



METAL ENERGY CARRIERS: RENEWABLE FUELS OF THE FUTURE

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M2I December 2020

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@ TU/e

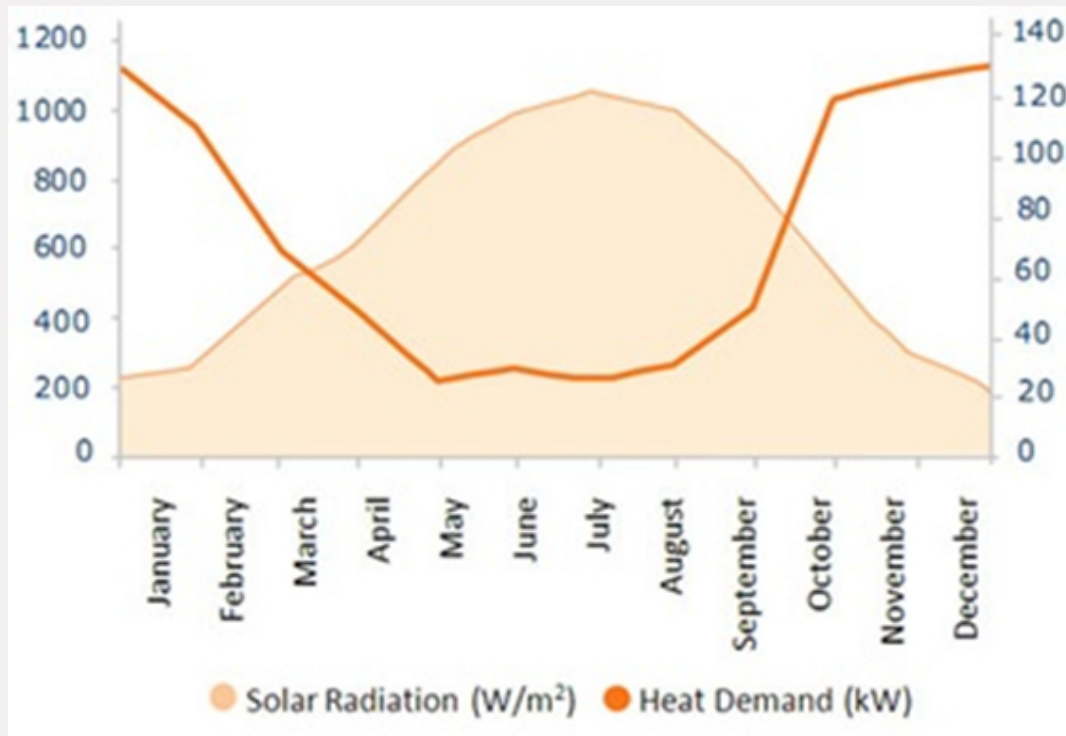
@ Metalot

4. Next steps & Conclusions



<https://blogs.nasa.gov/Rocketology/tag/rocket-fuel/>

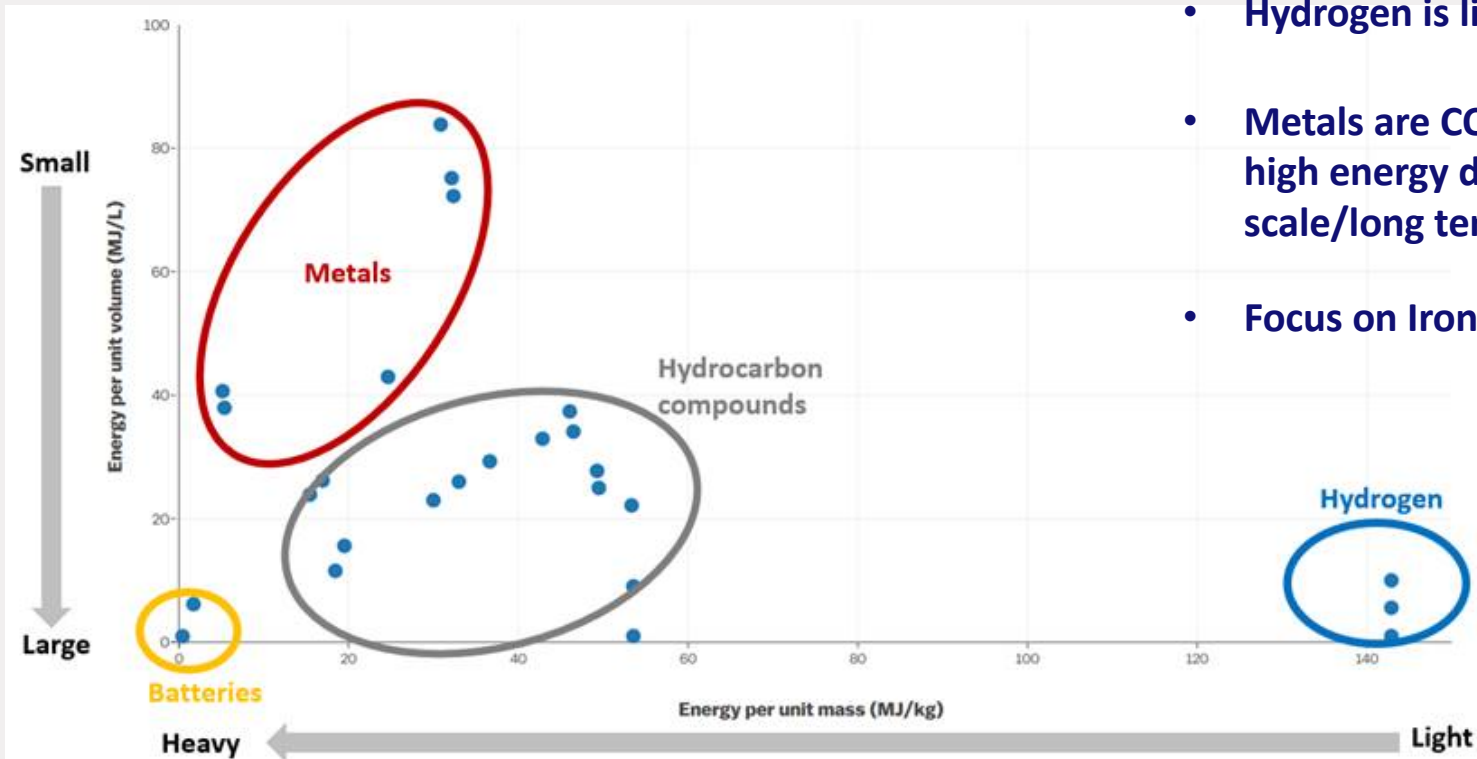
Energy Transition



The problems:

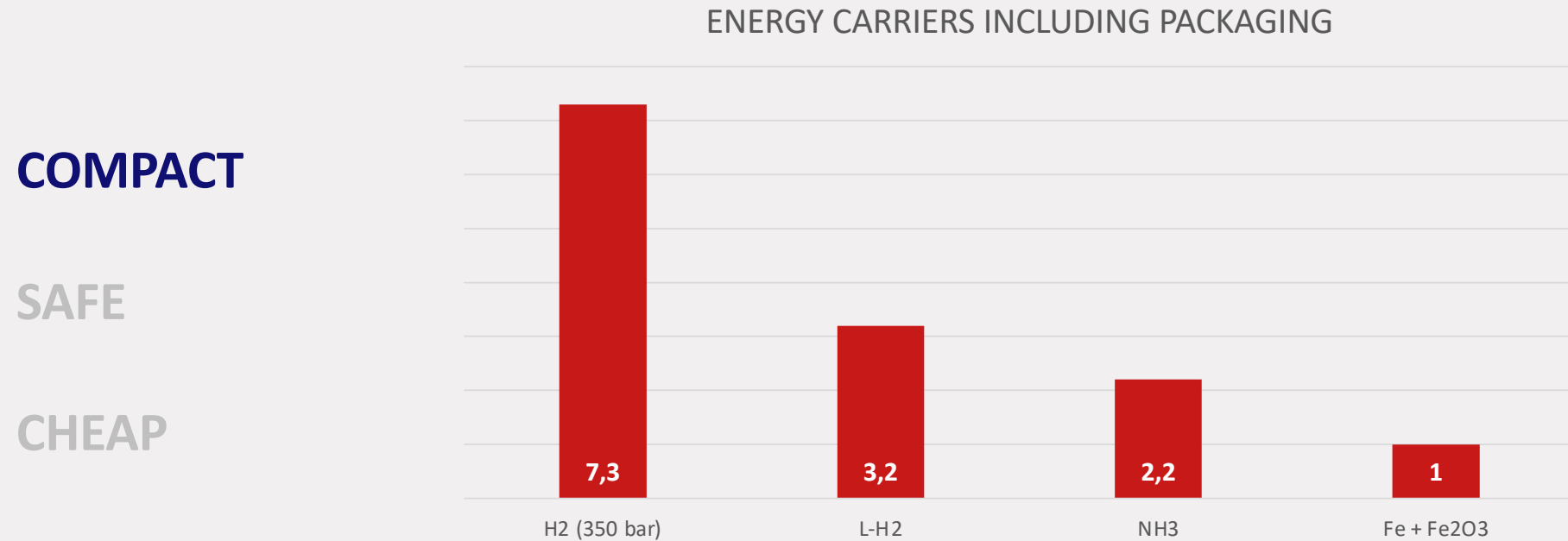
- (1) We need to scale up use of sustainable energy (wind/solar/..)
- But: current sustainable sources (solar/wind) are intermittent.
- However: energy should always be available at right time and at the right place
- (2) How can we store and/or move that energy to where and when we need it?

Energy Carriers









- Batteries are fine for small scale (E-mobility),
- Hydrogen is light but lacks energy density
- Metals are CO₂-free, are quite heavy, but have high energy density and very suited for large scale/long term storage
- Focus on Iron → WHY ?

Comparitive advantages of Iron Fuel



Comparitive advantages of Iron Fuel

	Flammable	Acute Toxic	Health Hazard	Corrosive	Environmental	Pressured Gas
						
COMPACT						
			X		X	
SAFE						
	X	X	X			
	X					X
CHEAP						
		X		X	X	X
	X					

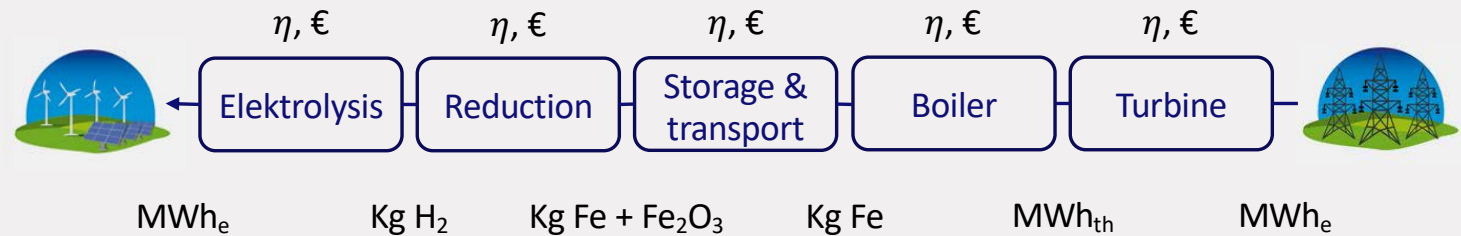
Comparitive advantages of Iron Fuel

- 4th element on earth crust: ~ 100 euro/ton (scrap)
- comparable efficiency as hydrogen (~ 50-70%)

COMPACT

SAFE

CHEAP



Berenschot: Techno-Economic Analysis

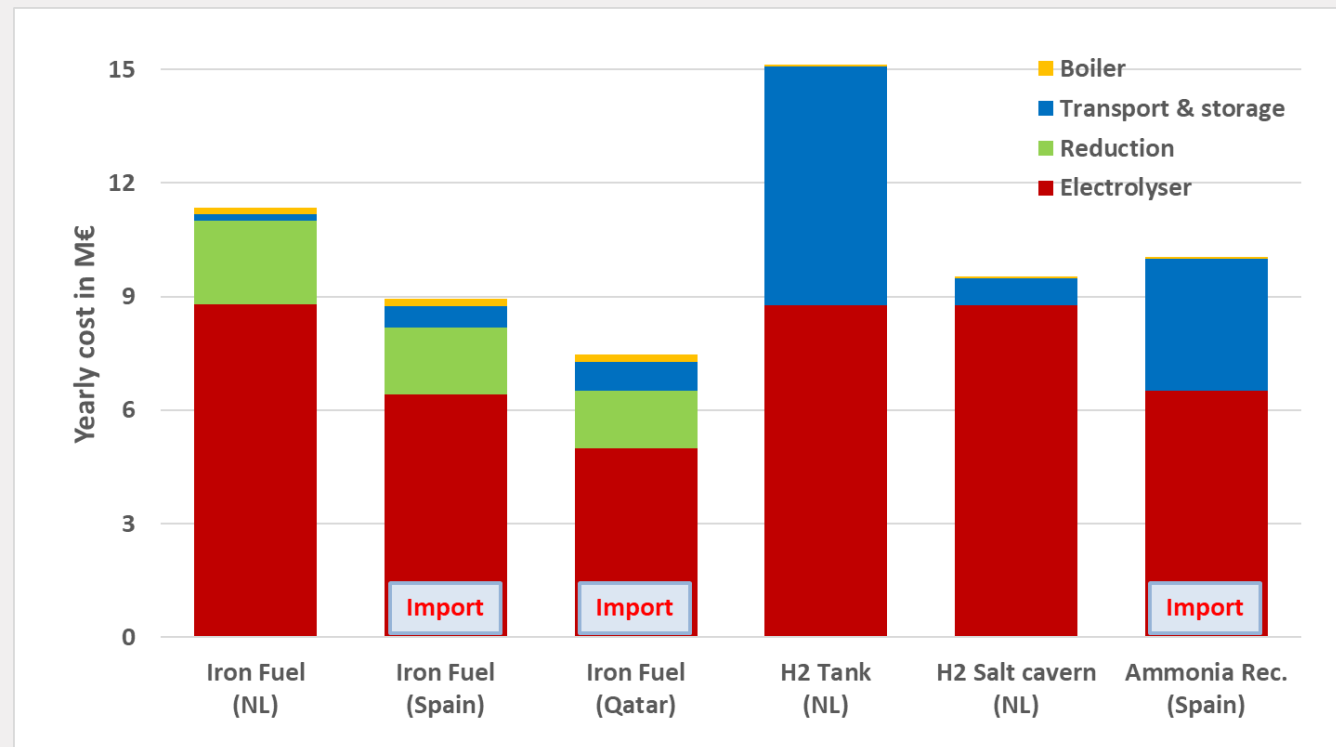
Comparitive advantages of Iron Fuel

COMPACT

SAFE

CHEAP

Yearly cost comparison of the total value chain for a 10 MW boiler (2030)



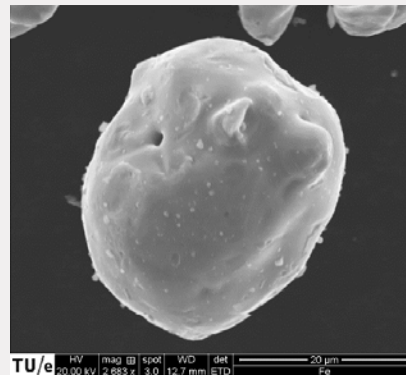
Berenschot: Techno-Economic Analysis

Comparitive advantages of Iron Fuel

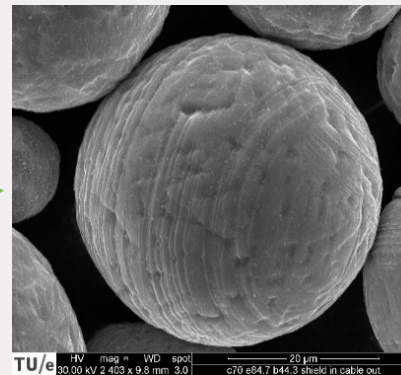
CLEAN

RECYCLEBLE

RETROFIT



Iron



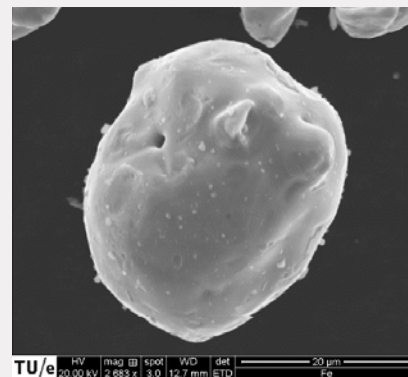
Iron oxide

Comparitive advantages of Iron Fuel

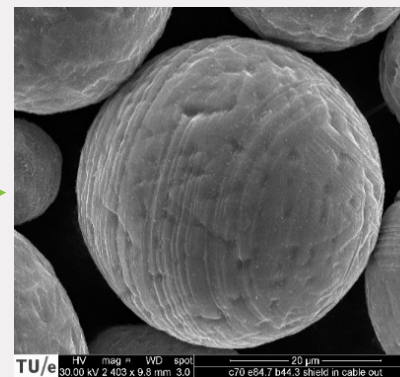
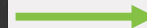
CLEAN

RECYCLEBLE

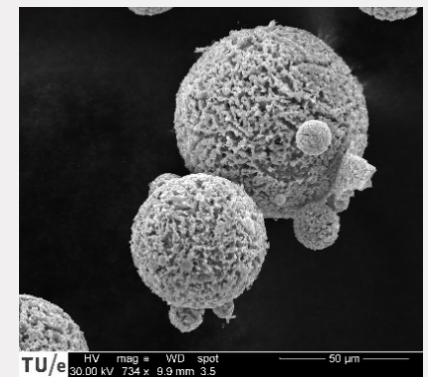
RETROFIT



Iron



Iron oxide



Iron



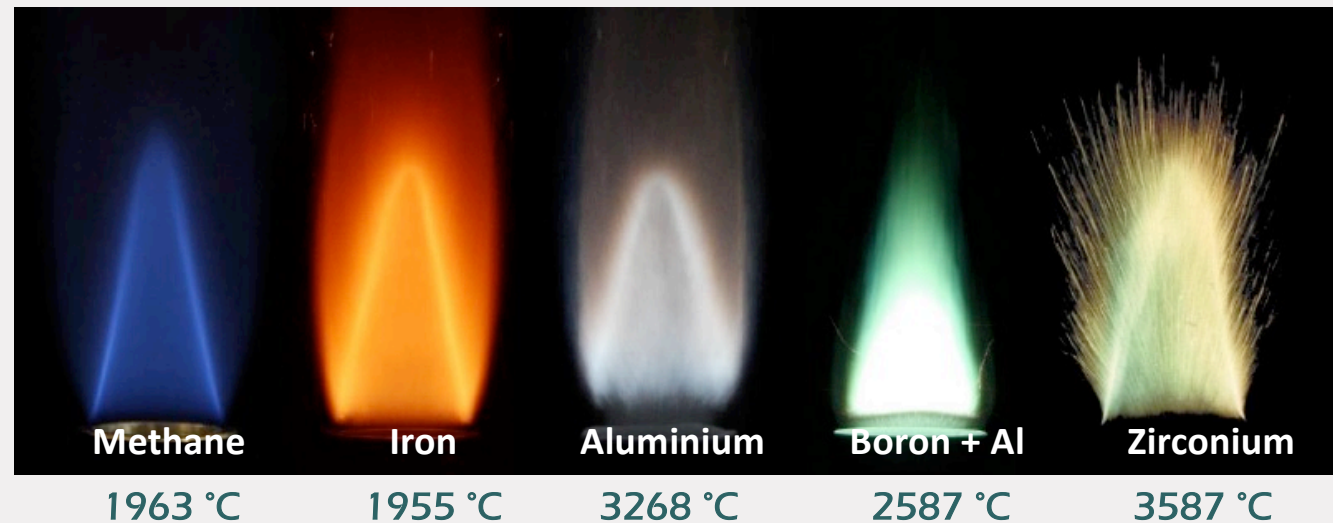
Comparitive advantages of Iron Fuel

CLEAN

RECYCLEBLE

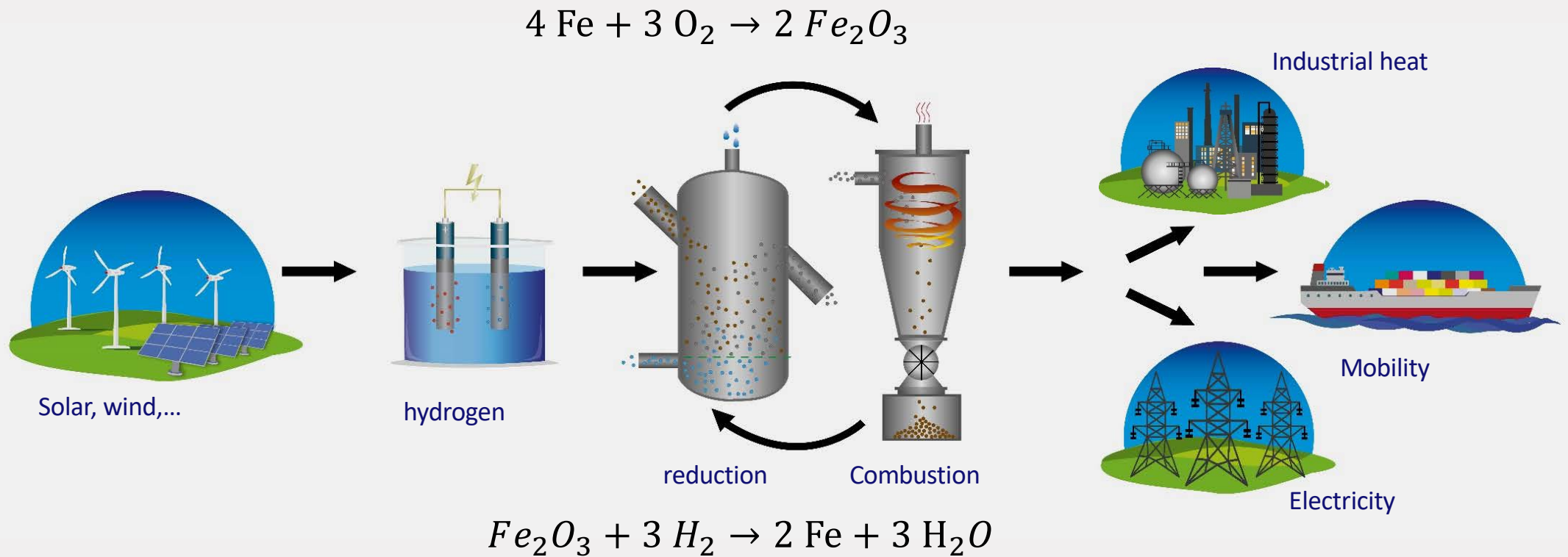
RETROFIT

Fossil → Iron



- Temperature & time scales similar as fossils
- Interesting for solid fuel systems like coal power

Iron Fuel: Cycle structure



Iron Fuel: clean energy carrier & application roadmap

Iron Fuel is a clean & renewable energy carrier that:

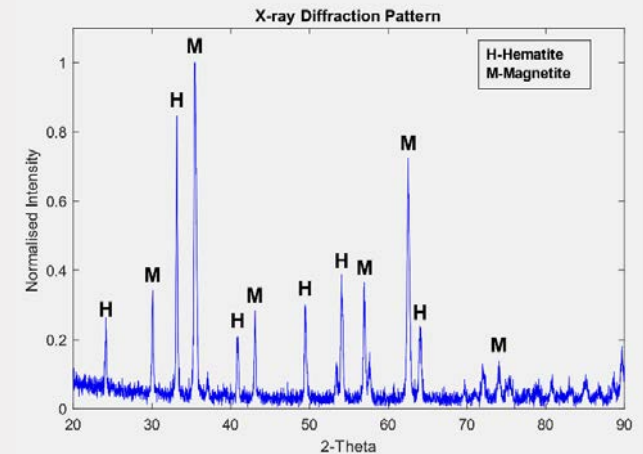
- Enables large scale energy storage for longer periods of time, safely with competitive costs,
- Can be transported from production sites to users safely,
- Is a marketable commodity,
- and can be implemented in existing infrastructure (retrofit).

Techno-economic analyses show that **Iron Fuel** can be used (in chronological order of application):

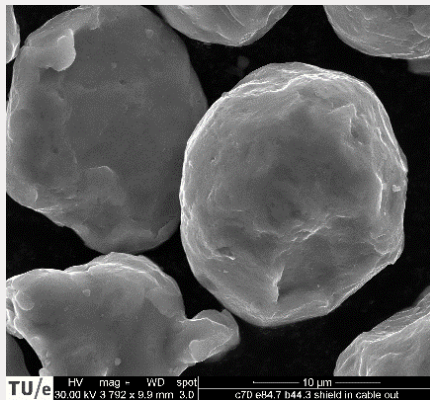
1. Off grid – or grid supporting – high & medium heat intensive applications,
2. Transporting (and using) renewable energy from energy dense locations to energy scarce locations with medium to long distance for heat and power generation, and
3. Expand technology to large scale power plants and maritime applications.

Iron oxide reduction @ TU/e

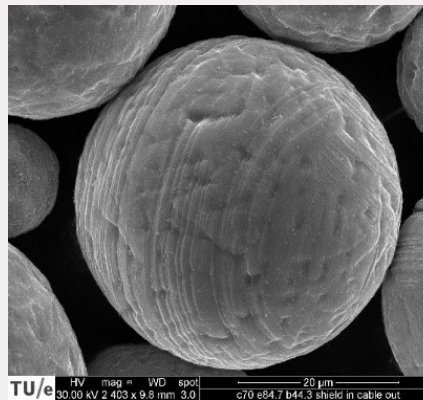
- Single particle reduction experiments and model/reactor development
- TGA: oxidation/reduction (H₂) kinetics → several cycles
- Particle Analysis using Q-XRD and SEM



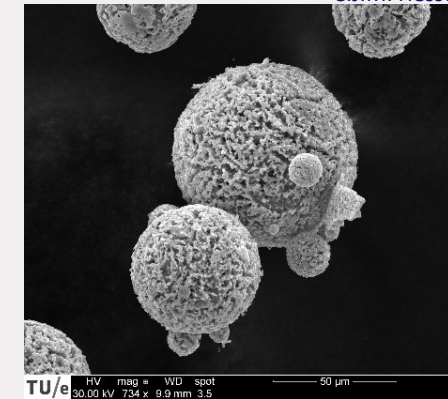
C.J.M. Hessels (2019)



CNPC FE400 Iron particles



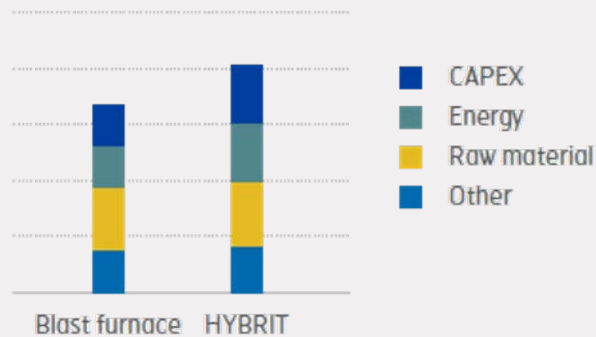
Iron oxide particles



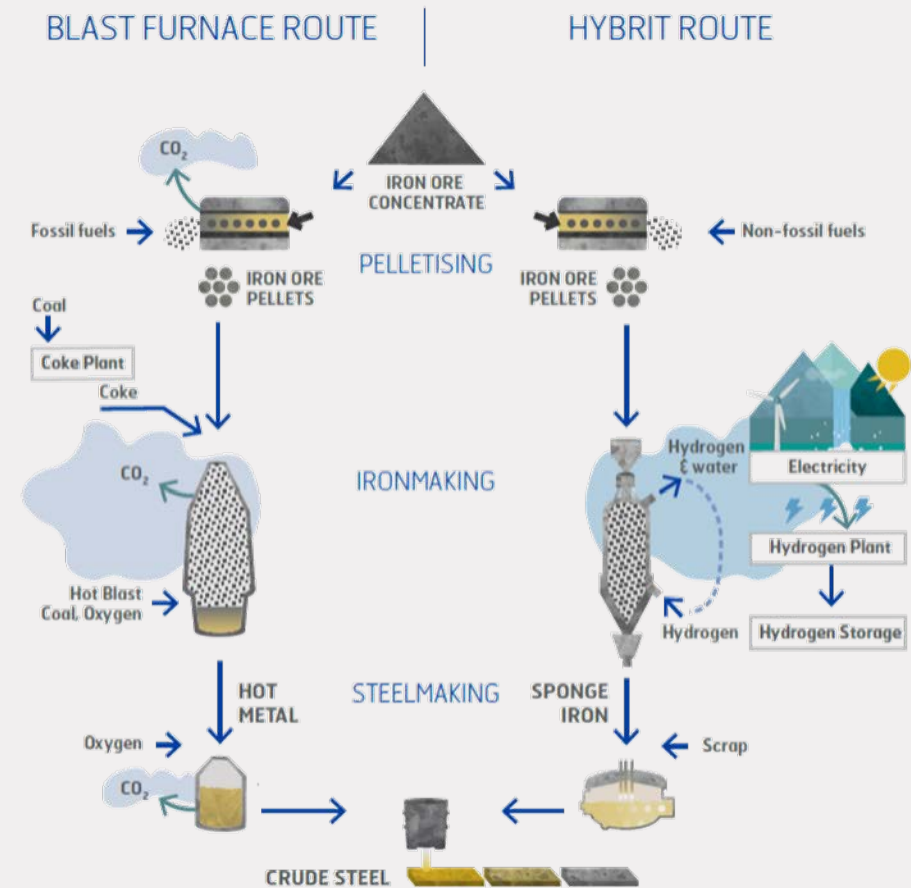
Iron particles after H₂ reduction of iron oxide particles

Iron oxide reduction @ steel industry

Cost comparison



Estimated crude steel production costs at greenfield conditions (HYBRIT prefeasibility study).

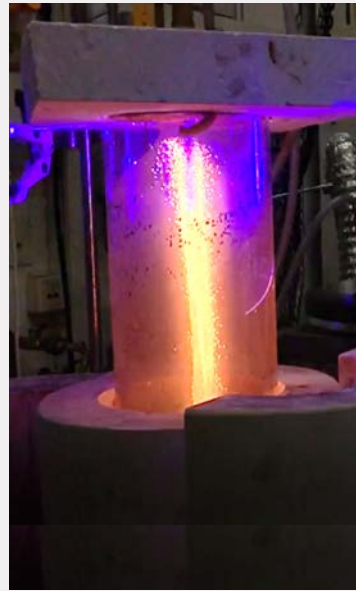


Iron combustion @ TU/e

Microburner
20 W



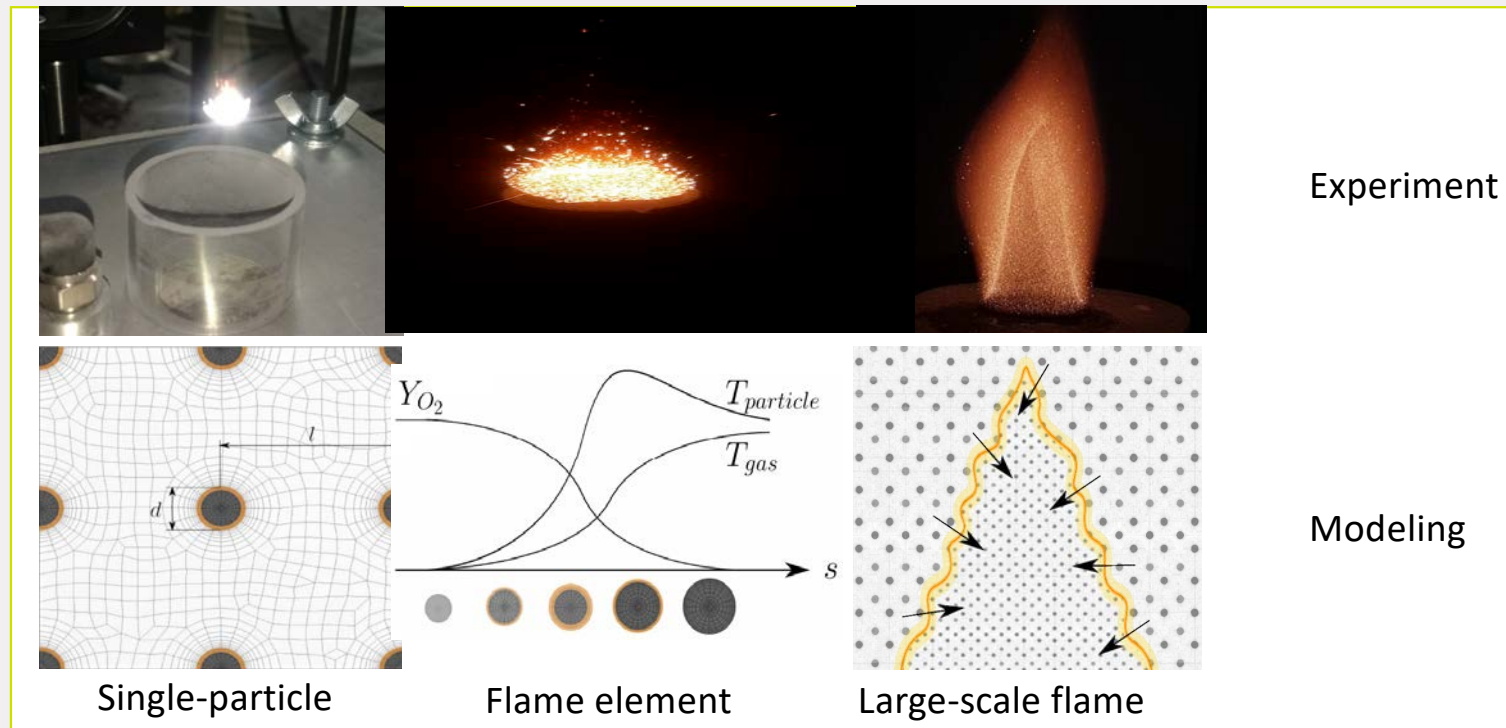
Tornado Burner
2 kW



Low Swirl Burner
20 kW

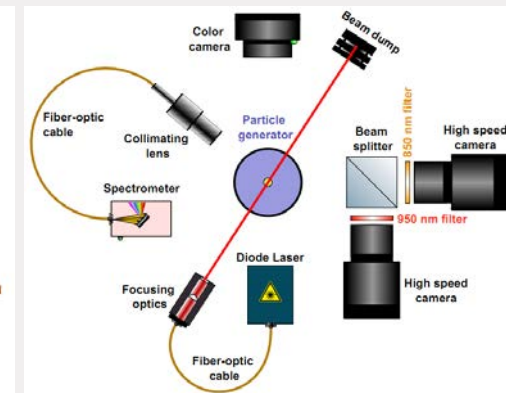
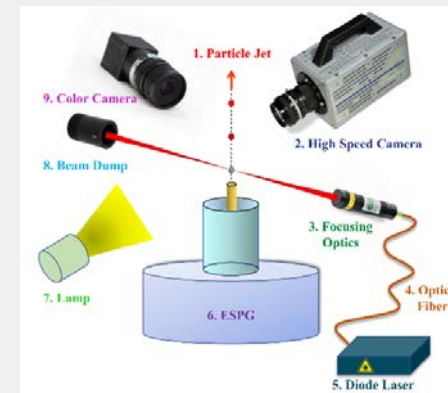
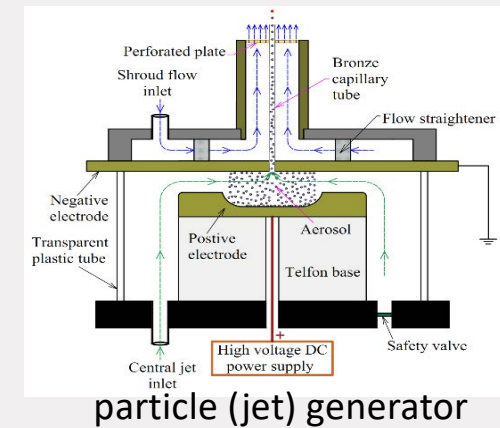
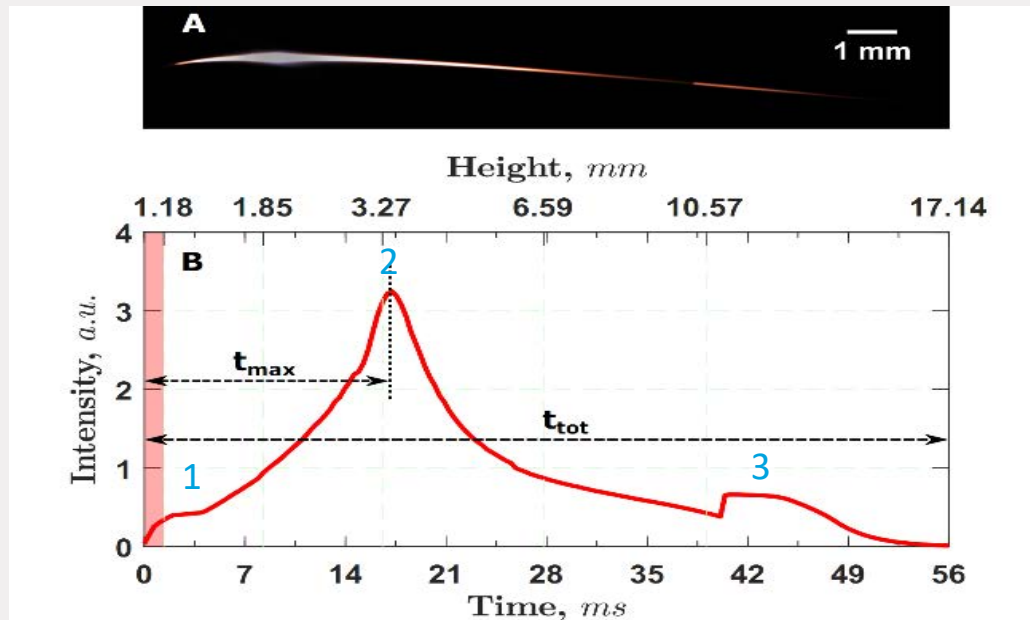


Iron combustion @ TU/e



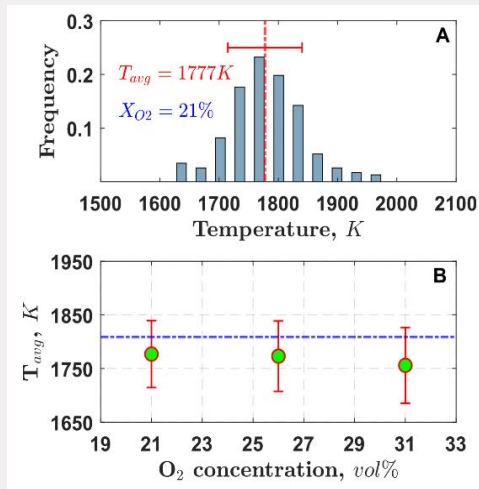
- 10 PhD /PD students on **multi-scale modeling & experiment** (NWO, ERC,..)
- **Exciting new field of science ! Some first results**

Iron combustion @ TU/e

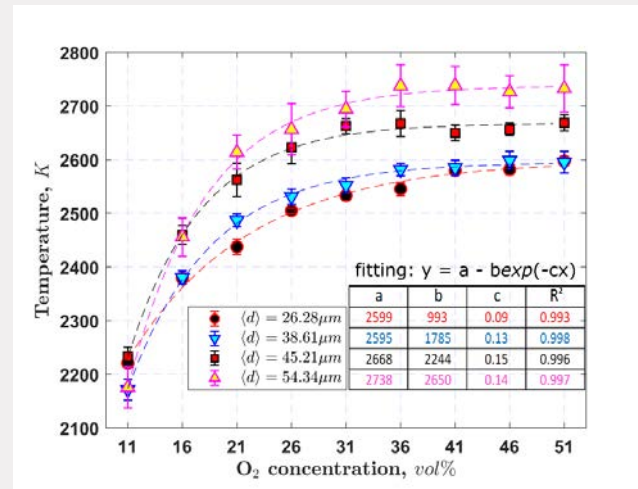


- Single particle combustion after laser-ignition
- Three phases: melting (1), combustion (2) & phase transition (3)

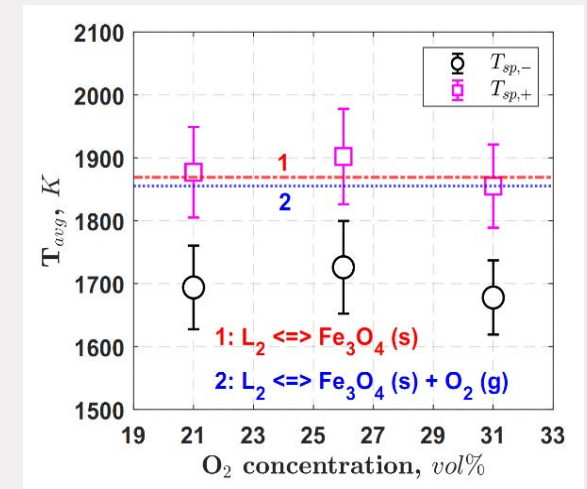
Iron combustion @ TU/e



Phase 1



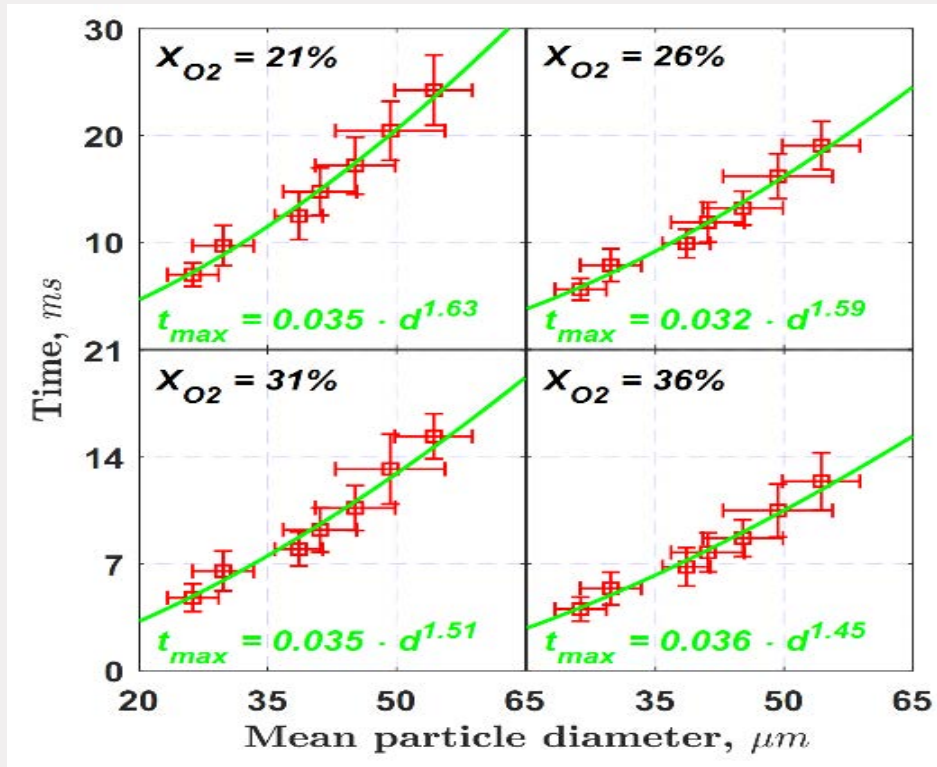
Phase 2



Phase 3

- Phase 1: Melting temperature (close to 1809 K value literature)
- Phase 2: Combustion peak temperature (varies with particle size and oxygen environment)
- Phase 3: Temperature jump (~150K) towards sudden solidification of liquid oxide

Iron combustion @ TU/e



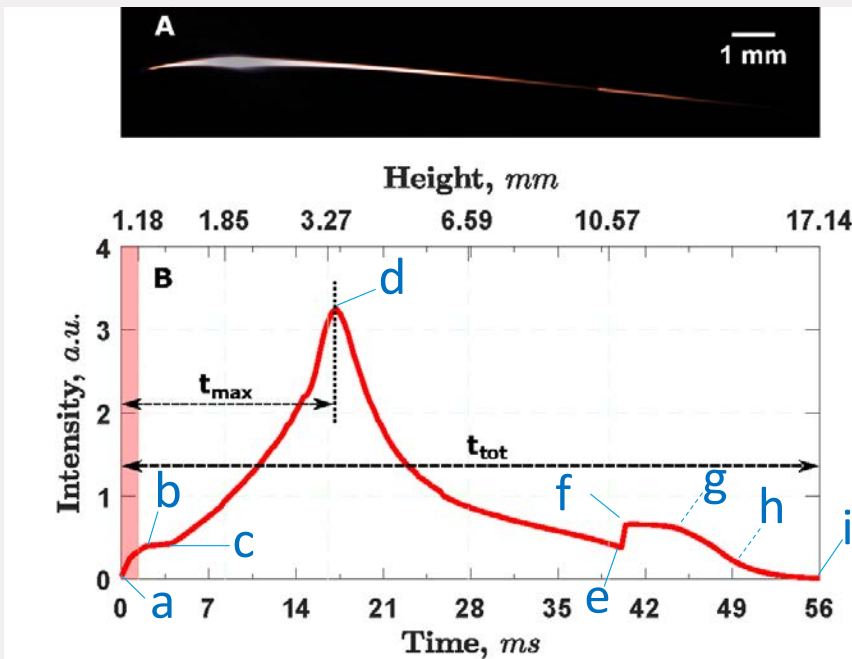
- Combustion times: $t \sim d^{1.6}$ diffusion limited
- Combustion time inversely proportional to X_{O_2}
- Process is diffusion limited

Iron combustion @ TU/e

➤ First identification of process steps

— well determined points - - - - - estimated points

Particle temperature: ■ measured ■ literature



limited by oxygen diffusion in gas phase

- a-b: $\text{Fe(s)} + \text{O}_2 \rightarrow \text{L2 (liquid oxide)}$,
- b-c: $\text{Fe(s)} \text{ melting + oxidization,}$
- c-d: $\text{Fe(l)} + \text{O}_2 \rightarrow \text{L2}$

$T_a \sim 1650\text{K}$
 $T_b \sim 1780$
 $T_{\text{Fe,melt}} = 1809\text{K}$
 $T_d \sim 2500\text{K}$

limited by oxygen diffusion in liquid phase

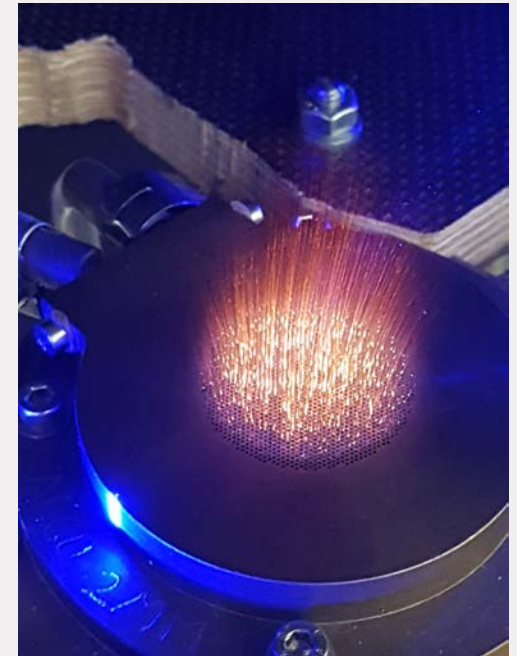
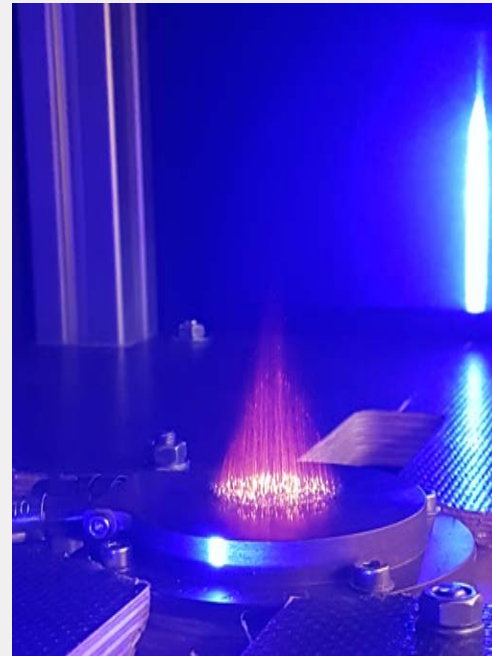
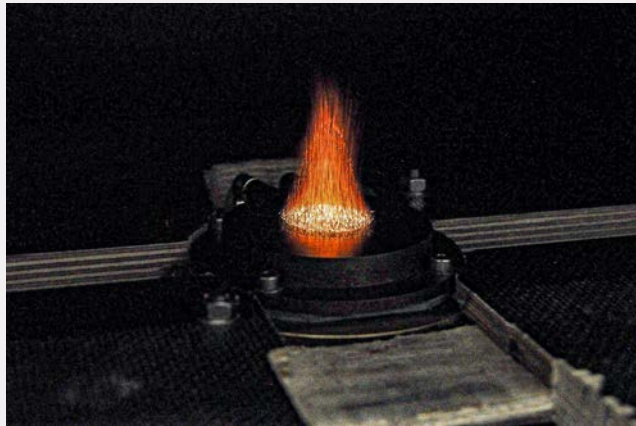
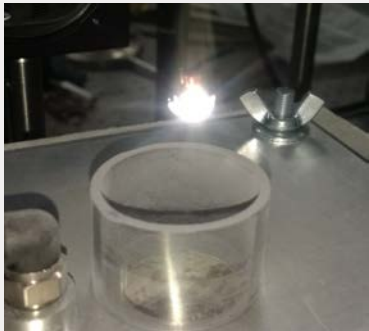
- d-e: $\text{Fe(l)} + \text{O}_2 \rightarrow \text{L2}$
- e-f: $\text{L2} \rightarrow \text{Fe}_3\text{O}_4(\text{s}) (+ \text{O}_2(\text{g})) \text{ solidific.}$
- f-g: $\text{L2} \rightarrow \text{Fe}_3\text{O}_4(\text{s}) (\text{or} + \text{O}_2(\text{g})) \text{ solidific}$

$T_e \sim 1700\text{K}$
 $T_f \sim 1870$
 $T_{\text{Fe}_3\text{O}_4,\text{melt}} = 1855\text{K}$

limited by oxygen diffusion in solid phase(Fe_2O_3 shell)

- g-h: inert cooling of $\text{Fe}_3\text{O}_4(\text{s})$, $T_h = 1730\text{K}$
- h-i: $\text{Fe}_3\text{O}_4(\text{s}) + \text{O}_2 \rightarrow \text{Fe}_2\text{O}_3(\text{s})$, $T_i \sim 1650\text{K}$

Iron combustion @ TU/e



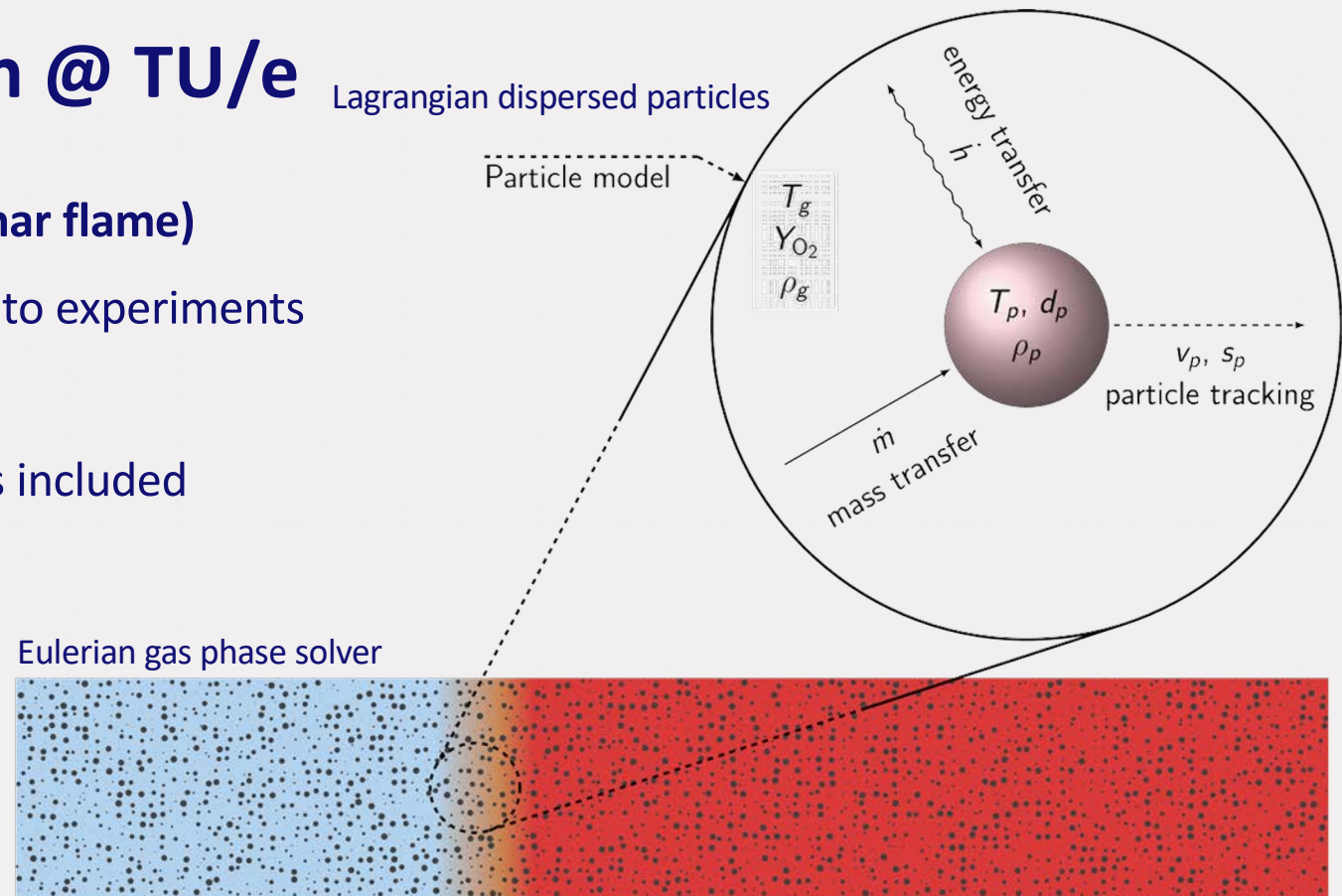
Next steps:

- **Micro-flame** (left, on jet burner) to study mutual ignition of particles leading to flame propagation
- Planar flame-element **Metalet** (right) to investigate propagation speed of flame front

Iron combustion @ TU/e

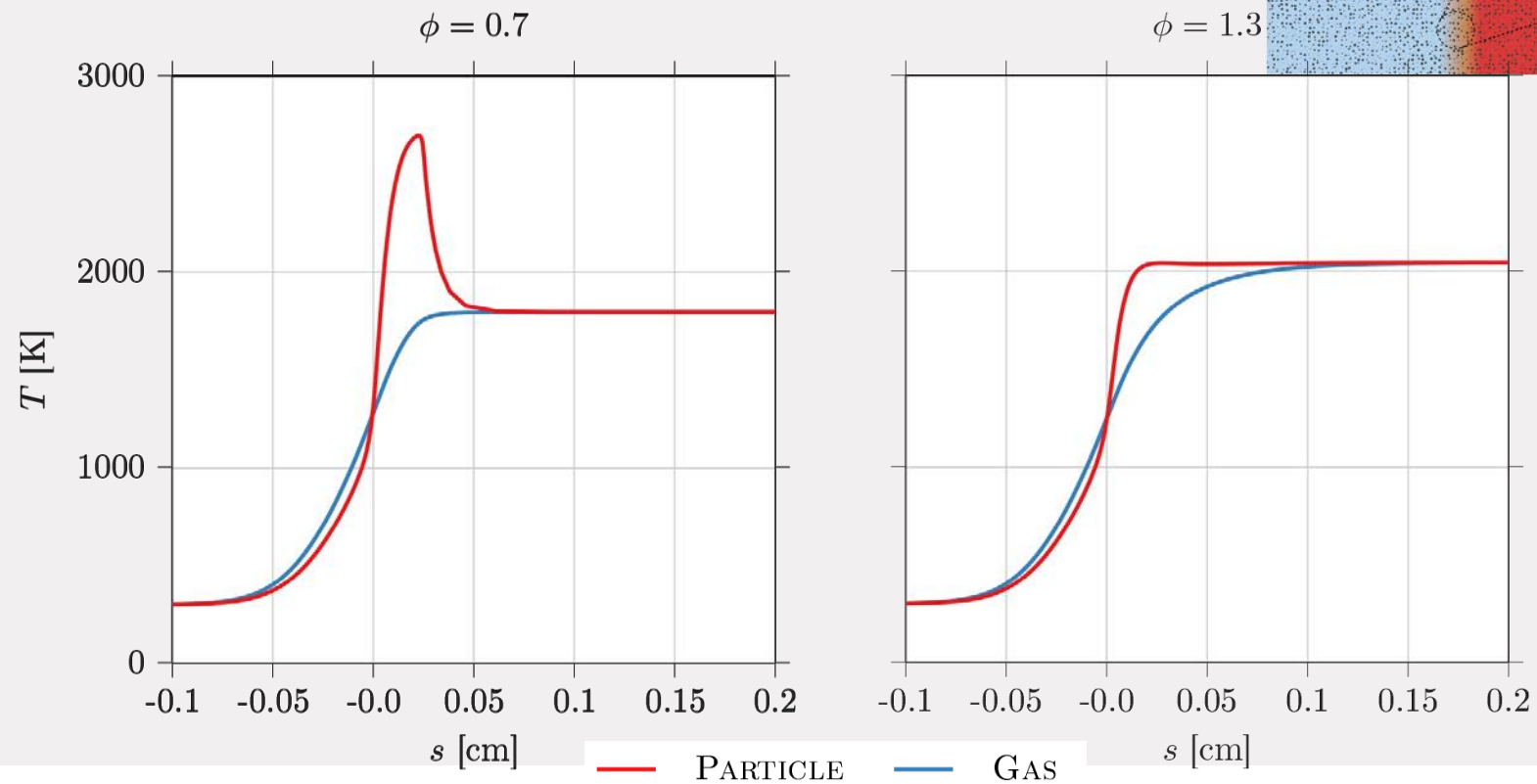
Metalet modelling (1D planar flame)

- Fit single-particle model to experiments
- Euler-Lagrange
- Major transfer processes included

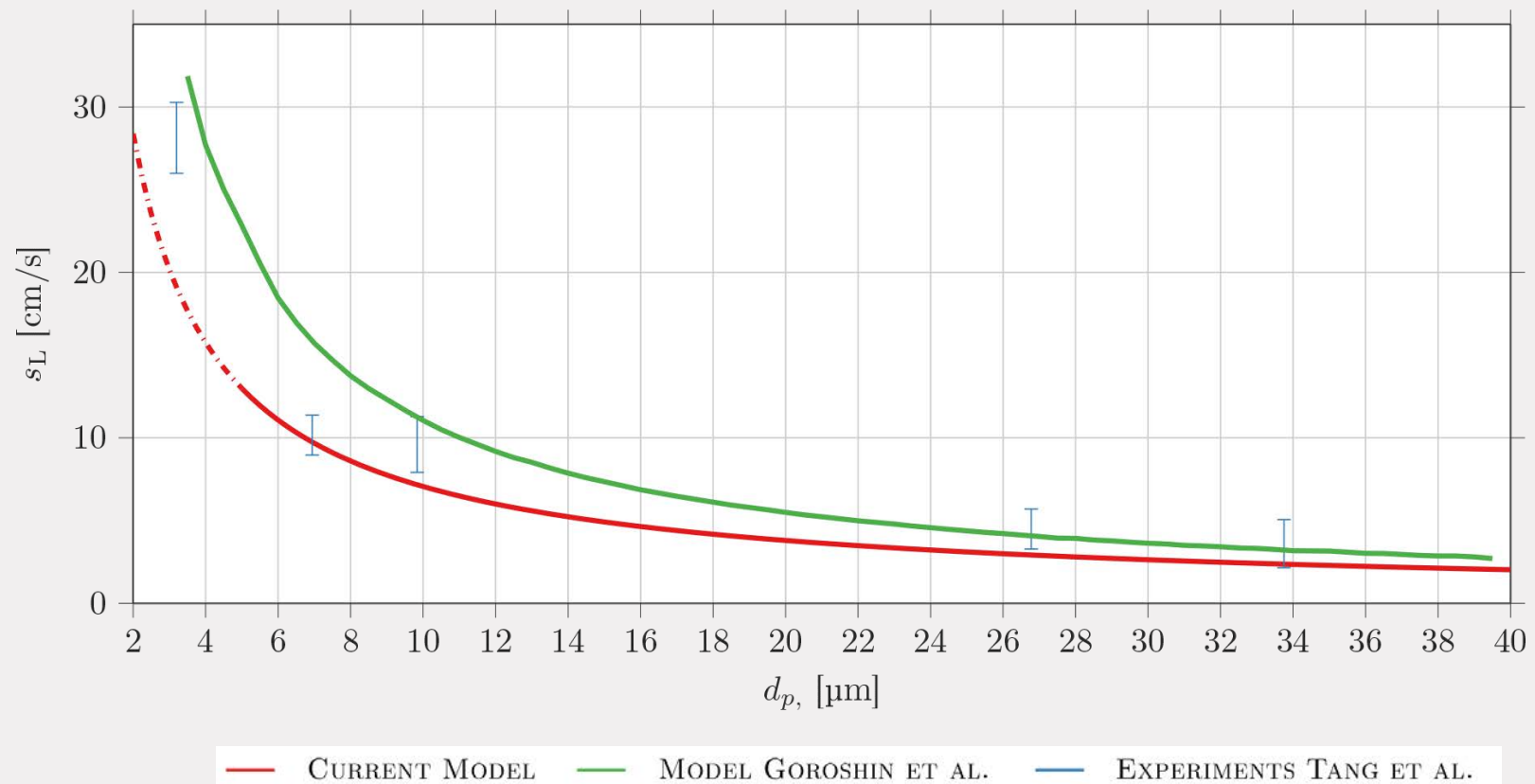


T. Hazenberg (2019)

Iron combustion @ TU/e



Iron combustion @ TU/e



Iron combustion @ TU/e

Status & next steps

- Currently performing small scale experiments & developing models to guide the developments

Question:

- Question: **how to bring this into practice and to the market ??**

Metalot



TRL 1-3

TRL 4-7

TRL 8-9

Fundamental
research
knowledge institutes
TU/e-EIRES



demonstration &
scaling-up:
Metalot



application &
Business creation
Metalot Sites



Market

To make future technology breakthrough possible, Metalot was founded’:

- ◆ Metalot supplies ‘missing link’ between academia & market
- ◆ Metalot develops eco-systems and joint projects with partners
- ◆ Metalot protects and distributes IP
- ◆ Metalot founding fathers: TU/e, PNB, Municipality Cranendonck & Nystar



Iron combustion @ Metalot: Metal Power (100 KW)



Provincie Noord-Brabant

TU/e EINDHOVEN
UNIVERSITY OF
TECHNOLOGY

TEAM
SOLID

metalot

ROMICO HOLD
ROMICO ENGINEERING
SOLUTIONS

EMGROUP
ENERGY AND ENVIRONMENTAL TECHNOLOGIES

HP **HEATPOWER**

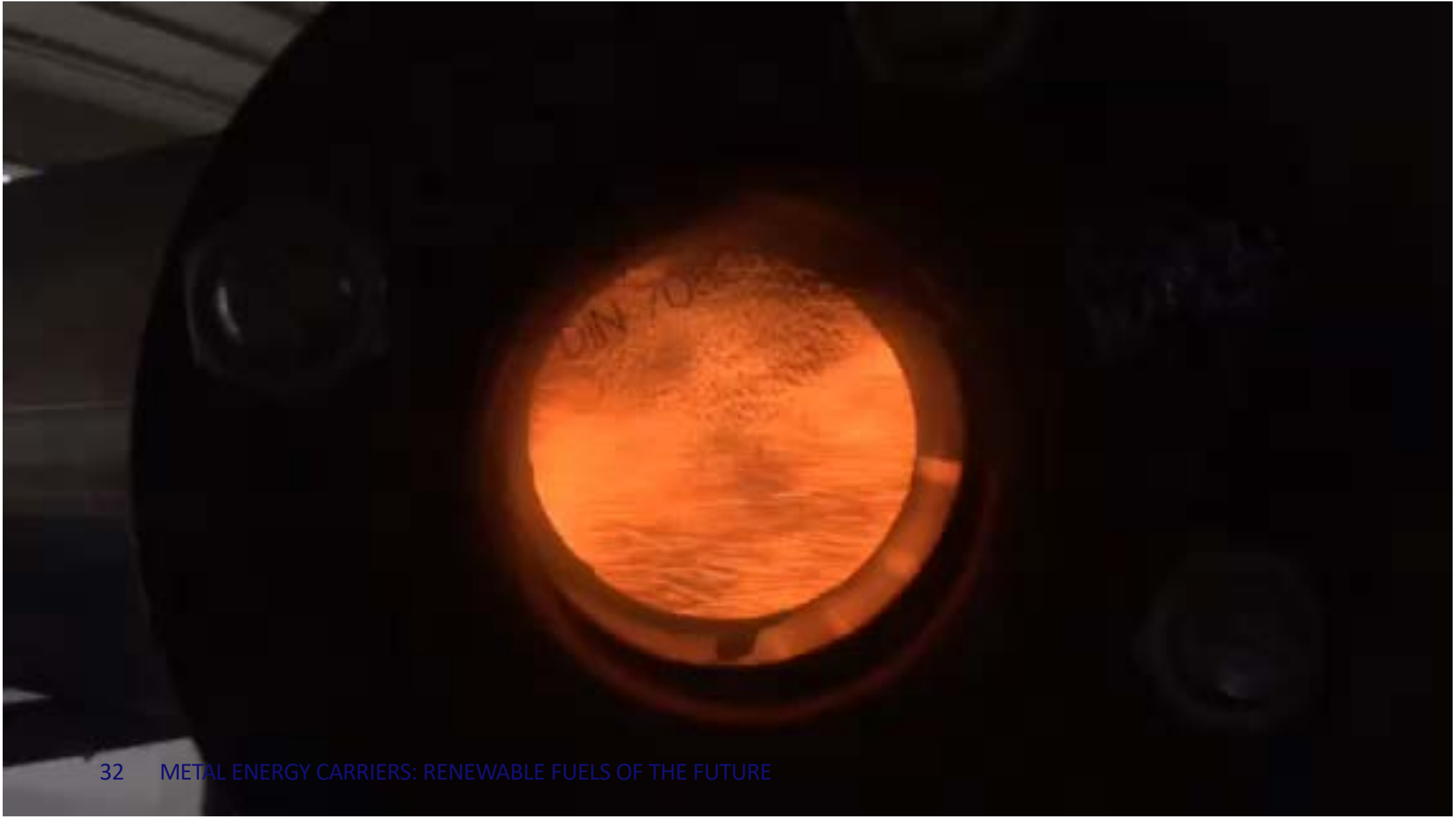
**uni
per**

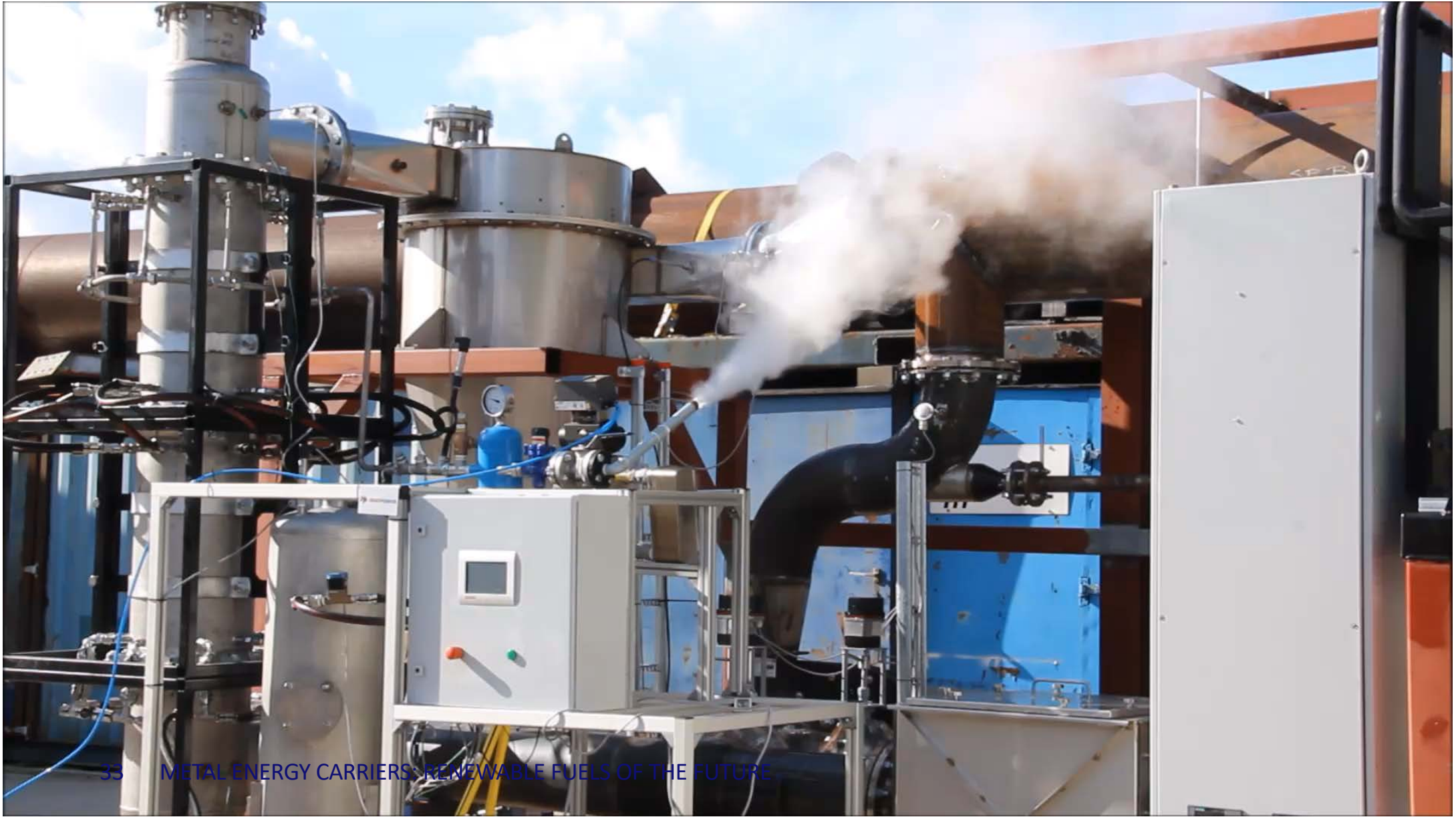
nyrstar

enpuls

MP100







Current projects: towards real application (Metalot)



Lighthouse
MP + MEC

0.1 MW

2020



OPZuid

1 MW

2021



City Plant

5-10 MW

2024



Coal power
station

1-2 GW

> 2030

Next Steps

Current development: pilot project (5 MW full cycle):

- Customer is interested in carbon free, renewable heat & safe/cheap storage in city centers
- District heating peak boilers (~5MW) for winter usage during peak load
- Reduction of oxide towards iron in harbor with sustainable hydrogen
- Proposal in development with existing & new partners

> 4 years: Spinoff to heat intensive industry

- in 4-5 jaar to 5 MW system for industry and build environment
- In 10 years to start with first refurbished coal power station

Conclusions

TU/e EIRES (TRL1-TRL3):

- **Fundamental research** combustion & reduction of metal-(oxides) → **First steps taken**

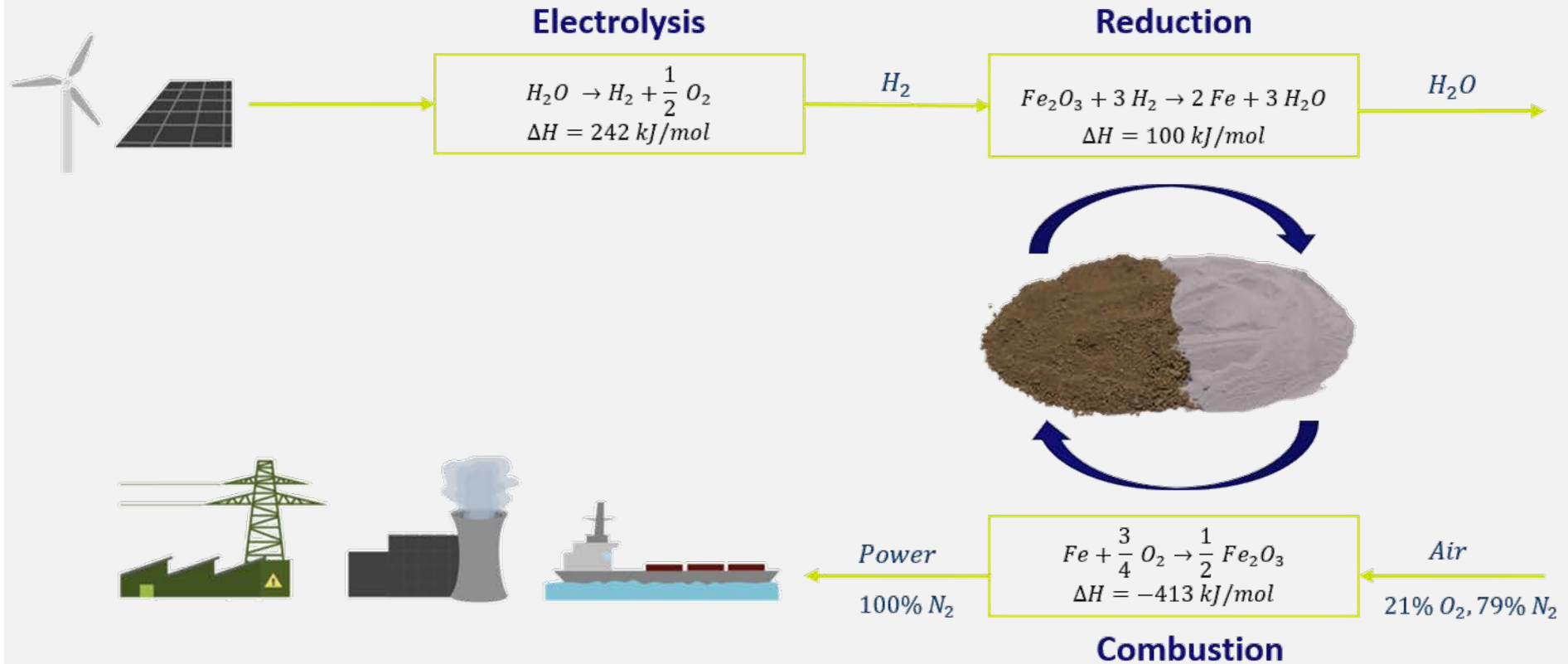
Metalot (TRL>3):

- **Applied research & scaling up** technology towards industrial application → **Metalot FEL started**
- Ecosystem building, IP governance & spin-off launching → **Under Construction**

Thank you !

Extra Slides

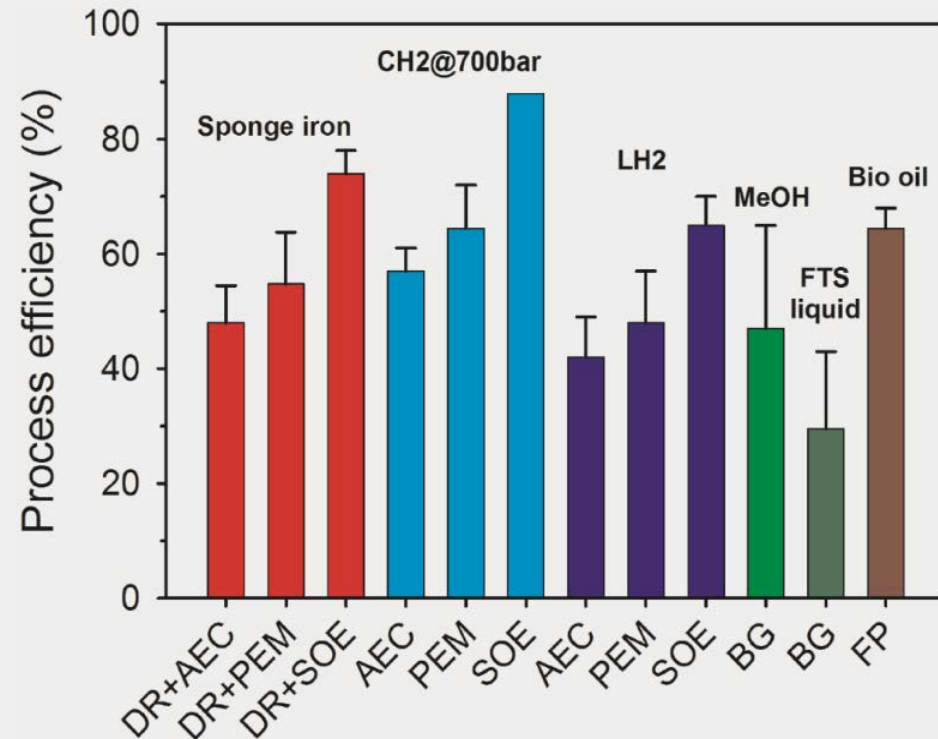
Iron Fuel: Cycle structure



Iron oxide reduction @ TU/e

Process efficiency / energy storage efficiency

- Efficiency of iron reduction process is comparable with other existing storage media



DR=direct reduction; AEC=alkaline electrolytic cell; PEM=polymer electrolytic membrane; SOE=solid oxide electrolyzers; BG=biomass gasification; FP=fast pyrolysis