (2024). *J. Hydrogen Energy* https://doi.org/10.1016/j.ijhydene.2023.10.004

Without scalable hydrogen storage, renewable energy hits a wall.

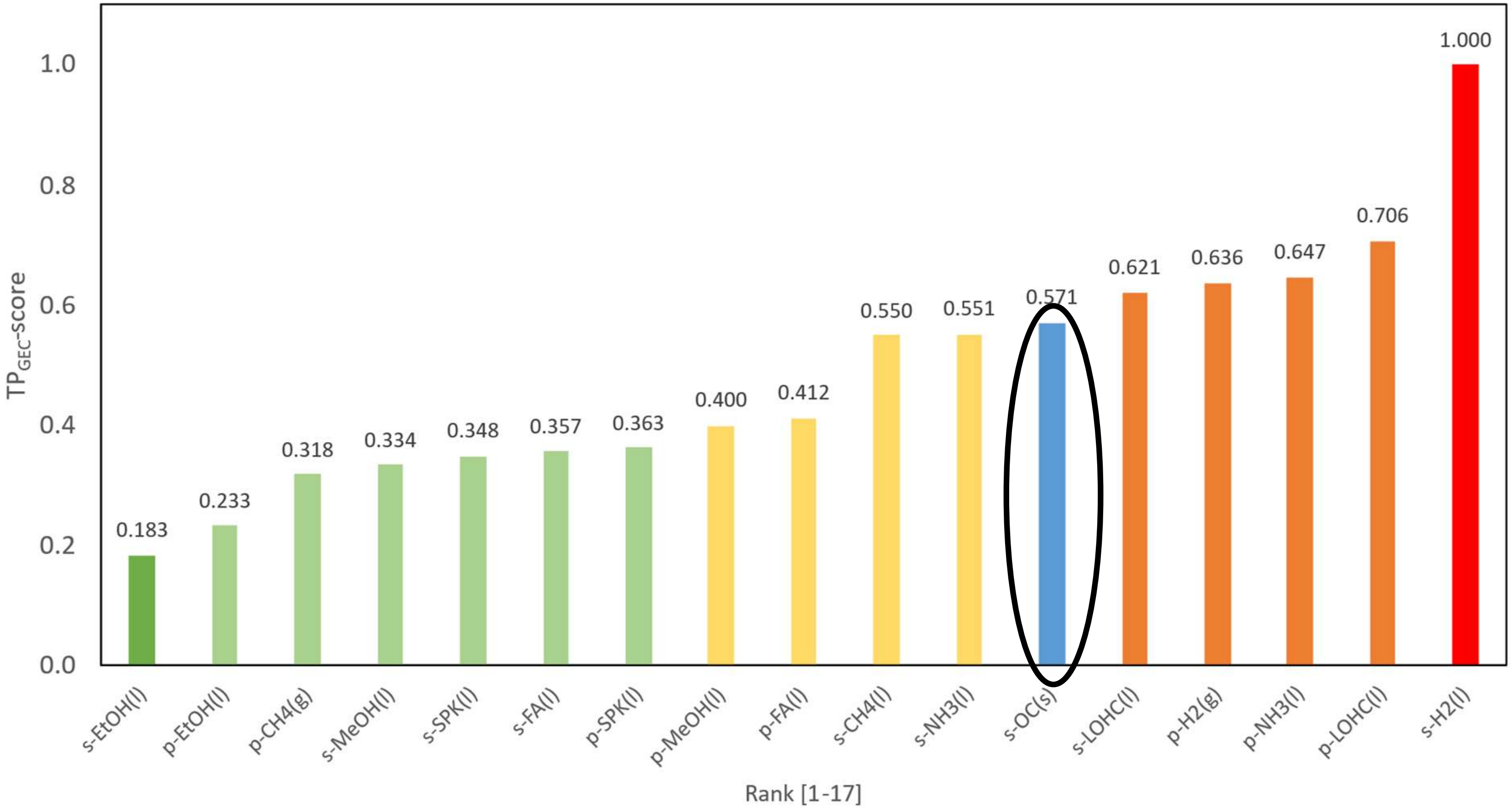
Transportation of Green Energy Carriers

- Evaluation Scores: Transport Performance score
- Hazard score: Hazards associated with the energy carrier
- Rigidity score: Versatility and ease-of-use
- Energy Transportation Cost score: standardized, unitless

$$TP_{GEC} = \frac{\left(ETC_{score} + H_{score} + R_{score}\right)^{highest}}{\left(ETC_{score} + H_{score} + R_{score}\right)_{GEC}}$$ GEC…Green Energy Carrier

[Kroon et al., A comparative cost and qualitative analysis for the transportation of green energy carriers, RSC, 2025]

Transportation of Green Energy Carriers



s…shipping
p…pipeline
Mediterranean transport for 557-2091 km transportation distance

[Kroon et al., A comparative cost and qualitative analysis for the transportation of green energy carriers, RSC, 2025]

Research Areas – Energy Carriers

Merit Bodner

Head of Working Group

- PEM fuel cells
- Water electrolysis
- Durability
- Advanced electrochemical materials

Susanne Lux

Deputy Head of the Institute

- Sustainable reaction engineering
- Process intensification
- Lithium-ion battery recycling

Marlene Kienberger

Deputy Head of the Institute

- Biorefining
- Lignin separation
- Recovery of bio-based chemicals

Viktor Hacker

Head of the Institute

- Green hydrogen
- Scalable fuel-cell technologies
- Iron-based energy carriers

Our Team and Research Areas

Merit Bodner

Head of Working Group

Increased Sustainability in Fuel Cells and Electrolysers

- Development and Impact Analysis of Novel, Non-Fluorinated Materials in Fuel Cells and Electrolysers
- Lifetime Extension and Second Life
- Designing Catalyst Layer Architectures

Diagnostic Techniques for Fuel Cell and Electrolyser Degradation

- Development and Harmonisation of Test Procedures
- Monitoring of Degradation Product Emission
- Improved Mechanistic Understanding of Degradation Processes

Alternative Electrochemical Processes

- Development of Sulphur Depolarised Electrolysis
- Optimise Operation Strategies and Material Development

SUPREME applies a PFAS-free qualification workflow

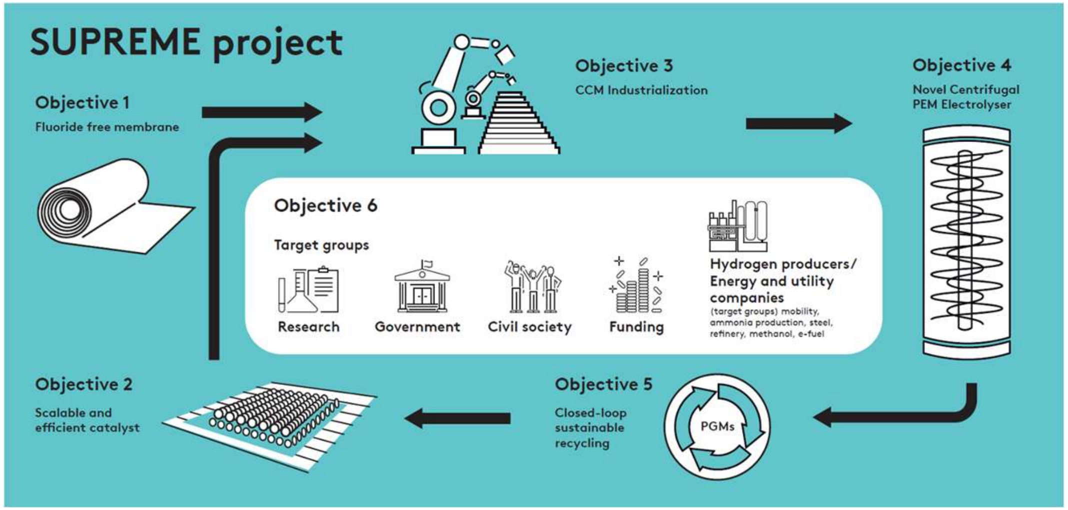
Industrialization of new generation sustainable, low-cost, high performance, novel water electrolysis material, production & system

Objectives

1) Advancing NF PEM scientific & market development
2) Electrocatalyst sustainable development and upscaling
3) Efficient MEA manufacturing and component validation
4) Novel centrifugal electrolyser design and operation
5) Catalyst material sustainable recycling
6) Commercialization and market expansion

KPIs

- 45 kWh/kg H_2 at a current density of 3 A/cm^2
- Reach TRL 5 based on a novel centrifugal electrolyzer
- Non-fluorinated proton exchange membrane (NF PEM) and high-performance recycled catalyst.



Project duration

December 2025 – November 2028

Project partners

TU Graz, SDU, AMES Goldsmith CEIMIG, TÜBİTAK, EoneE, Fraunhofer ISE

The SoutH2 Corridor initiative (Project of Common Interest)

3,300 km
length

> 65 %
repurposed infrastructure

> 4 Mtpa
Green Hydrogen Import potential

early 2030s
in operation

Abschnitt / Teilprojekte	Betreiber
Italian H_2 Backbone	Snam
H_2 Readiness of TAG Pipeline System	TAG
H_2 Backbone WAG + Penta-West	Gas Connect Austria
HyPipe Bavaria – The Hydrogen Hub	bayernets
Tunesien–Sizilien / North Africa H_2 Backbone	SeaCorridor

Our Team and Research Areas

Susanne Lux

Deputy Head of the Institute

Enhanced Hydrometallurgical Recycling of Lithium-Ion Batteries

- CO_2-Enhanced Selective Leaching of Lithium
- Solvent Extraction Technologies for Metal Recovery
- Process Intensification through Continuous Multiphase Operations in the Taylor-Couette Disc Contactor (TCDC)

Novel Plasma-Assisted Processes

- Synthesis of Ammonia from Green Hydrogen in a DBD reactor
- Novel Concepts for Carbon Capture and Utilization using Solid Sorbents and Plasma

Advanced Reactive Separation Technologies

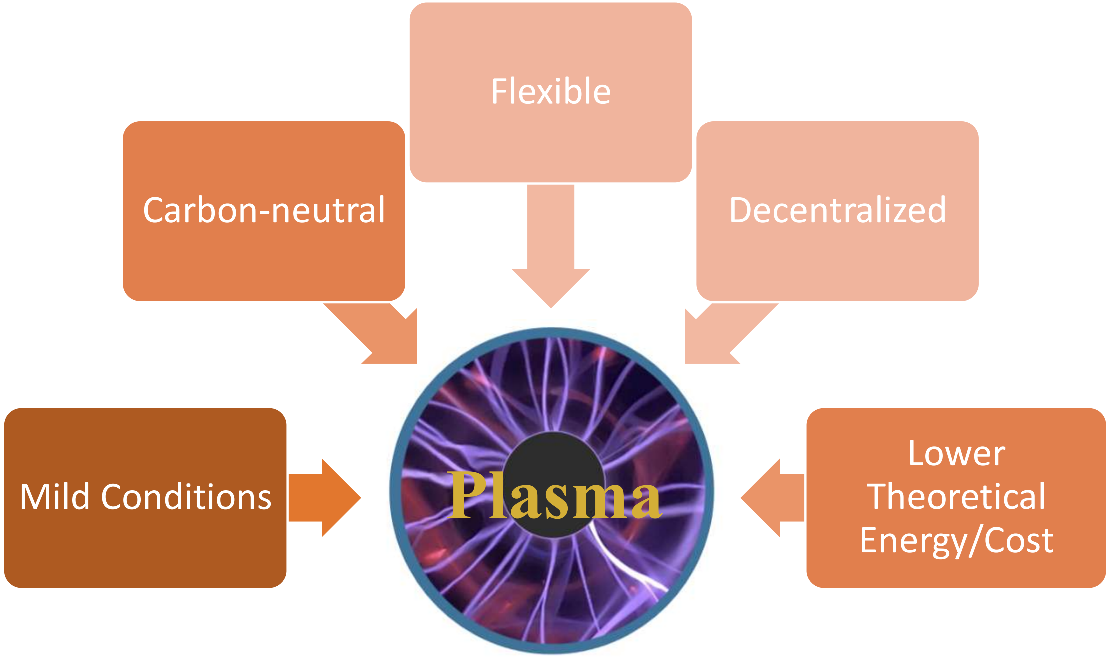
- Carbon Capture and Degassing using Novel Sorbents, Apparatuses and Technologies

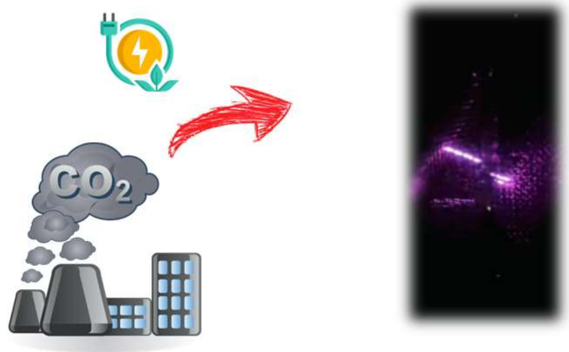
Intensification of Biotechnological Processes

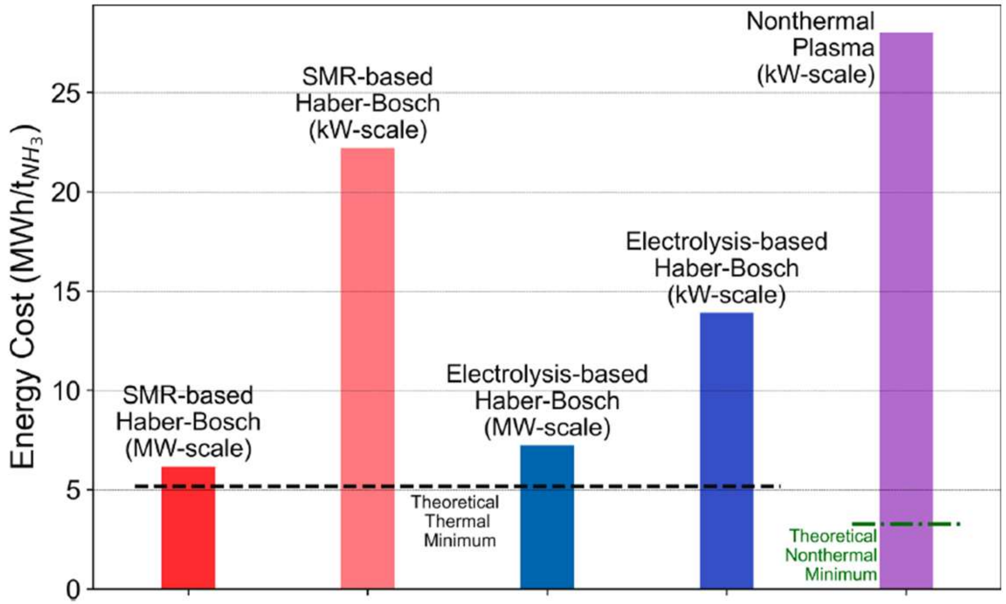
- Intensification of Microbial Synthesis through Application of TCDC Bioreactors
- Enhanced Technologies for Downstream Processing of Fermentation Broths

Plasma-Assisted Ammonia Synthesis

Advantages Compared to Haber-Bosch



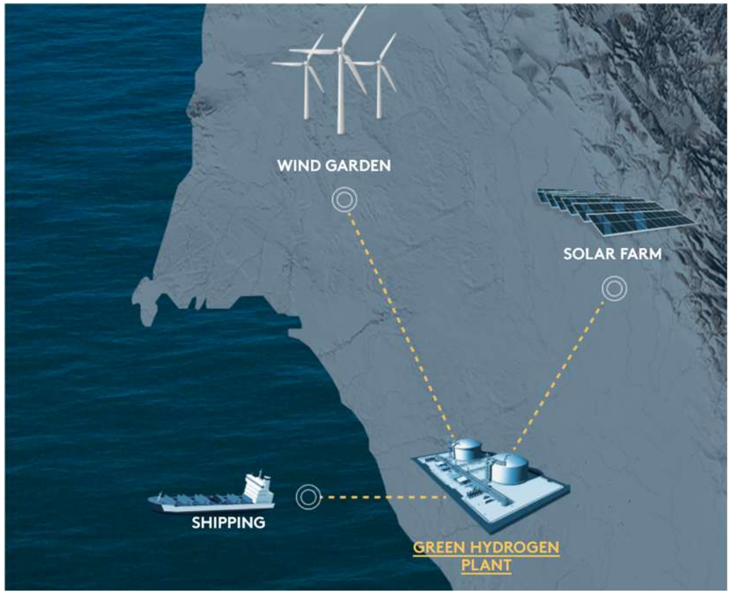




Kosca et al., *Energy Conversion and Management,* **2025,** 333, 119802
Kim et al., *Plasma Processes and Polymers*, 2017, 14(6), 1600157

NEOM Green Hydrogen Company, Oxagon, Saudi Arabia

- **Production of green hydrogen and green ammonia**
  2.2 GW PEM electrolysis, *4 GW of wind + solar*
- **Construction Progress** completed
- **Total Investment:** USD 8.4 billion
- **Target:** ~600 tons H_2/day → 1.2 Mtons NH_3/year
- **Offtake Agreement:** 30-year exclusive with Air Products
- **Planned Commissioning:** 2027
- **Export:** Green ammonia (maritime export to Europe and Asia)



Our Team and Research Areas

Marlene Kienberger

Deputy Head of the Institute

Development of biobased value chains

- Feed materials: industrial intermediate process streams, agricultural residues and biogenic CO_2
- Efficient water management in biorefineries by developing and adapting separation technologies (e.g. membrane processes)
- Removal of impurities such as nitrogen or inorganics from intermediate oily and lipid process streams in biorefineries
- Increased material utilization by investigation and modelling of solubilities of biogenic species (e.g. xylan, lignin)

Development, characterisation and application of novel solvents from renewable resources

- In absorption heat pumps
- For *in-situ* reactive extraction of carboxylic acids from fermentation broth
- For carbon capture
- Measurement of solvent properties for industrial application

Working group Biorefinery, Head of working group: Assoc.-Prof. Dipl.-Ing. Dr.techn. Marlene Kienberger

ToFuel – an integrated biorefinery concept for sustainable aviation fuel production from tomato residues

Sustainable aviation fuel

Fertilizer

Fodder

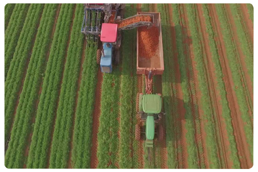
Nutritional oil

…

Funded by the European Union

Innovative biorefiney concept


Residues from Tomato production and processing




Topics @TUGraz
Project coordinator
Separation and purification of intermediate process streams (oils and lipids)
Water management for the wjhole biorefinery

ToFuel ...brings together

11 Partners from 7 European countries

€3.5 M for 48 months
EU-Funded
grant agreement
No 101235233

Start:
01/01/2026

Fraunhofer · Energy Efficiency in Industrial Processes · LUT University · ESEIA European Sustainable Energy Innovation Alliance · Montanuniversität Leoben · TU Graz · TU Wien Technische Universität Wien Vienna University of Technology · LNEG · Mutti · faculty of food technology and biotechnology University of Zagreb · Podravka Grupa

Funded by the European Union under Grant number 101235233. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them.

Our Team and Research Areas

Viktor Hacker

Head of the Institute

Manufacturing and Scale-Up of Electrochemical Components

- Slot-die coating for scalable electrode manufacturing processes
- Ultrasonic spraying: Simple and rapid fabrication of electrodes
- Electrospinning: Reproducible fabrication of structured electrodes
- Lifetime and durability testing

New Energy Carriers for a Renewable Energy Economy

- Metals such as iron as innovative and recyclable energy carriers
- Energy storage and transport systems for renewable energy

Chemical Looping & CO_2 Capture

- Contact materials for chemical looping processes
- CO_2 capture using calcium looping
- Hydrogen production via chemical looping

R&D Infrastructure Funding: Multipurpose Coater (Coat&Roll)

- Development and expansion of R&D infrastructure for internationally recognized research activities ("hot spots").
- Strengthening the competitiveness of companies engaged in research.
- Pioneering scientific research and high-quality education in future-oriented research fields as part of non-commercial activities.
- **Coat&Roll:** Research into the manufacture of electrochemical components for **fuel cells** and **electrolyzers**, as well as innovative **solar-cell technologies**.

Epishine AB, Sweden. R2R production of Organic Photovoltaics. Indoor OPV.

Argonne National Lab, USA. R2R production of Li-ion car batteries.

Institute of Chemical Engineering and Environmental Technology
Institute of Chemistry and Technology of Biobased Systems
Institute of Chemistry and Technology of Materials
Institute of Bioproducts and Paper Technology
Institute of Production Engineering
Institute of Fluid Mechanics and Heat Transfer
Institute of Electrical Measurement and Sensor Systems

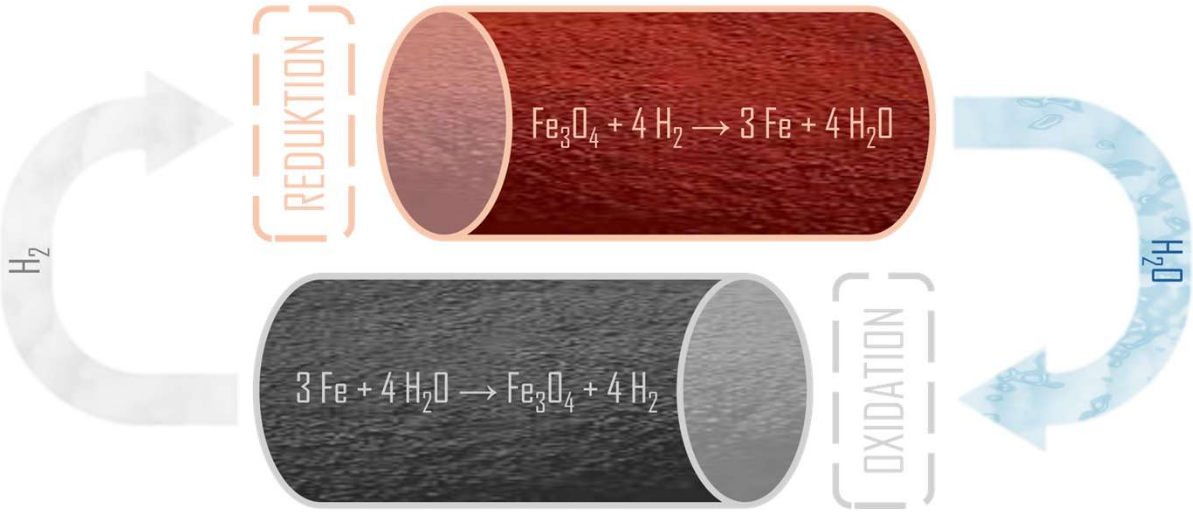
Why Solid-State? Why Iron?

- **Iron is abundant, cheap, and recyclable**
  → Available globally, with low extraction and processing cost.
- **Reversible redox cycling ($Fe + H_2O \leftrightarrow FeO + H_2$)**
  → Iron can **store hydrogen chemically** and release it cleanly through steam oxidation.
- **Solid-state = safer storage**
  → No high pressure, no cryogenics, no explosion risk or boil-off losses.
- **Environmentally benign**
  → Non-toxic, no hazardous chemicals or catalysts involved.
- **Integrates with chemical looping systems**
  → Enables continuous operation in closed energy cycles (e.g. HyLoop process)
- **Favorable energy density**
  → Comparable to hydrides on a system level , but cheaper and more stable.

Method	**Iron** (solid)
Pressure	1 atm
Temp	~800–1000°C
Energy Density	Medium–High*
Safety	☑
Toxicity	☑

"Iron offers a solid, scalable, and safer path toward hydrogen storage, without the trade-offs of current systems."

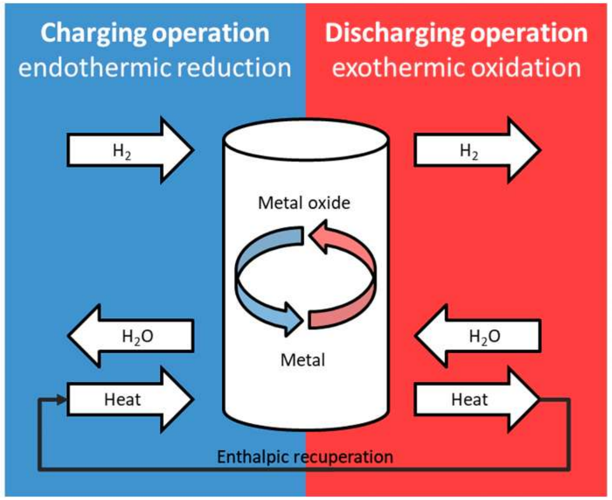
Chemical Looping Hydrogen (CLH)



- Reduction and oxidation typically at 650 – 900°C
- Heat required to heat up **1 kg of iron: 0.095 kWh/kg$_{Fe}$**
- Theoretical maximum energy storage density: **1.9 kWh$_{HHVH2}$/kg$_{Fe}$**

Iron-Based Redox Reactions: Foundations and HyLoop Pathway

- Reversible redox reaction: Metal + $H_2O \rightleftharpoons$ Metal Oxide + H_2
- The potential for hydrogen is stored and released via oxidation/reduction
- No need for compression, liquefaction, or high-pressure tanks
- Core mechanism for chemical looping hydrogen systems (e.g. HyLoop)



Generic formulae

Reduction of metal oxide for energy storage

$MO + H_2/CO \rightarrow M + H_2O/CO_2$

Oxidation of metal for H_2 release

$M + H_2O \rightarrow MO + H_2$

HyLoop

Reduction of iron oxide for energy storage

- $3\,Fe_2O_3 + H_2/CO \rightarrow 2\,Fe_3O_4 + H_2O/CO_2$
- $Fe_3O_4 + H_2/CO \rightarrow 3\,FeO + H_2O/CO_2$
- $FeO + H_2/CO \rightarrow Fe + H_2O/CO_2$

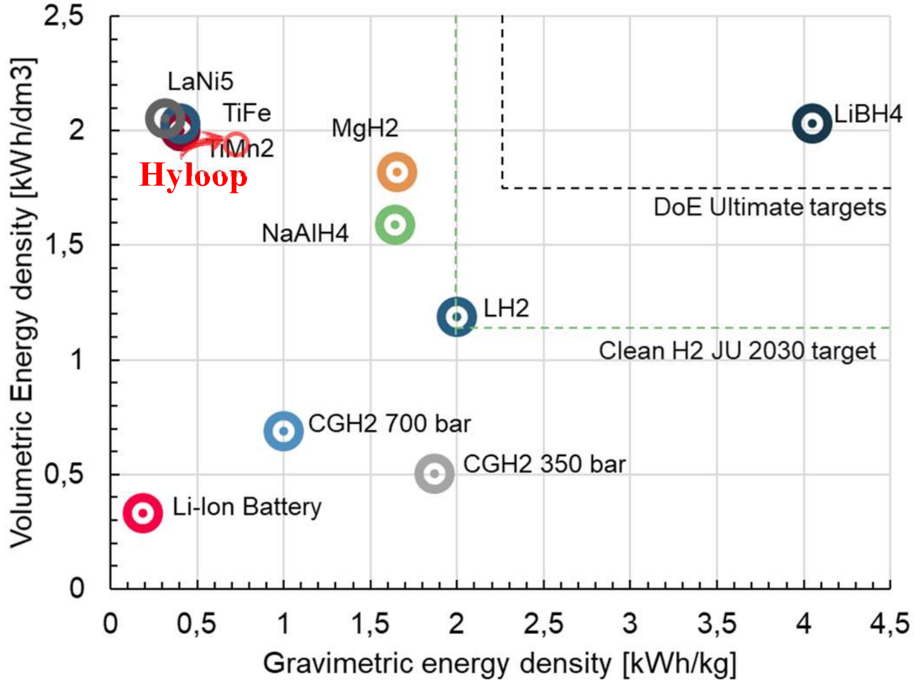
Oxidation of iron for H_2 release

- $Fe + H_2O \rightarrow FeO + H_2$
- $3\,FeO + H_2O \rightarrow Fe_3O_4 + H_2$

"From core reactions to full-scale looping , HyLoop translates redox chemistry into practical hydrogen storage."

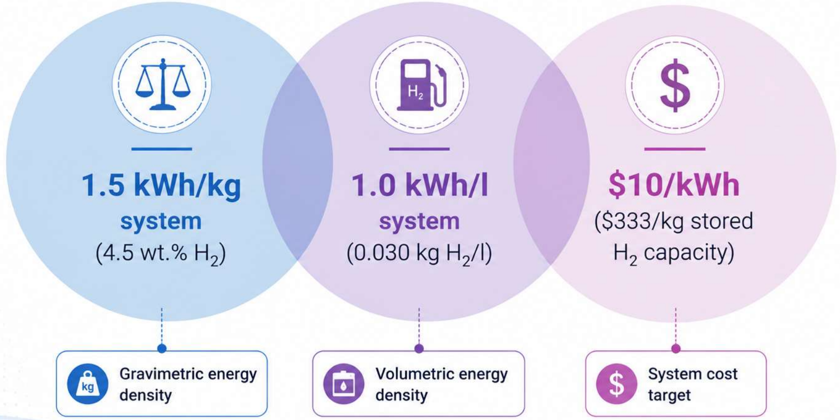
Comparison with Literature

- **HyLoop** achieves a balance between energy density and safety
- Outperforms hydrides in terms of cost and toxicity
- Avoids critical and scarce raw materials (e.g., Li, B)
- Comparable to DOE 2030 targets



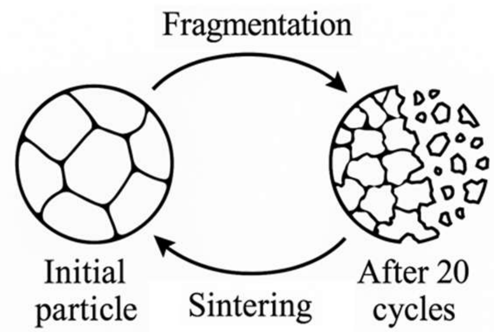
https://doi.org/10.1016/j.est.2023.108456

DOE Targets:



Material Challenges in Iron-Based Hydrogen Storage

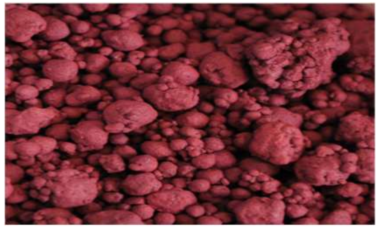
- **Sintering at high temperature**
  → Surface area loss, slower reactions
- **Pellet disintegration**
  → Poor mechanical integrity after cycling
- **Carbon deposition**
  → Blocks active sites, lowers efficiency
- **Redox-induced structural stress**
  → Fractures, deformation, cycle fatigue

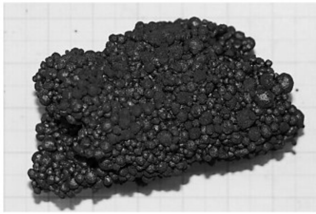


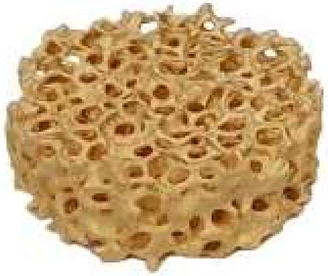
Iron-based hydrogen storage material

Cycles	H_2 Yield	Structural Integrity
0	100%	Excellent
25	95%	Partial cracks
50	85%	Disintegration

Material Development





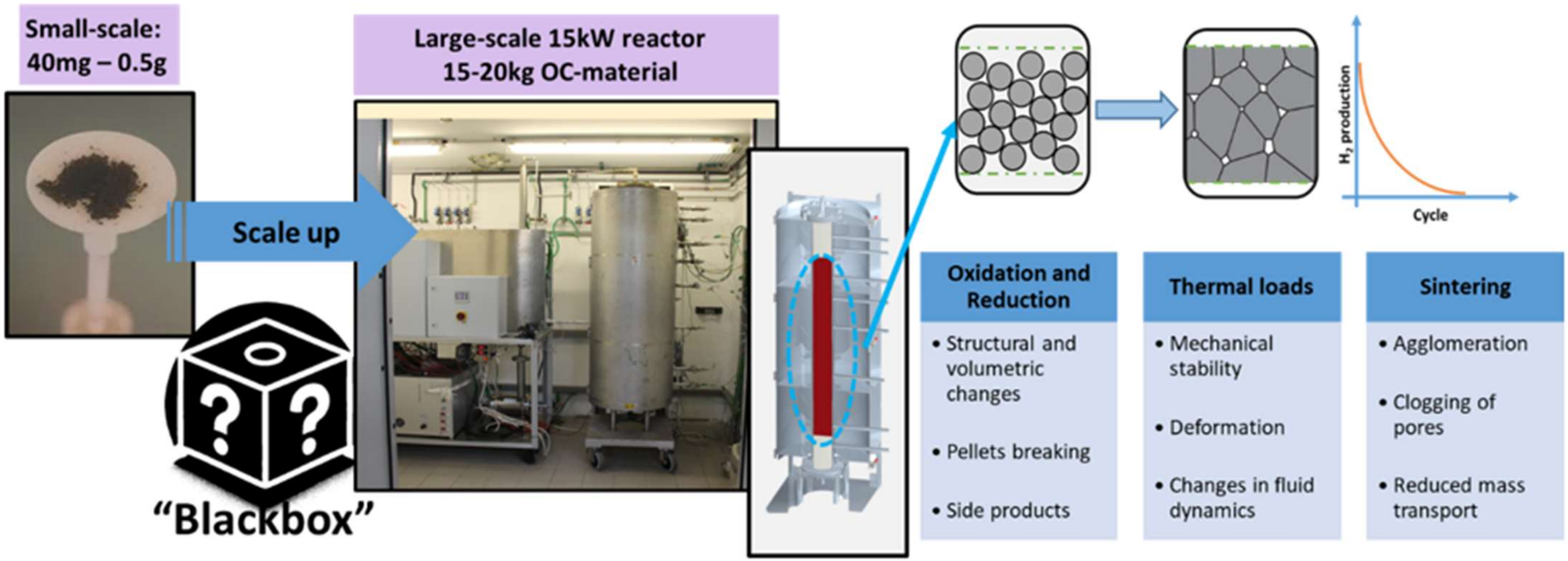


Starting Point

Improvement

Solution

Reasearch Focus



Source: Phd Thesis Fabio Blaschke, 2024

Technical Challenges

Ideal Energy Density
16.7 kWh/L
2.4 kWh/kg

The real Energy Density is dependent on

- Auxillary equipment
  - Reactor
  - Heat and media supply
- Material shape
  - Spherical
  - Cylindrical
  - Irregular
- Inert additives
  - Support structures
  - Intermixed stabilisers

Application of CLH: Caloric Utilisation - Thermal Power Plant

- 10–100 µm iron powder
- Combustion in existing coal-fired power stations
- The resulting oxides can be recycled metallurgically
- The first burner system was installed in 2020 in Bavaria (Metalot)

Flame of Iron Powder
Eindhoven University of Technology

FIRES: Flexible Iron Redox Energystorage System

Development of an innovative storage technology and enhanced oxygen carrier materials, leading to the construction of FIRES test bench

TU Graz	**Project coordinator and contributor across all work packages**
LANXESS Energizing Chemistry	Synthesis, characterization, and selection of iron-based materials
INTECO	Plant and storage system design
dwh technical solutions simulation services	System simulation
FH JOANNEUM University of Applied Sciences	Life Cycle Analysis
kelag	Techno-Economic Analysis and Sector Coupling for future H_2 economy
ENERGIE AGENTUR Steiermark	Communication with stakeholders and event organisation

Hydro-Mat: Hydrogen and Energy Storage Materials for Sustainable Solutions

H_2 production using defect-engineered Energy Storage Oxide Materials (ESOMs), coupled with advanced reactor designs

SINTEF	**Project coordinator and contributor across all work packages**
Cerpotech	ESOMs manufacturing and optimization
TU Graz	Development of reactor system design and testing ESOMs
CSIC Consejo Superior de Investigaciones Científicas	ESOMs development, reaction kinetics, moving bed reactor testing
RGH2	Industrial validation via testing ESOMs in developed reactor concepts

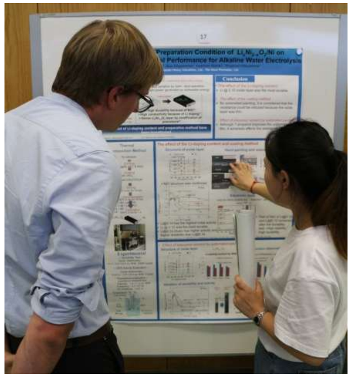
FFG Forschung wirkt.

H2 Hydro-Mat M-ERA.NET

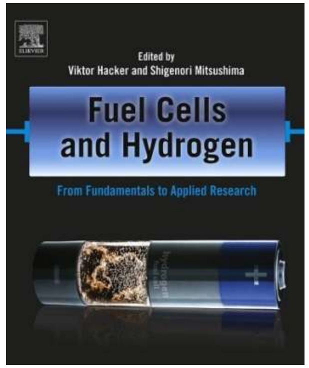
International Summer School on PEFCs & Hydrogen

Group photo, Yokohama National University

- Yearly organized summer school in co-operation with Yokohoma National University
- September 2026, Yokohama
- International lecturers and participants from Japan, Austria, Germany, France, Italy, South Africa, Slovenia, etc.
- Students and researchers discuss the most interesting and important aspects of fuel cell development & application.



Summary of lectures published in ***Fuel Cells and Hydrogen - From Fundamentals to Applied Research***
Viktor HACKER, Shigenori MITSUSHIMA (eds.)
ISBN: 9780128114599 ,
Elsevier, 276 pages, (2018).



www.tugraz.at/go/fcsummerschool

Research Center for Green Hydrogen and Fuel Technologies (H2rc)

Institute of Chemical Engineering and Environmental Technology
Fuel cells and hydrogen
Electrochemistry laboratory
Industrial system solutions

Institute of Thermodynamics and Sustainable Propulsion Systems
Sustainable propulsion systems and mobility solutions
Emissions and immissions
Thermodynamics and electrochemistry

Institute of Thermal Turbomachinery and Machine Dynamics
Turbomachinery optimization, CFD
Metrology in turbomachinery
Laser optical metrology

Institute of Thermal Engineering
Research in the field of high-temp. electrolysis and fuel cells, hydrogen burners for industry and sustainable solutions for heat technology

Large Engines Competence Centre
Sustainable energy and transport systems based on hydrogen and hydrogen-derived fuels

BEST
Bioenergy and Sustainable Technologies

HyCentA
HYDROGEN CENTER AUSTRIA

Bioenergy and Sustainable Technologies
Bio-based economy and sustainable energy systems.
Hydrogen from biomass and utilisation to create high-quality products for industry

Austria's only R&D centre for hydrogen technologies
Application-oriented R&D for industry, energy and mobility
Electrolysis, storage, distribution and fuel cells

Coordinator: Prof. V. Hacker

50 years of successful R&D in the Field of Hydrogen
Combined Expertise of more than 250 Scientists

Summary

- **Hydrogen:** Links renewable power with electrolysis and fuel cells; storage and transport remain the main bottlenecks.
- **Green hydrocarbons:** Convert biogenic residues into fuels and chemicals; sustainable feedstocks and efficient separation determine their value.
- **Green ammonia:** Combines high hydrogen density with established logistics; safer and more efficient synthesis remains essential.
- **Green iron:** Offers abundant, non-toxic solid-state storage; cycle stability and thermal integration determine practical performance.

Thanks to the team

SCIENCE
PASSION
TECHNOLOGY

Thank you very much for your attention!