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Beyond Iron: use of various other metals as energy carriers

Metalot@Work, June 25, 2025

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Metalot@Work June 25

Beyond Iron

15:30 - Walk-in

15:40 - Introduction

15:45 - Metals as sustainable energy carrier, beyond iron - by Jeff Bergthorson - McGill University (live)

16:00 - State-of-the Art on Aluminum combustion - by Thijs Hazenberg - TU Darmstadt (live)

16:15 - State of the Art in Aluminium - Water Reaction for Peak Demand in Buildings - by Yvonne Bäuerle - OST (online)

16:30 - Aluminum battery development- by Michiel Kruijf - ZemQuest (live)

16:45 - Short break

17:00 - Magnesium as energy carrier- by Cornelius Schonnenbeck - Université de Haute Alsace (online)

17:15 - Zinc oxidation/reduction cycle - by Ellen Molleman - Nyrstar

17:30 - Iron from water sludge - by Roy Hermanns - TU/e

17:45 - Ambassador Awards

18:00 - Closure & drinks together

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Metals as sustainable energy carrier, beyond iron

by Jeff Bergthorson - McGill University

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Metals as sustainable energy carrier, beyond iron

Jeff Bergthorson

Director, Alternative Fuels Laboratory (afl)

Associate Director, Centre for Innovation in Storage and Conversion of Energy

Professor, Department of Mechanical Engineering

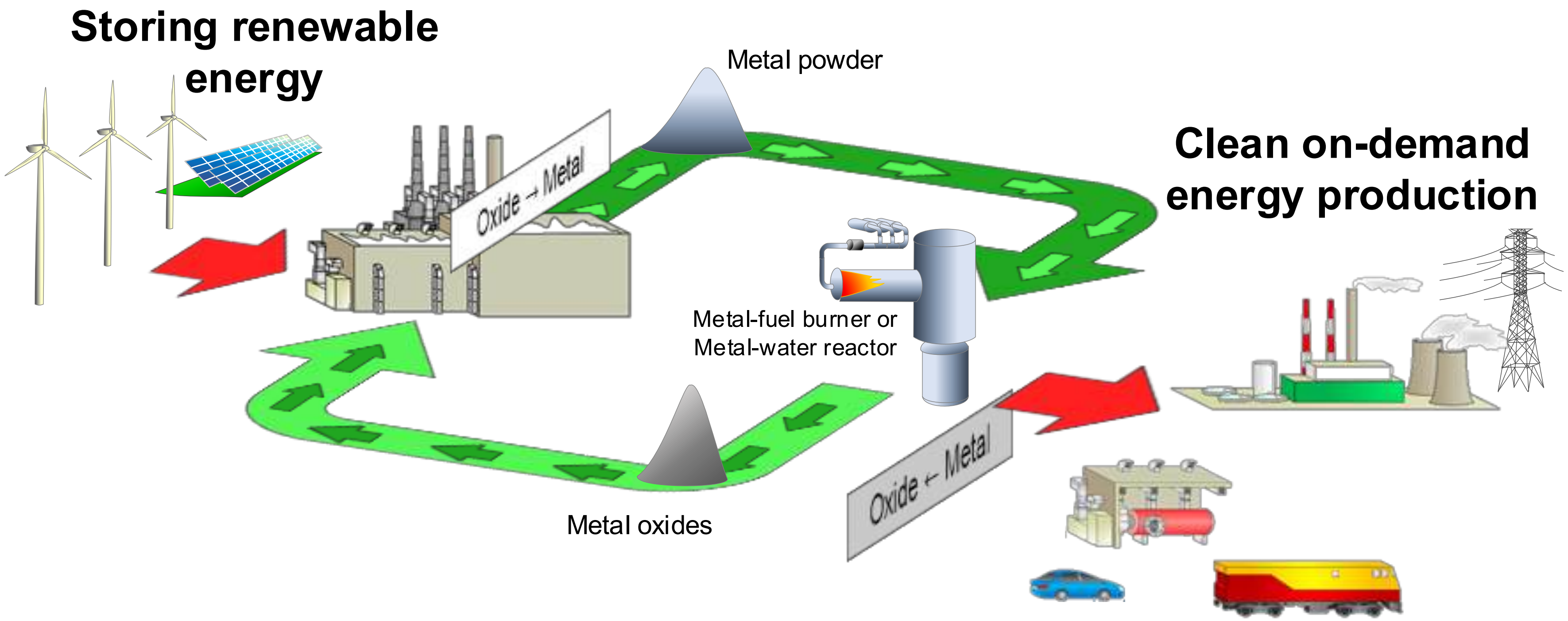
McGill University

Metalot@Work

Budel, Netherlands

25 June 2025

Key Takeaways: Metals are excellent renewable fuels



- Metal fuels are clean recyclable **circular fuels** & **renewable energy commodities**
  - Solid combustion products simplify collection and recycling to close the loop
- Metal fuels can be directly burned with air to produce heat (Dry Cycle)
- **Metal fuels can be reacted/burned with water to produce heat & H_2 (Wet Cycle)**
- Metal fuels are cost effective and safer options than hydrogen/ammonia/e-fuels

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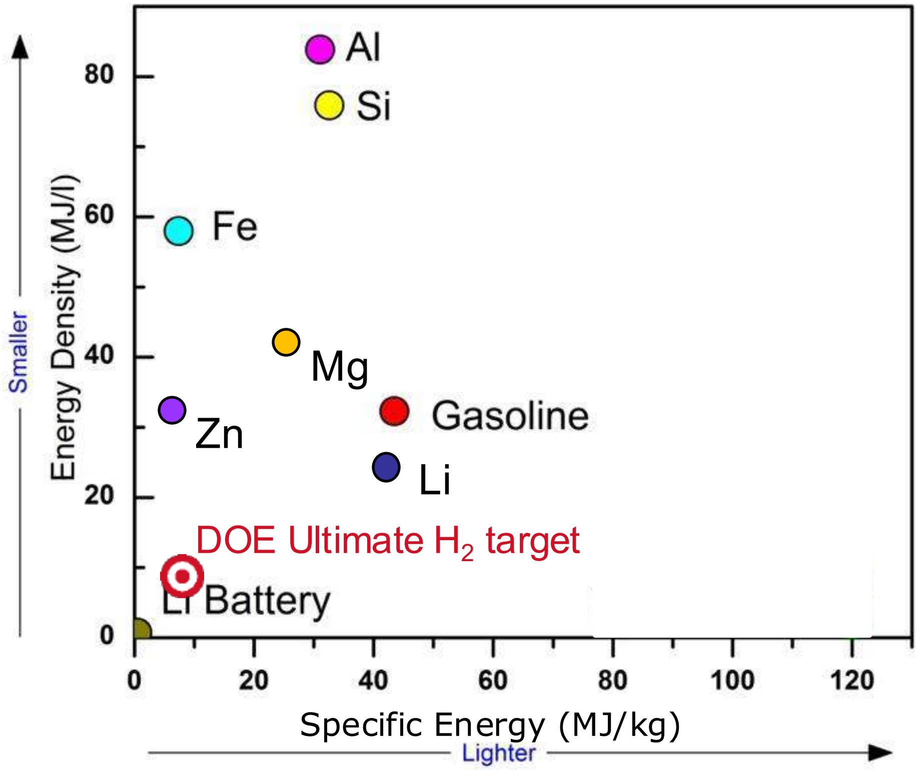
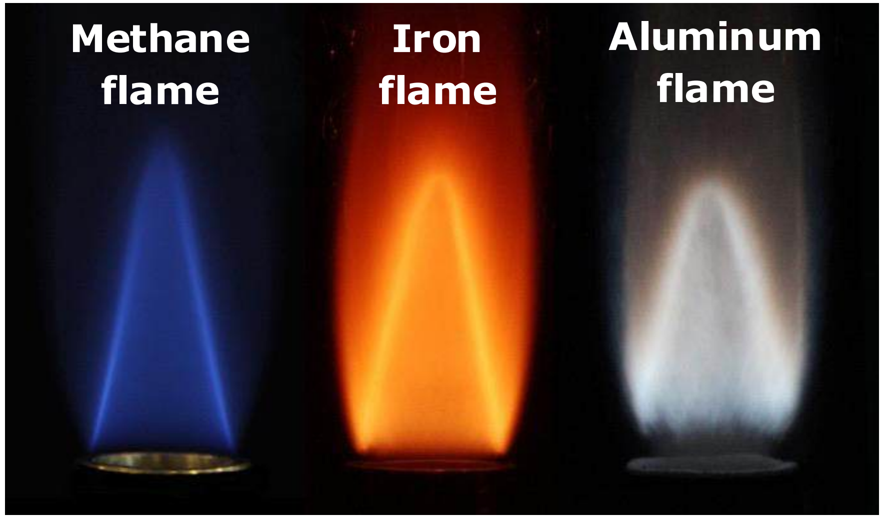
Metal fuels – zero-carbon recyclable energy carriers





Silicon flame

- Metal energy densities surpass fossil fuels
- Metal fuels burn in air producing heat

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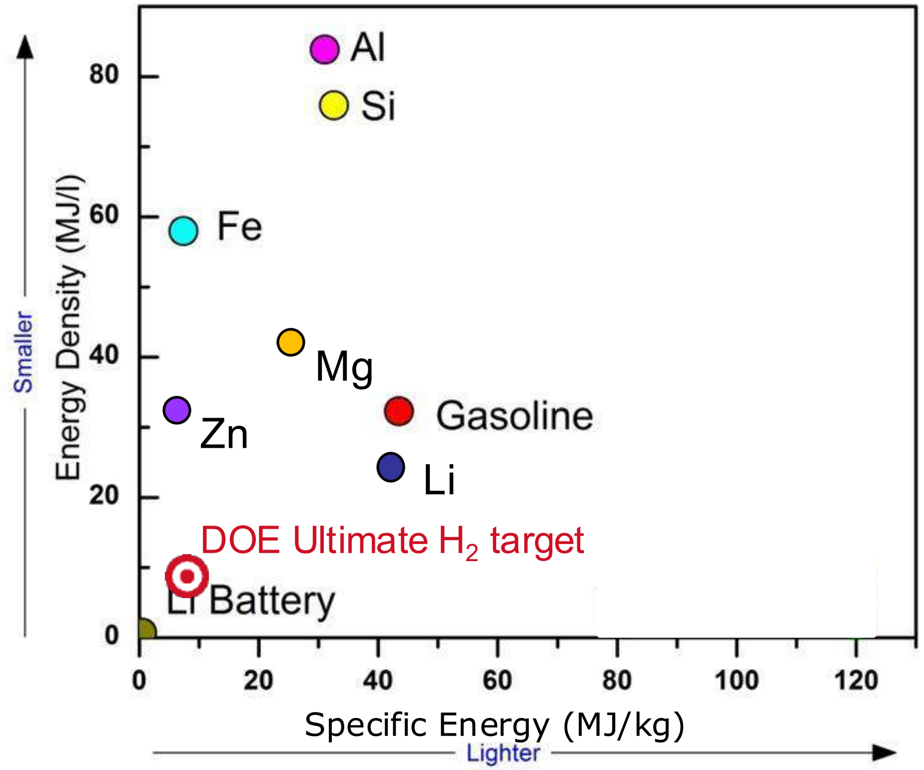
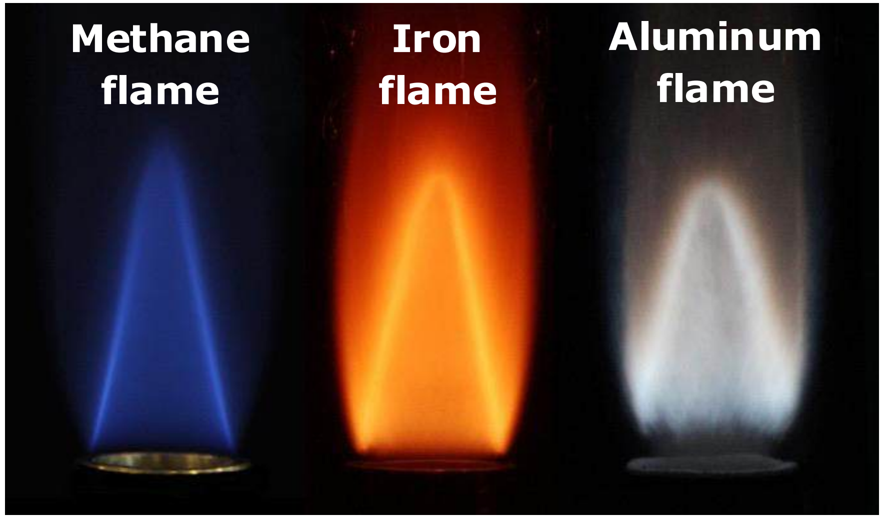
Metal fuels – zero-carbon recyclable energy carriers

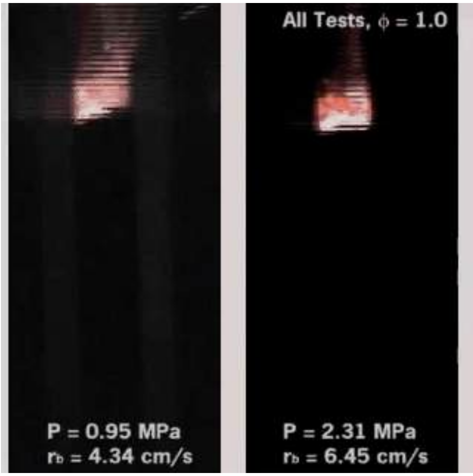


- Metal energy densities surpass fossil fuels
- Metal fuels burn in air producing heat
- Metal fuels burn in water producing hot H_2
- Heat (and H_2) can be converted to power
- Combustion product is solid metal oxide
  - no CO_2, CO, or UHC emissions



Silicon flame

Aluminum-water propellant



Risha et al. (2007), Proc. Combust. Inst, 31:2029-2036

ALICE rocket (aluminum-ice)

Purdue University

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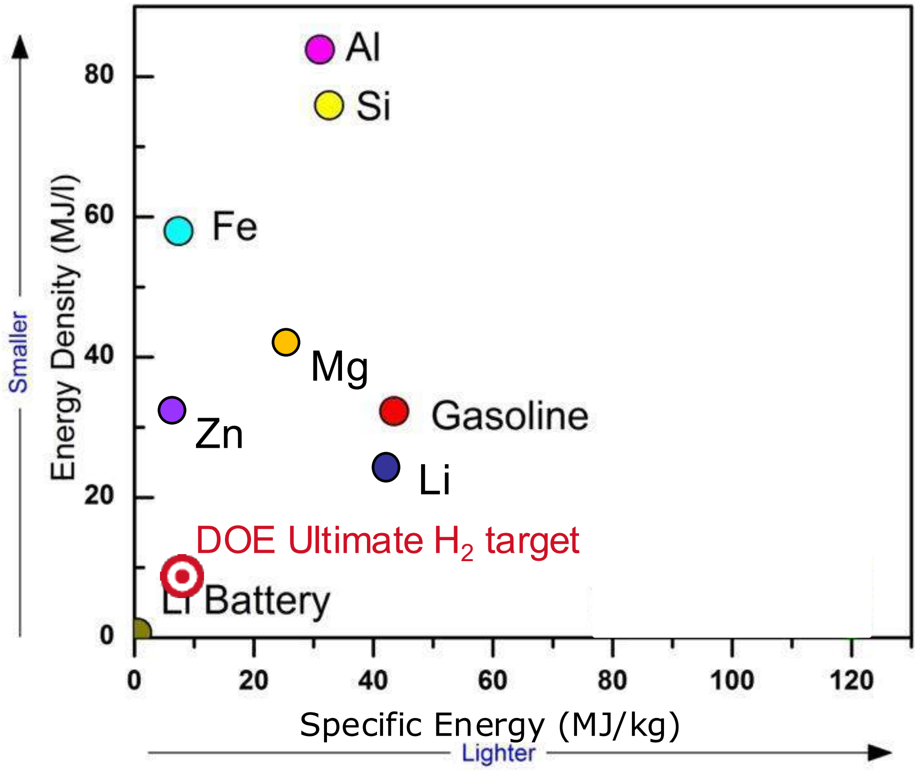
Metal fuels – hydrogen and heat carriers



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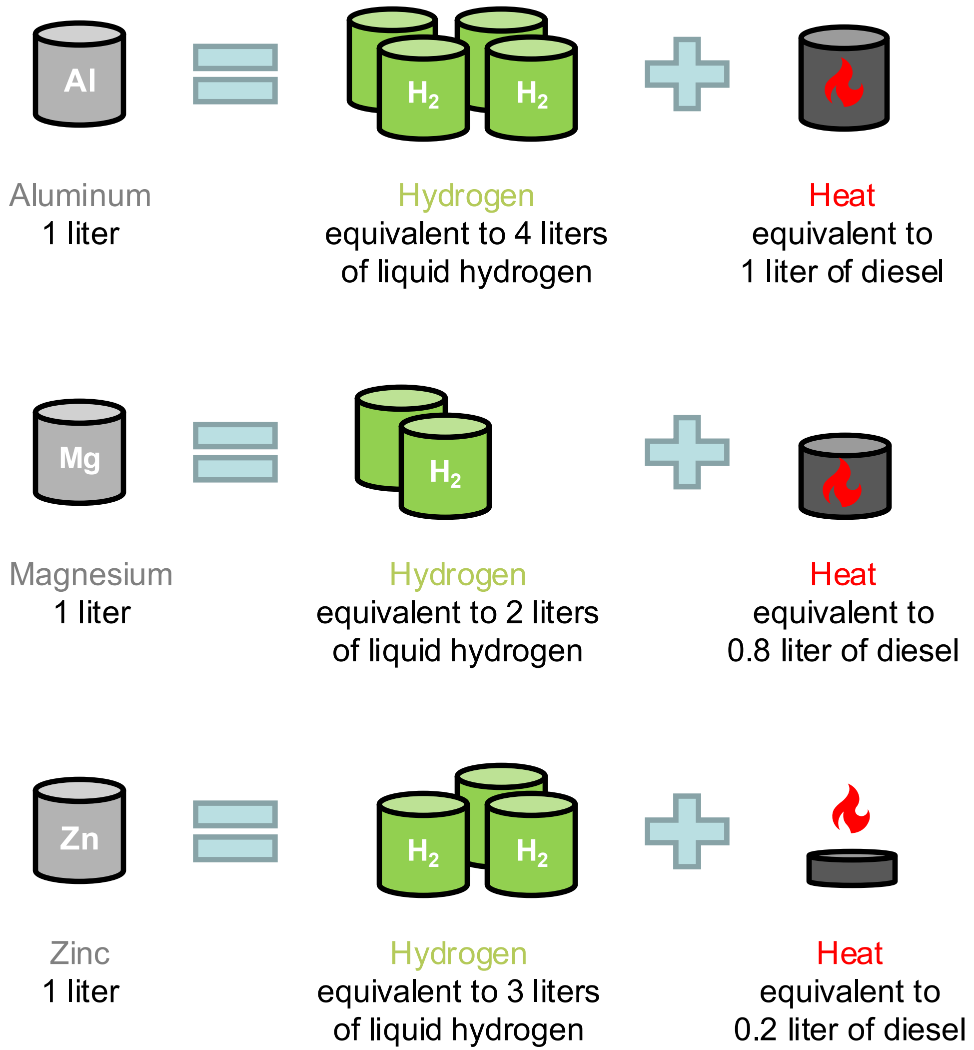

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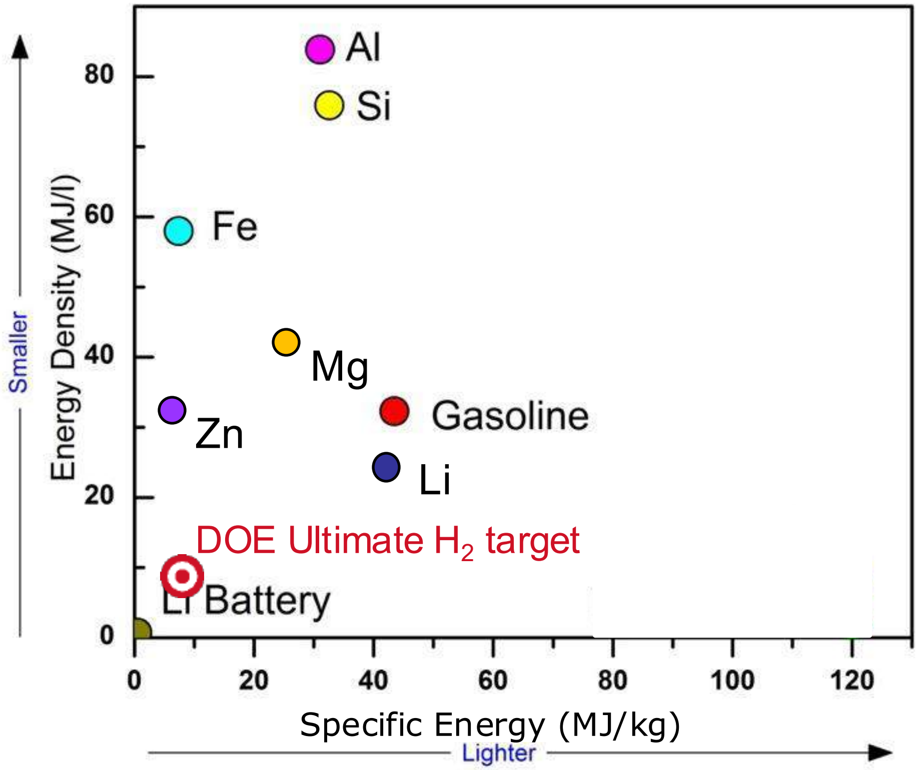
Metal fuels – hydrogen and heat carriers



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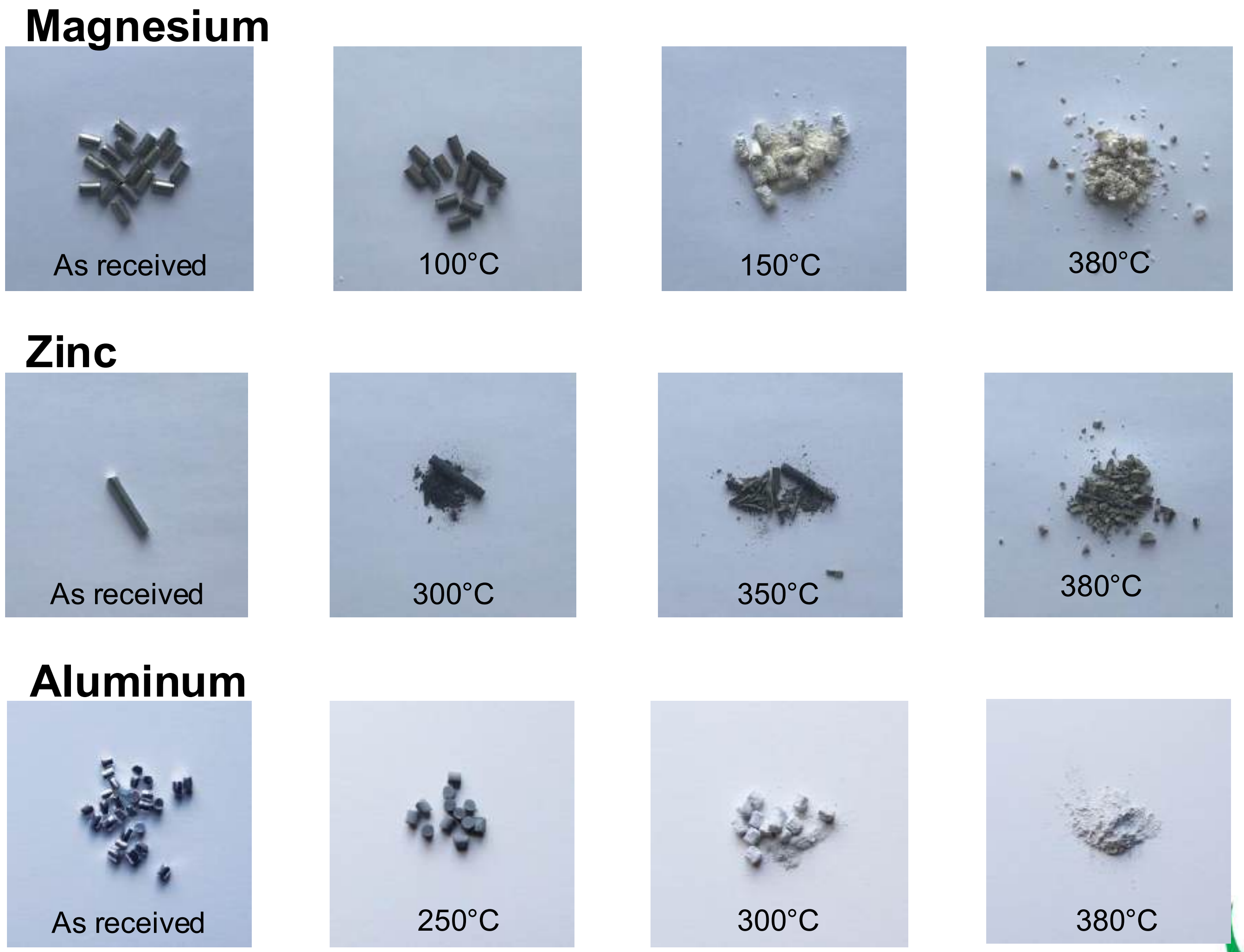

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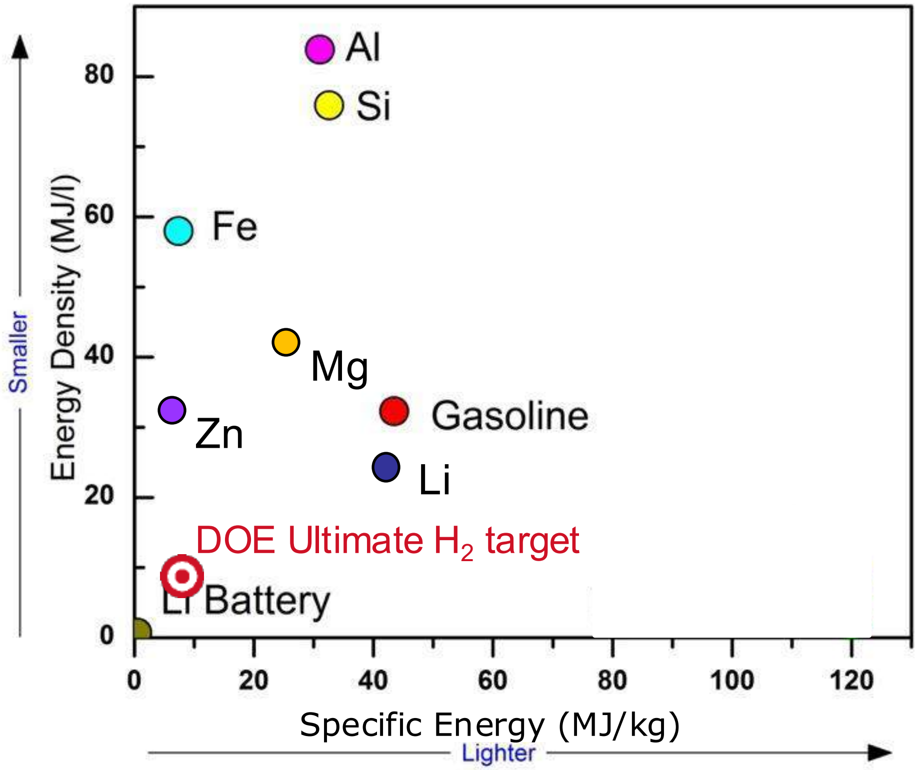
Metal fuels – hydrogen and heat carriers



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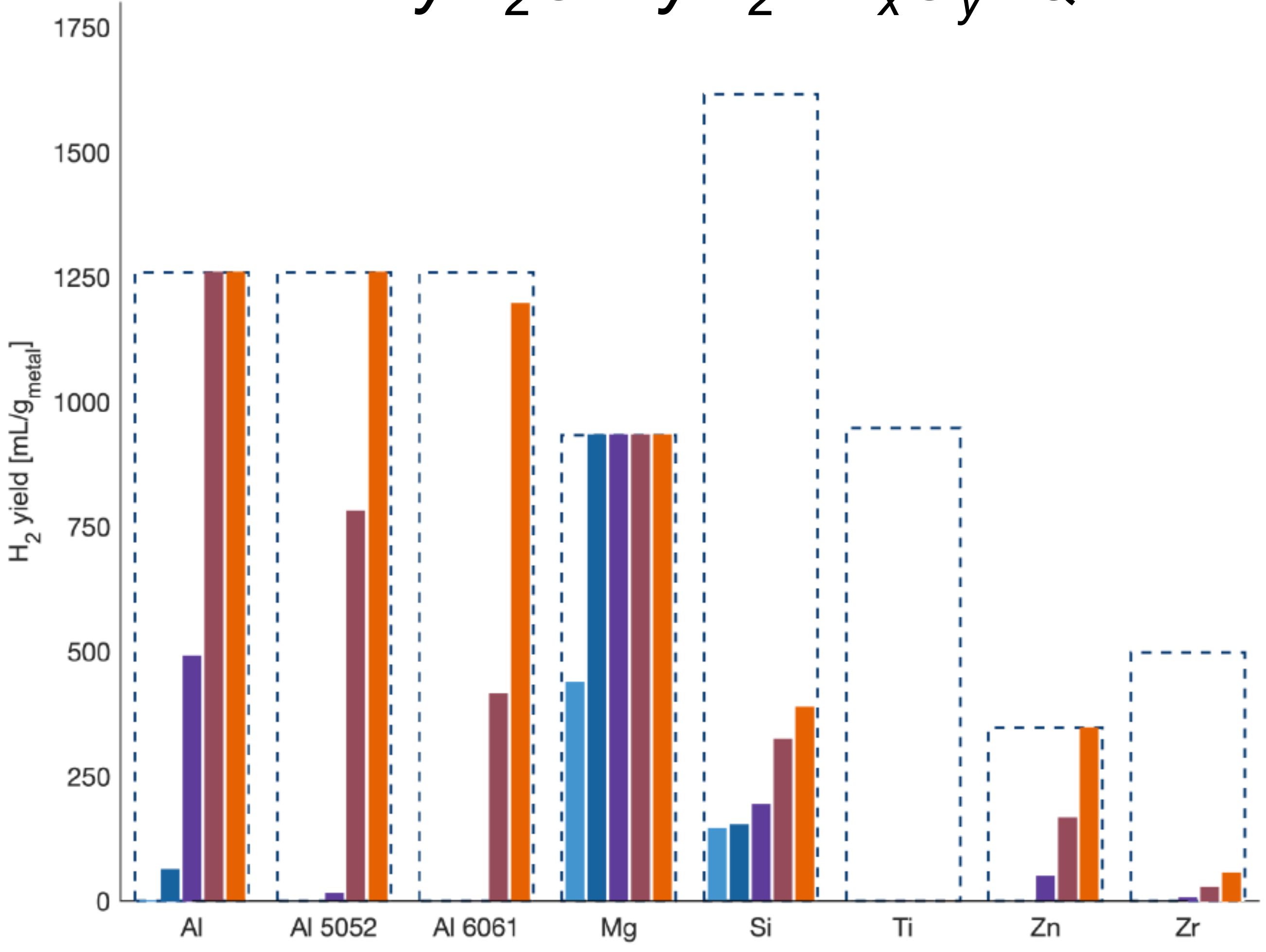
$$xM + yH_2O \rightarrow yH_2 + M_xO_y + Q$$



Trowell et al. (2022), 2022. Hydrogen production via reaction of metals with supercritical water. *Sustainable Energy & Fuels* 6:3394-3401.

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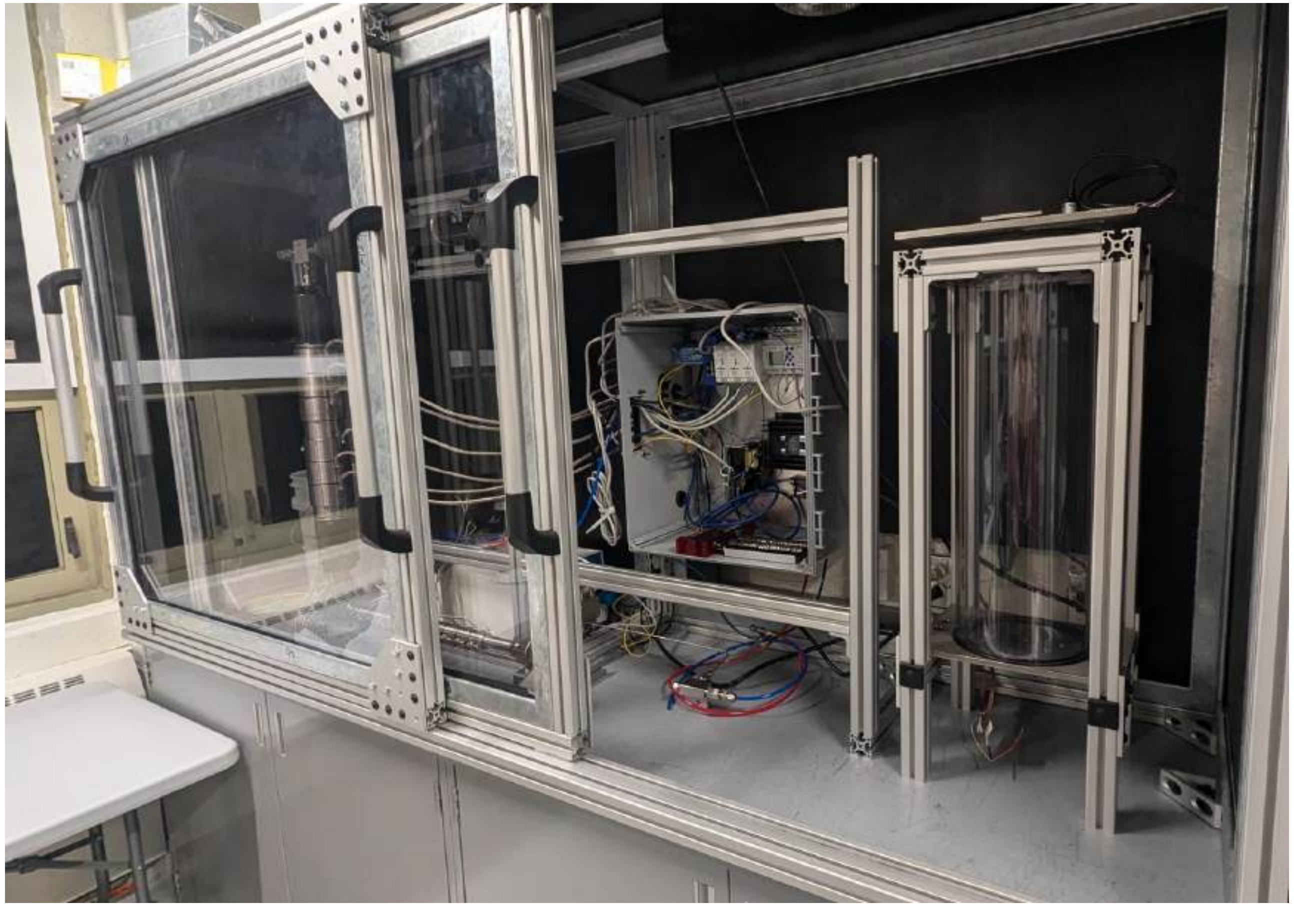
Prototype of supercritical continous reactor



Reactor Conditions

- Nominal Pressure: 300 bar
- Nominal Temperature: 400 °C

- Nominal Output:

  350W Heat & 1.8 L/min H_2

Project Goals

- Scale up of current batch reactors
- Observe effect of product presence on the reaction
- Eventually a self-sustaining system

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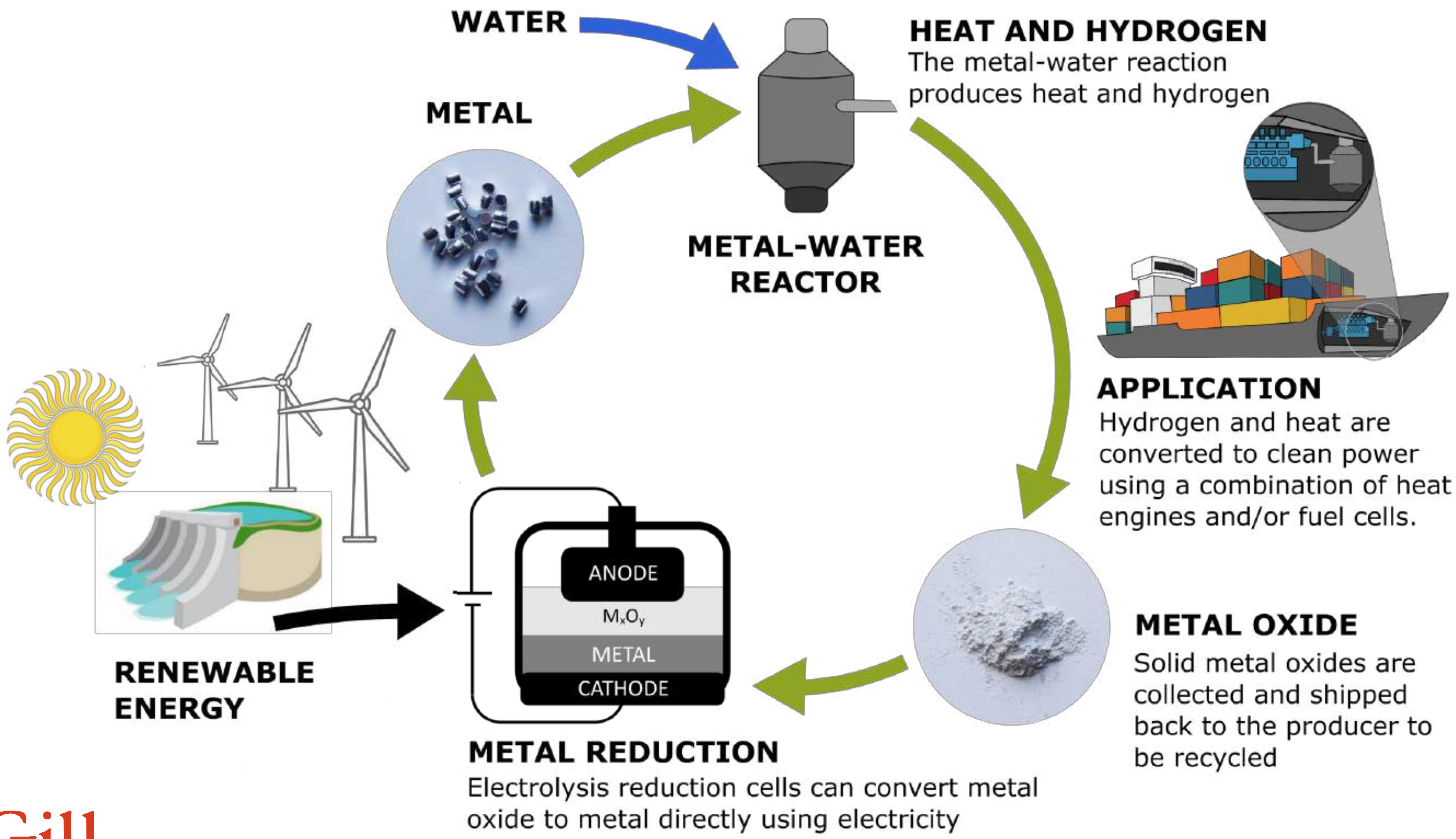
What is the cost of recharging metal fuels using electrolysis?



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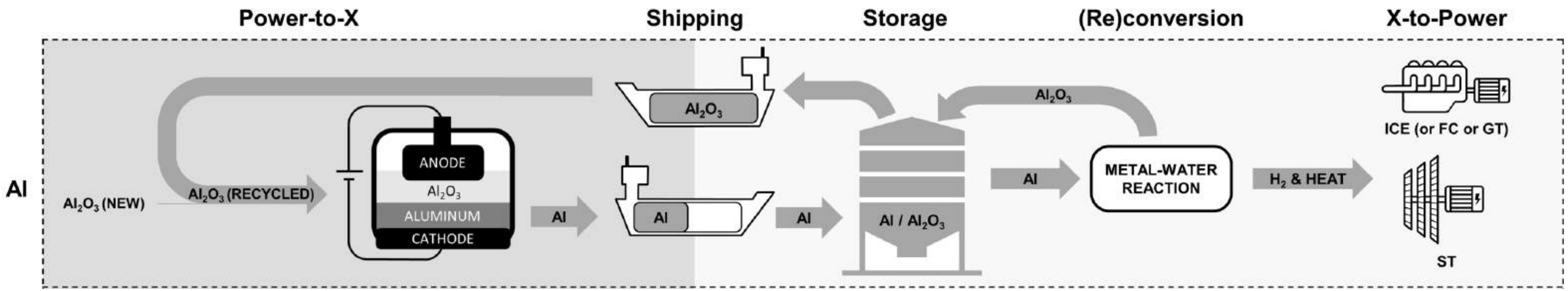
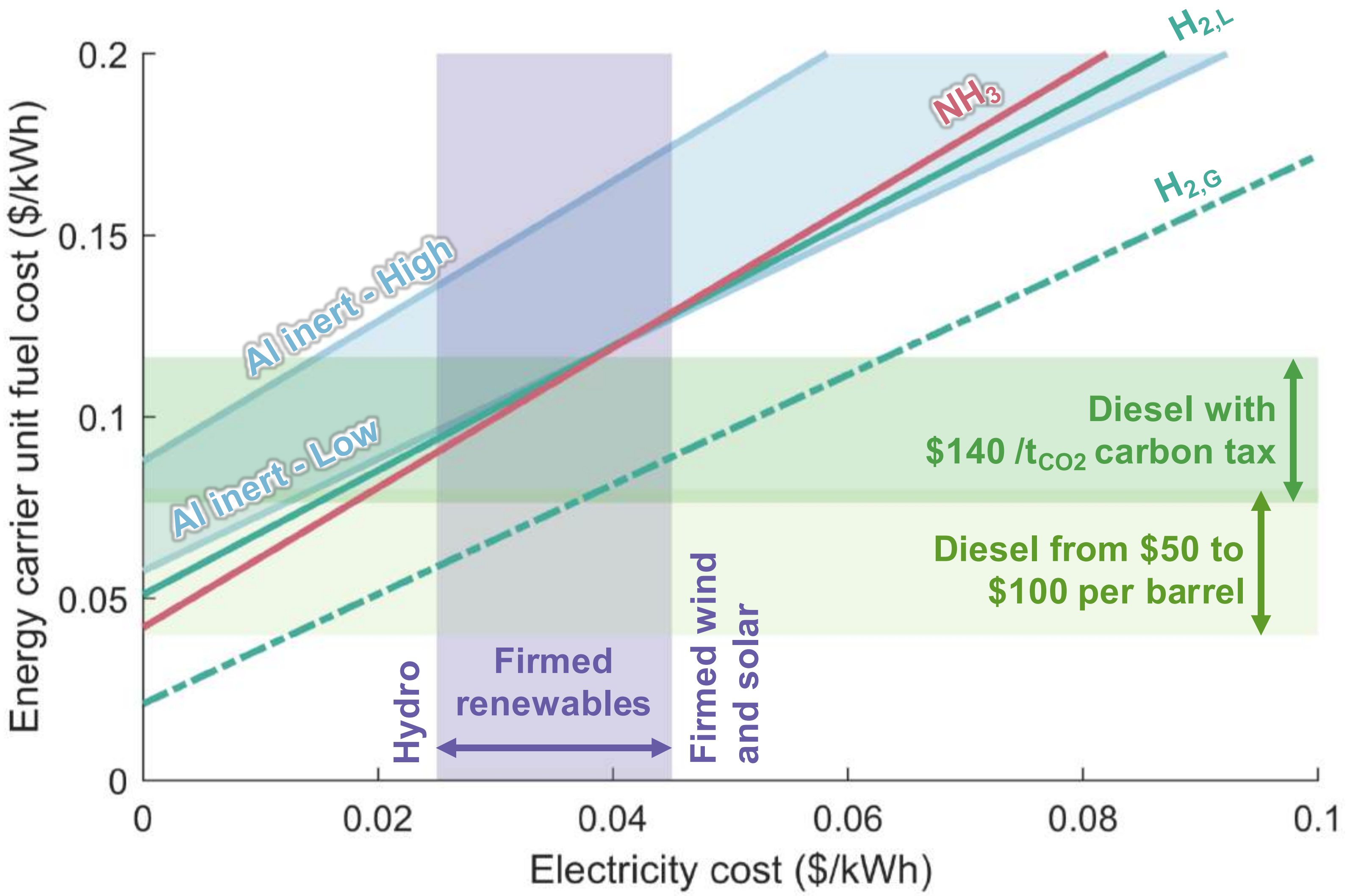
Techno-economics of aluminum vs other carbon-free fuels



Aluminum is competitive with other energy carriers



- Aluminum would require firmed renewables (cannot sustain frequent start/stop procedures)
- Canada carbon tax will reach ~140 USD/tCO_2 in 2030
- Aluminum can be cost competitive with NH_3 or LH_2
- Aluminum will need to take advantage of most of the benefits of inert anodes

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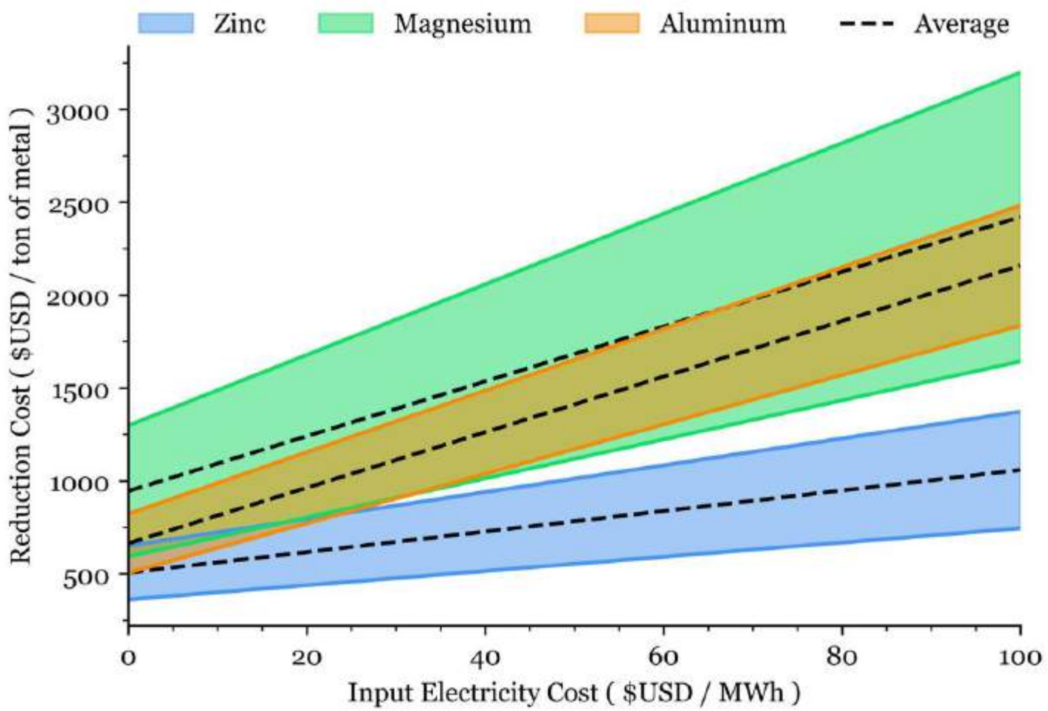
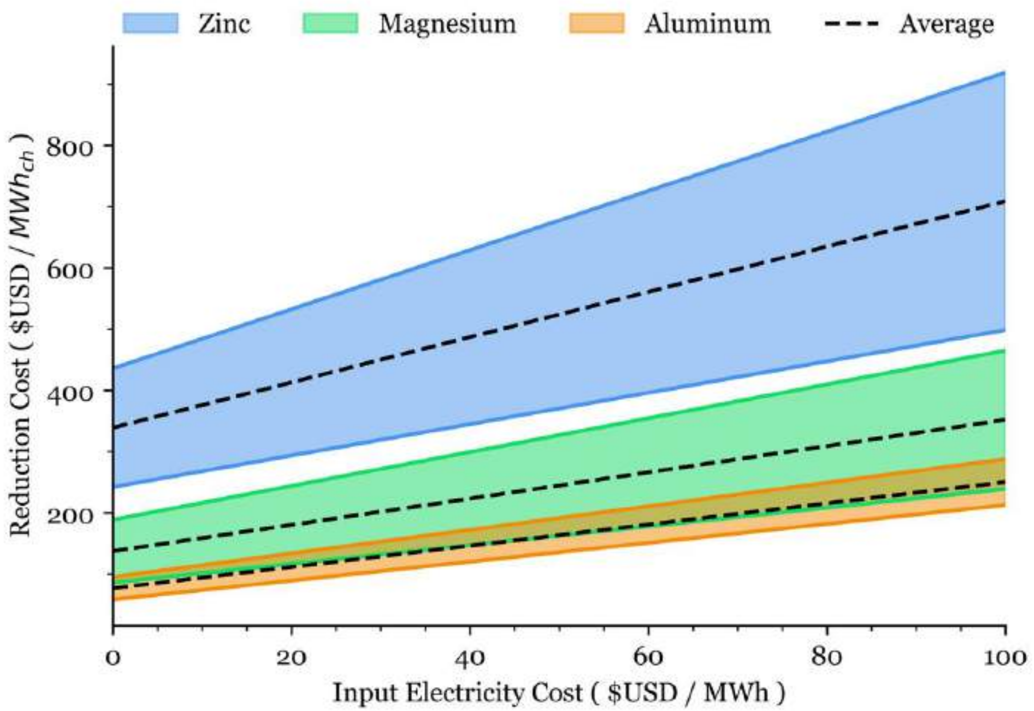
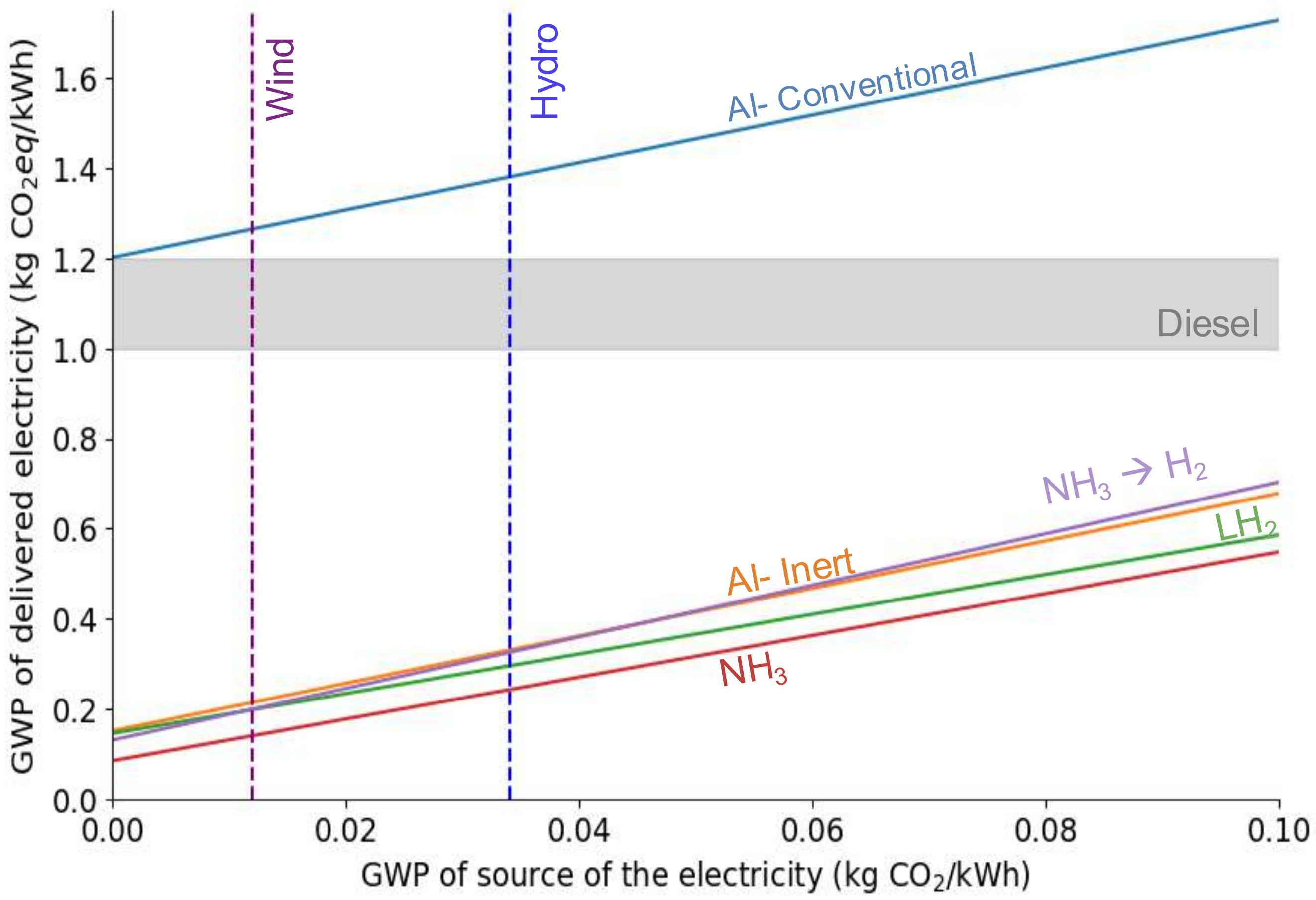
Cost of circular metal fuels on a mass and energy basis

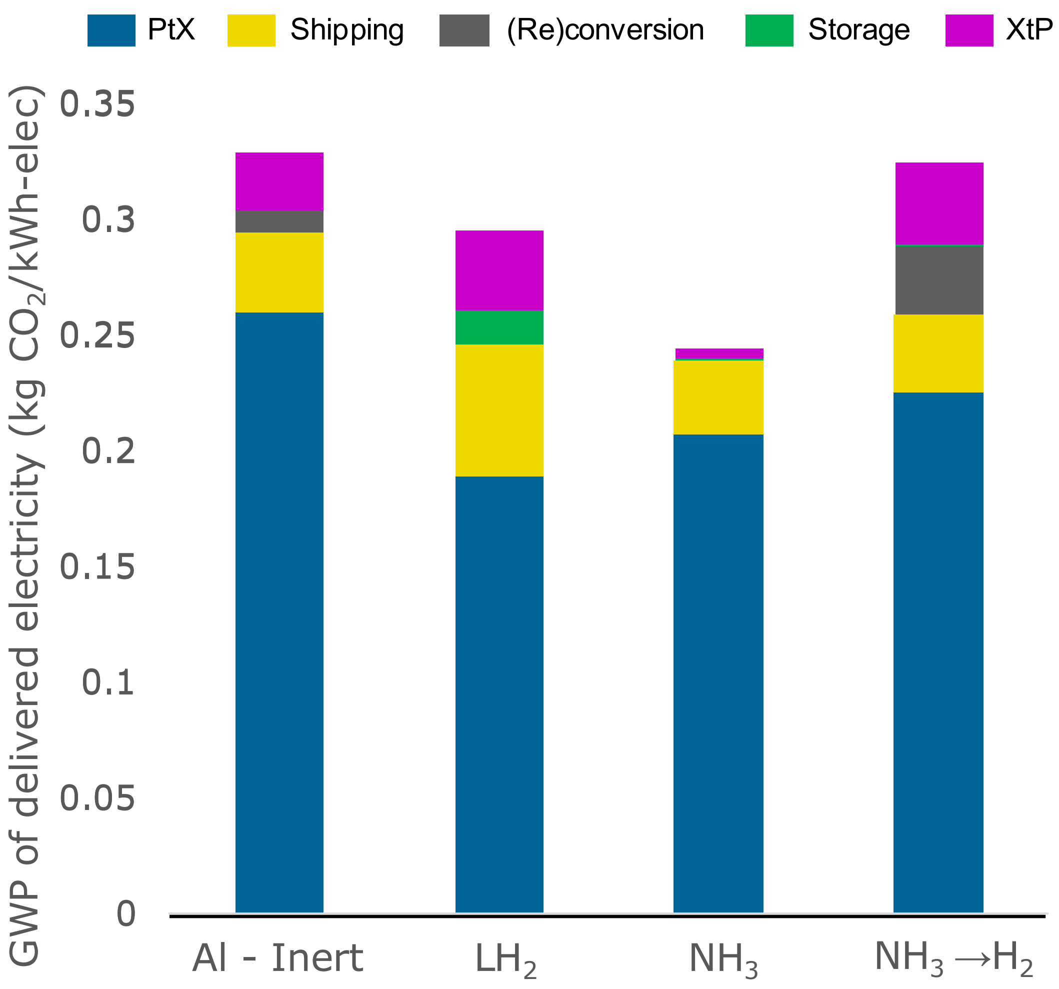




Comparison of Reduction Cost of Metal Fuels on a Mass and Energy Basis.

Global Warming Potential (GWP) of metal fuels for remote power





GWP of electricity production in the remote mine assuming the use of hydro electricity in Quebec (GWP of 34.5gCO_2/kWh)

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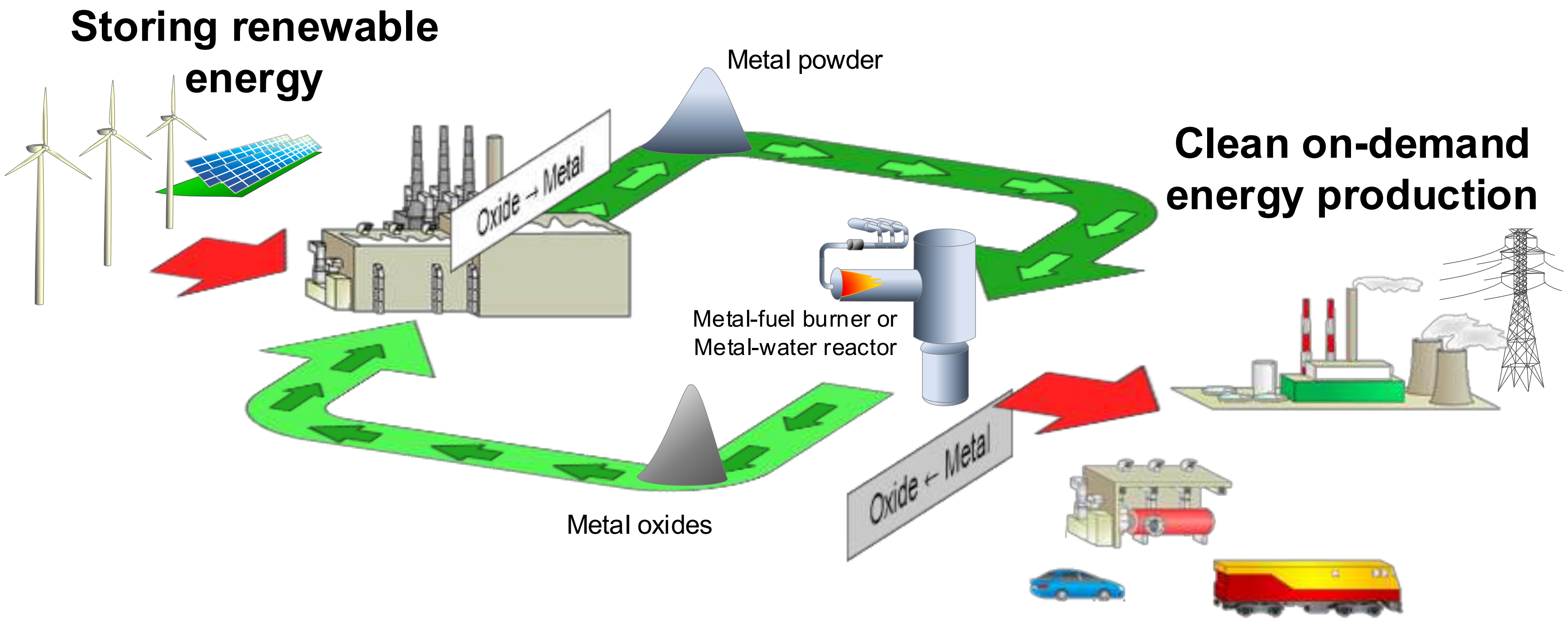
Key Takeaways: Metals are excellent renewable fuels



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Acknowledgements

- **Industrial partners:**

SIEMENS energy
TATA STEEL
AGNICO EAGLE
FeX ENERGY
GKN HOEGANAES
Hydro Québec
RioTinto
Teck
altiro energy

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Fonds de recherche Nature et technologies Québec
PRIMA Advanced Materials Moving Forward
esa
CSA ASC
Canada Research Chairs
axelys Développement et transfert de l'innovation du Québec
INNOVATION Canada Foundation for Innovation Fondation canadienne pour l'innovation
The McGill Sustainability Systems Initiative (MSSI)
TISED Trottier Institute for Sustainability in Engineering and Design
McGill
Centre for Innovation in Storage and Conversion of Energy

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McGill
compute • calcul CANADA

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McGill and AFL Research Team

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- Fiona Zhao

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- M. Schiemann (RU Bochum)
- F. Halter (U. Orléans)
- E. Shafirovich (UTEP)

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- ***M.Eng.:*** Michelle McRae, Frederic Blais, Samson Bowen-Bronet, Martin Aralov, Nicholas Pinkerton & others…
- ***Undergraduate:*** Aki Fujinawa, Joël Jean-Philyppe, Keishi Kumashiro, & others…

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State-of-the Art on Aluminum combustion

by Thijs Hazenberg - TU Darmstadt

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THE A STEAM

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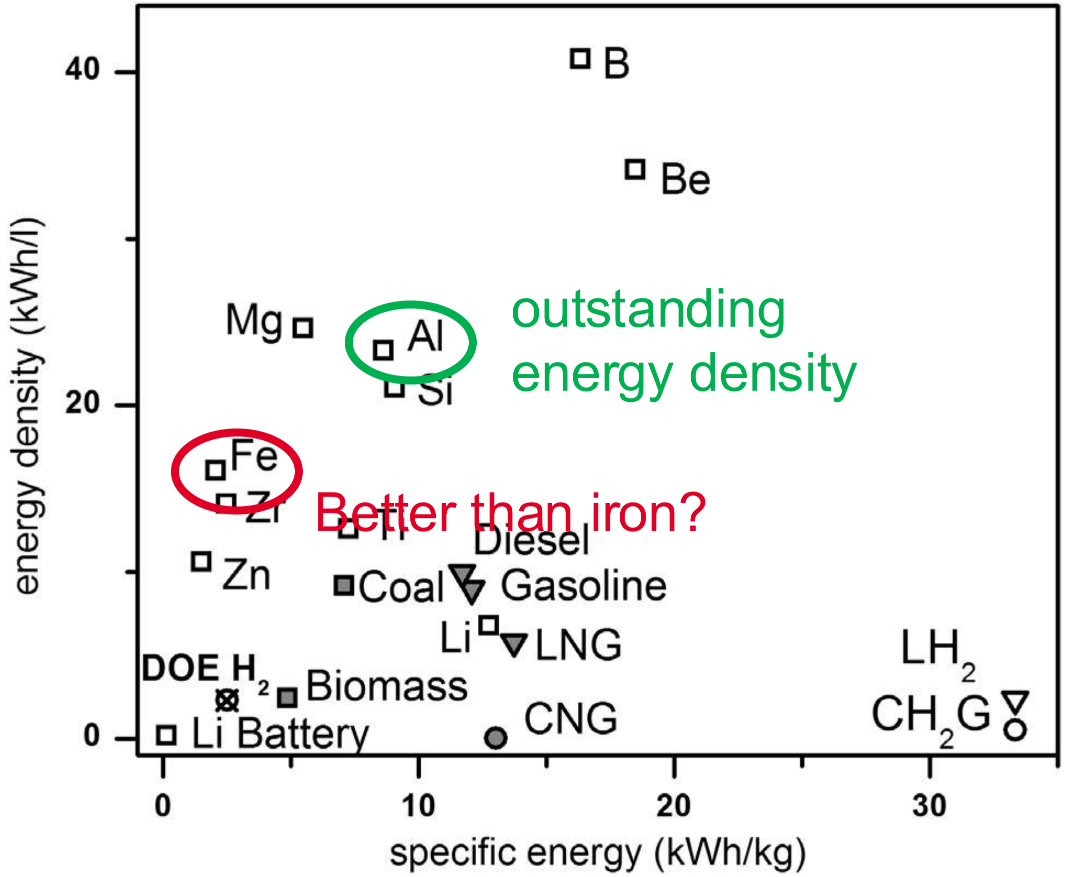
THIJS HAZENBERG 25.06.2025

ALUMINUM(-STEAM) COMBUSTION

ERC PROJECT @ STFS/RSM

WHY STORE ENERGY IN ALUMINUM?

TECHNISCHE UNIVERSITÄT DARMSTADT



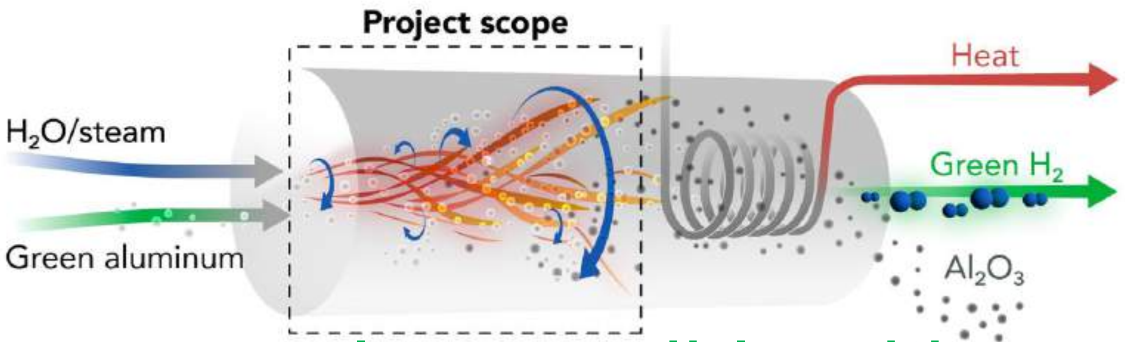
J. Bergthorson et al. “Direct combustion of recyclable metal fuels for zero-carbon heat and power”, Applied Energy 160 (2015) 368–382

Video: RSM, TU Darmstadt

Pourpoint et al. „Feasibility Study and Demonstration of an Aluminum and Ice Solid Propellant“, International Journal of Aerospace Engineering (2012), 874076

PHENOMENOLOGY OF ALUMINUM PARTICLE COMBUSTION

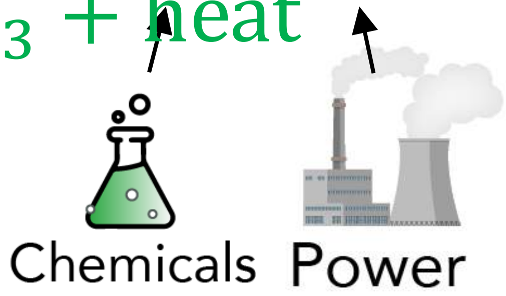
TECHNISCHE UNIVERSITÄT DARMSTADT

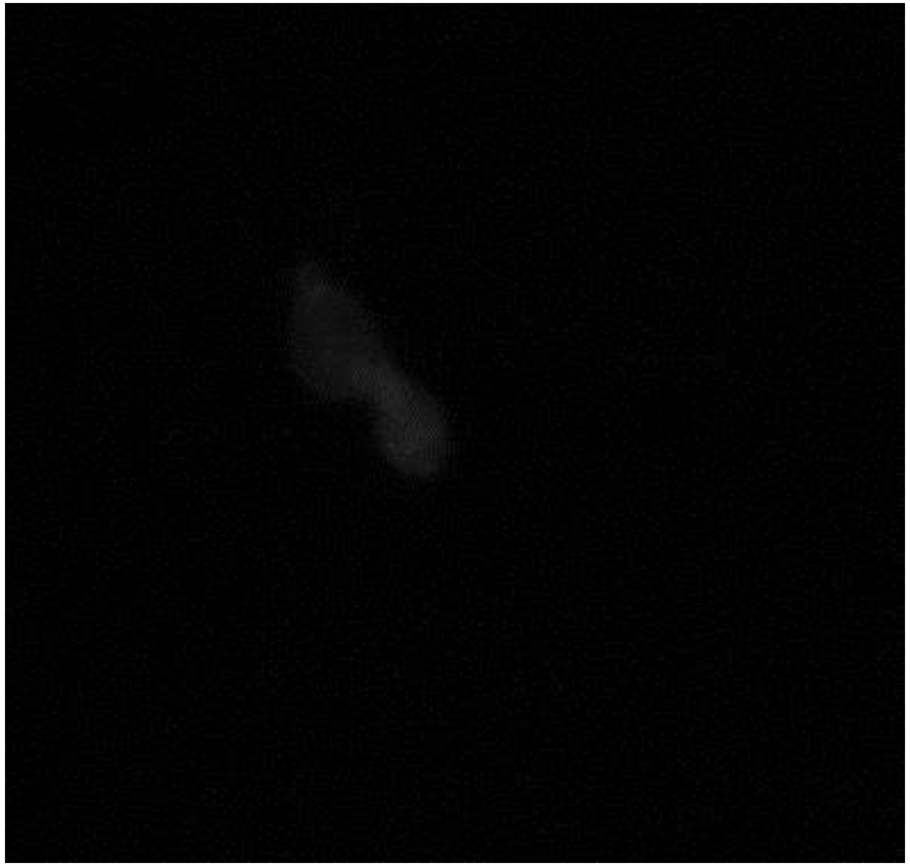


Of course, also possible with oxygen

$$2\mathrm{Al} + 3\mathrm{H_2O} \rightarrow \mathrm{Al_2O_3} + 3\mathrm{H_2} + \text{heat}$$

$$4\mathrm{Al} + 3\mathrm{O_2} \rightarrow 2\mathrm{Al_2O_3} + \text{heat}$$





Video: Fabian Halter, 5th Clean Circles Mini Symposium (FF2), Darmstadt, 11.07.2023

PHYSICS OF SINGLE PARTICLE COMBUSTION

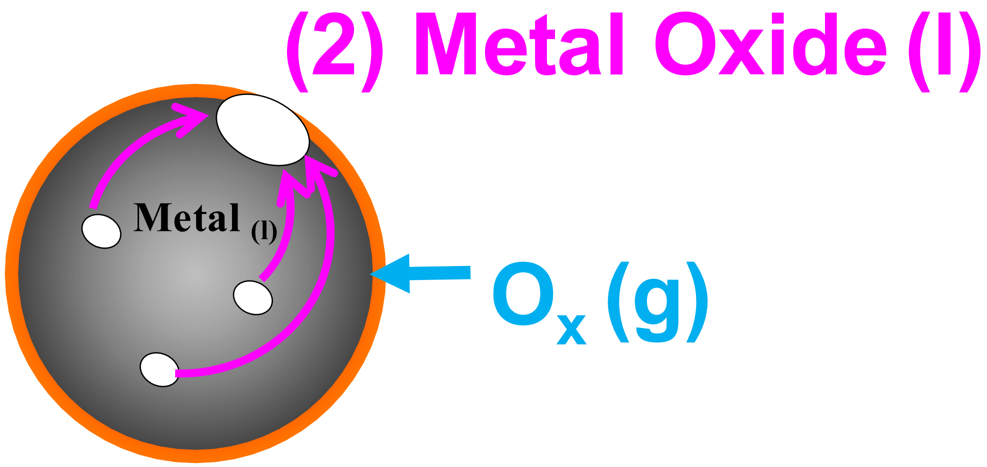
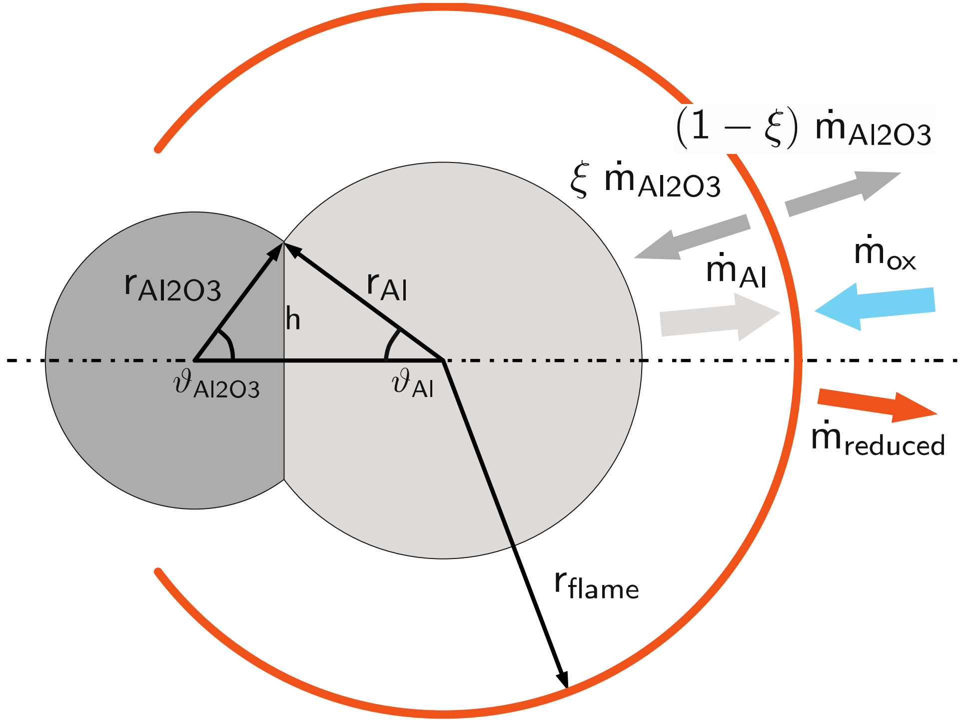
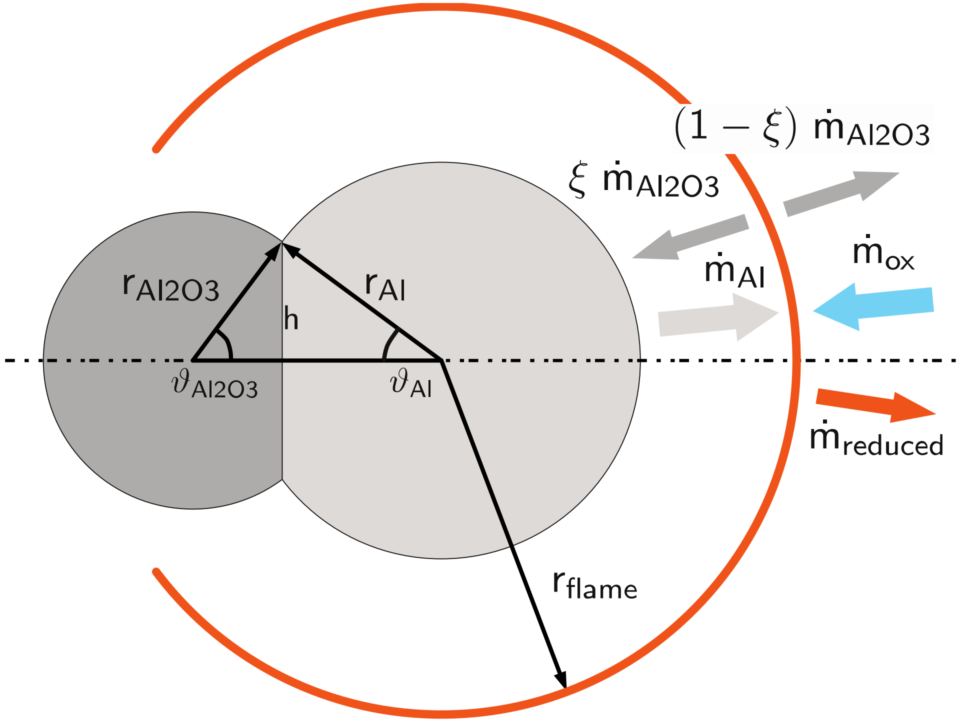
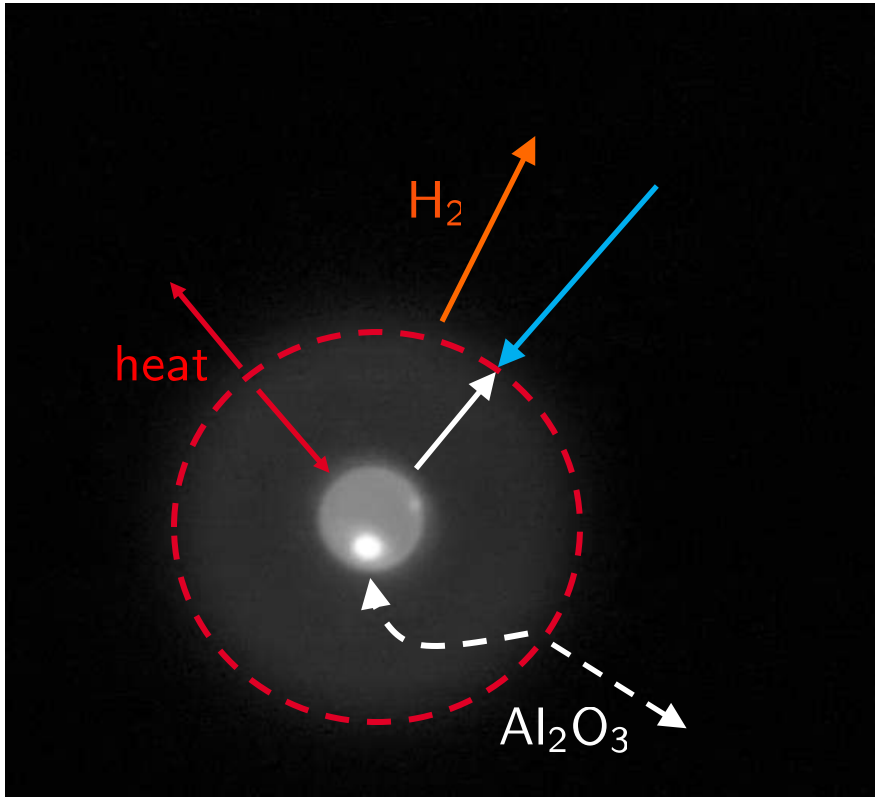


Image: Fabian Halter, 5th Clean Circles Mini Symposium (FF2), Darmstadt, 11.07.2023



PHYSICS OF SINGLE PARTICLE COMBUSTION

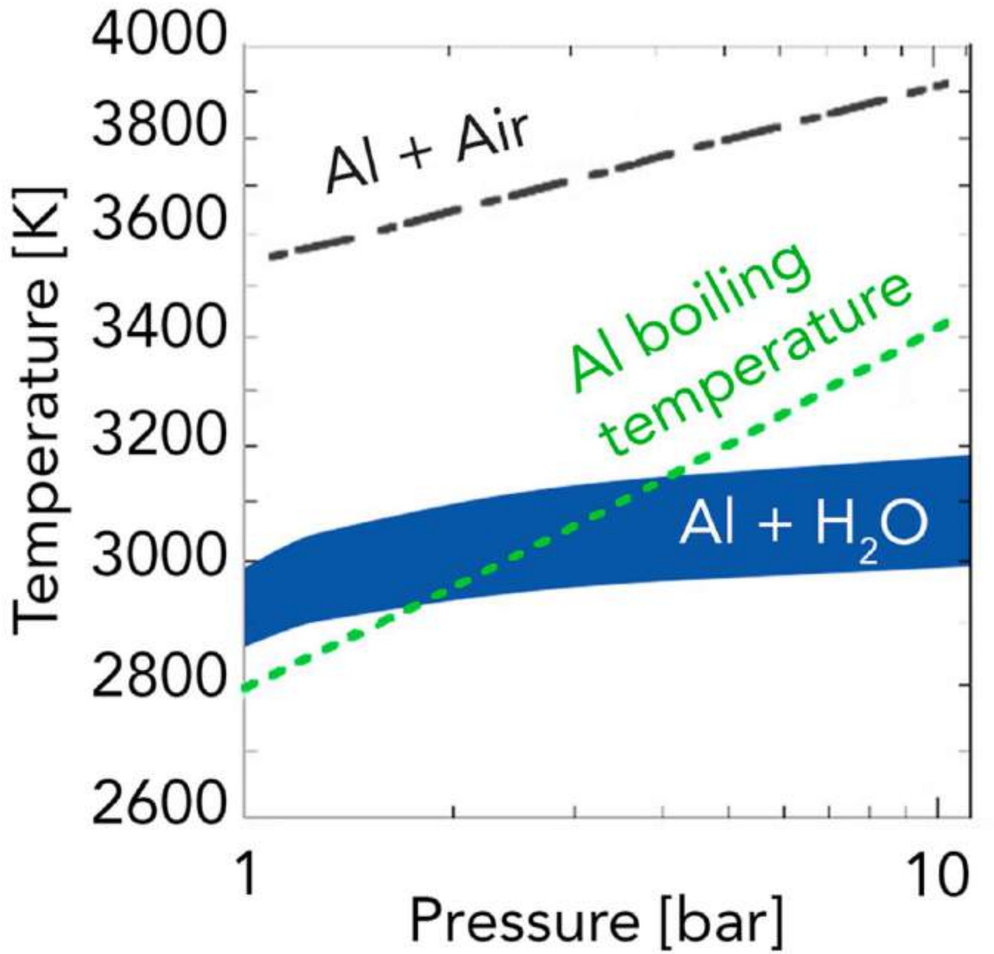




PHYSICS OF SINGLE PARTICLE COMBUSTION

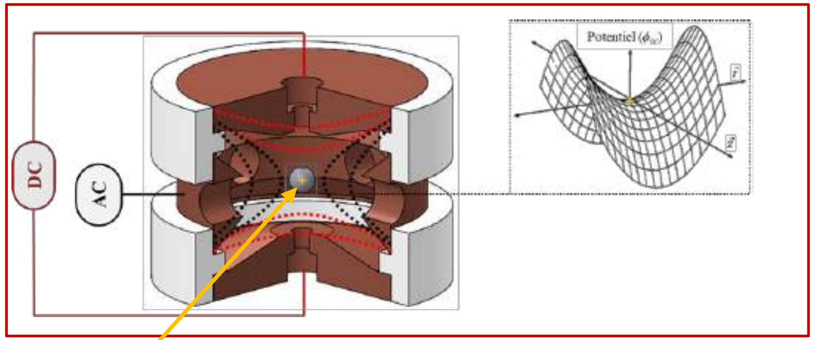
Challenge renewable aluminum:
Maximize deposition on main particle

Our solution:
Steam and increased pressure

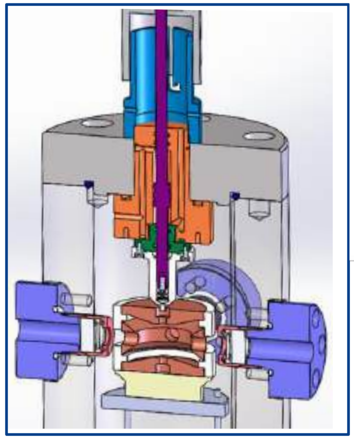


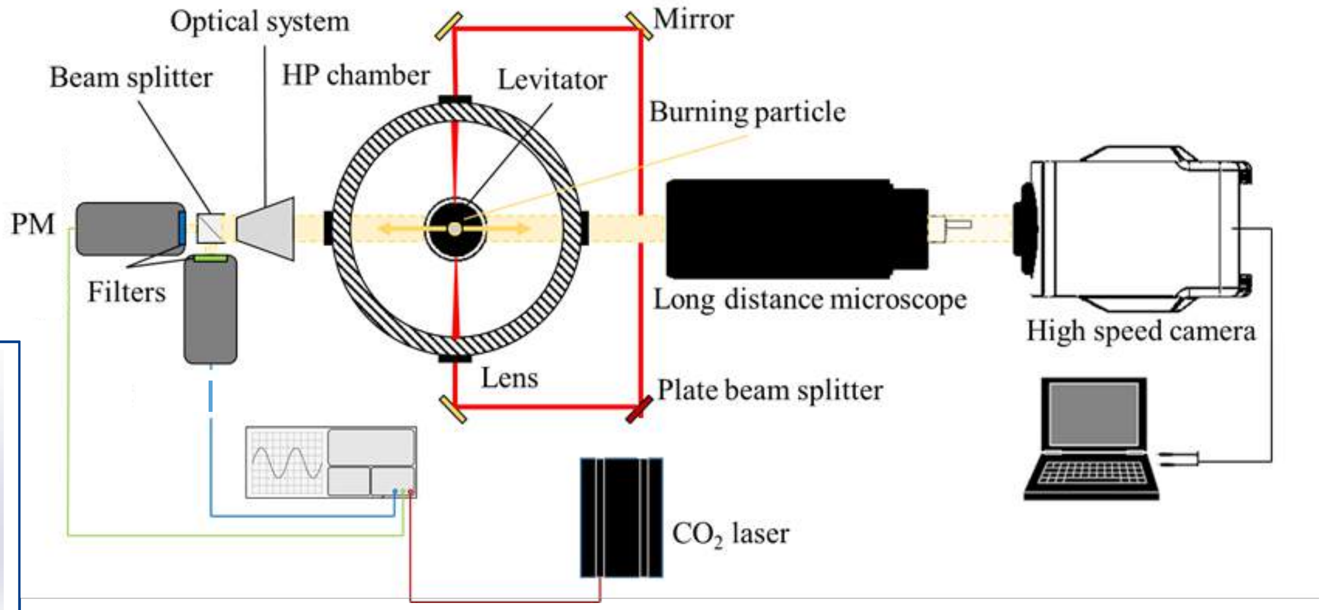
CURRENT BEST EXPERIMENTS FOR SINGLE PARTICLE

Electrostatic Levitator



Levitating aluminum particle





Setup at Fabian Halter his group.
Slide from 5th Clean Circles Mini Symposium (FF2), Darmstadt, 11.07.2023

SINGLE PARTICLE EXPERIMENTS @ RSM

TECHNISCHE UNIVERSITÄT DARMSTADT

New experimental setup

- Combustion in exhaust of H2 flame
- Control over dilution
- Control over temperature

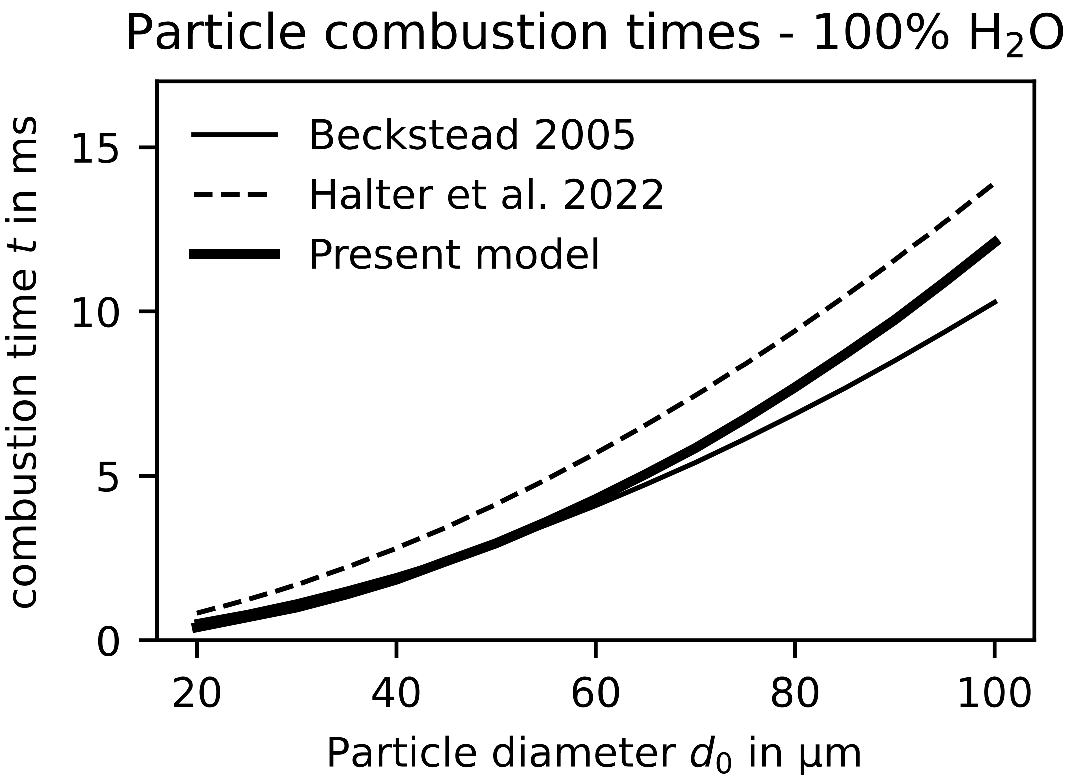
Challenge for use:

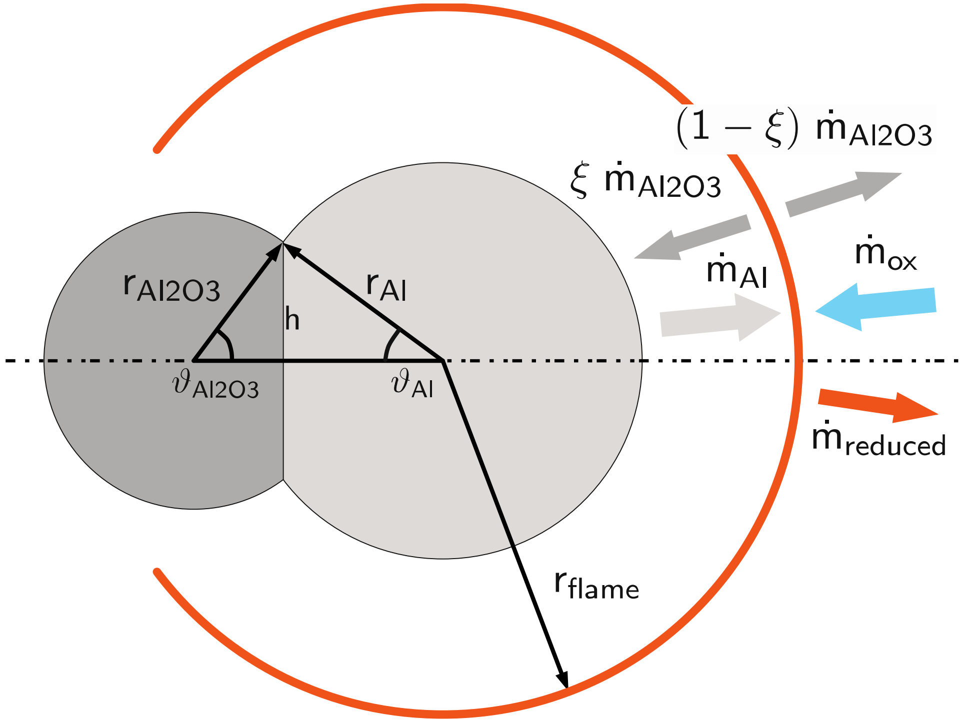
No 100% steam measurements

ALUMINUM FLAMES

Video: Fabian Halter, 5th Clean Circles Mini Symposium (FF2), Darmstadt, 11.07.2023

FLAME MODEL DEVELOPMENT @ STFS





[1] M.W. Beckstead, Correlating Aluminum Burning Times, Combust. Exp. Shock Wav. 41 (2005) 533-546
[2] F. Halter et al., Peculiarities of aluminum particle combustion in steam, Combust. Flame (2023)

CONCLUSION & OUTLOOK

Conclusions

- Modeling of single particle more challenging than iron
- Nano-particle formation must be controlled
- Single particle results promising

Outlook @ RSM/STFS:

- Single particle validation in 100% steam
- 3D modeling of aluminum steam/air flames
- Experiments of flames in steam

The A (s)team:

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State of the Art in Aluminium Water Reaction for Peak Demand in Buildings

by Yvonne Bäuerle - OST - Ostschweizer Fachhochschule

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REVEAL

COVERING WINTER HEAT AND ELECTRICITY

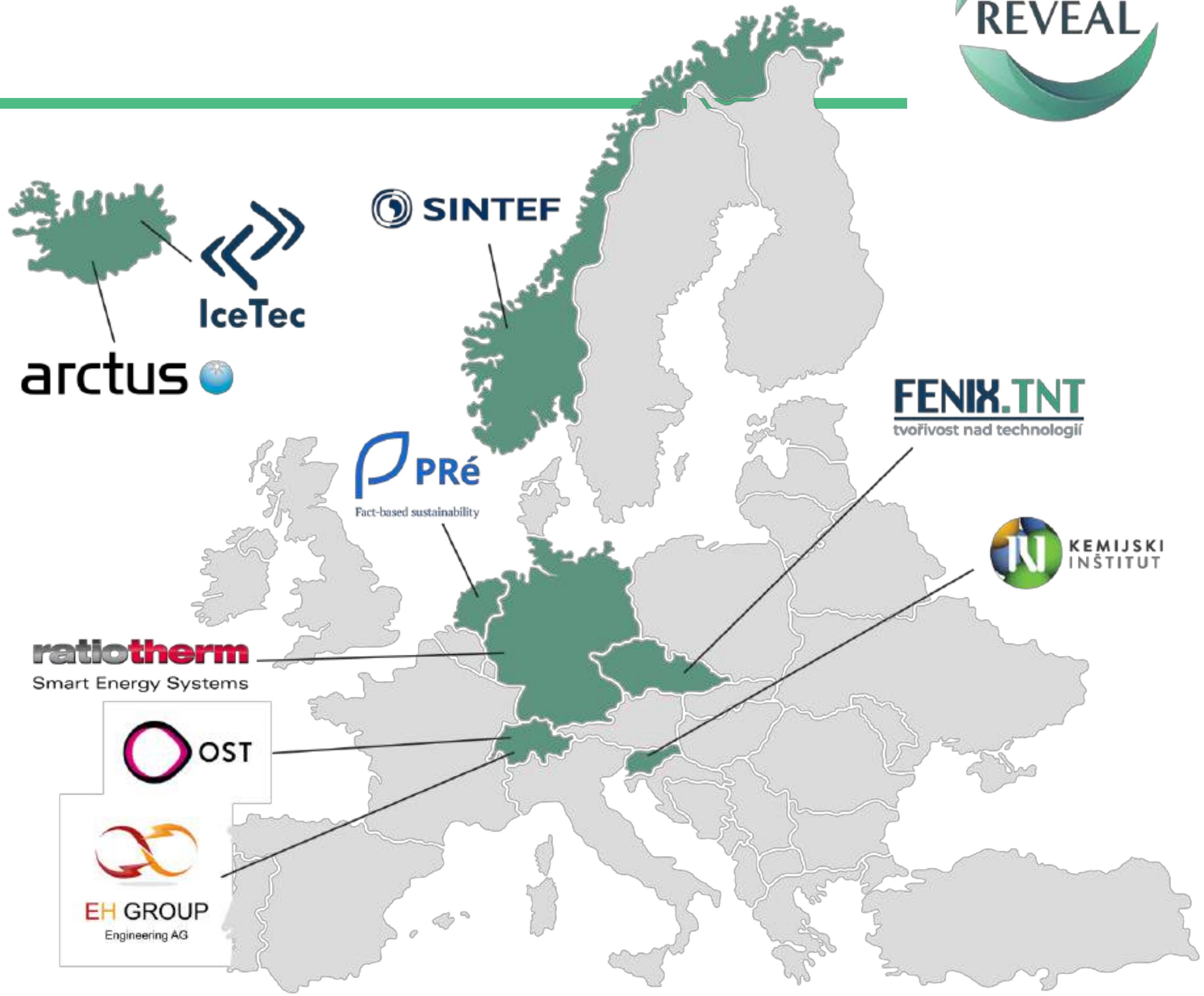
REVOLUTIONARY ENERGY STORAGE CYCLE
WITH CARBON FREE ALUMINIUM

Project specs

June 2022 until June 2026

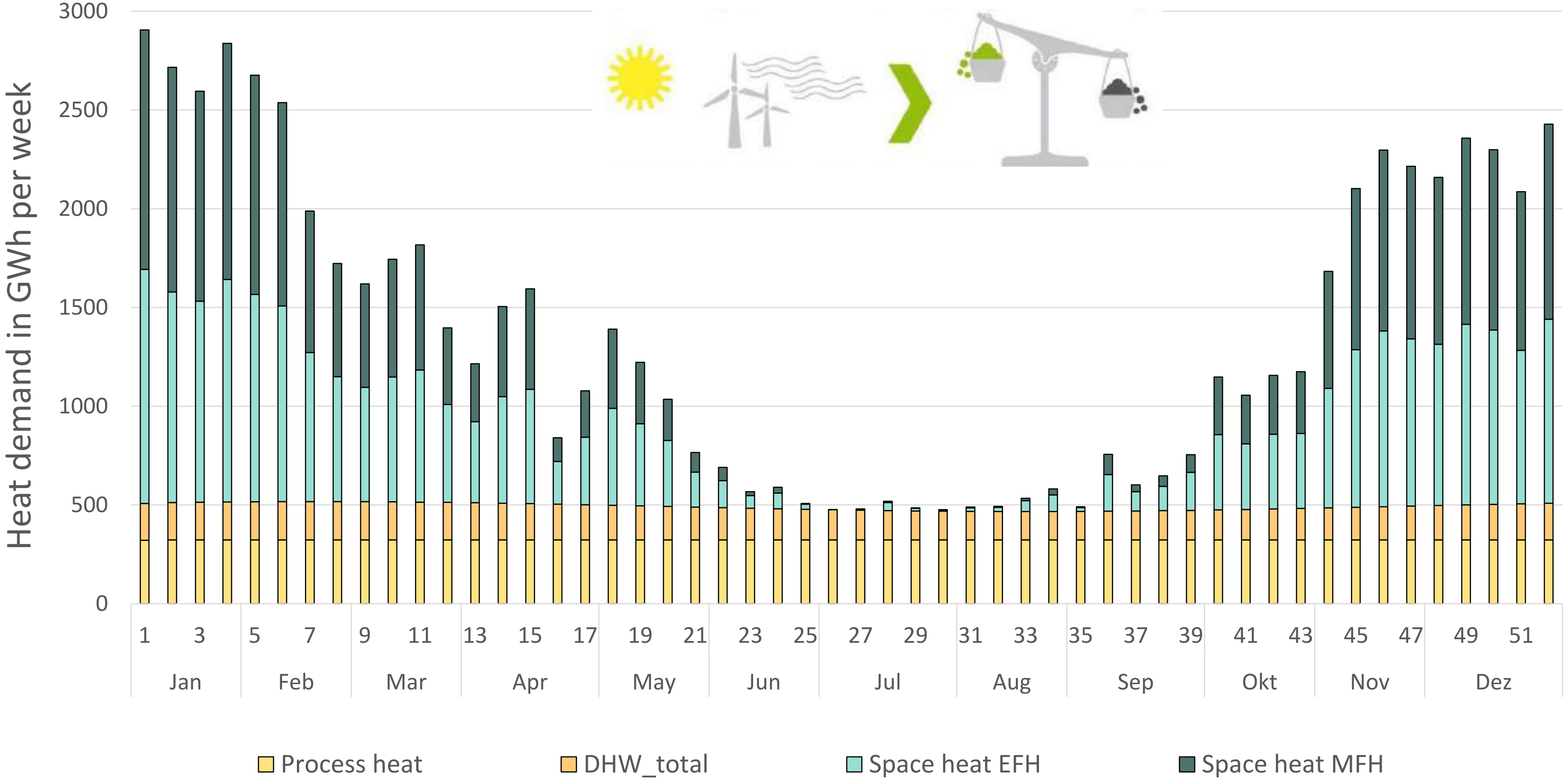
Cooperation of **9 partners** from **7 European countries.**

Iceland, Slovenia, Norway, Netherlands, Czech Republic, Germany and Switzerland



CH Scenario 2050: Heat demand of buildings and industry

Where will our winter heat come from in a carbon-free energy system?

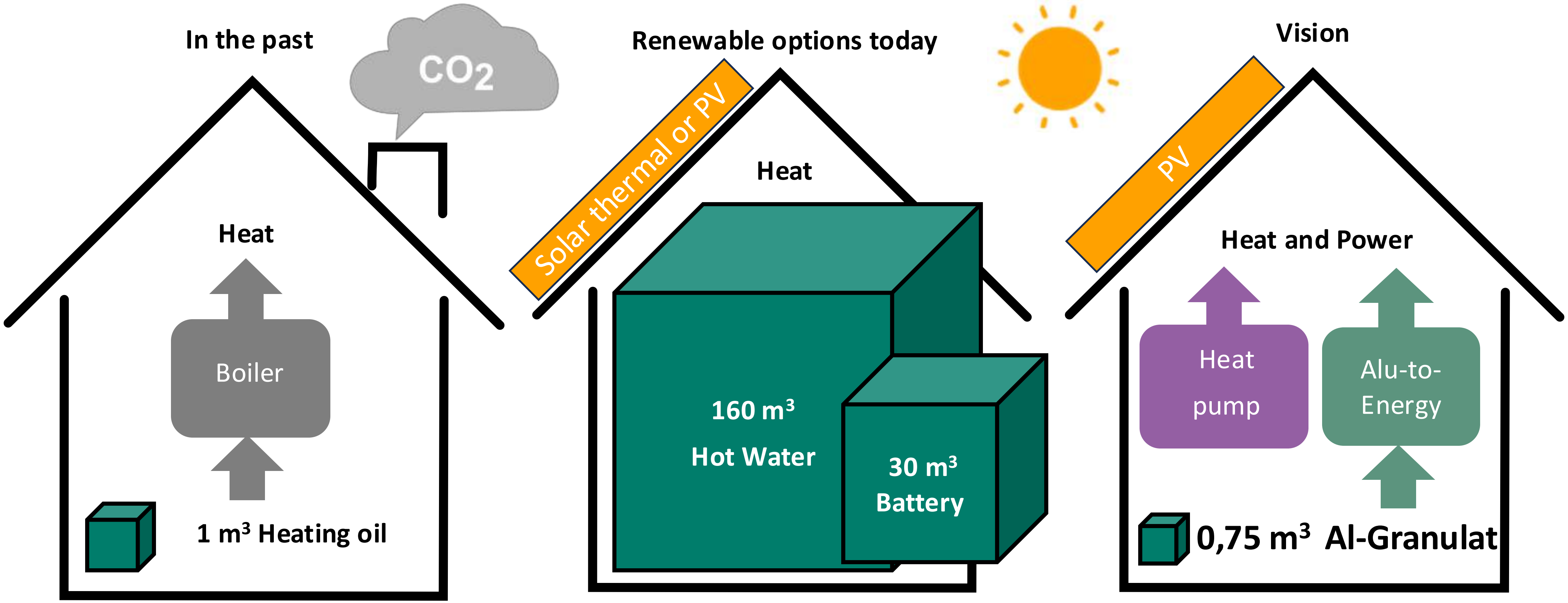


Yearly space heat & DHW	55 TWh_{th}
Winter space heat & DHW (Oct. – Mar.)	**43 TWh_{th}**

- Process heat and DHW needs are constant

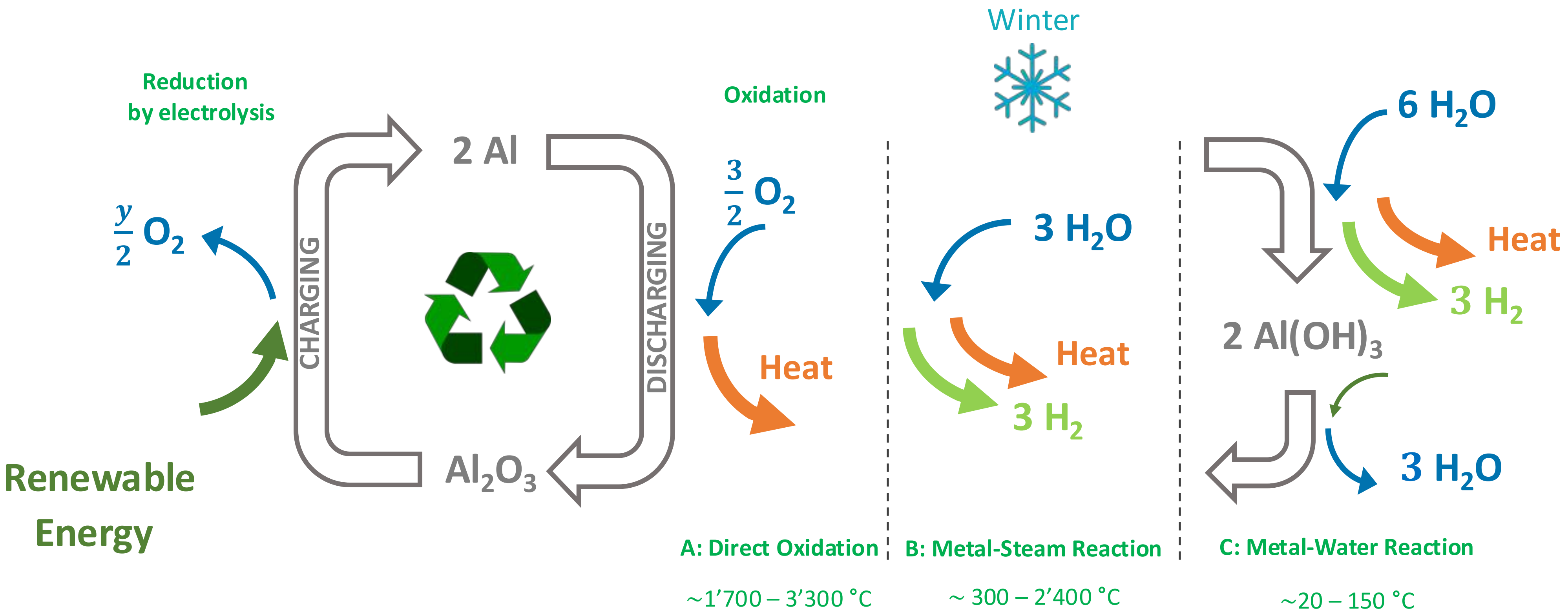
Vison

Where will our winter heat come from in a carbon-free energy system? (without district heating network)



Storage volume requirement to provide a winter heat demand of **11’000 kWh.**

Concept: Aluminium covering winter heat and electricity in buildings



Power-to-Alu

Alu-to-Energy Options

Energy is stored during the reduction of Aluminiumoxide

Energy release takes place during the aluminium oxidation reaction

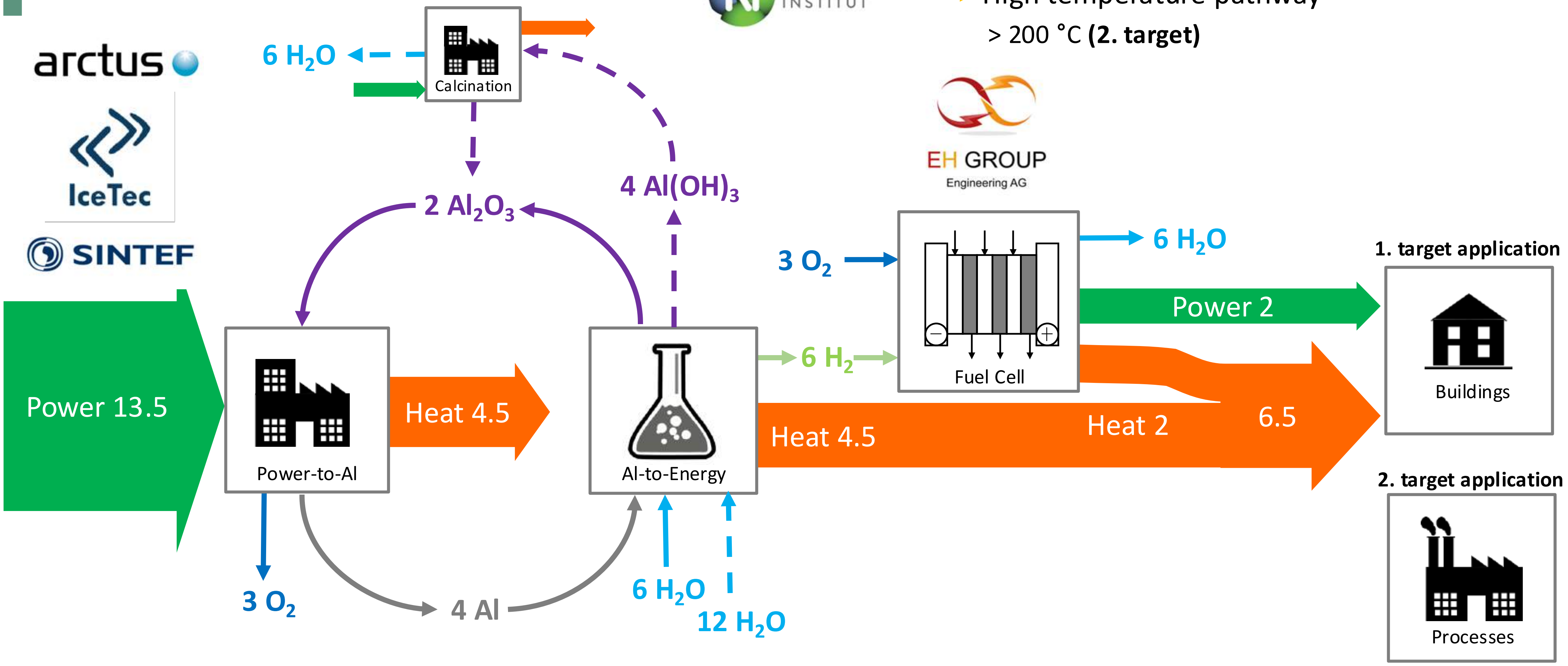
Source: SPF

Aluminium energy storage cycle

Patent was submitted in 2024

Low temperature pathway < 100 °C **(1. target)**

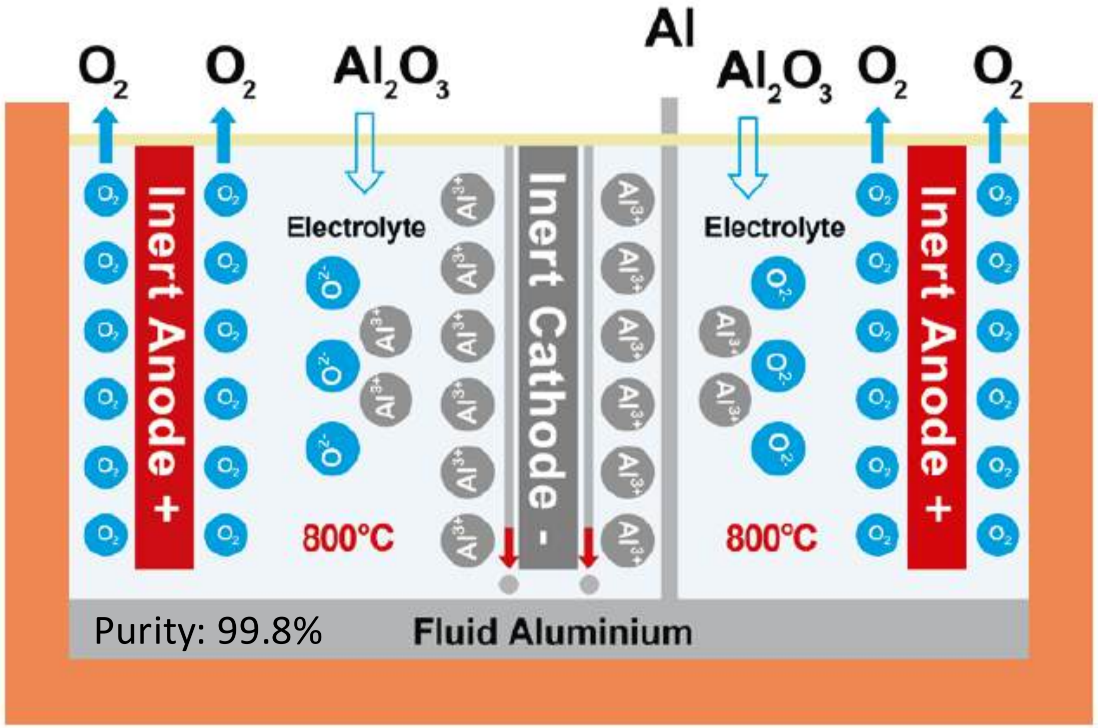
High temperature pathway > 200 °C **(2. target)**



Power-to-Aluminium Revolution

Power-to-Aluminium with zero direct CO_2 emissions

$$2\ Al_2O_3 + e^- \longrightarrow 4\ Al + 3\ O_2$$



Vertical Inert Anode and Cathodes in low temperature electrolyte

Illustration by Arctus Aluminium of concept cell. ©Arctus Aluminium

arctus SINTEF IceTec

Benefits compared to traditional Hall Héroult process

- Zero CO_2 compliance costs & taxes
- 20% less energy
- Modular power feeding during peak hours & power shortage periods for optimal power price
- 50% less space required for same production capacity
- 40% less investment cost
- 30% less operation cost and no carbon anodes

Achievements for Arctus and IceTec vertical inert cell development

REVEAL

- 2018 Proof of concept
- 2020 Long tests in the laboratory
- 2024 Pilot Plant
- 2028 Demonstration Plant
- 2030 Start conversion of the first aluminium smelter

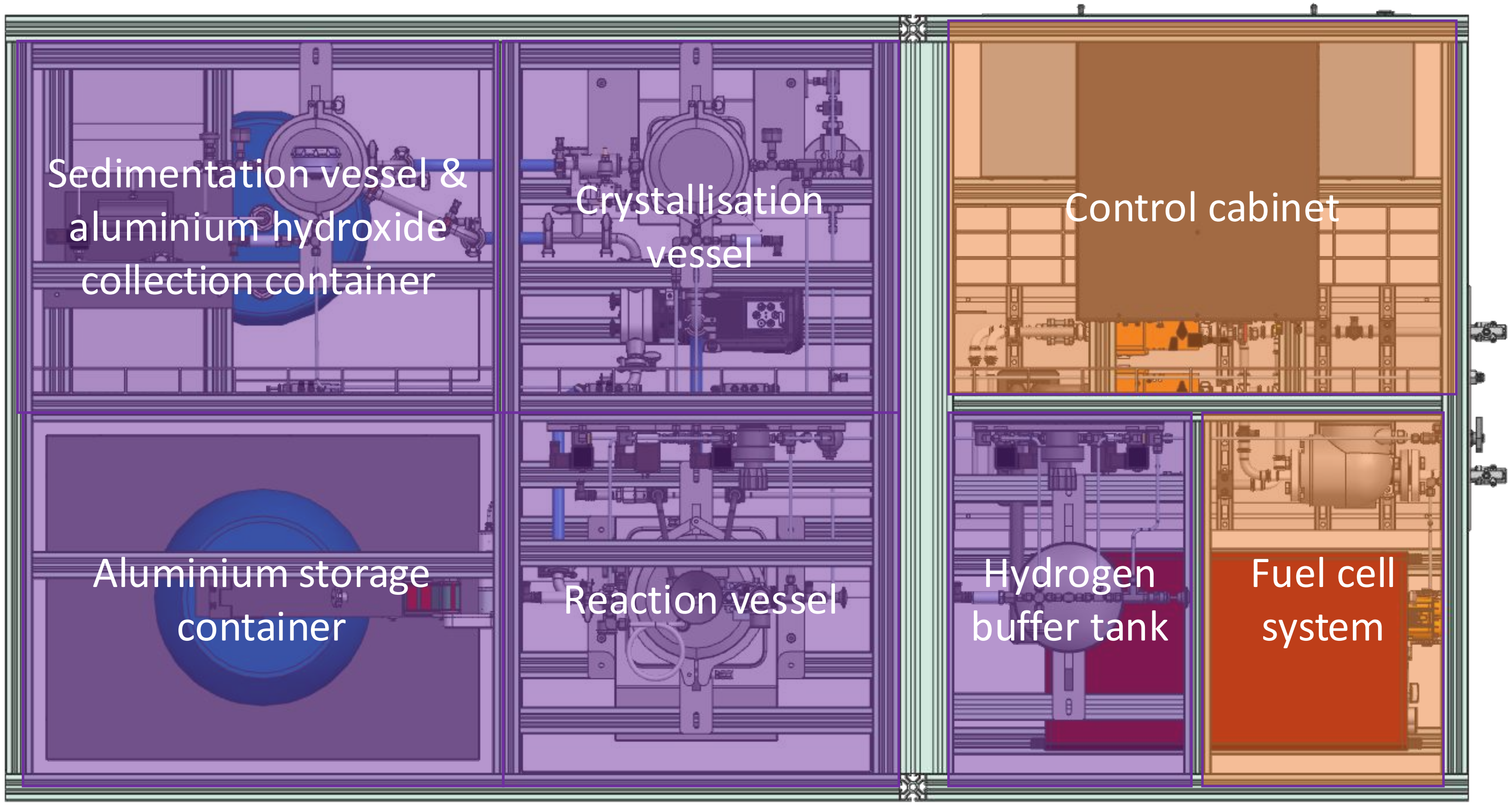
arctus

IceTec

REVEAL – producing batches of green aluminium

Aluminium-to-Energy development @ 60 °C for peak demand in buildings

Design of a 4 kW Alu-to-Energy Prototype



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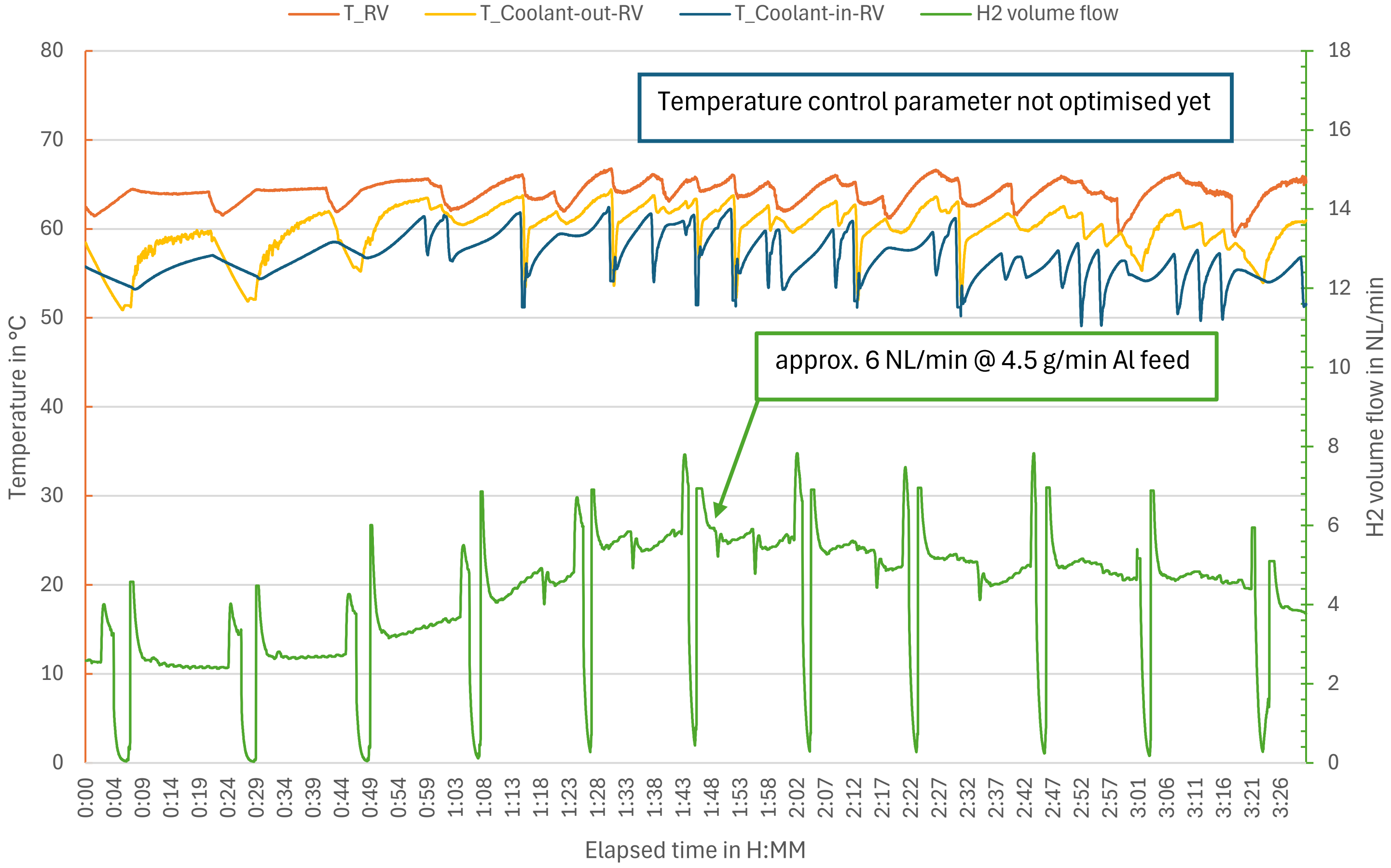


- **1 gram of aluminium produces up to ~1.25 L of H2** (at STP, 0 °C & 1 atm) under ideal conditions and 100% conversion.
- 4 kW Alu-to-Energy prototype can produce max. of ~10 NL of H2 per minute (1 kW electric)
- To separate aluminium hydroxide, the reaction fluid is exchanged every ~20 minutes by increasing and releasing pressure in the vessel.

Summary

Power-to-Alu

- Inert anode electrolysis cells enables aluminum production with zero direct CO2 emissions, powered entirely by renewable electricity in Iceland (hydro power & geothermal).
- This CO_2-free aluminum production technology is on track for full commercialization by 2030.

Alu-to-Energy

- OST-SPF developed an innovative Alu-CHP pilot plant that generates 2 kW of heat plus 2 kW of hydrogen from aluminum.
- For winter peak demand covered in Central European homes, we need 500-1,000 kg of aluminum per dwelling - that's less than 0.75 cubic meters of storage space.
- The aluminum concept enables 100% solar-powered multi-family homes, providing both heat and electricity with complete seasonal energy independence.
- By 2040, we project realistic energy costs of 0.3 Euro per kWh for end-consumers, making this a cost-effective solution for renewable energy storage.

SOCIAL MEDIA

Follow the **REVEAL** latest news on the **project website** and **social media profiles!**

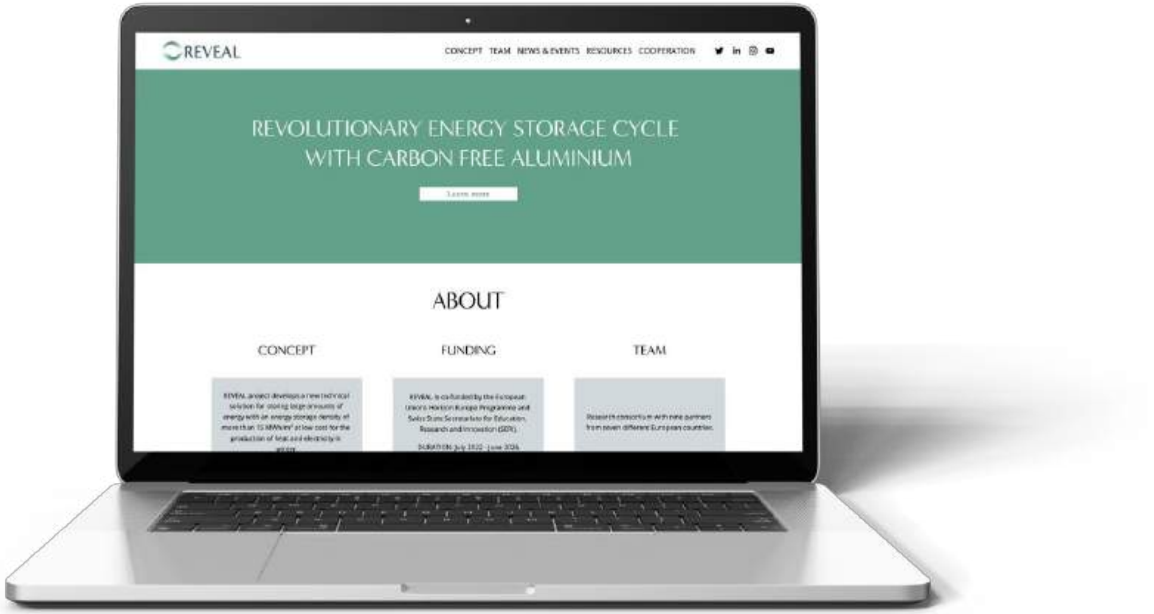
@reveal_storage

@reveal_storage

@reveal-storage

Reveal-Storage

www.reveal-storage.eu



www.reveal-storage.eu

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Reveal-Storage

Yvonne Bäuerle

yvonne.baeuerle@ost.ch

Aluminum battery development

by Michiel Kruijf - ZemQuest

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ZemQuest

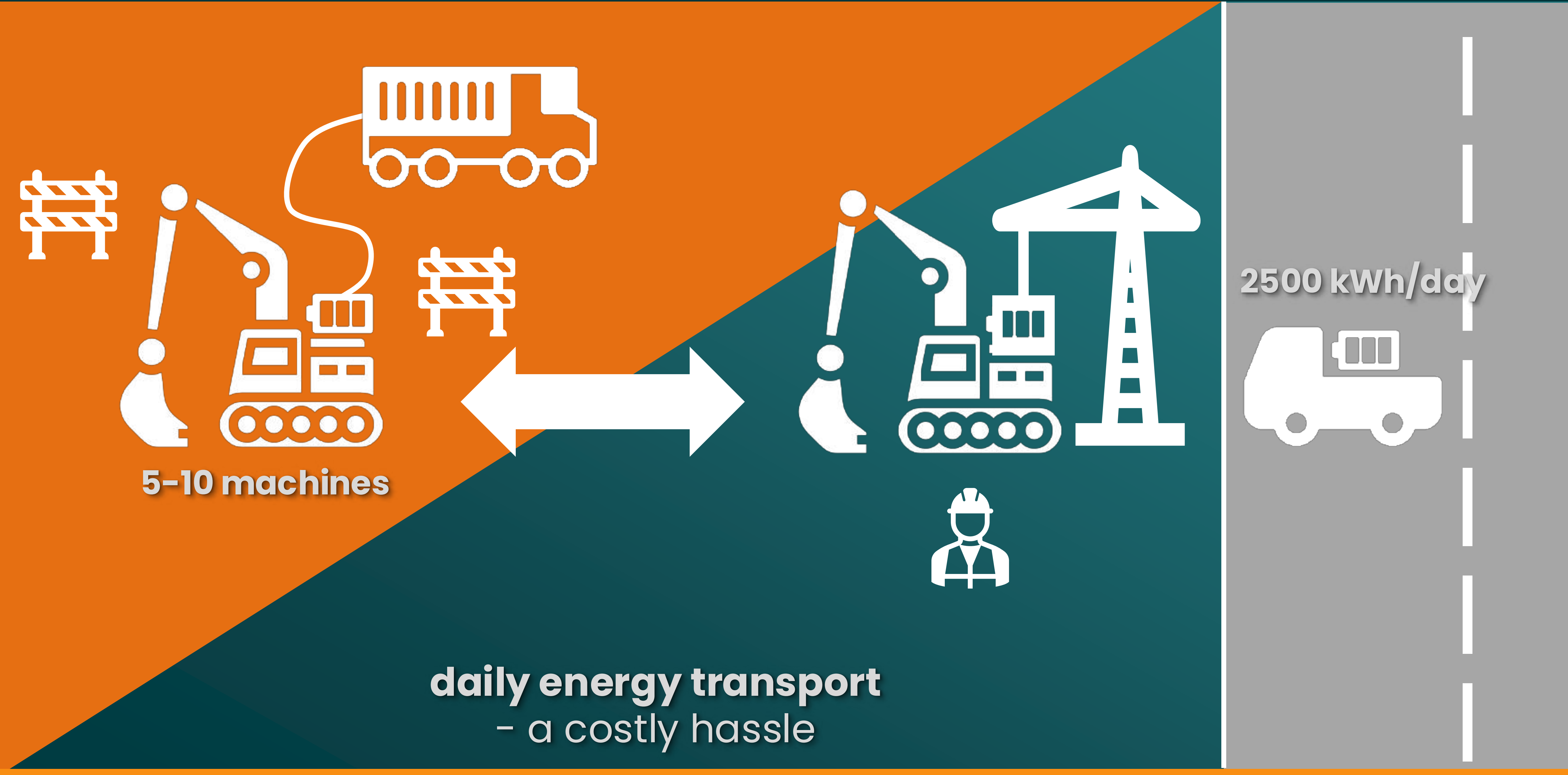
emission-free energy on-site

cheaper, safe & hassle-free

we sell solid fuel

Michiel Kruijff, Metalot 25 June 2025

The bottleneck for off-grid electrification



Where current solutions fall short

1-2 €/kWh

Problems with lithium-ion "only"

- Low endurance
- Logistics costs for offsite charging
- Fire hazard

Problems with hydrogen

- Complex infrastructure
- Transport & storage limitations
- Fire hazard

H_2

3-4 €/kWh

DEME · VAN TUNEN · VolkerWessels · DURA VERMEER

costly, logistic hassle and not safe

Value Proposition

5x Endurance
- 5x Higher energy density
- Compact & highly scalable

5x Less operational hassle
- Grid independent & 5x less logistics
- No downtime & 24/7 ops

Emission-free **energy** delivery **on-site**
for off-grid machinery :
more compact, safe & hassle-free

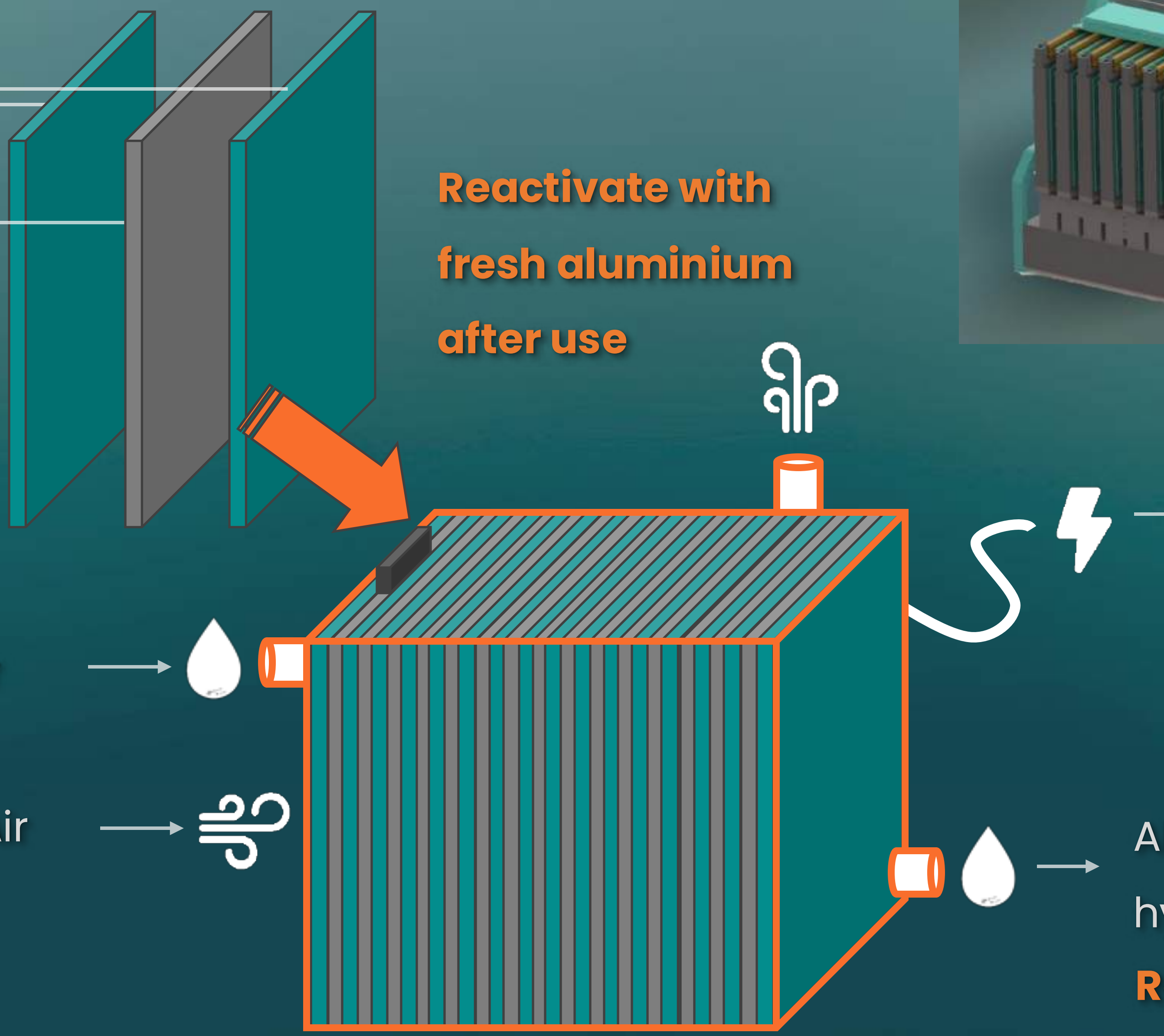
with **aluminium** as a
circular fuel

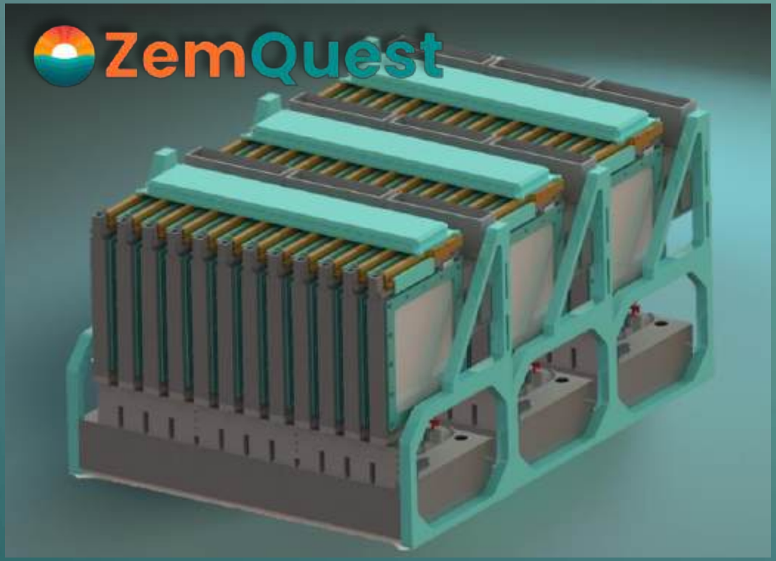
Sustainable
- No CO_2 / NOx emissions
  & 50x less rare earth minerals
- Fully circular & >1000 uses

20-40% Lower cost
- Low investment
- Low TCO

100% Safe
- Non-flammable
- Non-toxic

Solid Fuel Technology Explained



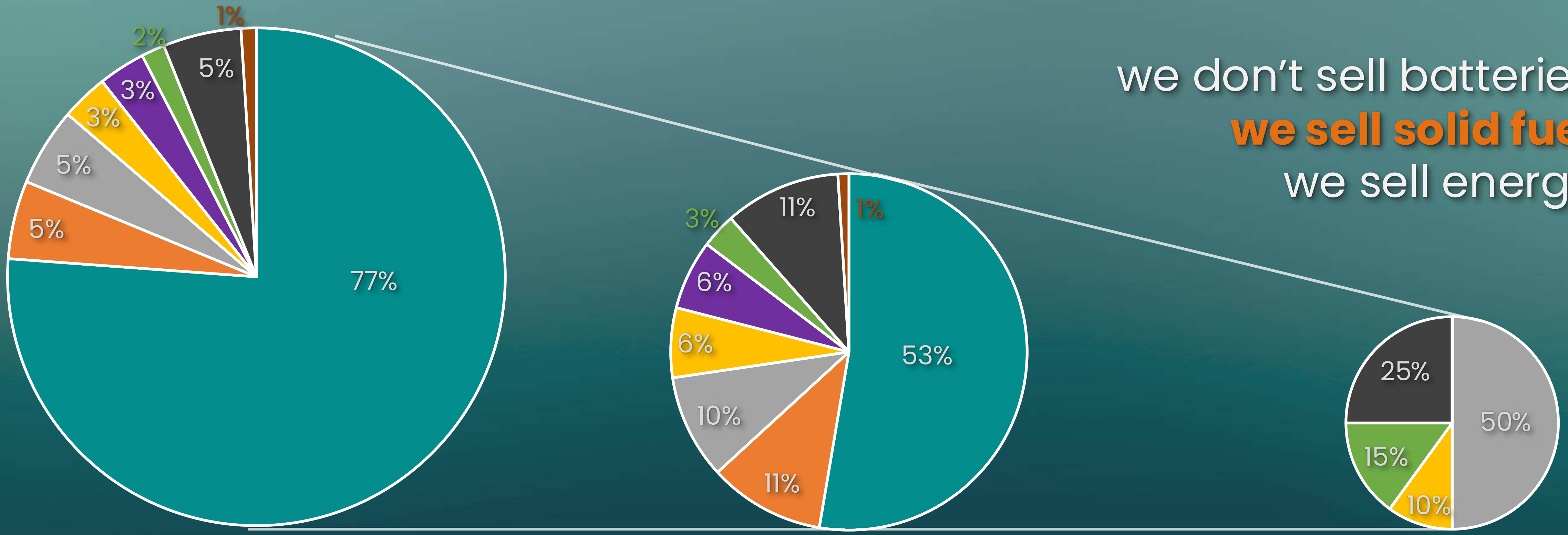


Proven performance in lab (TRL4)

- **Patented** technology
- Modular **scale up** for large machinery
- Enabling **fast & on-site reactivation** concept
- Repeatable **performance in full-scale cells**: 25W/cell, 2.5 kWh/kg, 10+ hours, restart capability
- Designed for **circularity**: non-toxic, macrocomponents, monomaterials, fully reusable

Market Size Estimation

we don't sell batteries
we sell solid fuel
we sell energy



€1,9 Trillion

Total Addressable Market (TAM)

(Market energy consumables new electric vehicles 2030)

€9,4 Billion

Serviceable Addressable Market (SAM)

(Market fit for our aluminum batteries)

€200 Million

Projected Revenue

(=20% of Serviceable Obtainable Market, SOM)

(Market serviceable geographically and production wise)

Business model

Energy-as-a-service ZemQuest

=

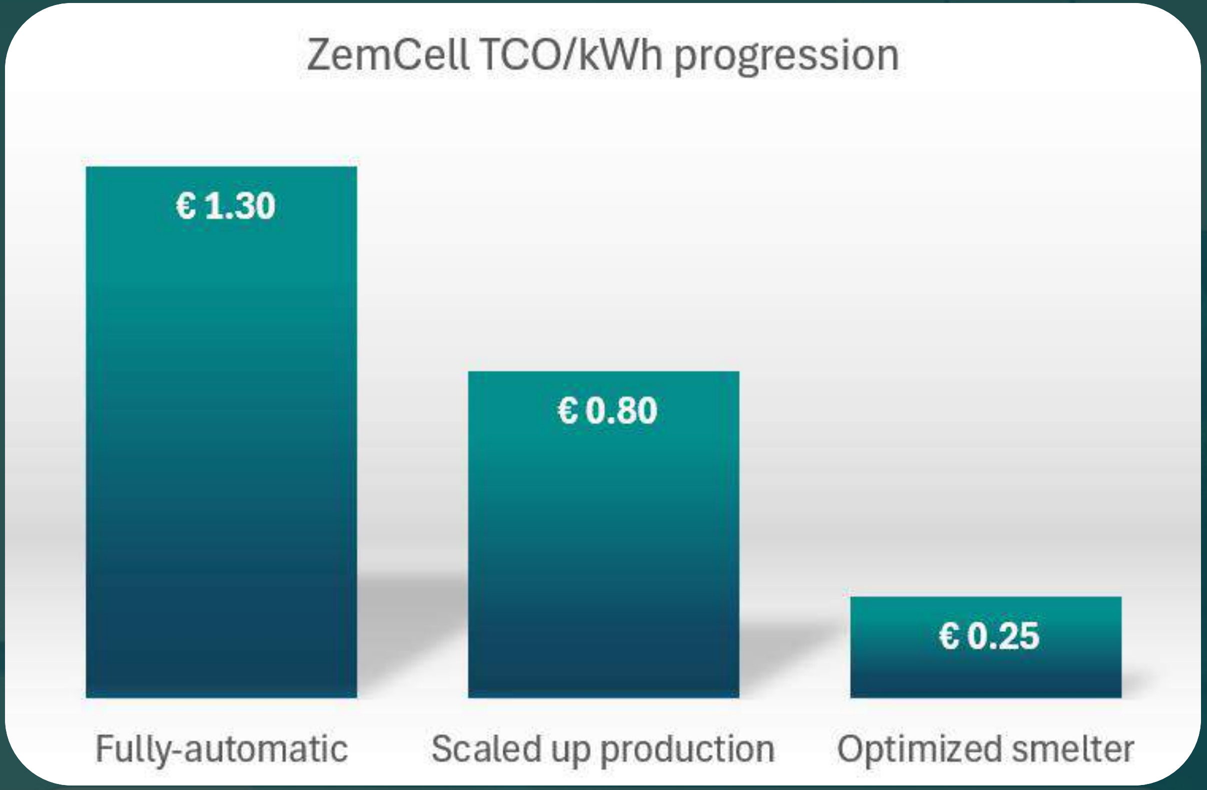
Fuel cell assembly — VDL

Power interface & front end — QuinteQ

Fuel (cell) delivery & pick-up — Jan de Rijk Logistics

Reactivation & waste recovery ZemQuest

Waste resmelting — aludium, Hydro



Full cycle emission: 750 gCO2e/kWh ⟹ 25-50 gCO2e/kWh

Higher full-cycle efficiency than hydrogen

Go-to-market and product roadmap

Stepwise productization

1. Containers for **on-site charging**
2. On-site **full project** storage
3. **Range extension** current vehicles
4. **OEM** design for swapping

Construction NL

AGV NL
Excavators NL

Agricultural NL
Mining EU, CA

Service vehicles, drones, aircraft, **trucks**

Users & partners:

DURA VERMEER
VolkerWessels
VDL
VAN TUNEN
DEME
AGXEED
HERRENKNECHT Tunnelling Systems
SANDVIK
JAN DE RIJK LOGISTICS

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Funding advisory

Thank you!

ZemQuest

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Metalot@Work June 25

Beyond Iron

~~15:30 - Walk-in~~

~~15:40 - Introduction~~

~~15:45 - Metals as sustainable energy carrier, beyond iron - by Jeff Bergthorson - McGill University (live)~~

~~16:00 – State-of-the Art on Aluminum combustion - by Thijs Hazenberg - TU Darmstadt (live)~~

~~16:15 – State of the Art in Aluminium - Water Reaction for Peak Demand in Buildings - by Yvonne Bäuerle - OST (online)~~

~~16:30 - Aluminum battery development- by Michiel Kruijf - ZemQuest (live)~~

16:45 - Short break

17:00 - Magnesium as energy carrier- by Cornelius Schonnenbeck - Université de Haute Alsace (online)

17:15 - Zinc oxidation/reduction cycle - by Ellen Molleman - Nyrstar

17:30 – Iron from water sludge - by Roy Hermanns - TU/e

17:45 - Ambassador Awards

18:00 - Closure & drinks together

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Magnesium as energy carrier

by Cornelius Schönnenbeck - Université de Haute Alsace

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Liberté
Égalité
Fraternité

UNIVERSITÉ HAUTE-ALSACE

Magnesium/Air combustion as a new source of clean energy

C. Schönnenbeck, J-F. Brilhac, A. Brillard
Laboratoire Gestion des Risques et Environnement
Université de Haute-Alsace (LGRE UHA UR 2334), cornelius.schonnenbeck@uha.fr

Metalot@Work, Eindhoven, 25 june 2025

Why magnesium as a new energetic vector?

Magnesite/Dolomite ($MgCO_3$-$CaCO_3$)
~2%$_{wt}$ of the earth crust

Magnesium chloride
($MgCl_2$)
~0.1%$_{wt}$ in Water

	Energy per mass unit (MJ/kg)	Energy per volume unit (MJ/L)
Mg	25	43
Al	30	81
Fe	8	60
Diesel	43	35

Particularities of Mg

	Melting point	Boiling point	Flame temperature	Oxide	Melting point	Boiling point
Mg	650°C	1090°C	2817°C	MgO	2852°C	3597°C
Al	660°C	2470°C	3268°C	Al2O3	2072°C	2977°C
Fe	1538°C	2861°C	1955°C	Fe2O3	1539°C	---*

* decomposes

Mg :

- Boiling point of Mg << Flame temperature
- MgO melting point > Flame temperature

Modes of combustion :

→ Vapor-phase droplet combustion of Mg.

→ Heterogeneous reaction without flame at T < 650°C

Research developed at LGRE-UHA for the investigation of magnesium/air combustion

Homogeneous combustion of Mg.

(**Fast combustion** in a Mg/air flame)

Heterogenous combustion of Mg.

(**Slow combustion** of Mg at temperature up to 600°C)

Objectives

To design and to develop a **pilot-scale combustion chamber** to produce **stable magnesium/air flames**.

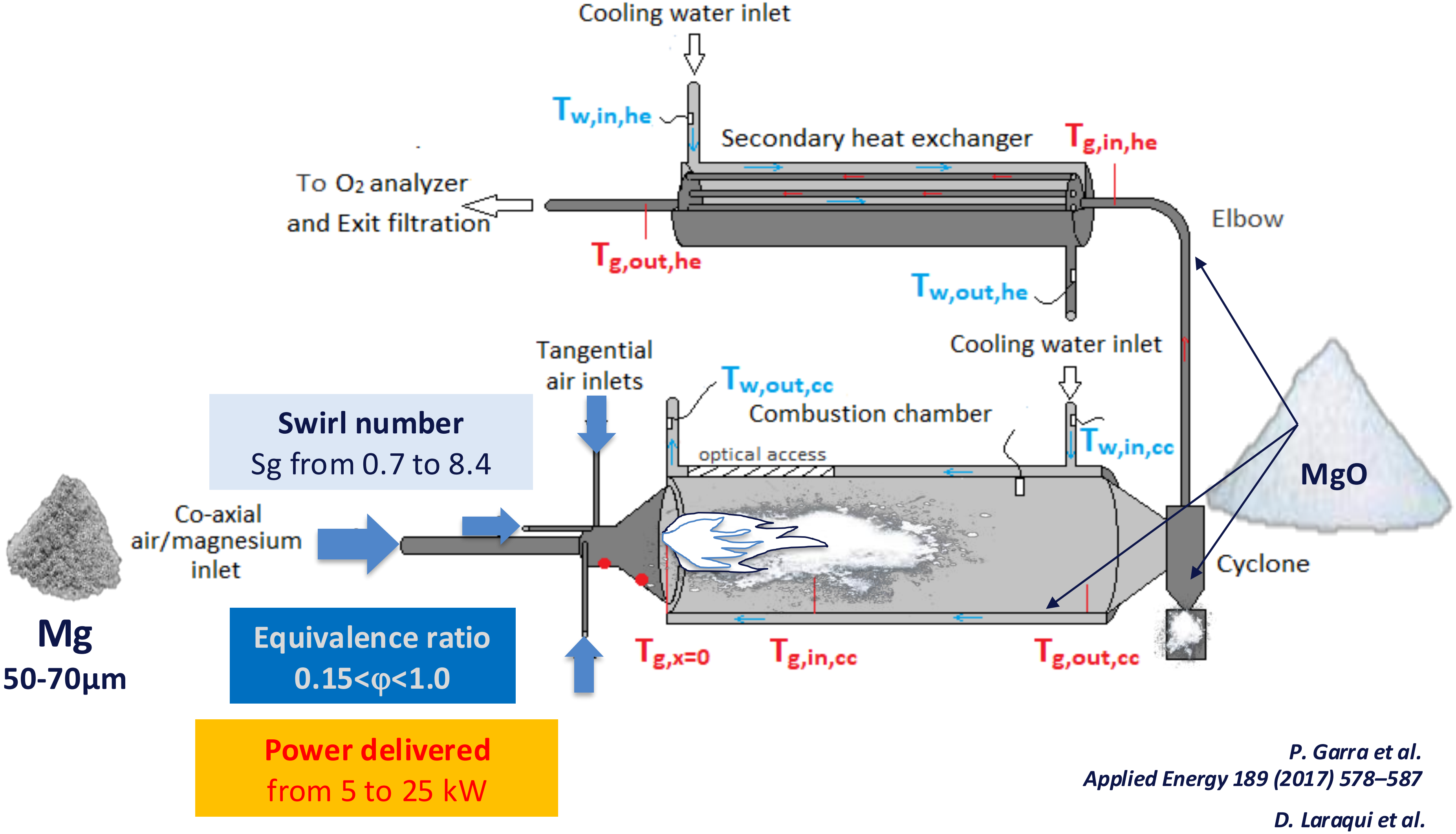
Challenges addressed:

i) what is the efficiency of the magnesium combustion? what are the **solid products** of the combustion process? How to collect these solid products?

i) what are the **pollutants emitted** during the combustion process? Nitrogen oxides (NOx)? MgO aerosol?

i) how to **simulate Mg combustion** in this pilot burner?

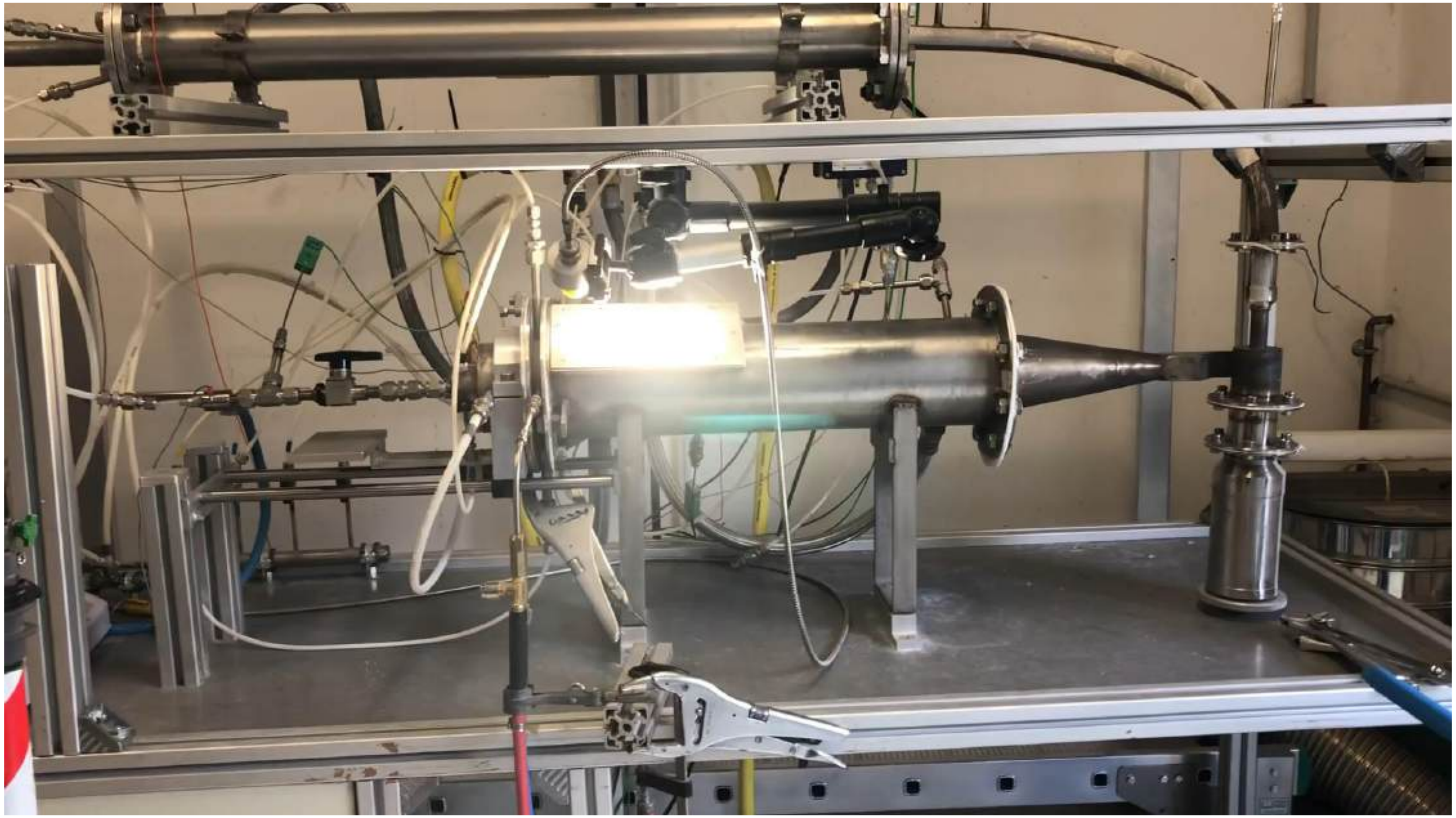
Mg/Air combustion system at LGRE



P. Garra et al.
Applied Energy 189 (2017) 578–587

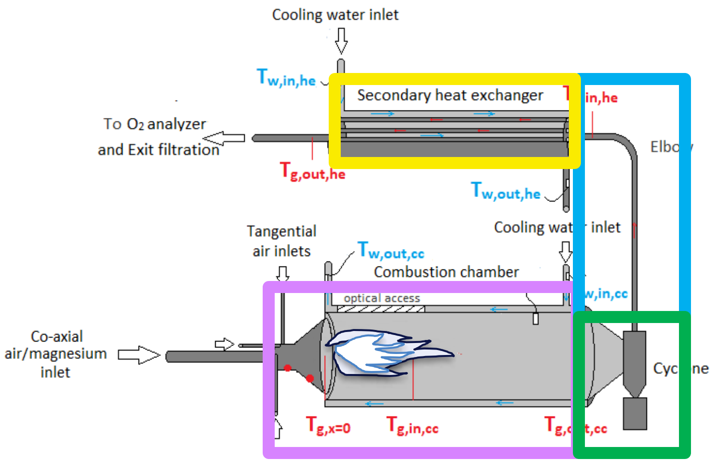
D. Laraqui et al.
Applied Energy 264 (2020) 114691

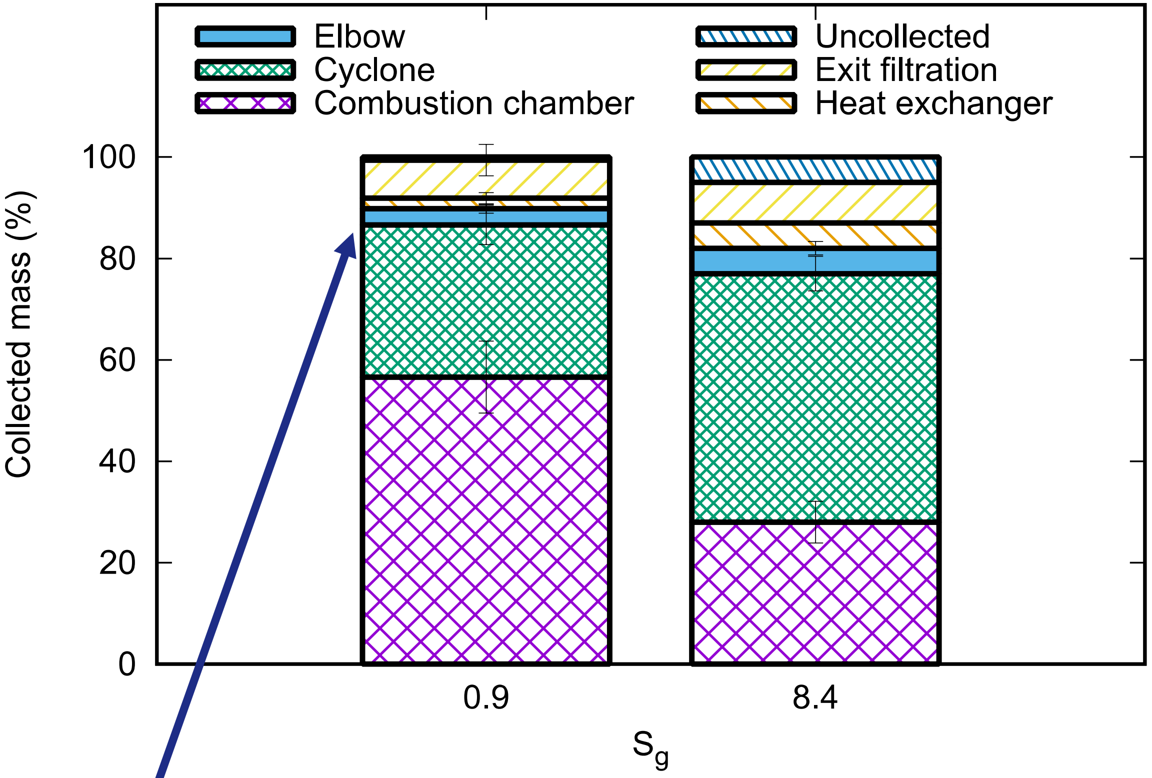
Mg/Air combustion system



Mass fraction distribution of collected MgO

for Sg=0.9 and 8.4



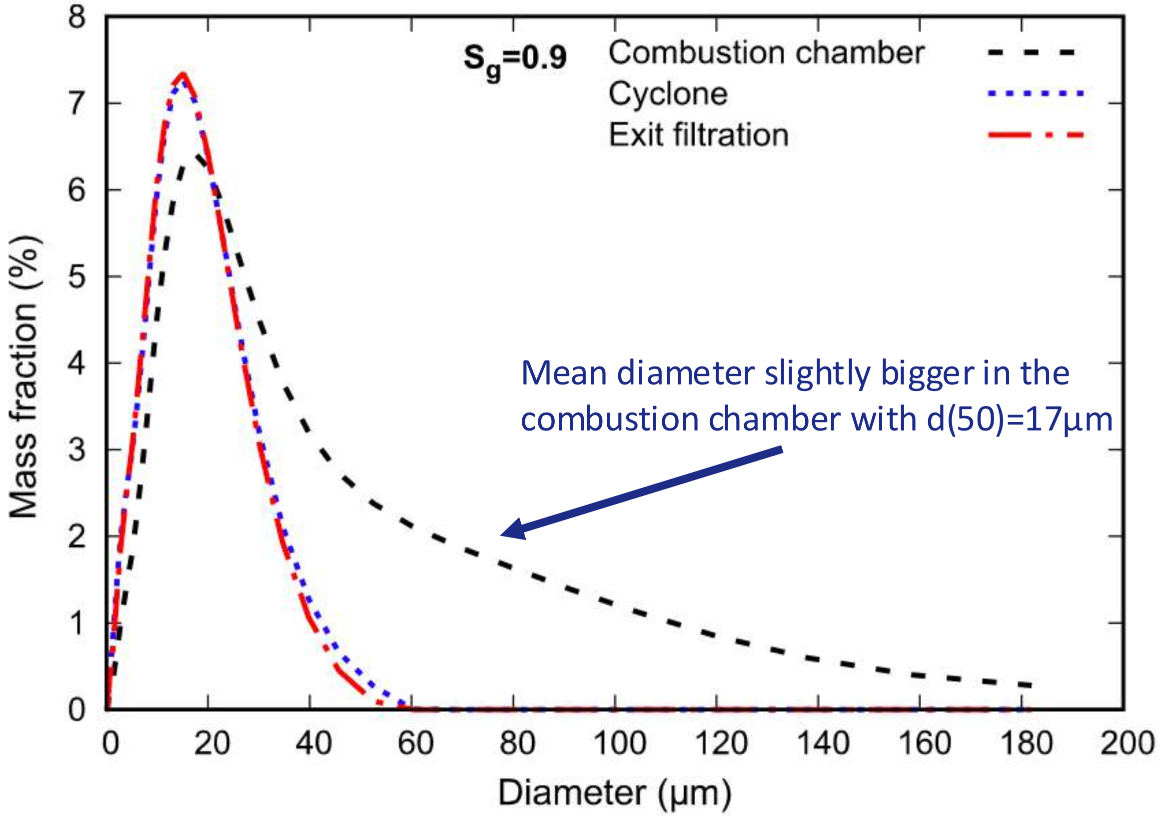


More than 90 %wt of MgO is trapped in the system (for regeneration)

D. Laraqui et al.
Applied Energy 264 (2020) 114691

Particles produced from Mg combustion (Sg=0.9)

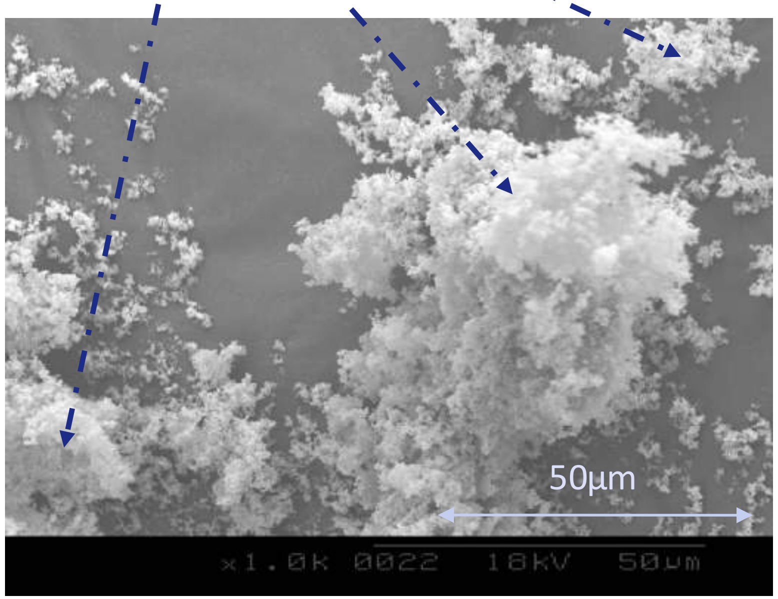
MgO particle size determination
(Laser granulometer Scirocco 2000M from MALVERN® λ=532 nm)

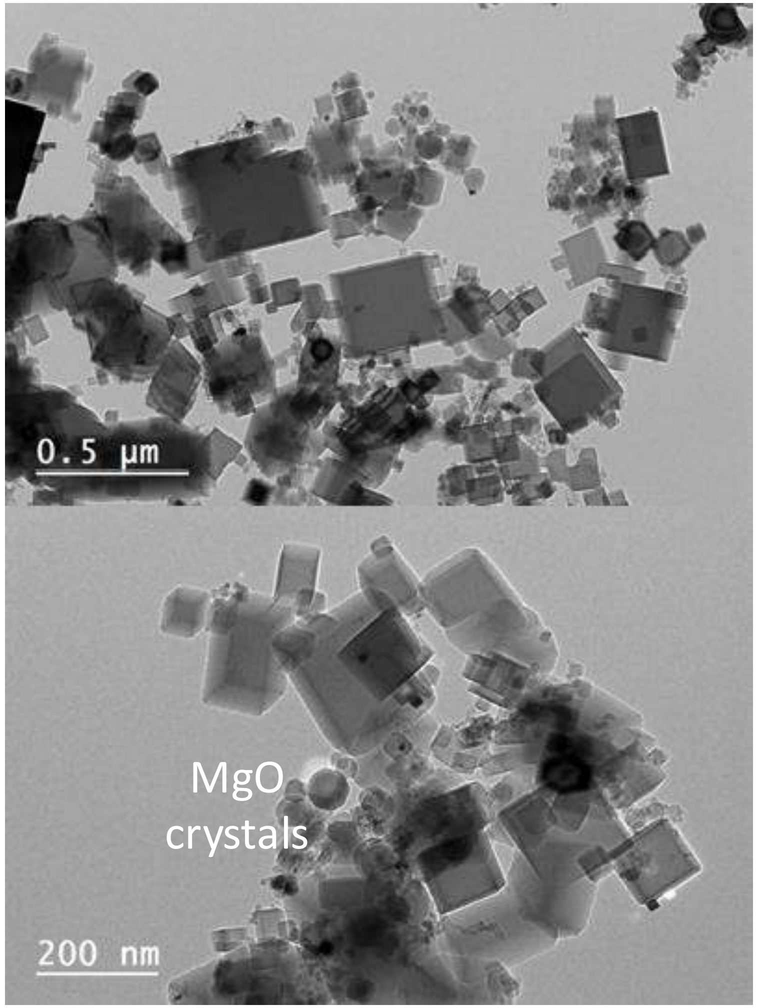


D. Laraqui et al.
Applied Energy 264 (2020) 114691

SEM and TEM photos of MgO particles for Sg=8.4

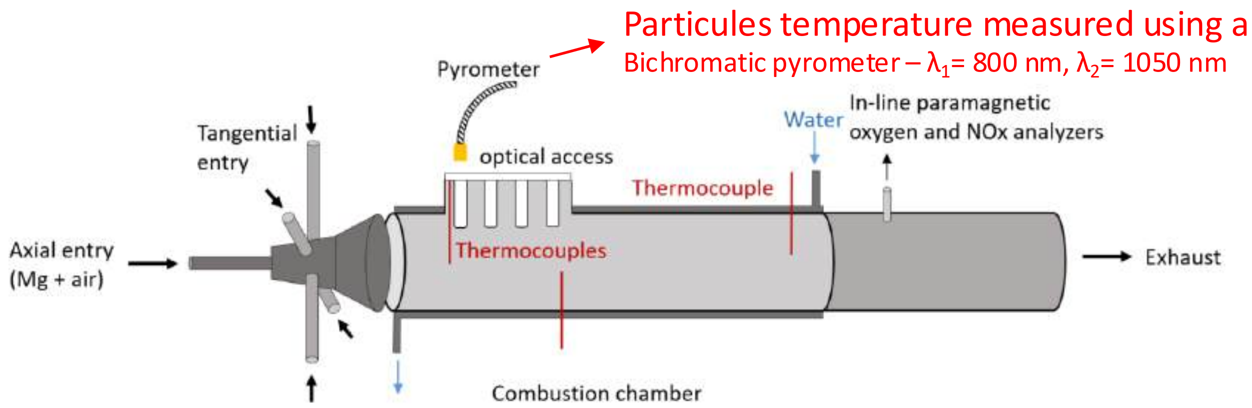
Agglomerates of aggregates of MgO crystals

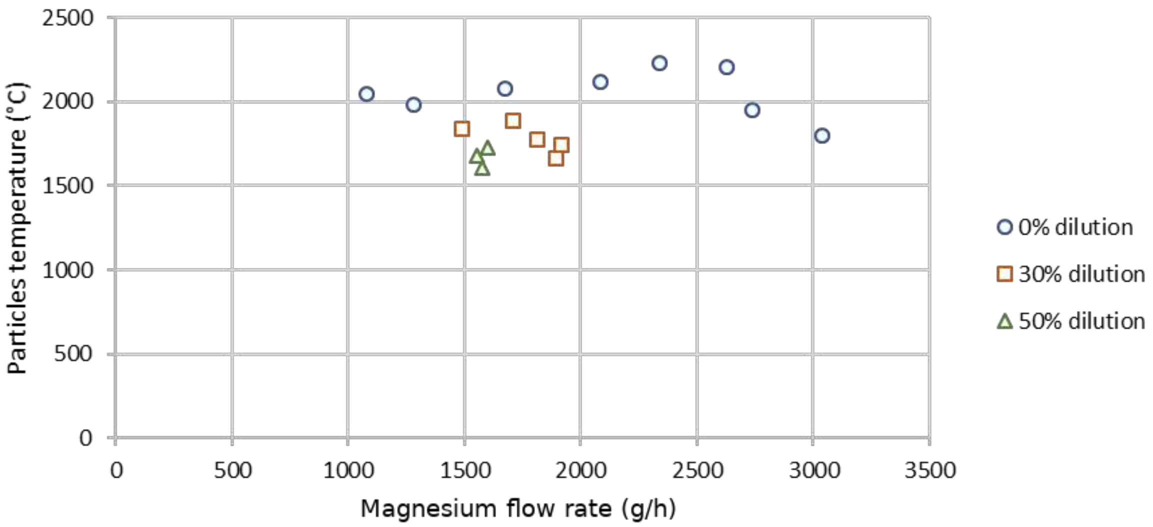




D. Laraqui et al.
Applied Energy 264 (2020) 114691

Particles temperature for Sg=7.3





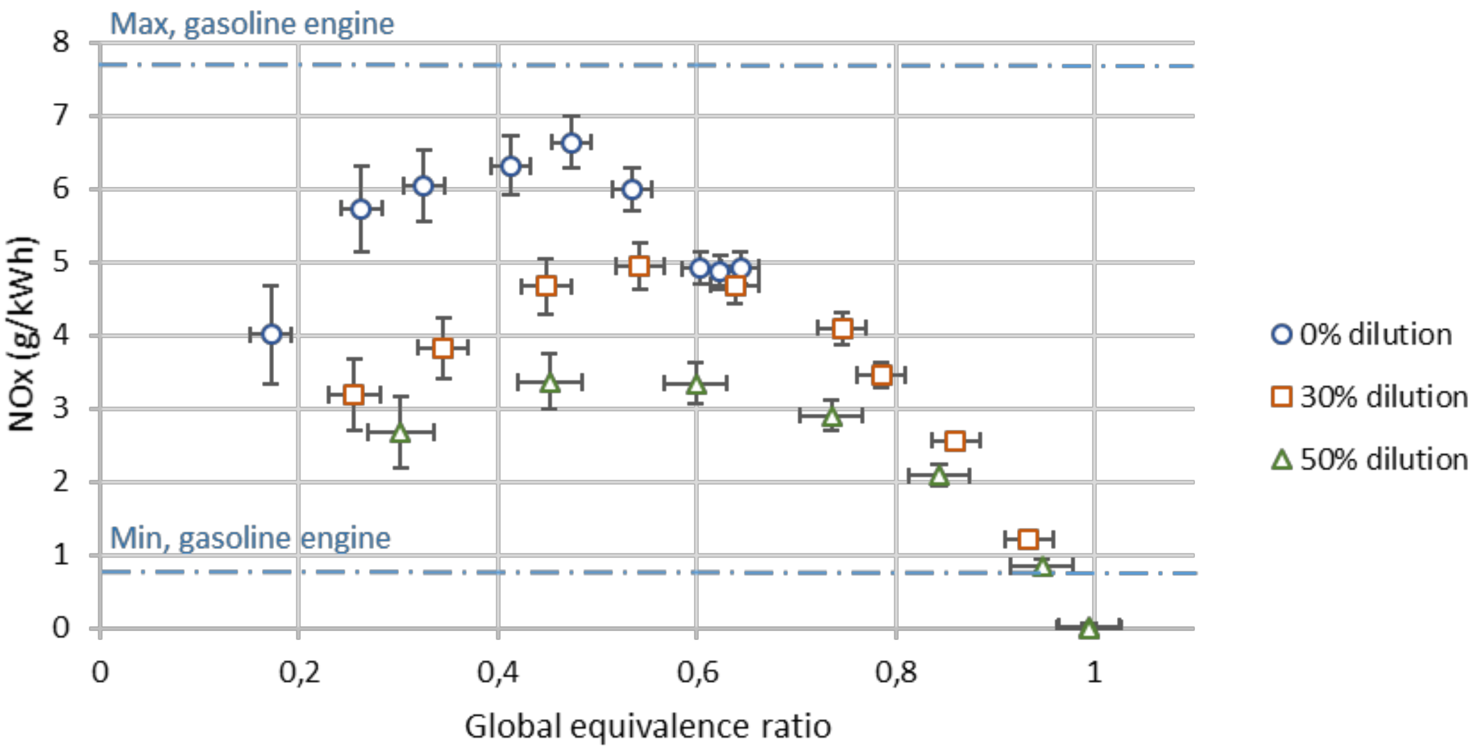
The observed temperature is below the flame adiabatic temperature (water-cooled walls, cooled MgO screen).

Particles temperature is not influenced by the global equivalence ratio.

Influence of Dilution by N2 is small

Andrieu A. et al.
Fuel 341 (2023) 127702

NOx emissions depending on equivalence ratios and N_2 dilutions

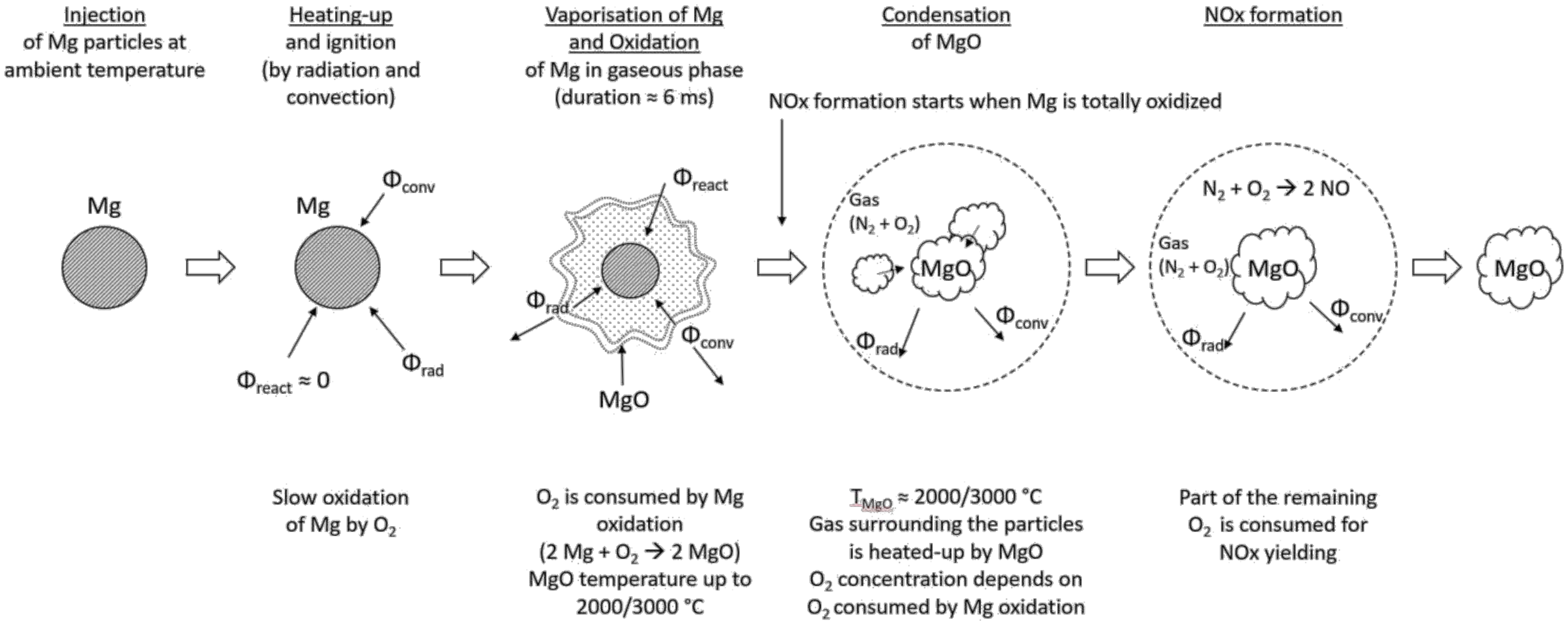


Level of NOx emissions depends on equivalence ratio and N_2 dilution

=> flue gas recirculation should reduce NOx production

Andrieu A. et al.
Fuel 341 (2023) 127702

Mechanism proposed for Mg oxidation and subsequent NOx production

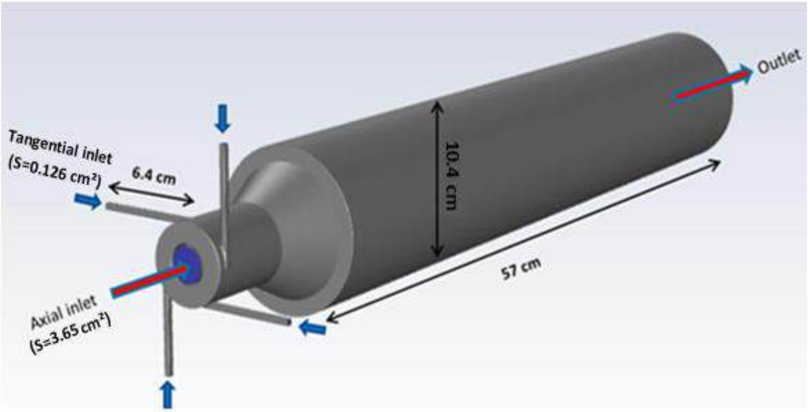


Andrieu A. et al.
Fuel 321 (2022) 124011

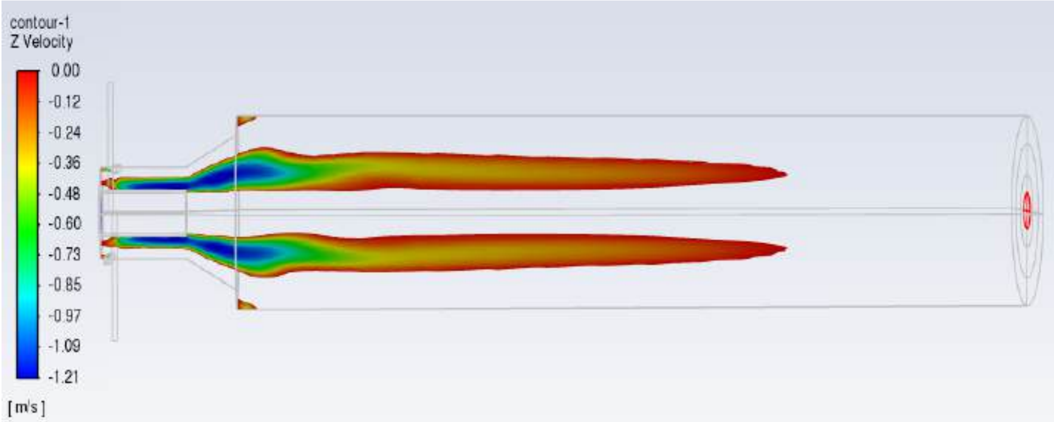
CFD simulation of magnesium combustion in the swirled-combustion chamber (under FLUENT)

1. **Simulation of the cold and monophasic (gas) flow** in the combustion chamber under Fluent: distinction between low swirl number (standard k-ε model) and high swirl number (Reynolds stress model).

Scheme of the combustion chamber



Simulation of the gas recirculation zone



Experimental validation using a plexiglas replica of the combustion chamber (Constant Temperature Anemometry).

T. Wronski et al.,
European Journal of Mechanics - B/Fluids
Volume 96, 2022

Magnesium/Air combustion as new energetic vector : Research developed at LGRE

Homogeneous combustion of Mg.

(**Fast combustion** in a metal flame)

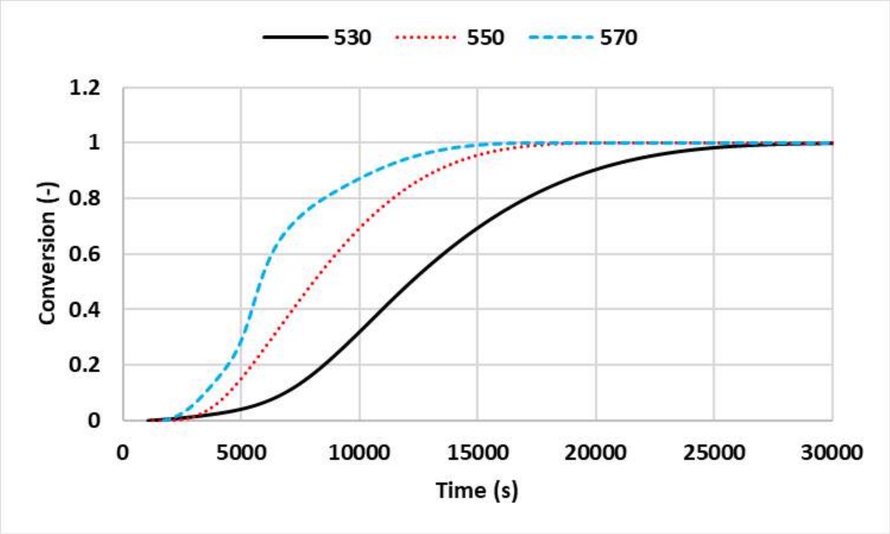
Heterogenous combustion of Mg.

(**Slow combustion** at temperature up to 600°C)

Slow oxidation of Mg powder (50-71 µm) in fluidized bed

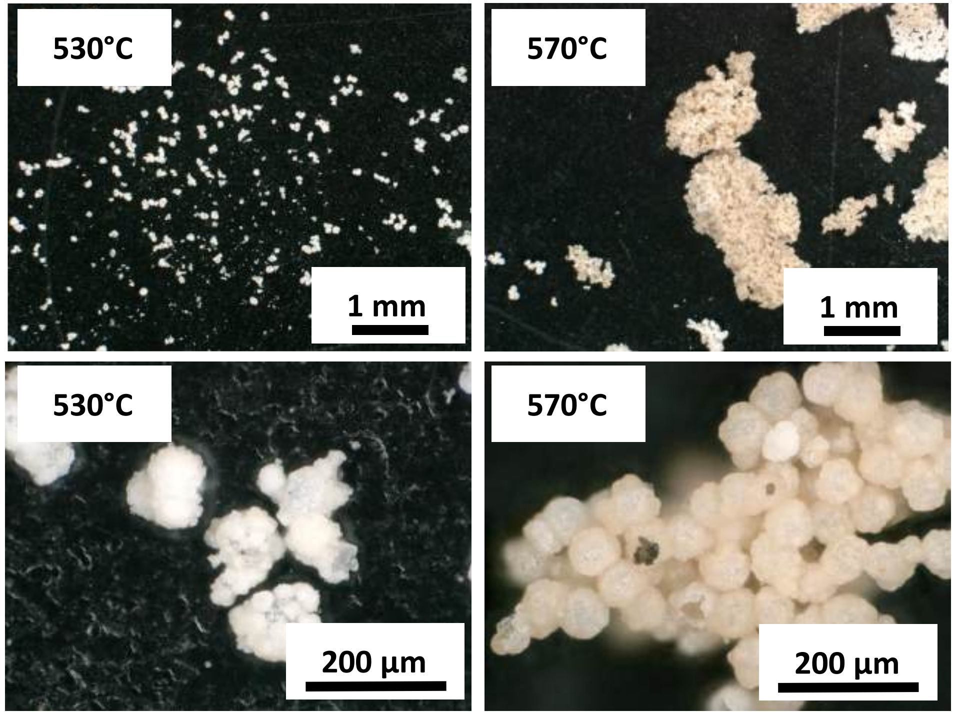
Oxidation in a fluidized bed at constant temperature (530, 550 and 570 °C), **under air**

Normalized extend of conversion



Optical microscopy observations
of magnesium samples at 530 and 570 °C

(Digital microscope KEYENCE VHX - 6000)

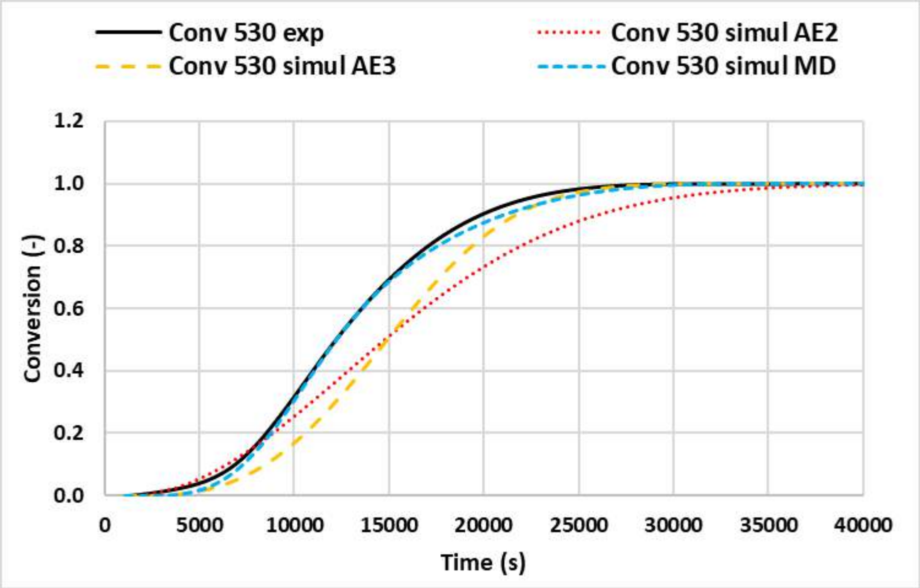


A. Wittmann et al.
Combustion and Flame 272 (2025) 113853

Slow oxidation of Mg powder (50-71 µm) in fluidized bed

Simulation of Mg conversion using

- Avrami-Erofeev model n=2 (AE2)
- Avrami-Erofeev model n=3 (AE3)
- Mampel-Delmon model (MD)



MD model:

- Nucleation rate rises faster with temperature than rate of growth of nuclei
- Activation energy of nucleation is virtually the same than AE3 activation energy

AE model:

- Interesting due to low computational coast

A. Wittmann et al.
Combustion and Flame 272 (2025) 113853

Conclusions

- **Laboratory scale combustion chamber:**
  - Gives design specification for the heat source
  - Demonstrates that NOx emissions can be controlled
  - And more than 90%wt of the MgO produced is trapped in the system
- **Slow oxidation of Mg**
  - Oxidation of Mg can be maintained in homogeneous phase
  - Size of MgO particles is about the same as initial particles

Many thanks to:

Dr. P. Garra (post-doc 2015),
Dr. G. Moser (PhD 2016-19),
Dr. D. Laraqui (PhD 2017-20),
Dr. A. Andrieu (PhD 2019-22),
Dr. T. Wronski (PhD 2019-22),
A. Wittmann (master thesis 2023),
`

and (permanent staff)

O. Allgaier, Dr. G. Leyssens, Dr. N. Zouaoui-Mahzoul,
Pr. J.F. Brillhac, Pr. A. Brillard, Pr. V. Tschamber

Thanks for attention

Zinc oxidation/reduction cycle

by Ellen Molleman - Nyrstar

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Nyrstar

Resources for a Changing World

Metalot @ Work
June 2025

nyrstar

Agenda

- Over Nyrstar
- Clean jarosite
- Zn burning

Nyrstar operations – international footprint

Nyrstar is an international producer of critical minerals and metals essential for a low carbon future.

With a market leading position in zinc and lead, Nyrstar has mining, smelting and other operations located in Europe, the U.S. and Australia and employs approximately 4,000 people. Its Corporate Office is based in Budel-Dorplein, the Netherlands.

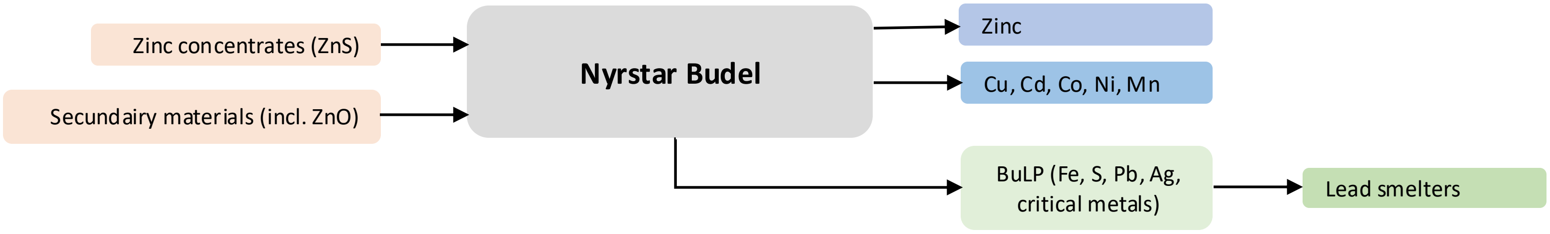
The company's operations are located close to key customers and major transport hubs to facilitate reliable and efficient delivery of raw materials and distribution of finished products.

Nyrstar's operating business is wholly owned by Trafigura, one of the world's leading independent commodity trading and supply chain logistics companies.

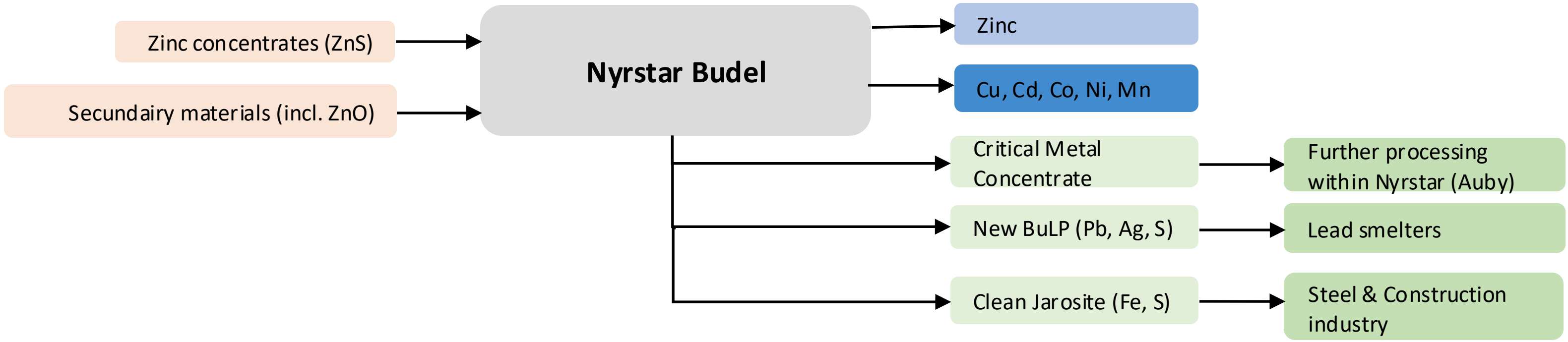
Nyrstar European footprint

Clean Jarosite

- Current flowsheet



- Recovery of critical metals from Budel flowsheet (mainly germanium, indium) requires a flowsheet change, which makes production of another quality Budel Leach Product logical



Clean Jarosite - products

Current Flowsheet	Processed by:	CJ Flowsheet	Processed by (currently being investigated):
Jarosite containing: • Iron, Lead, Sulphur, Arsenic, Silver, Copper, Germanium, Indium	Lead Smelters: • Nyrstar PP, Stolberg • Third party	Clean Jarosite containing: • Iron, Sulphur	Possible outlets: • Cement/concrete additive • Further processing into hematite for the steel industry (Metalot?)
		Lead-Silver product	Lead Smelters: • Nyrstar PP, Stolberg
		Pre-Hydrolysis product containing: • Copper, Arsenic, silver, germanium, indium	• Nyrstar Auby • Nyrstar PP

Clean Jarosite Project – calcination

105˚C 300 ˚C 650 ˚C 700 ˚C 900 ˚C

	Clean jarosite	Gecalcineerd op 900 oC	Gecalcineerd en gewassen
Fe	32,0%	50,5%	75,5%
K	6,70%	9,45%	0,02%
S	12,18%	5,21%	< 0,50%
Zn	0,77%	1,14%	< 0,20%
Massa	100,0%	64,0%	45,2%

Clean Jarosite Project

Link with Metalot

- Use of clean jarosite in iron reduction proces -> make pure Fe
  - Conversion of S to SO_2 – requires off-gas systeem
- Use the produced hematite as feed material for the iron reduction proces
  - Production of hematite from clean jarosite is CAPEX intensive

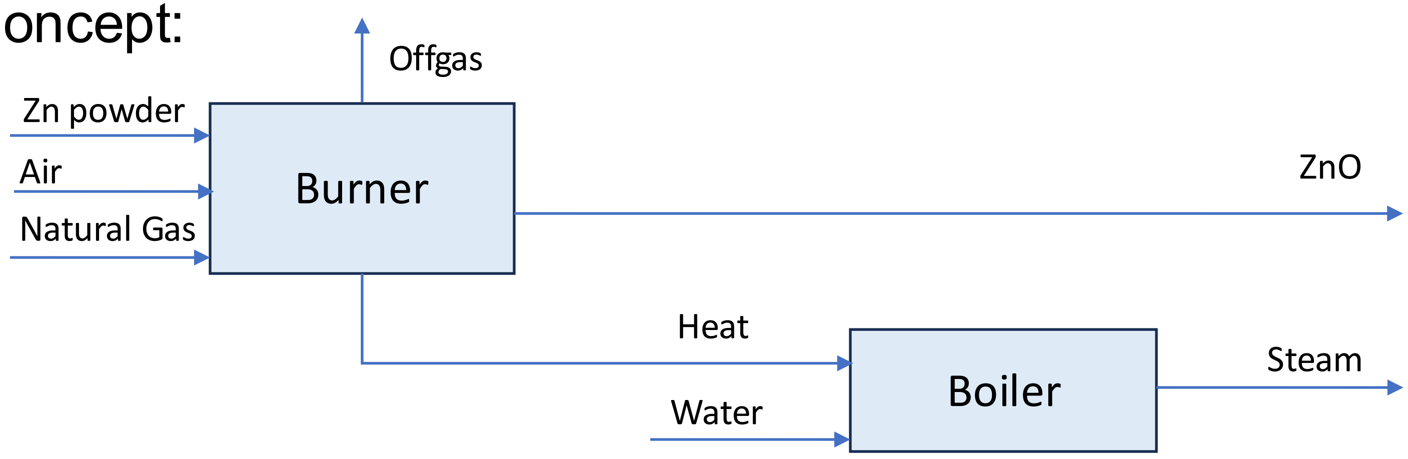
Zn verbranding

First Concept - compares with Fe burning:

- Nyrstar produces its own zinc powder (required in the process) of molten zinc
- Nyrstar requires (relative pure) ZnO for the proces when we want to produce a critical metal concentrate -> currently shortage of suitable ZnO on the market
- Nyrstar requires back-up steam generation capacity (currently using 2 electrical boilers)
- Research by graduate student at TUE has already shown that Zn burning is not self-sustaining (requires additional natural gas)

Zn verbranding

First Concept:

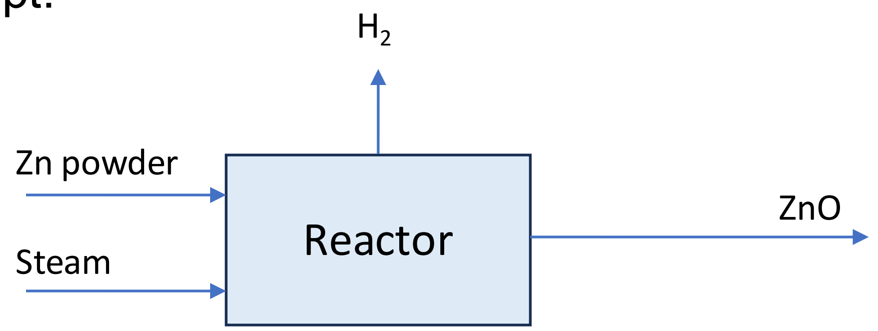


Quick calculations show:

- Require about 5,000 t Zn/a to meet current steam demand (back-up)
- Energy costs are about 2x as high compared to e-boiler
- CO_2 can be used in our effluent treatment plant

Zn verbranding

Follow-up Concept:



Quick calculations show:

- Use produced steam to react Zn powder with steam -> generating H_2 and ZnO
- ZnO will be converted to Zn in our electrolysis process
- Currently Nyrstar produces H_2 for effluent treatment plant via reformer (by natural gas)
- Estimated cost for H_2 production in this circuit is about 4 €/kg H_2.
- Costs for grey H_2 is around 1 €/kg H_2
- Cost for green H2 around 4.5 €/kg H_2

Questions

Iron from water sludge

by Roy Hermanns - TU/e

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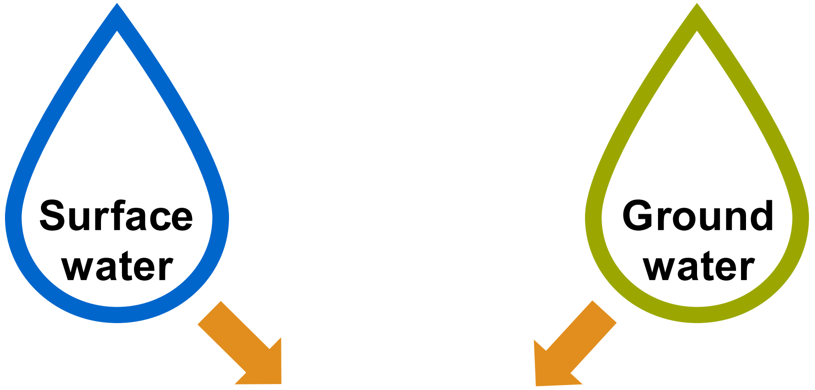
IJzer uit waterslib (Iron Sludge)

METALOT@WORK, JUNE 25, 2025

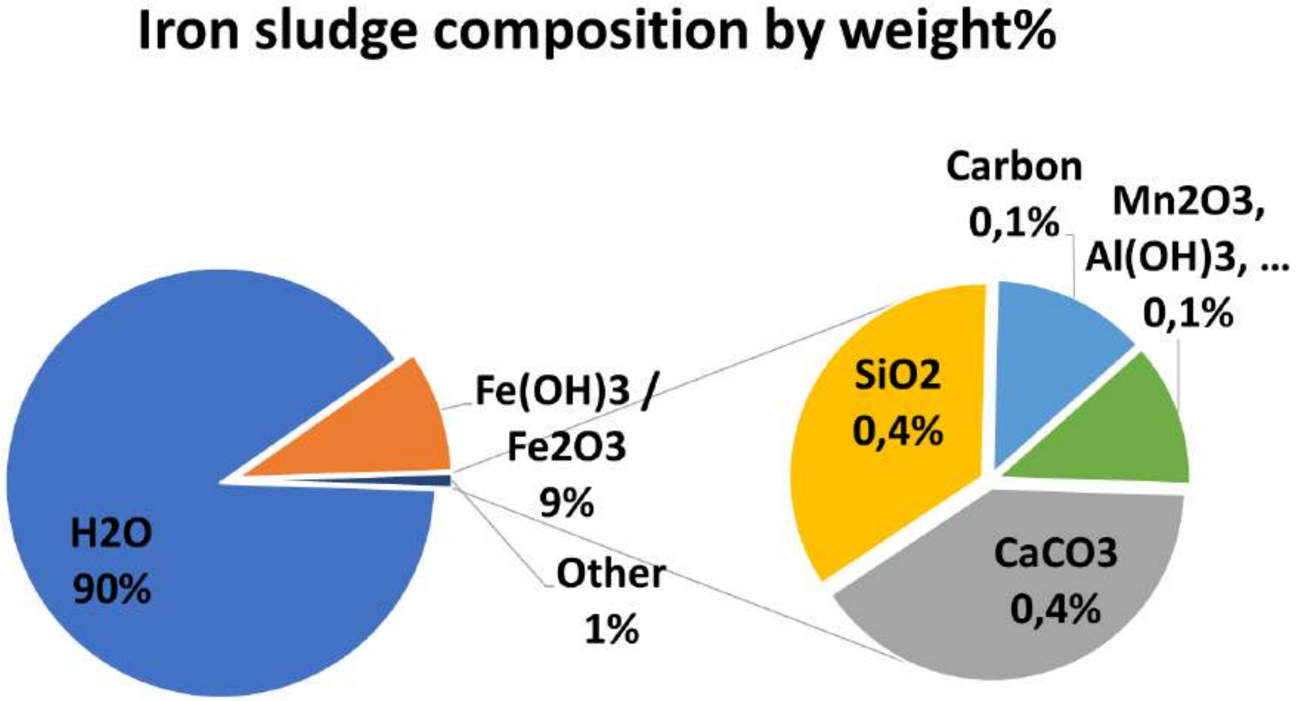
Roy Hermanns

Iron sludge from drinking water production



90.000 ton/year iron sludge

- Production 4800 ton/year of Fe (after reduction) currently
- Major impurities:
  - H, C, O, Ca, Al, Mn, Si

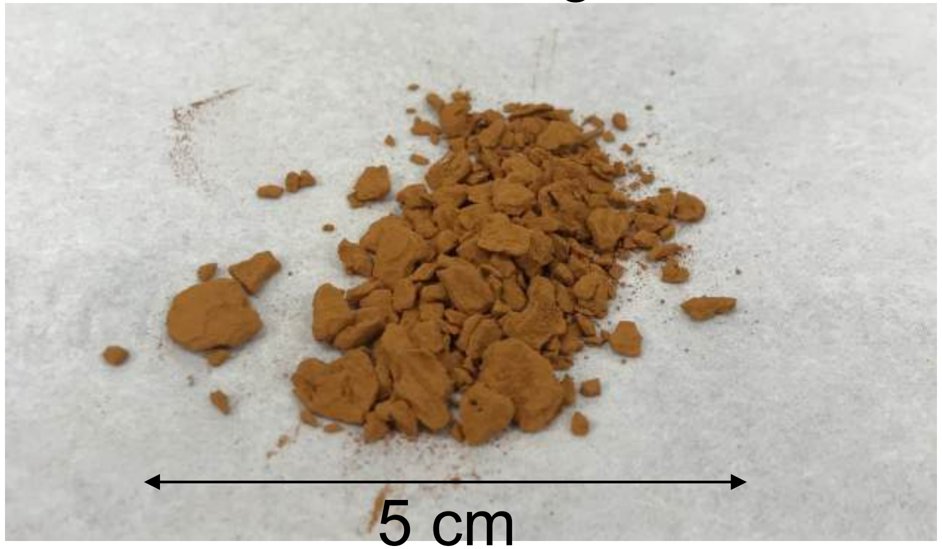


TU/e

Comparison

Iron powder

Iron sludge



~50% Fe

$FeO(OH)$

$CaCO_3$

SiO_2

+*others*

Valorization options of Iron Sludge

Application	Expected Particle size	%Fe	Si / Ca / P / …
Hydrogen carrier	500 – 15000 µm	>70% Fe; Possible already usable	In small amounts not a problem ??
Metal Fuel	<150 µm	>95% desirable??	In small amounts not a problem ??
Biological nitrification	<150 µm	All purities can be used	No problem
Metal production	No requirement	Higher Fe% is better	No problem, Mn unwanted
Soil purification	<500 µm	Higher Fe% is better	No problem
Biodigester	<150 µm	Higher Fe% is better	No problem

Goal of WiCE project

- Reduction performance of Pilot vs Standard
  - ❑ Find optimal reduction conditions for groundwater sludge
  - ❑ Compare to surface water sludge
  - ❑ Give process conditions advice to Pometon
- Suitable for both Wet-cycle as well as Dry-Cycle?
- Economic viable?

POWDER GRINDING, DRYING & COMPOSITION

Ossendrecht (before)

Ossendrecht (after)

Ground water

Surface water

Andijk

XRD (@TU/e)

- Initial material is non-crystalline
- Mostly **<u>Ferrihydrite</u>**

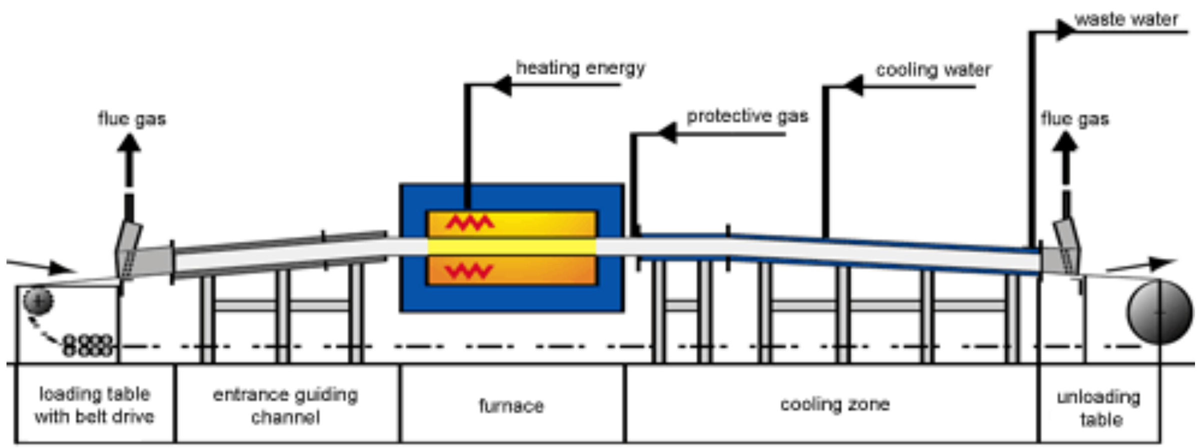
ICP-MS (from Eurofins)

- Pilot shows much less Al, Ca, P_2O_5, Mn, organic carbon → logical
- Pilot is dryer then non-pilot → 22,8 wt% vs 12,2 wt% dry matter → logical

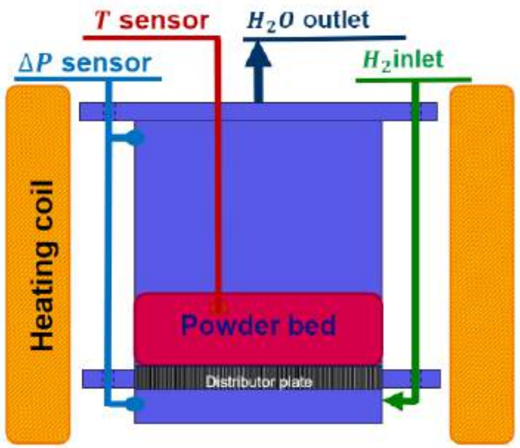
Drying (@TU/e)

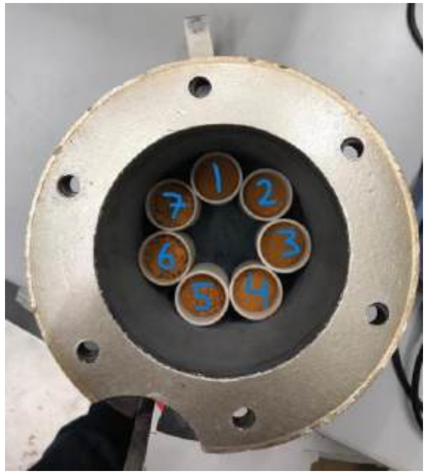
- 200ºC overnight in vacuum
- Pilot 82 wt% dry matter, non-pilot 77 wt%

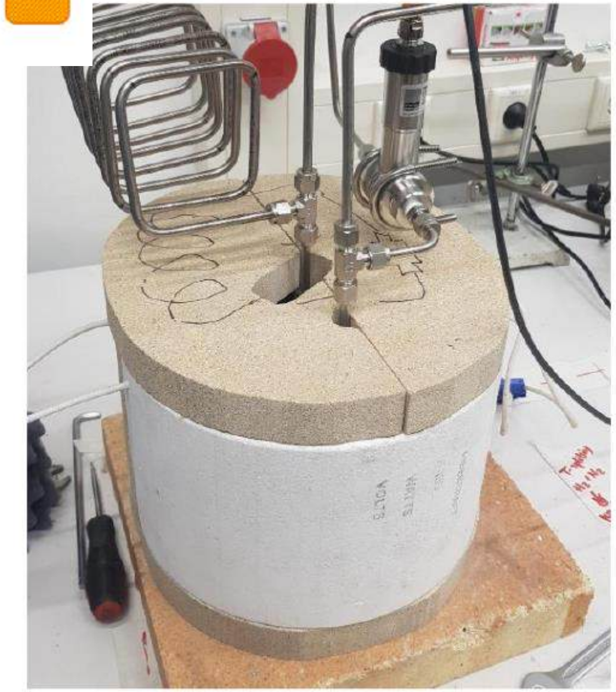
POMETON BELT FURNACE



TUE PACKED BED REACTOR







TARGETED OPERATING RANGE

PROPERTY	POMETON BELT FURNACE		TUE PACKED BED	
Maximum temperature	< 1075ºC		**< 800ºC**	
Maximum H_2 concentration	66% (+ 34% N_2)		66% (max 100%)	
Maximum H_2 flow rate	189.6 NLPM (12 m^3/h @15ºC)		= 1.65 NLPM (max 10 NLPM)	
Max refresh rate (@T_{max})	10 seconds		= 4.38 seconds (@1.65 NLPM)	
Powder layer thickness	20 mm	30 mm	= 20 mm	= 30 mm
Amount of powder	11.5 L	17.2 L	0.10 L (= 7x)	0.15 L (= 7x)
NLPM H_2 / L powder	11	16.5	= 11	= 16.5

Main goal is to match our experiments to POMETON's conditions ("excess amount of H_2")

Approach to determine of mass change

ASSUMPTIONS

1. All **iron**-atoms (from Eurofins ICP-MS) is initially in Goethite form (FeO(OH)) (**incorrect**)
2. Other compounds are negligible
3. Vacuum drying (200 ºC | overnight) removes all **absorbed** H_2O
   - $FeO(OH) + H_2O \rightarrow FeO(OH)$
4. Calcination removed **adsorbed** H_2O + volatile (organic) compounds
   - $2\ FeO(OH) \rightarrow Fe_2O_3 + H_2O$
5. Reduction removed all O_2 from Fe_2O_3
   - $Fe_2O_3 + 3\ H_2 \rightarrow 2\ Fe + 3\ H_2O$

RAW
Pilot = 100 wt%
Non-pilot = 100 wt%

→ Vacuum: $\Delta m_{pilot} = 18\ \%$, $\Delta m_{non-pilot} = 23\ \%$ →

DRIED
Pilot = 82 wt%
Non-pilot = 77 wt%

→ N_2: $\Delta m_{pilot} = 8.7\ \%$, $\Delta m_{non-pilot} = 9\ \%$ →

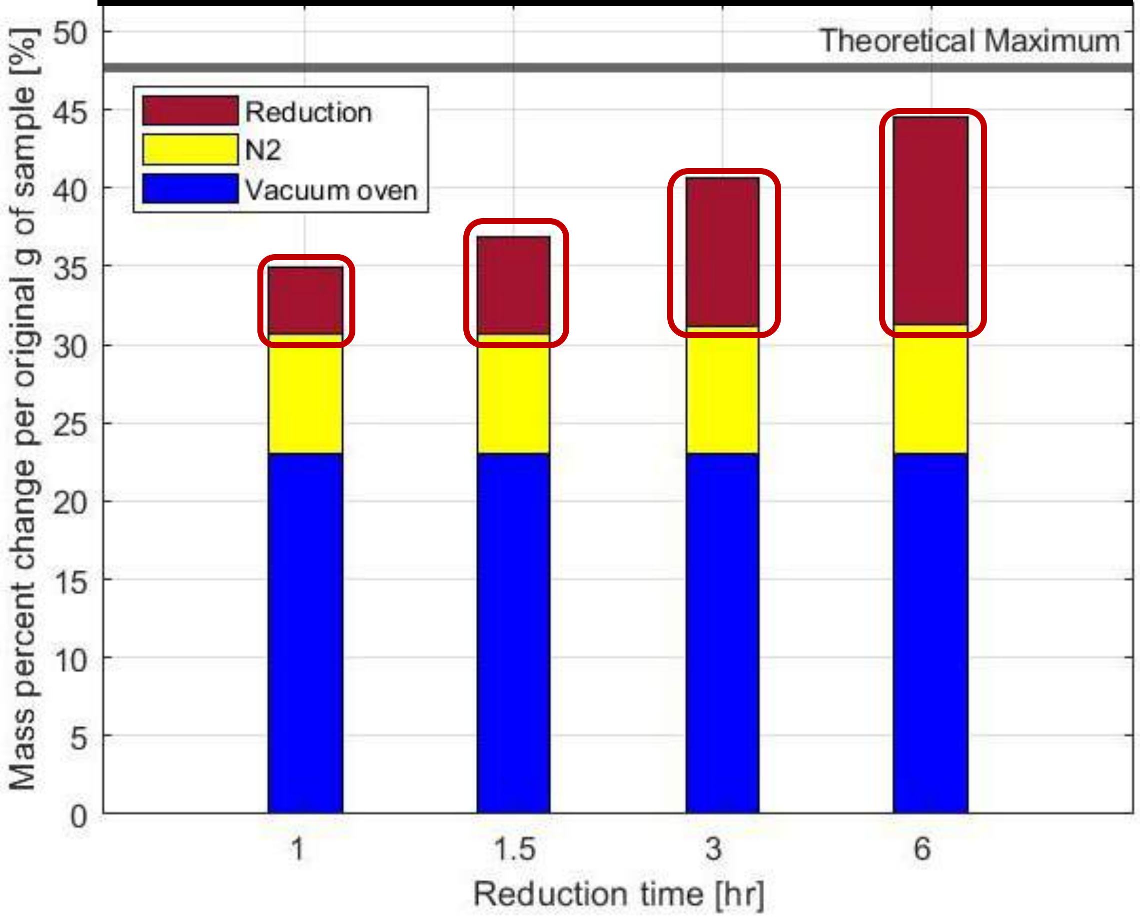
CALCINATED
Pilot = 73.3 wt%
Non-pilot = 68 wt%

→ H_2: $\Delta m_{pilot} = 23.2\ \%$, $\Delta m_{non-pilot} = 24\ \%$ →

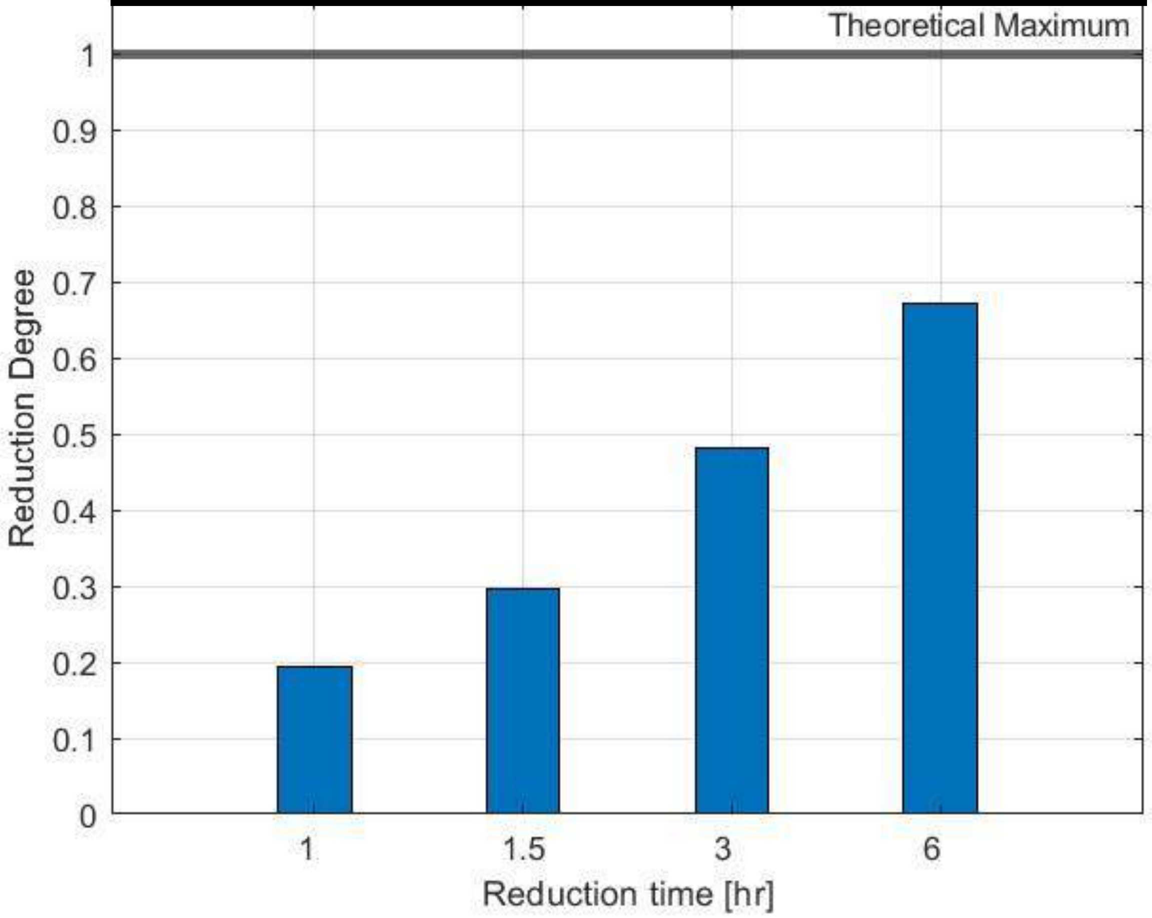
REDUCED
Pilot = 50.1 wt%
Non-pilot = 43.9 wt%

RESULTS (MASS CHANGE TO REDUCTION DEGREE)

MASS CHANGE



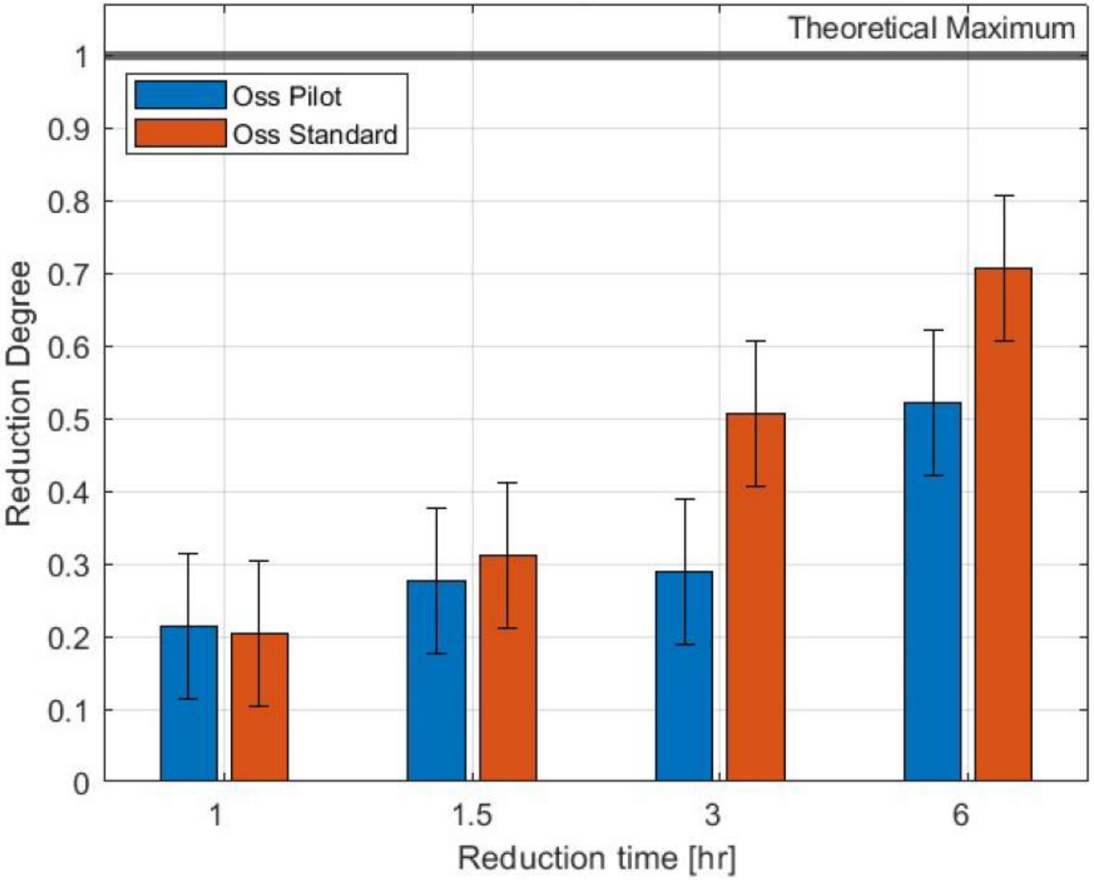
REDUCTION DEGREE



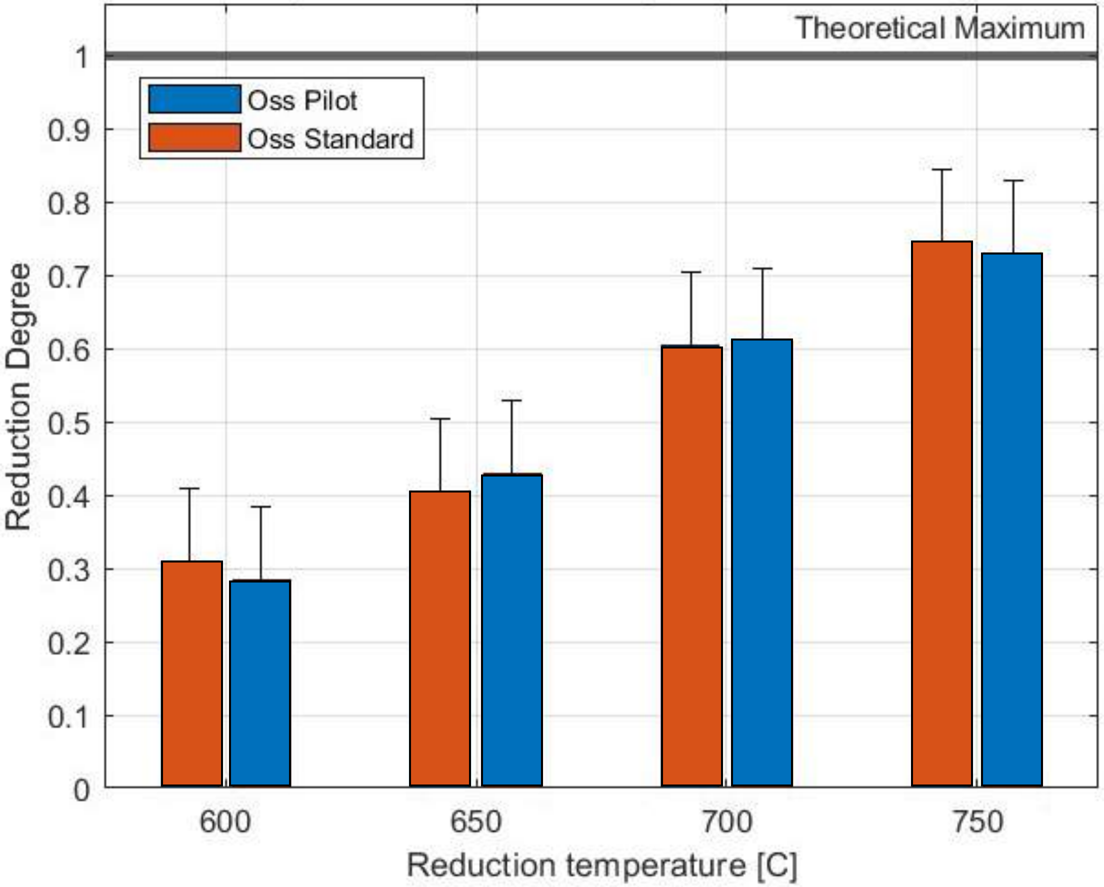
LONGER REDUCTION TIMES STILL IMPROVE RESULTS FOR 600ºC

REDUCTION DEGREE RESULTS

TIME @ 600ºC



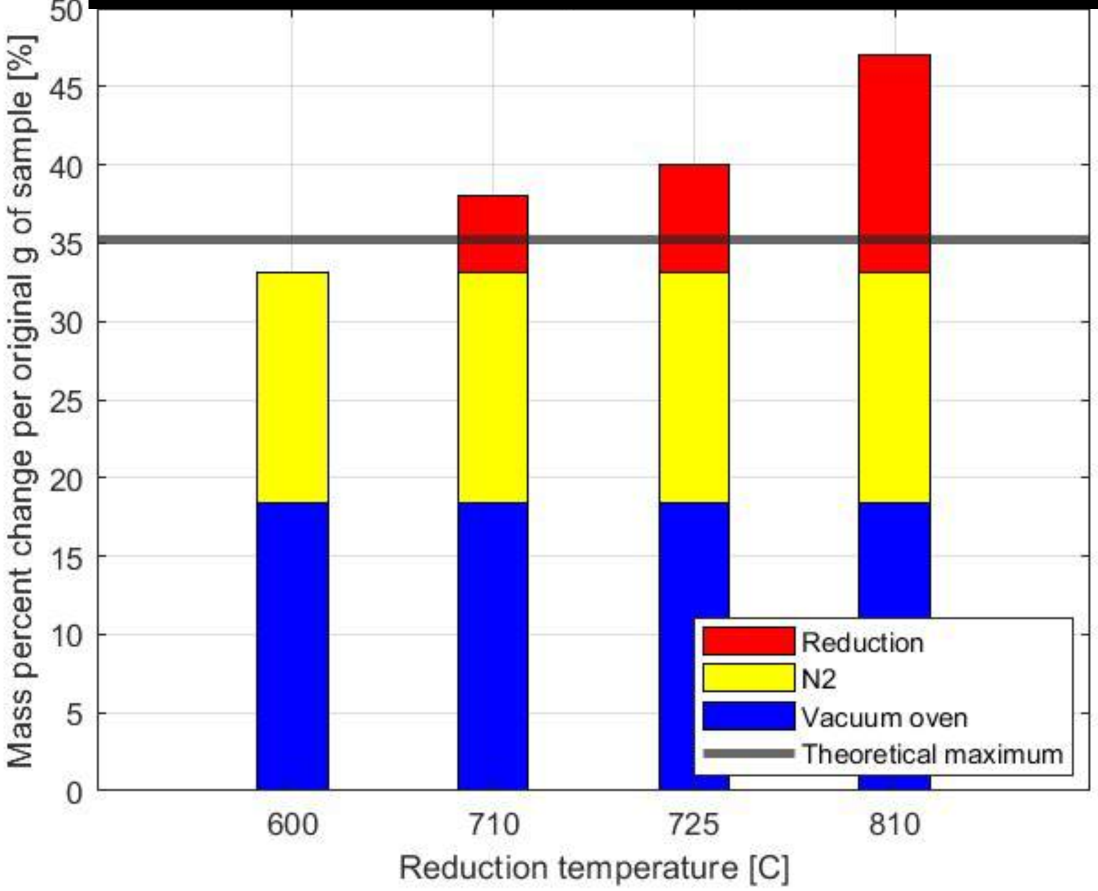
TEMPERATURE @ 1.5h



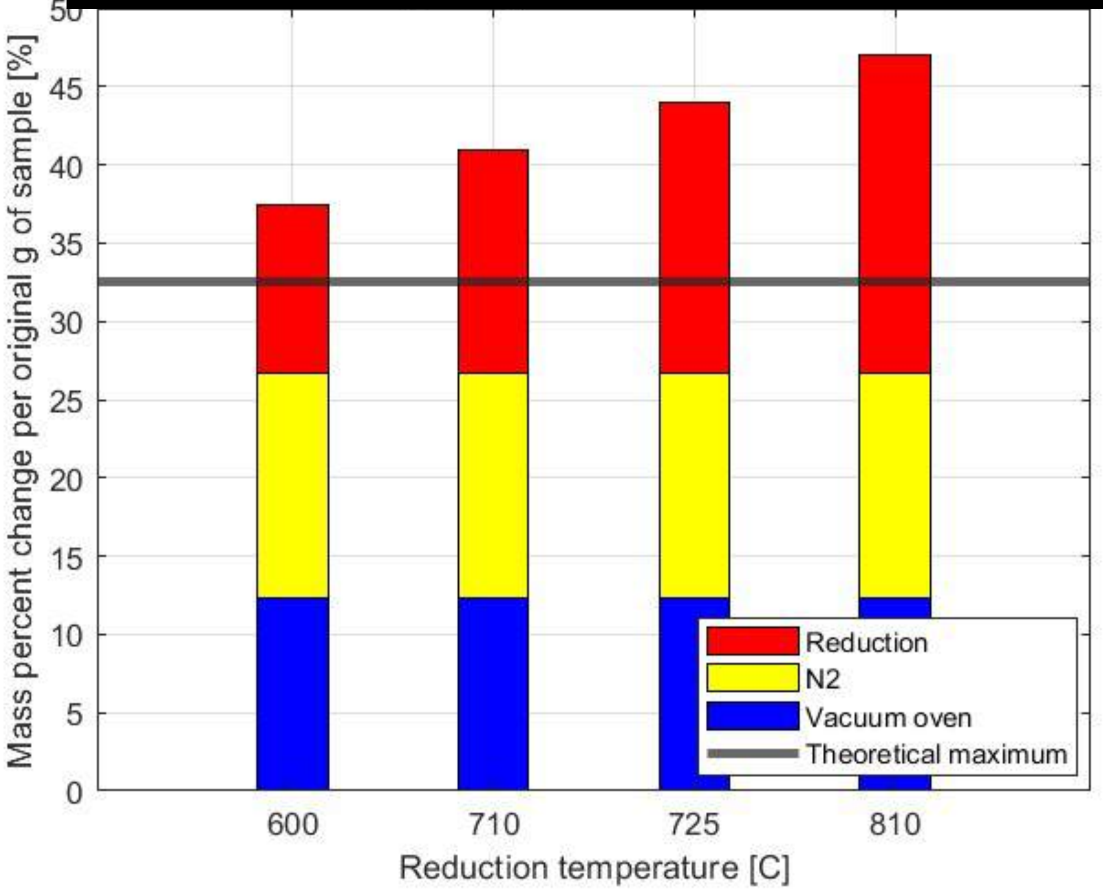
1. **OPTIMAL CONDITIONS: 750ºC AND 1.5 HOUR**
2. **HIGHER TEMPERATURES MIGHT STILL IMPROVE THE REDUCTION PERFORMANCE**

SURFACE WATER SLUDGES

LOENDERVEEN



ANDIJK



THEORETICAL CALCULATIONS DO NOT MATCH WITH EXPERIMENTS…….

Summary

- The **surface water sludges** show a lot **more organic material and other impurities** (e.g. SiO_2 and $CaCO_3$) compared to the ground water sludge(s).
  - ➢ At first glance, they do not seem to influence the reduction behaviour.
- Between the two **ground water** sludges, **little difference** is observed in the reduction behavior over time and temperature.
  - ➢ For both sludges the reduction increases with temperature and time, with an increase in temperature being more efficient (less use of hydrogen).
- **Ground water:** Ossendrecht standard sample better than pilot
  - ➢ Due to applied additional filters of Phosphorous compounds?
- The **surface water** (Andijk) sludge seems to show a higher mass change (per gram of as-received sludge) during reduction with hydrogen than the Loenderveen sludge.
  - ➢ This might indicate a higher reduction rate at similar conditions
- Overall: The reduction degree by variation of temperature & time experiments has been determined
  - ➢ Still room for improvement by applying higher temperatures

Acknowledgement

- Noah Jansema
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- Conrad Hessels (TU/e)

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Thank you for your attention!

metalot

Metal Power **Ambassador**

Summer 2025

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Metalot@Work June 25

Beyond Iron

~~15:30 – Walk-in~~

~~15:40 - Introduction~~

~~15:45 - Metals as sustainable energy carrier, beyond iron - by Jeff Bergthorson - McGill University (live)~~

~~16:00 – State-of-the Art on Aluminum combustion - by Thijs Hazenberg - TU Darmstadt (live)~~

~~16:15 – State of the Art in Aluminium - Water Reaction for Peak Demand in Buildings - by Yvonne Bäuerle - OST (online)~~

~~16:30 - Aluminum battery development- by Michiel Kruijf - ZemQuest (live)~~

~~16:45 - Short break~~

~~17:00 - Magnesium as energy carrier- by Cornelius Schonnenbeck - Université de Haute Alsace (online)~~

~~17:15 – Zinc oxidation/reduction cycle - by Ellen Molleman - Nyrstar~~

~~17:30 – Iron from water sludge - by Roy Hermanns - TU/e~~

~~17:45 - Ambassador Awards~~

18:00 - Closure & drinks together

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