METAL ENERGY CARRIERS: RENEWABLE FUELS OF THE FUTURE

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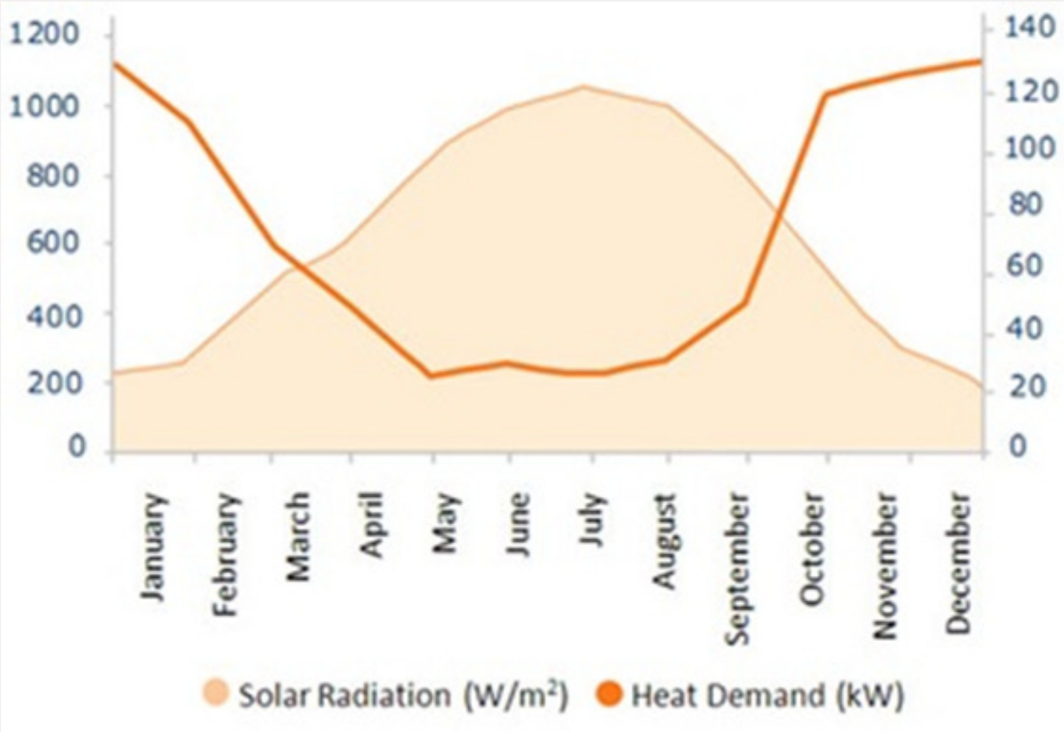
Contents

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?

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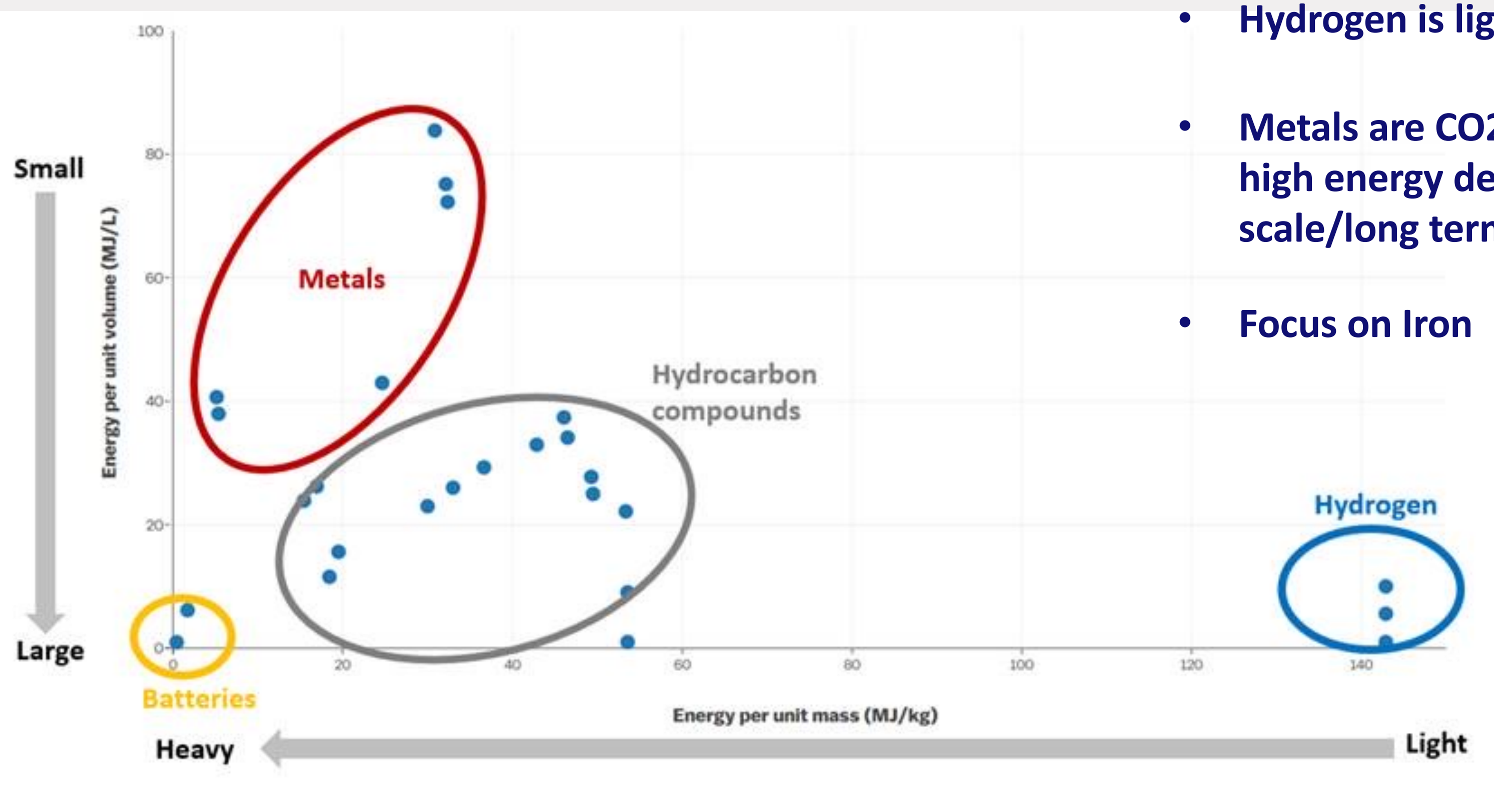
Energy Carriers



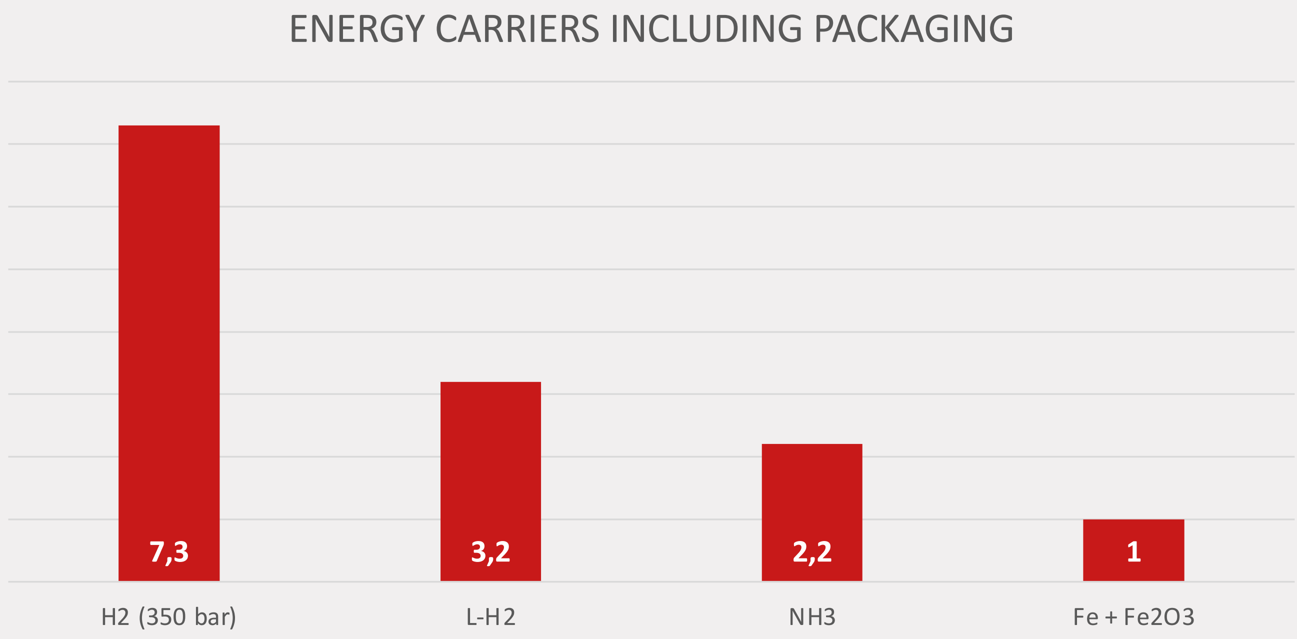
- **Batteries are fine for small scale (E-mobility),**
- **Hydrogen is light but lacks energy density**
- **Metals are CO2-fee, are quite heavy, but have high energy density and very suited for large scale/long term storage**
- **Focus on Iron → WHY ?**

Comparitive advantages of Iron Fuel

COMPACT

SAFE

CHEAP



Comparitive advantages of Iron Fuel

COMPACT

SAFE

CHEAP

	Flammable	Acute Toxic	Health Hazard	Corrosive	Environmental	Pressured Gas
Heavy Fuel Oil (HFO)			X		X	
Methanol (CH_3OH)	X	X	X			
Hydrogen (H_2)	X					X
Ammonia (NH_3)		X		X	X	X
Iron (Fe) and Fe_2O_3	X					

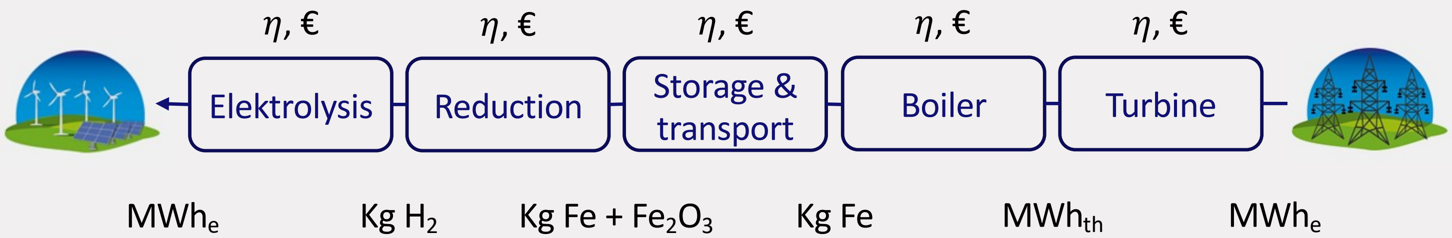
Comparitive advantages of Iron Fuel

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

COMPACT

SAFE

CHEAP



Berenschot: Techno-Economic Analysis

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Comparitive advantages of Iron Fuel

COMPACT

SAFE

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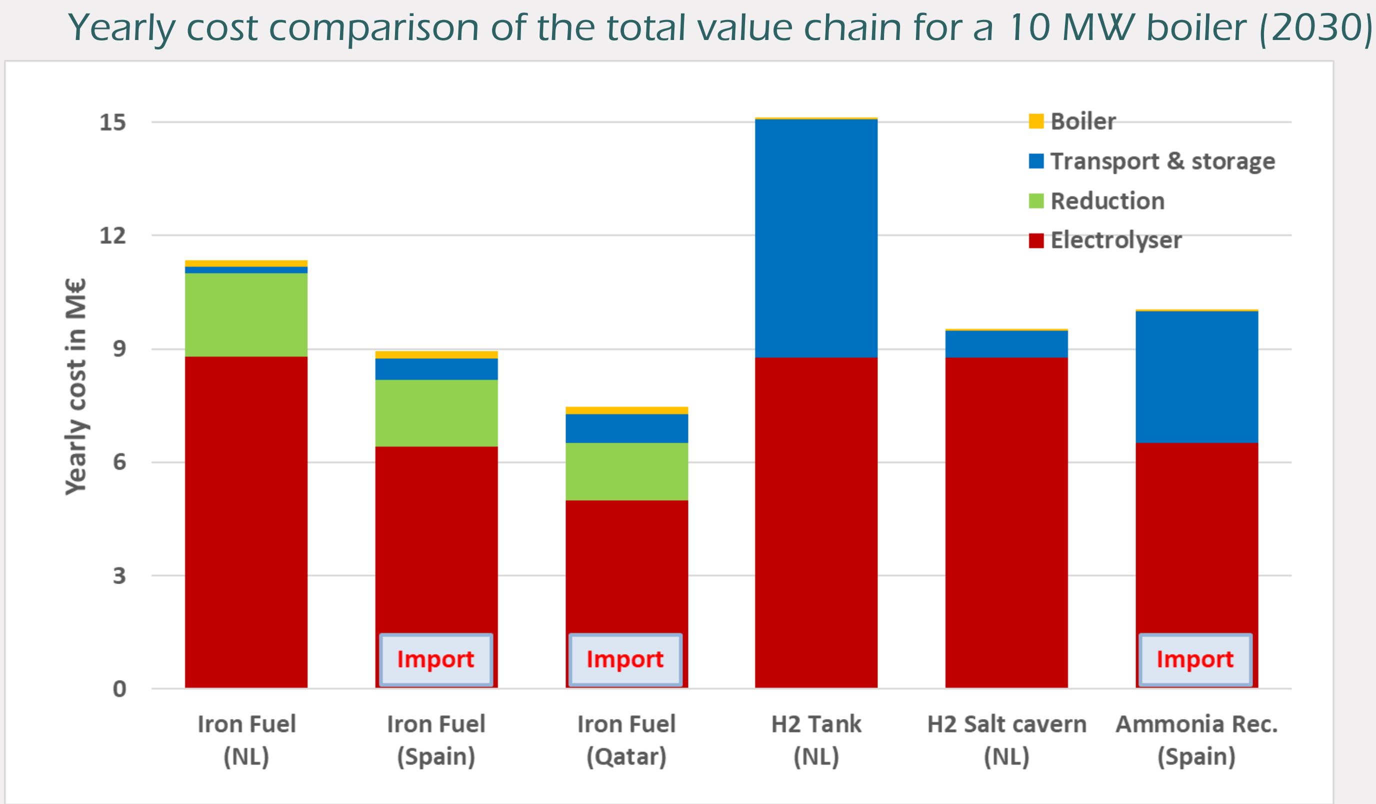


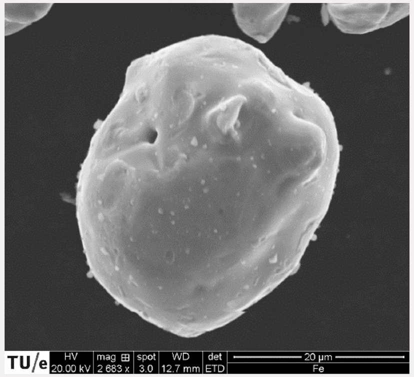
Berenschot: Techno-Economic Analysis

Comparitive advantages of Iron Fuel

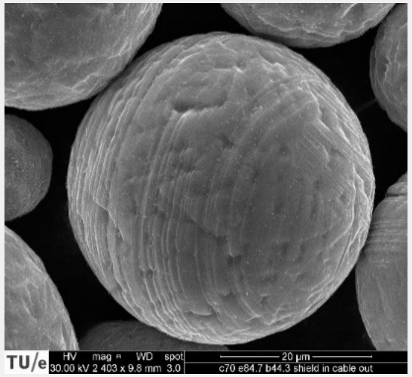
CLEAN

RECYCLEBLE

RETROFIT



Iron



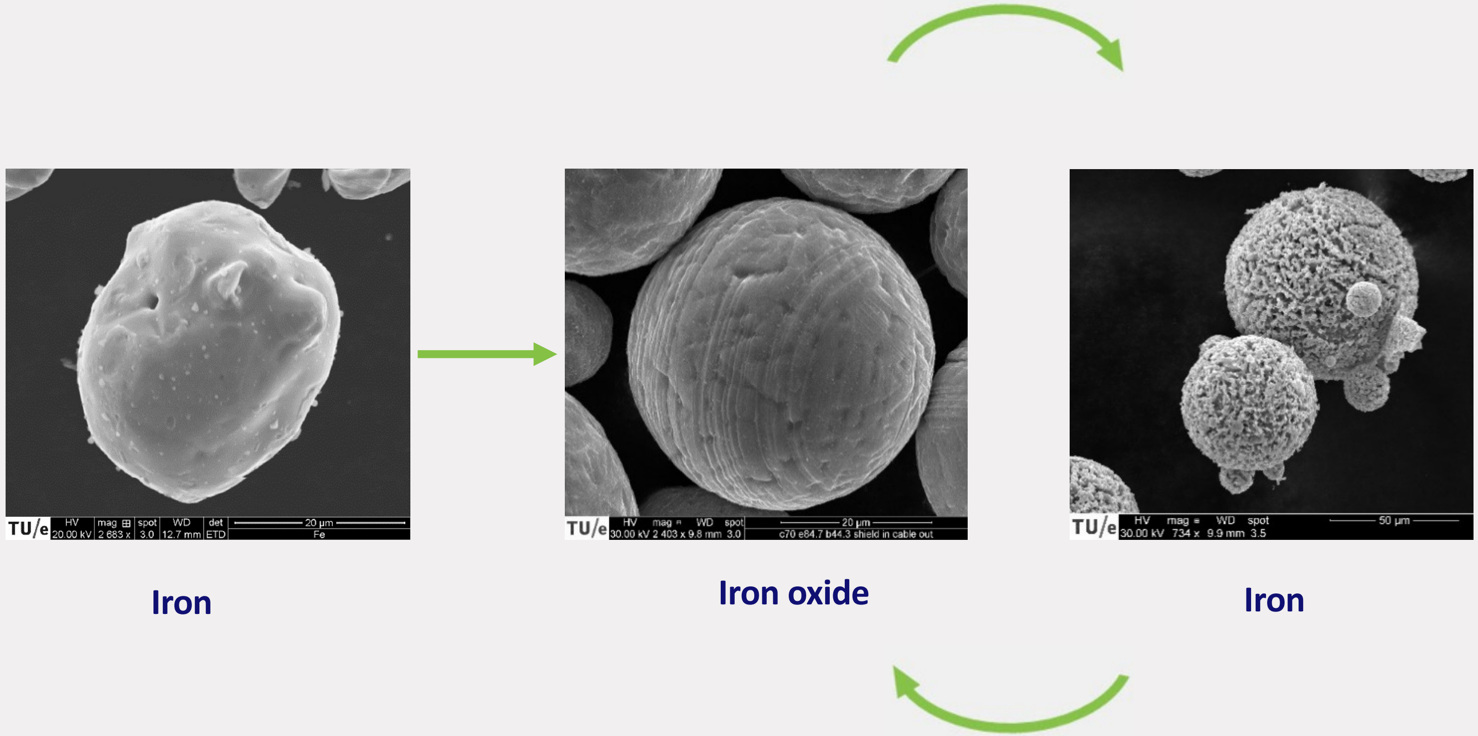
Iron oxide

Comparitive advantages of Iron Fuel

CLEAN

RECYCLEBLE

RETROFIT



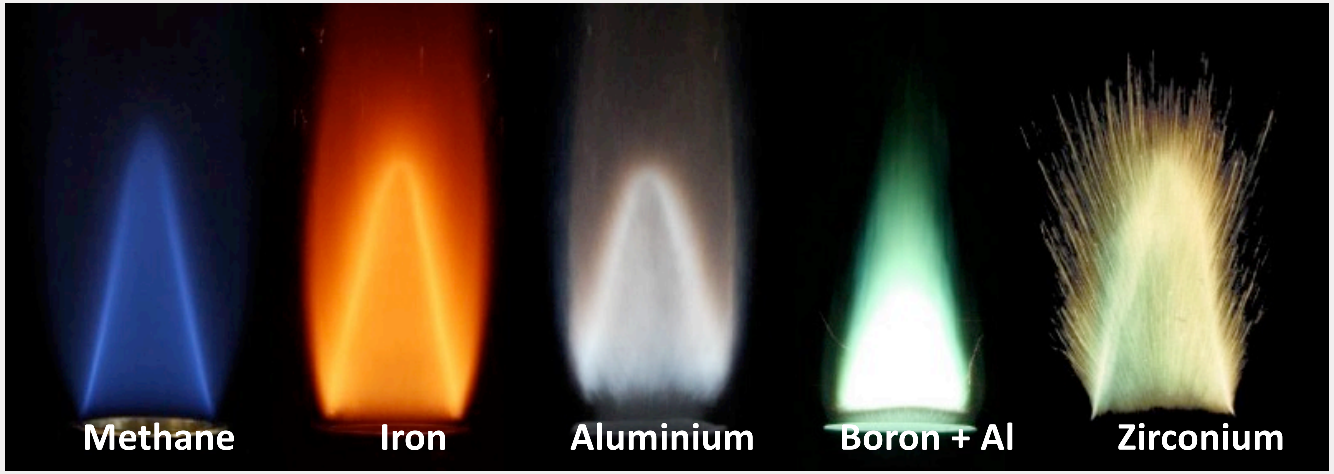
Comparitive advantages of Iron Fuel

CLEAN

RECYCLEBLE

RETROFIT

Fossil → Iron

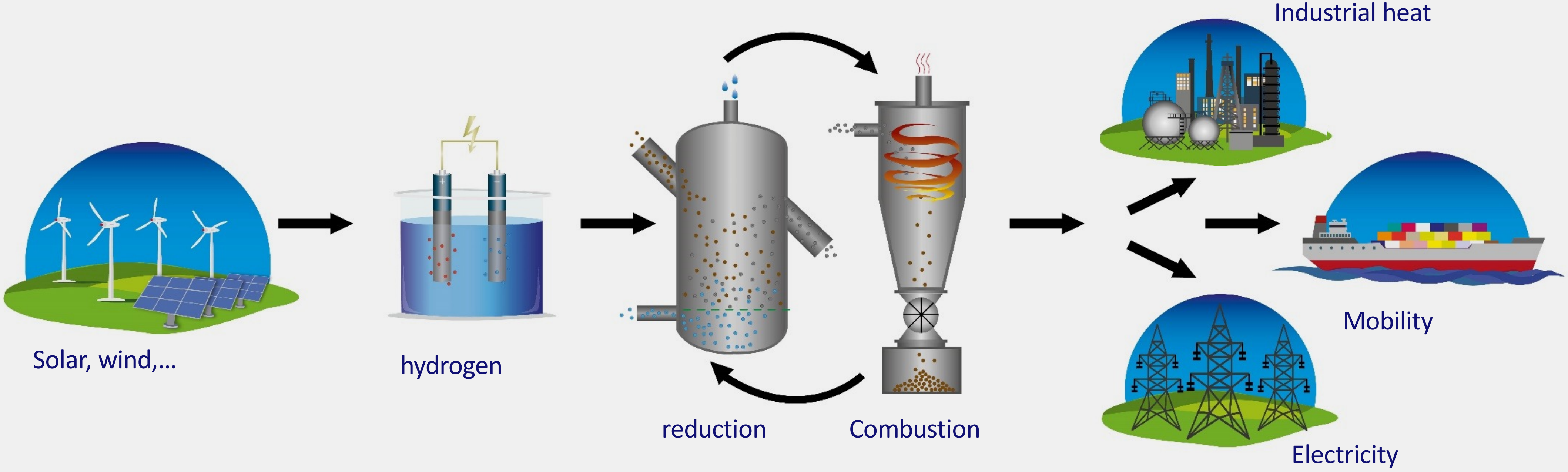


1963 °C 1955 °C 3268 °C 2587 °C 3587 °C

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

Iron Fuel: Cycle structure

$$4\ \mathrm{Fe} + 3\ \mathrm{O}_2 \rightarrow 2\ Fe_2O_3$$



$$Fe_2O_3 + 3\ H_2 \rightarrow 2\ \mathrm{Fe} + 3\ \mathrm{H}_2O$$

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).

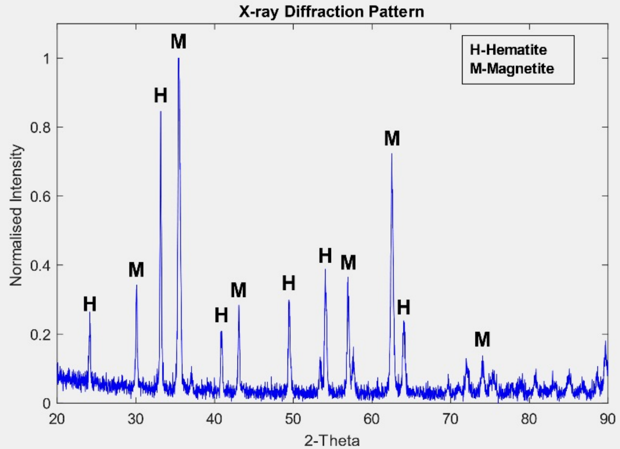
Techno-economic analyses show that **Iron Fuel** can be used (in chronological order of application):

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.

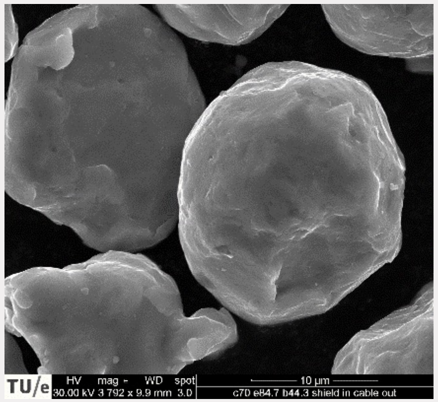
TU/e

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

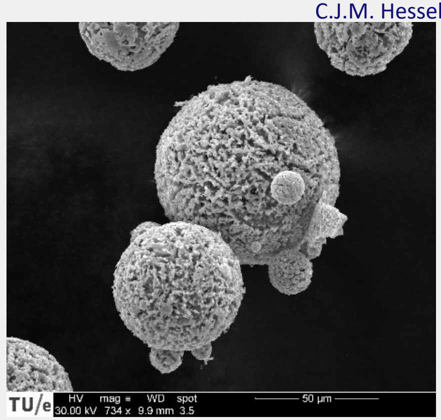


C.J.M. Hessels (2019)



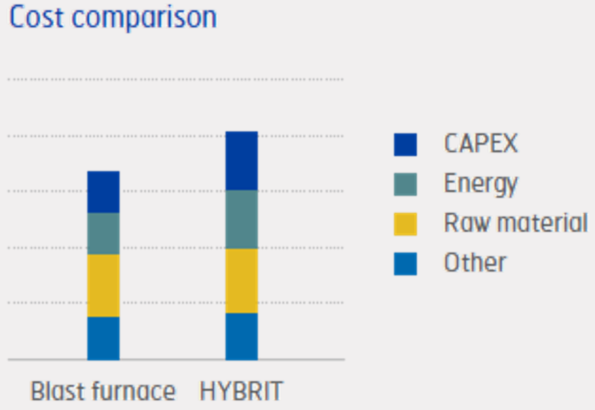
CNPC FE400 Iron particles

Iron oxide particles

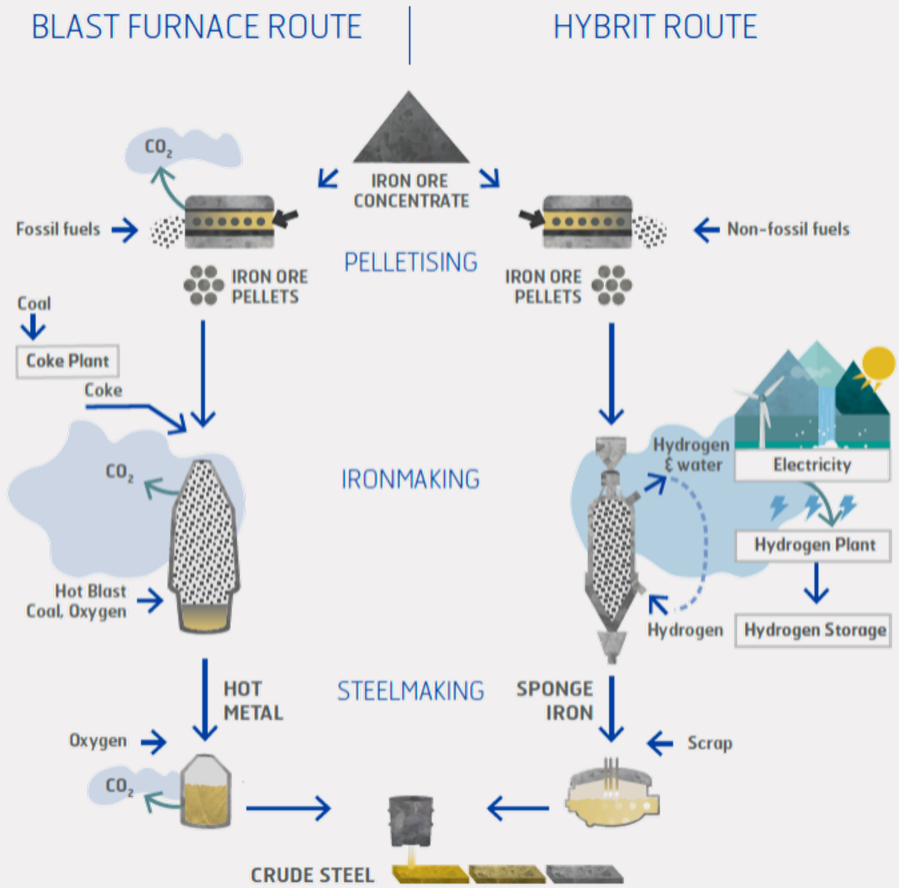


Iron particles after H_2 reduction of iron oxide particles

Iron oxide reduction @ steel industry

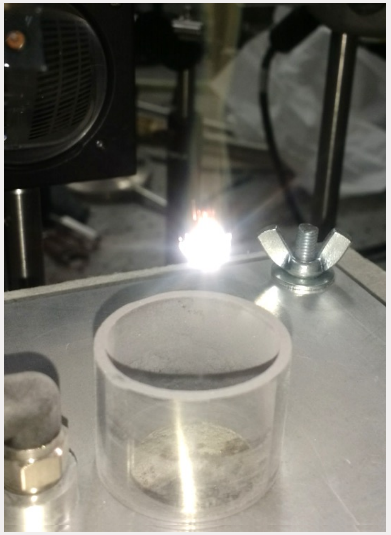


Estimated crude steel production costs at greenfield conditions (HYBRIT prefeasability study).

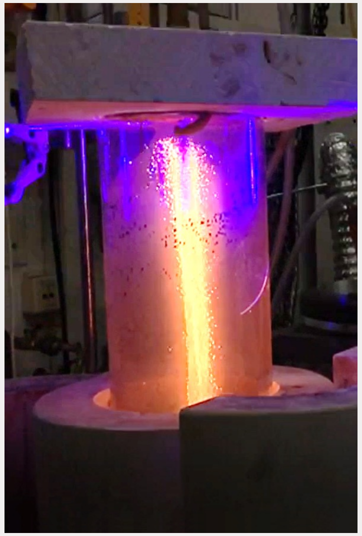


Iron combustion @ TU/e

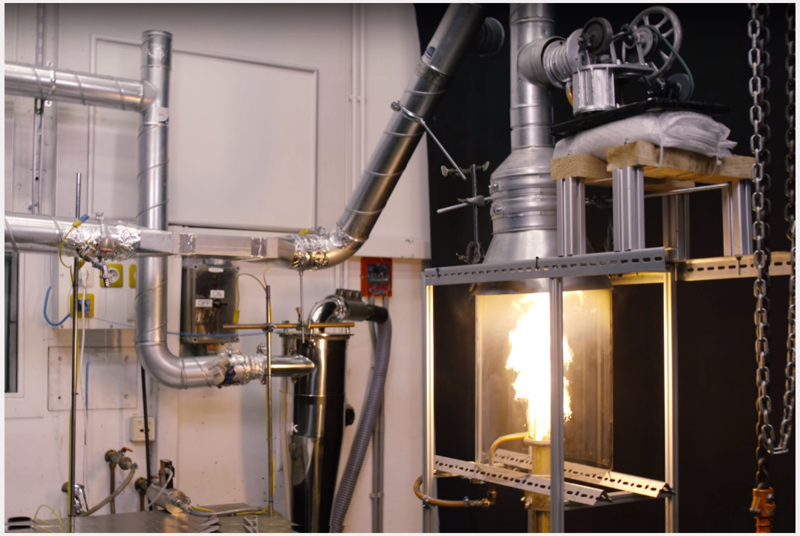
Microburner
20 W



Tornado Burner
2 kW

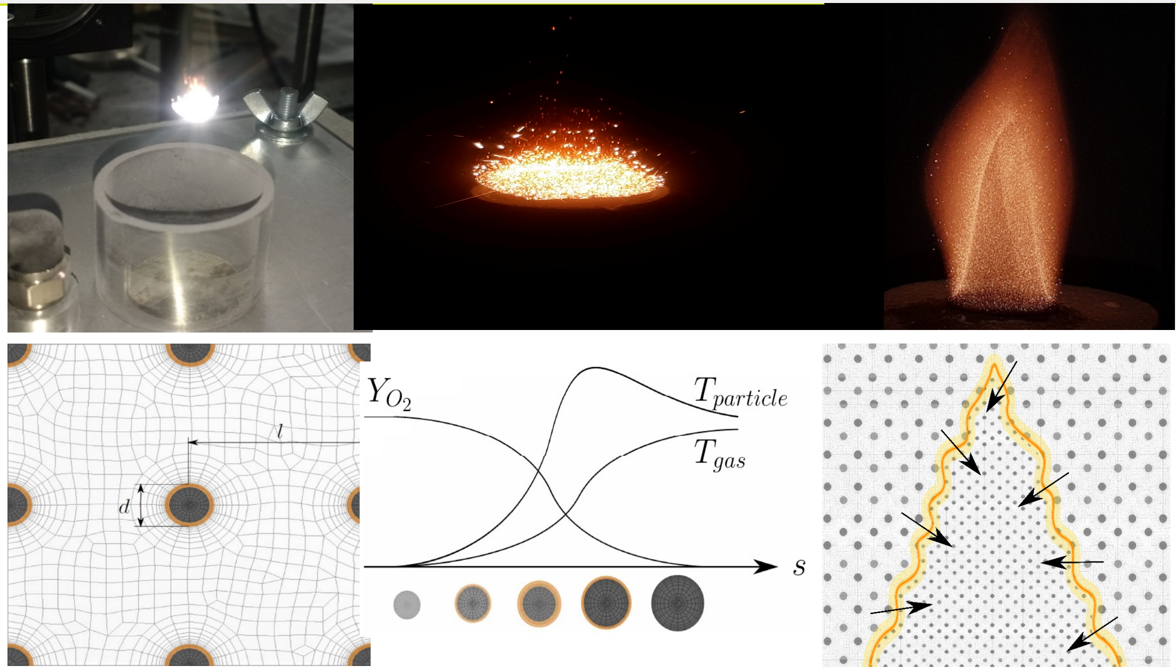


Turbulent Burner
20 kW



TU/e

Iron combustion @ TU/e



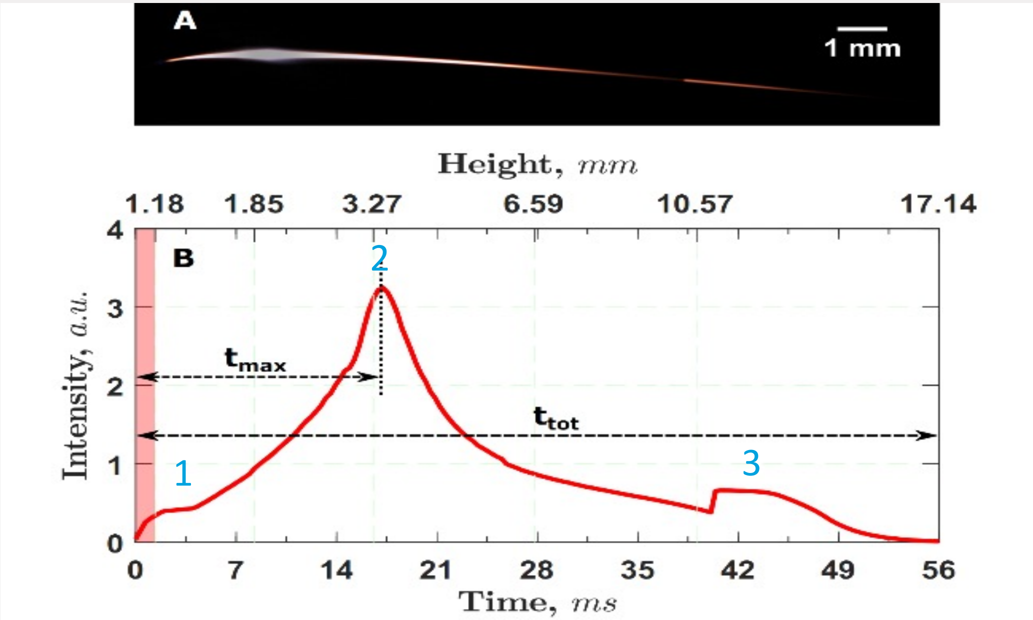
Experiment

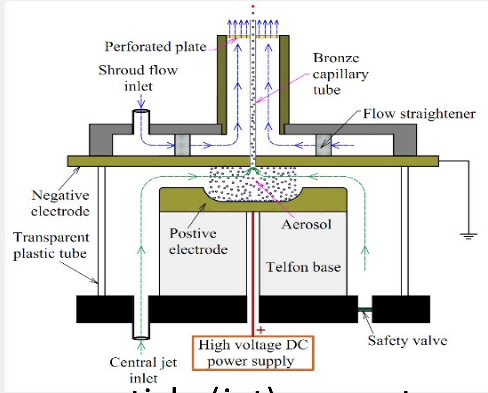
Modeling

Single-particle   Flame element   Large-scale flame

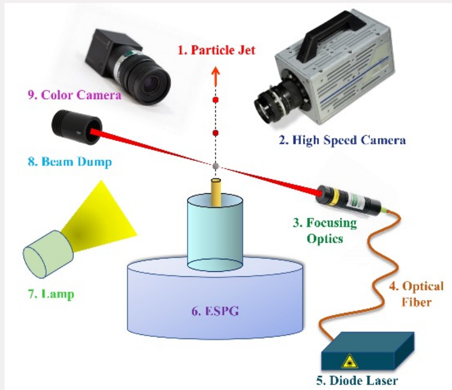
- 10 PhD /PD students on **multi-scale modeling & experiment** (NWO, ERC,..)
- **Exciting new field of science !   ……. Some first results**

Iron combustion @ TU/e

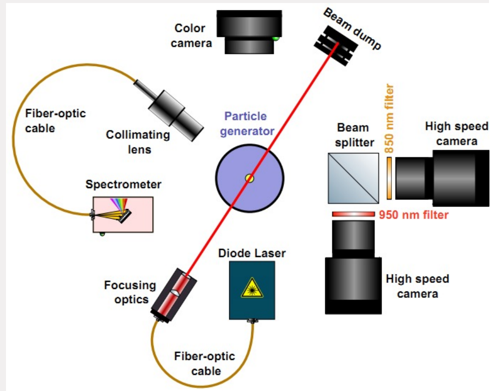




particle (jet) generator



Laser-ignition

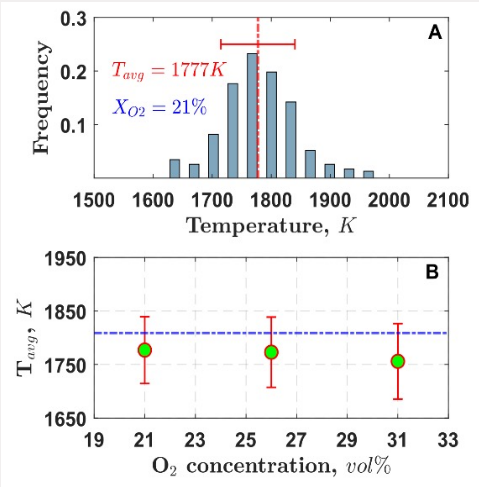


Two-color pyrometer

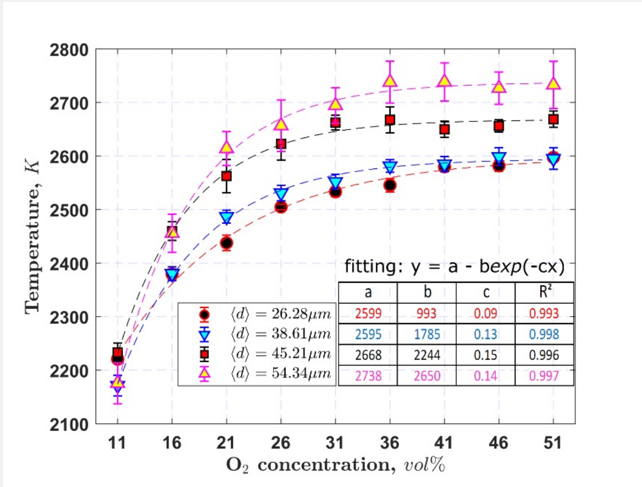
- **Single particle combustion** after laser-ignition
- **Three phases: melting (1), combustion (2) & phase transition (3)**

D. Ning et al.

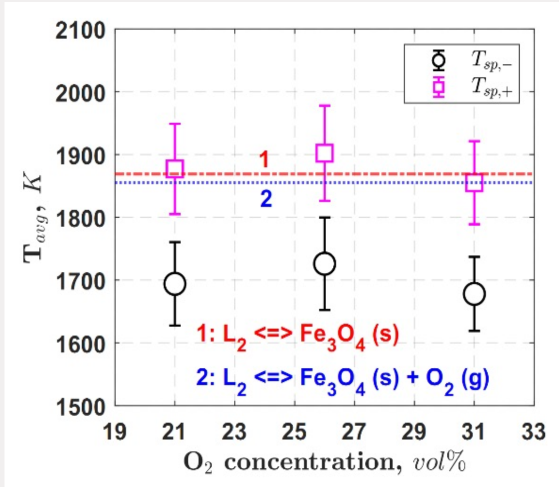
Iron combustion @ TU/e



Phase 1



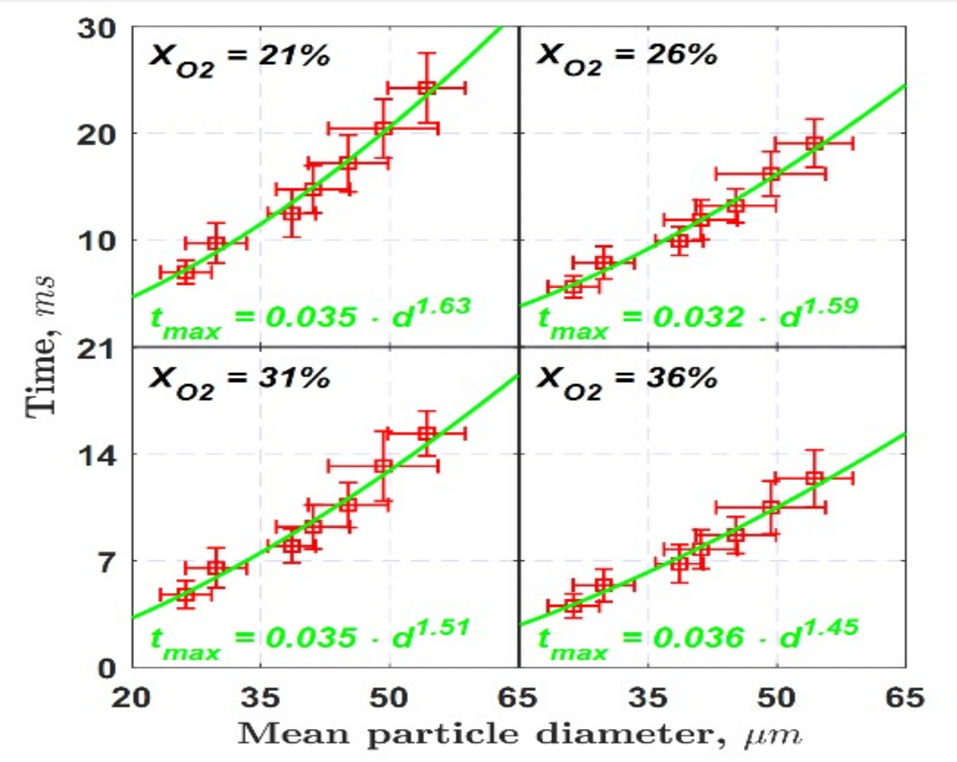
Phase 2



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



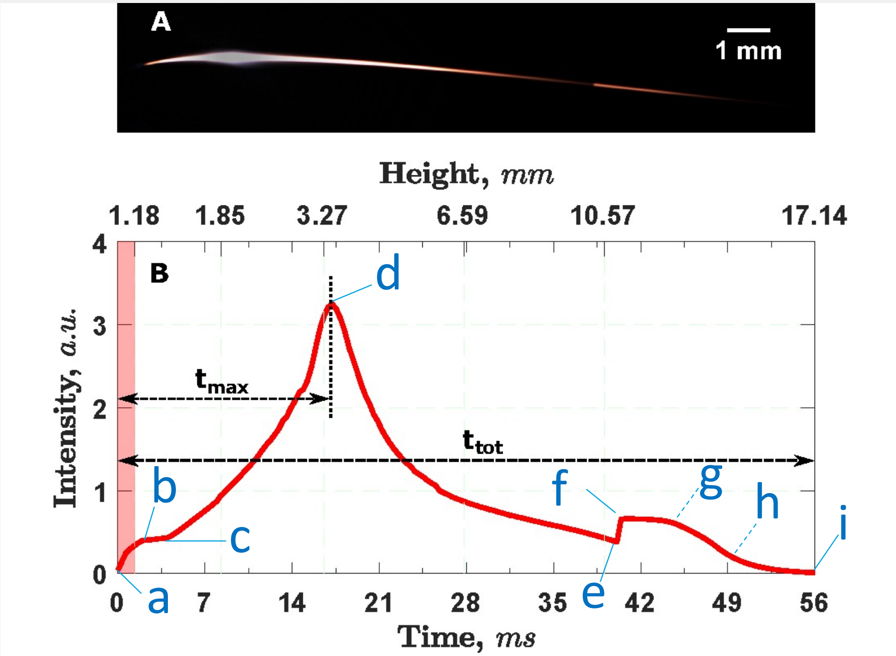
- Combustion times: $t \sim d^{1.6}$
- Combustion time inversely proportional to X_{O2}
- Process is diffusion limited

TU/e

Iron combustion @ TU/e

➢ **First identification of process steps**

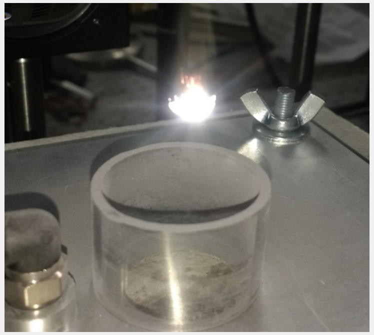
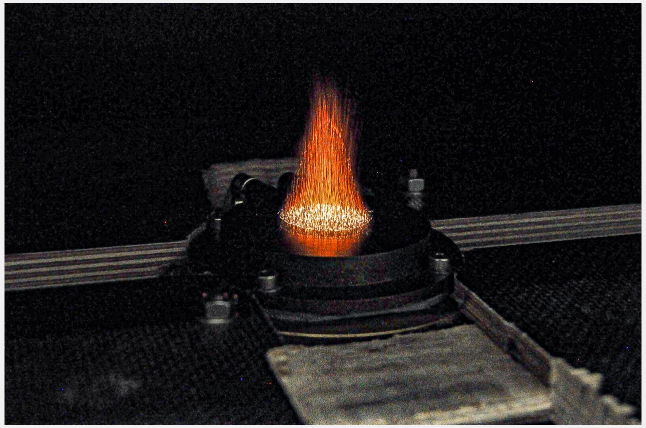
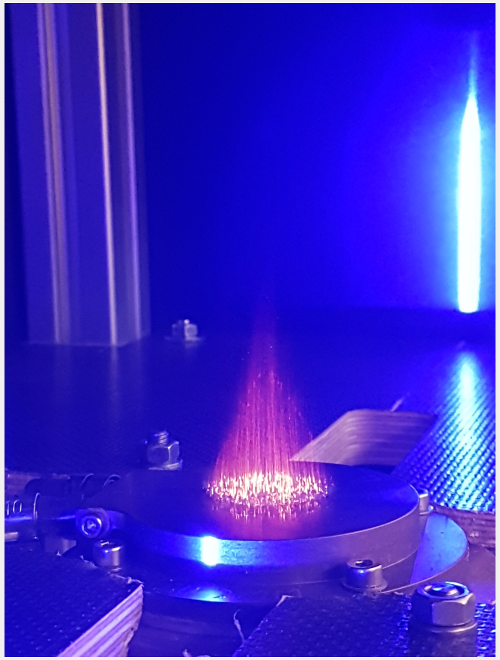
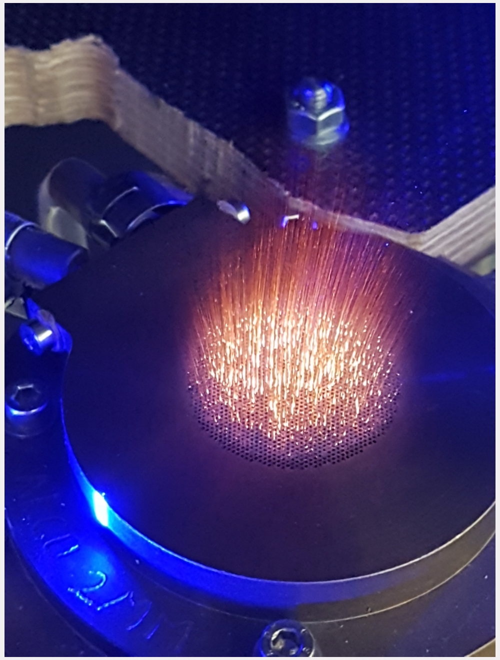
well determined points ······ **estimated points**



Particle temperature: ■ measured ■ literature

limited by oxygen diffusion in gas phase	a-b: Fe(s) + O2 → L2 (liquid oxide),	Ta ~ 1650K
	b-c: Fe(s) melting + oxidization,	Tb~ 1780
		$T_{Fe,melt}$=1809K
	c-d: Fe(l) + O2 → L2	Td~ 2500K
limited by oxygen diffusion in liquid phase	d-e: Fe(l) + O2 → L2	Te~ 1700K
	e-f: L2→ Fe3O4(s) (+ O2(g)) solidific.	Tf ~ 1870
		$T_{Fe3O4,melt}$ = 1855K
	f-g: L2→ Fe3O4(s) (or + O2(g)) solidific	
limited by oxygen diffusion in solid phase(Fe2O3 shell)	g-h: inert cooling of Fe3O4(s),	Th = 1730K
	h-i: Fe3O4(s) + O2 →Fe2O3(s),	Ti ~ 1650K

Iron combustion @ TU/e

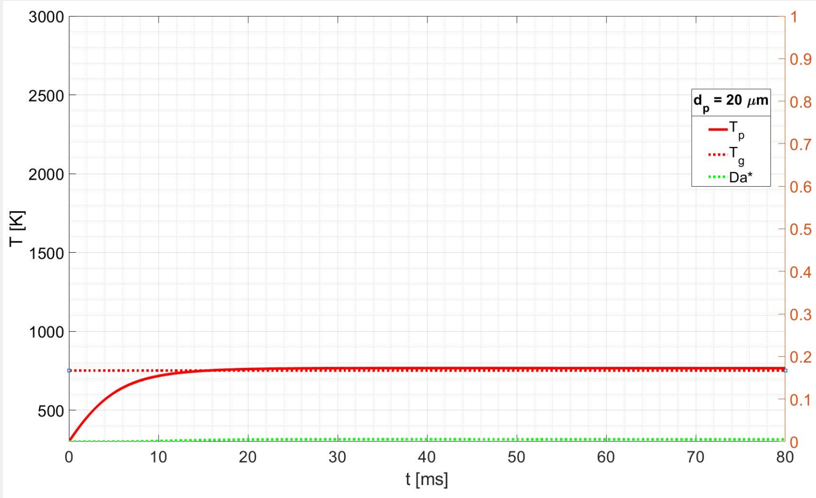
Next steps:

- **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

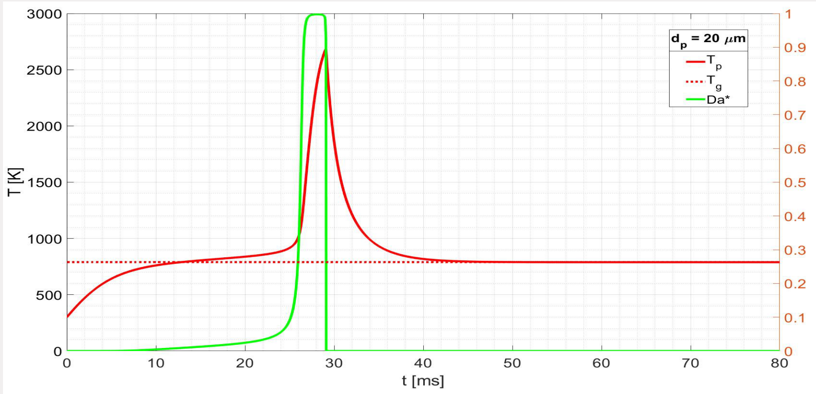
Iron combustion @ TU/e

Single particle ignition modelling in hot flow

- **Kinetics: fit to experiments of single particles**
- **=> Auto-ignition around 800 K**
- **Process is diffusion limited (single step)**
- **Thermodynamics of Fe-O simplified**



At T_g = 750K

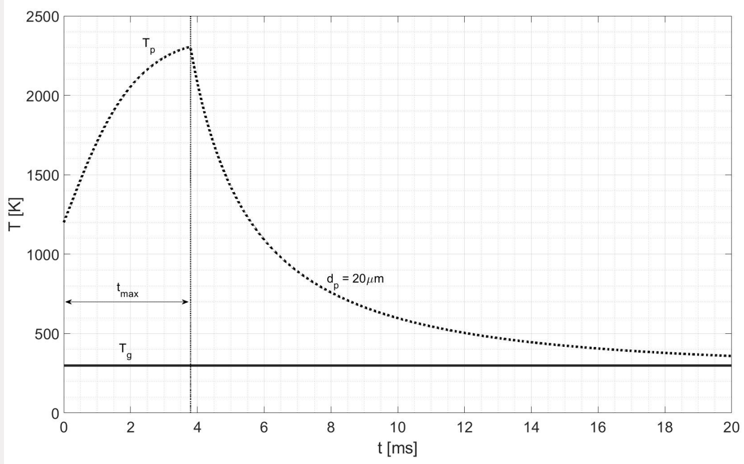


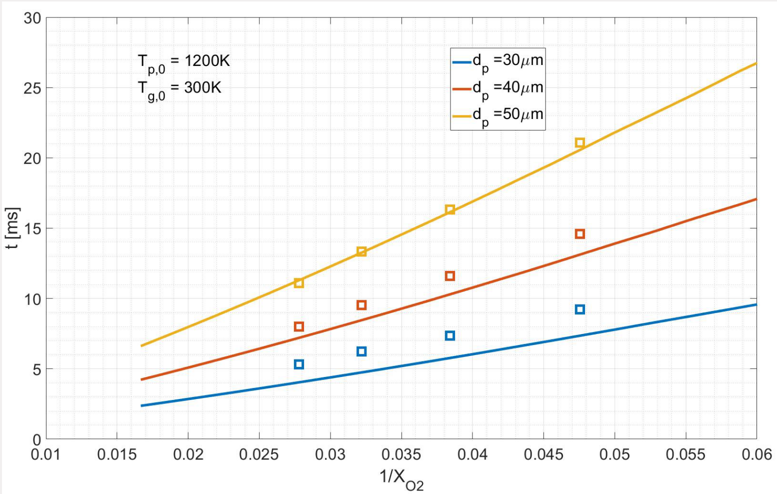
At T_g = 789K

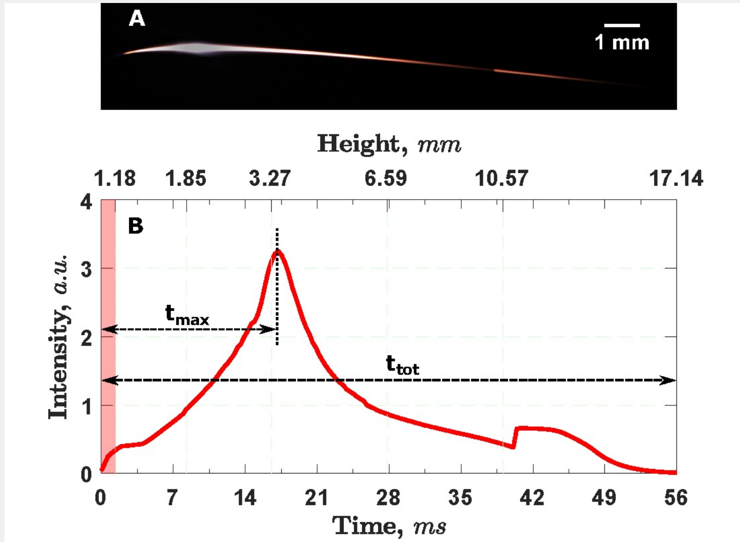
Iron combustion @ TU/e

Single heated particle in cold flow (exp Ning)

- Tp=1200 K and Tg=300 K
- Exp time to peak t_max well reproduced





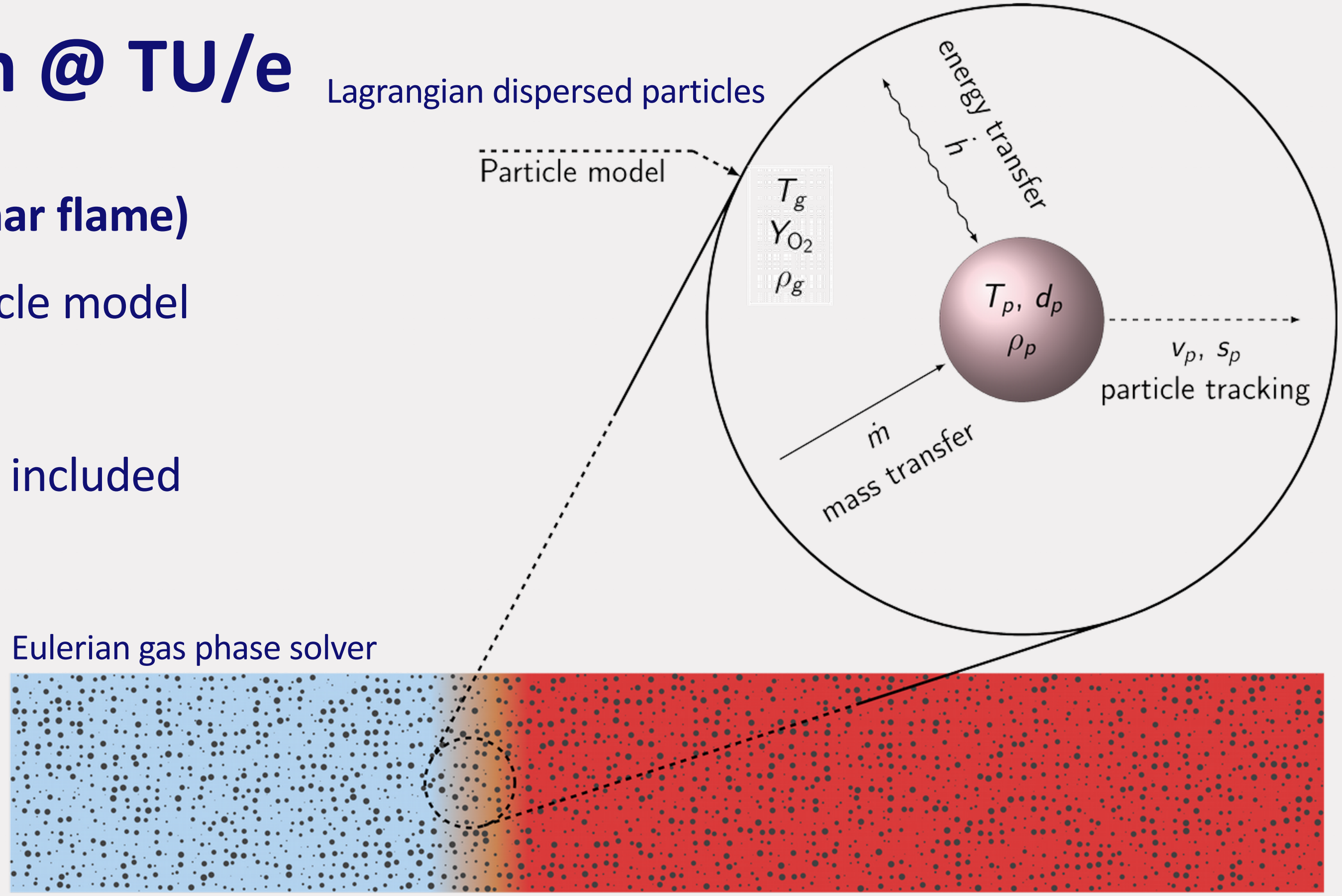


TU/e

Iron combustion @ TU/e

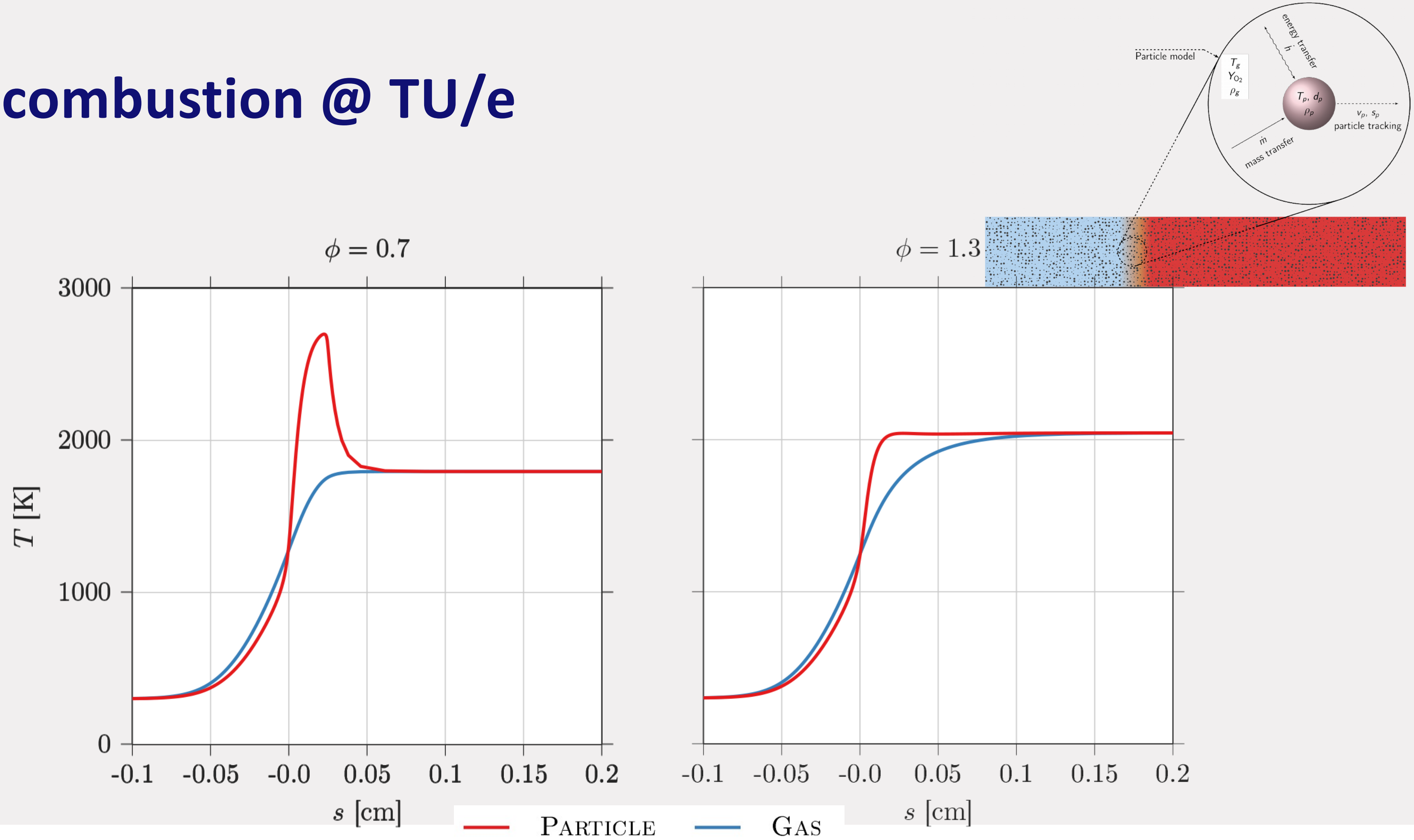
Metalet modelling (1D planar flame)

- Simple fitted single-particle model
- Euler-Lagrange
- Major transfer processes included
- Simple thermodynamics



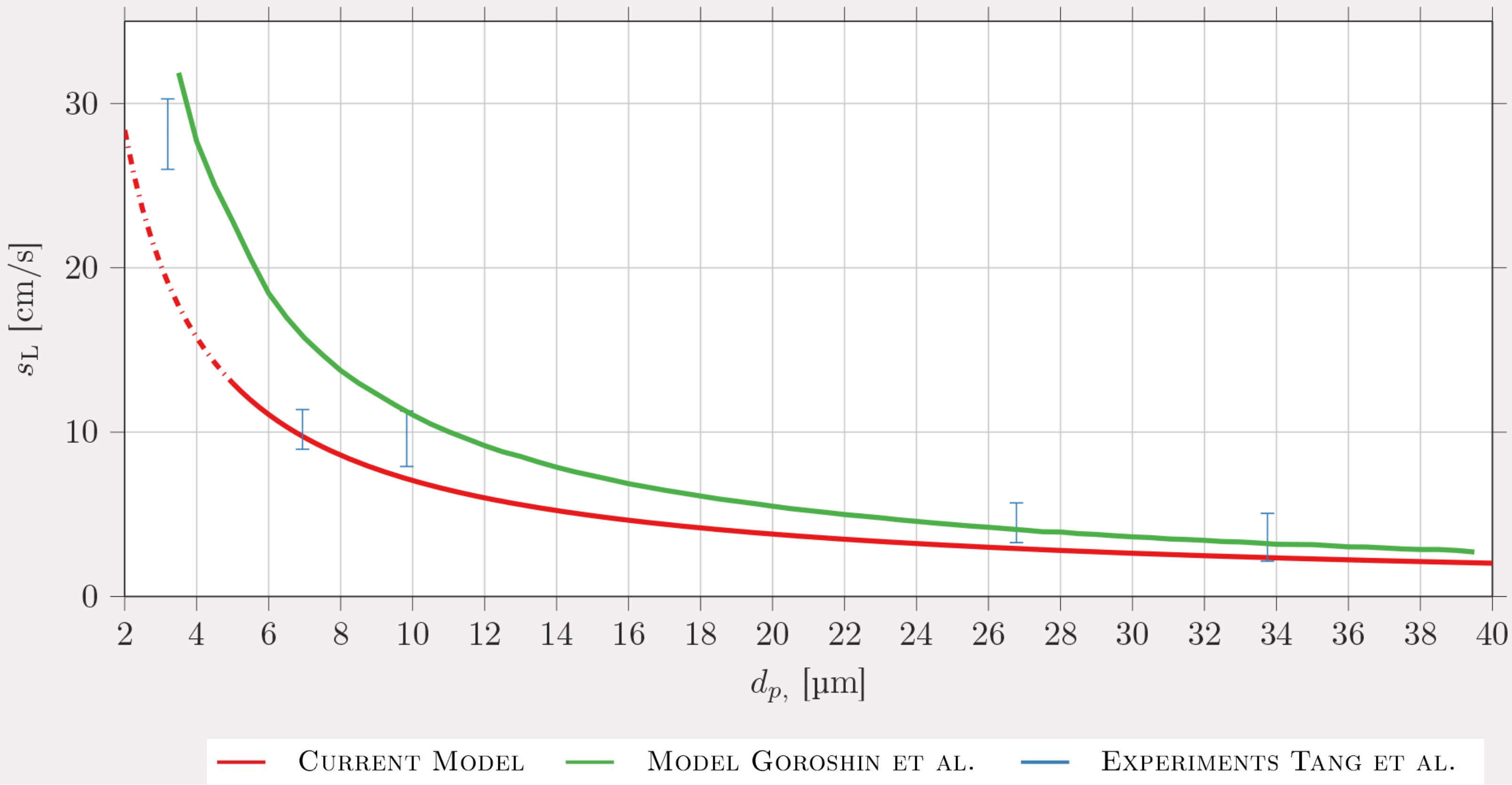
T. Hazenberg et al. (2019)

Iron combustion @ TU/e



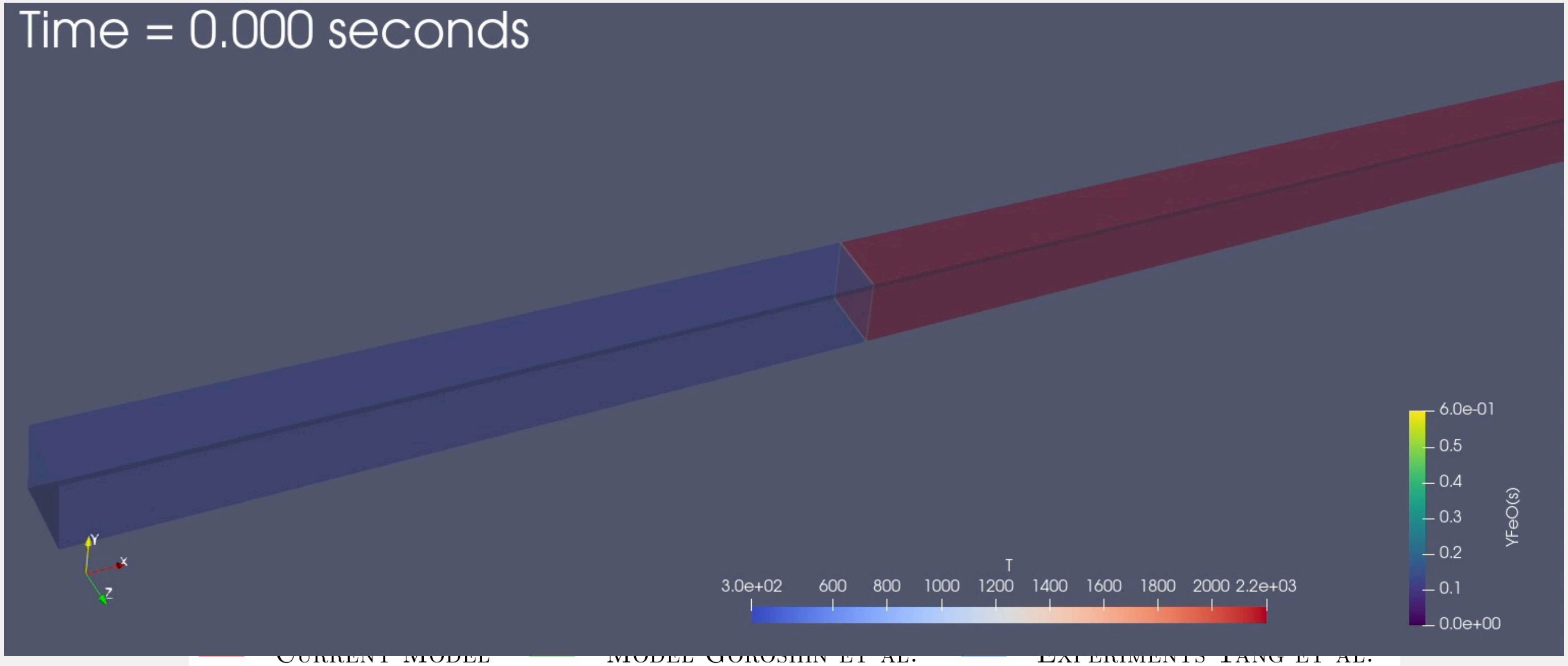
TU/e

Iron combustion @ TU/e



Iron combustion @ TU/e

First Metalet propagation: iron in methane/air



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

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

HEATPOWER

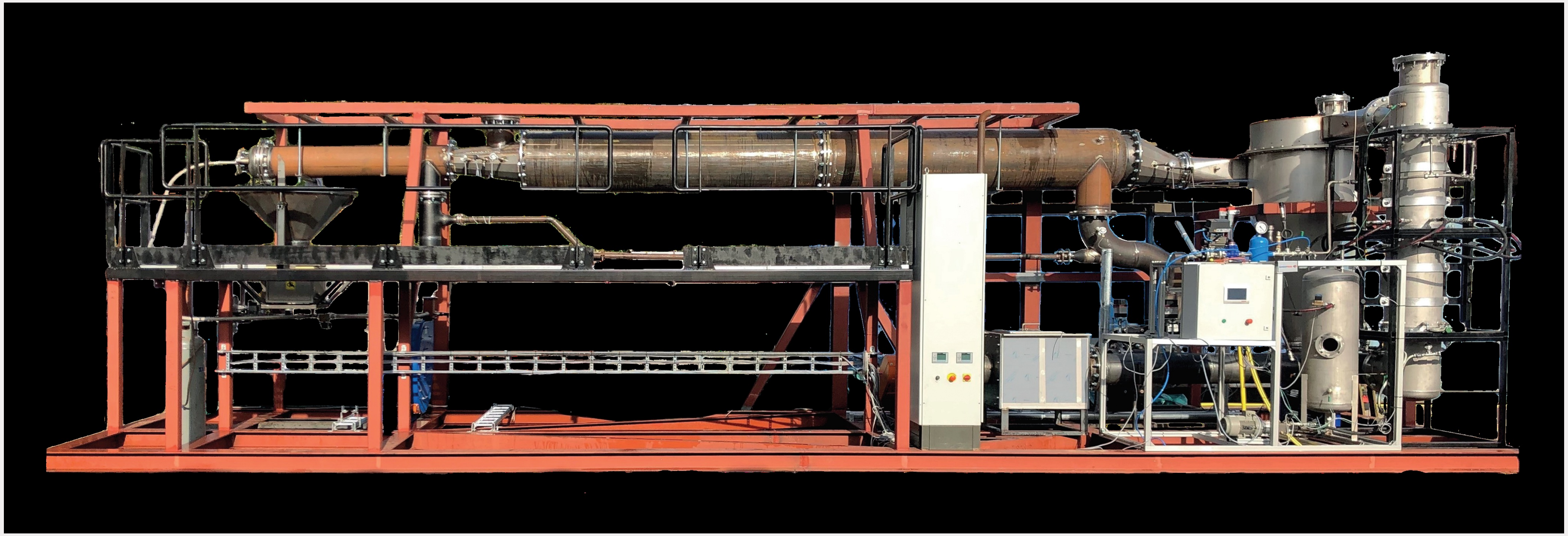
uniper

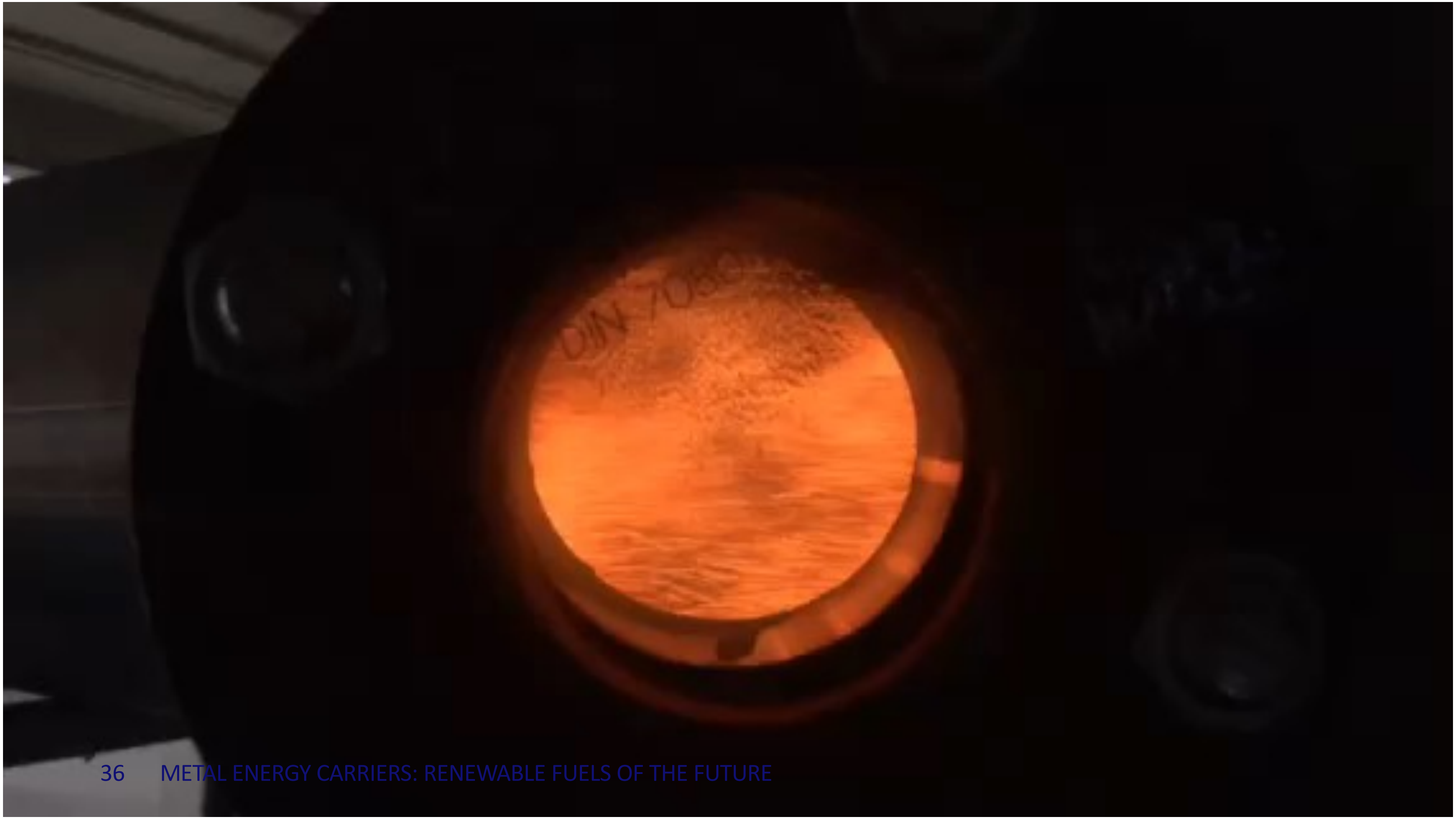
nyrstar

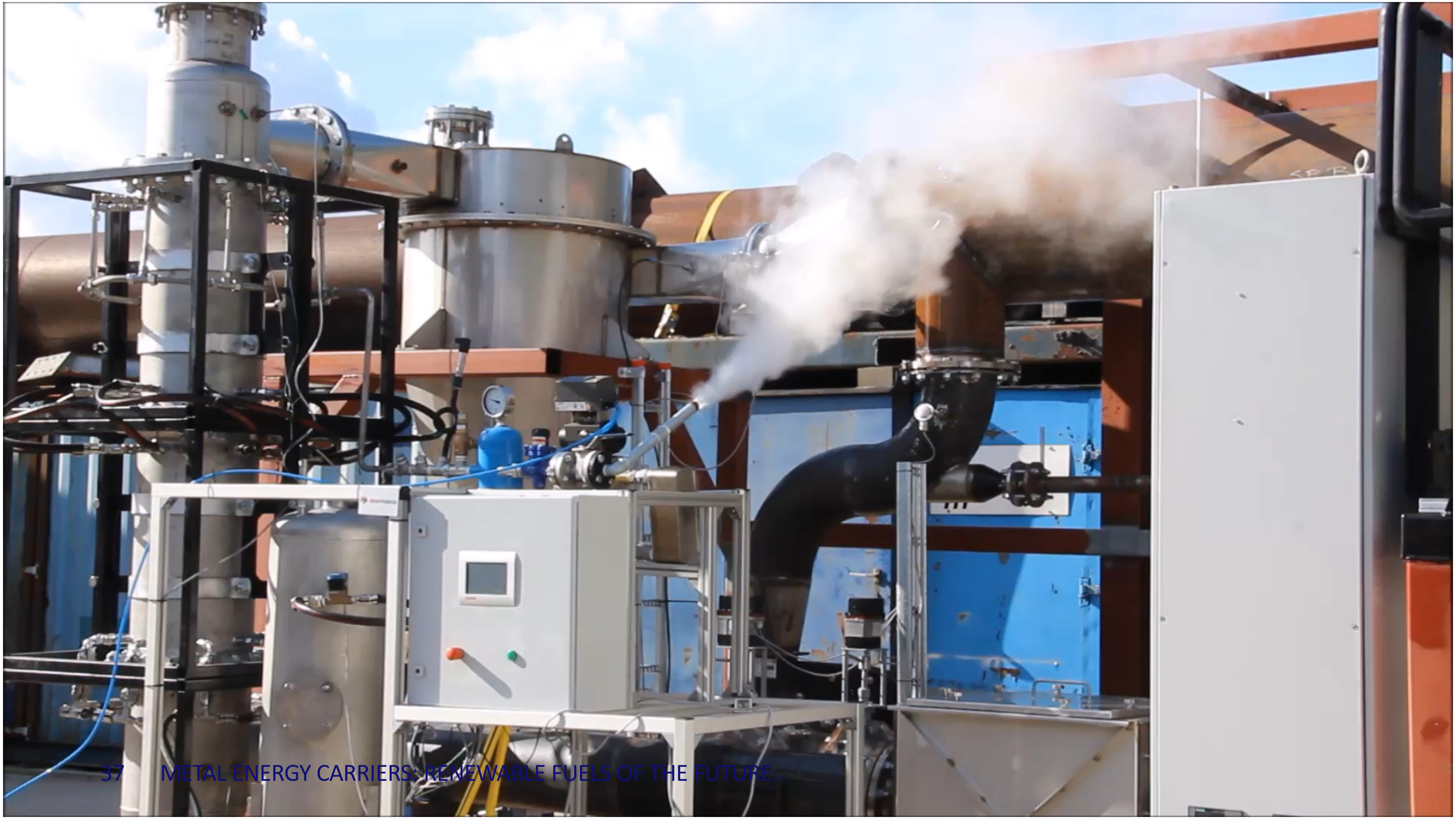
enpuls

TU/e

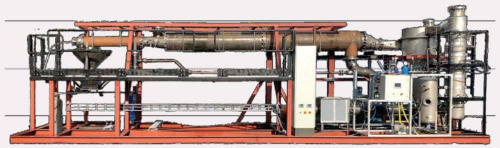
MP100







Current projects: towards real application (Metalot)

			
Lighthouse MP + MEC	OPZuid	City Plant	Coal power station
0.1 MW →	1 MW →	5 MW →	1-2 GW
2020	2021	2024	> 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**

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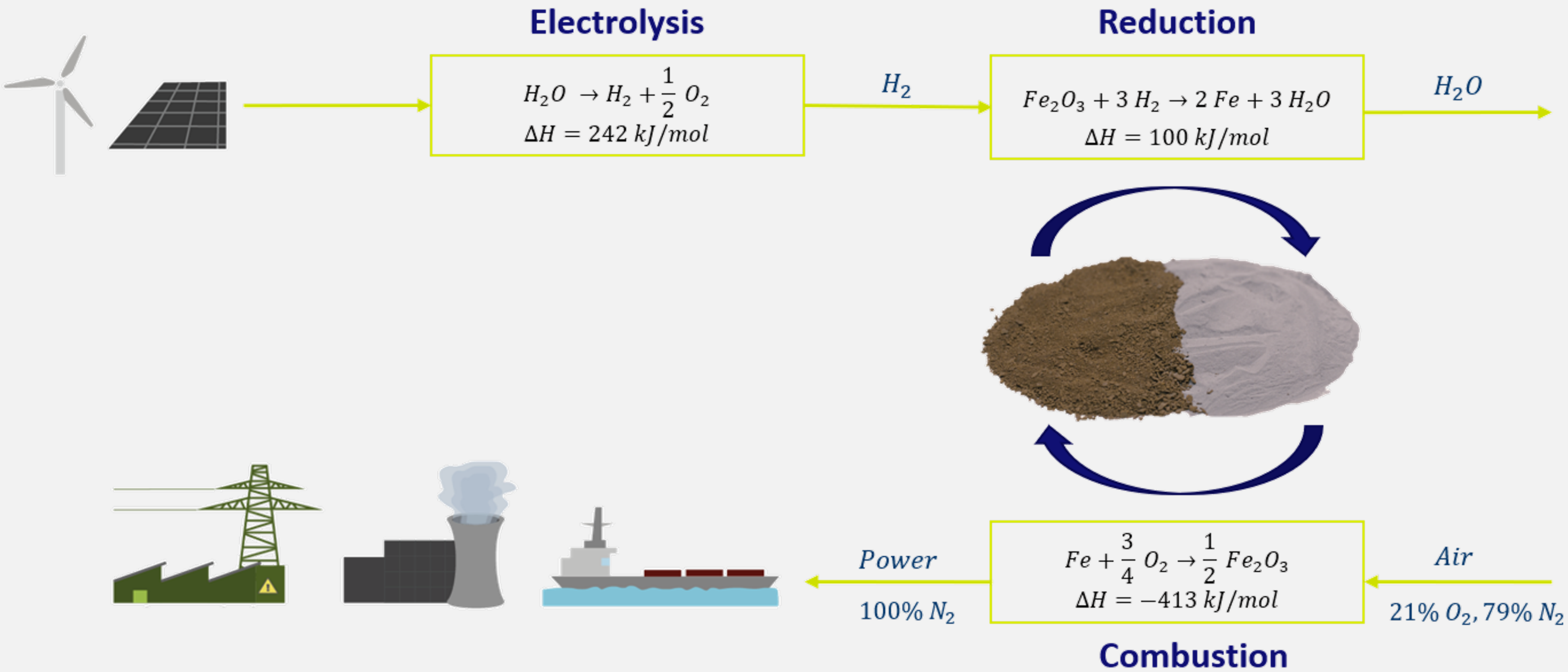
Thank you !

Extra Slides

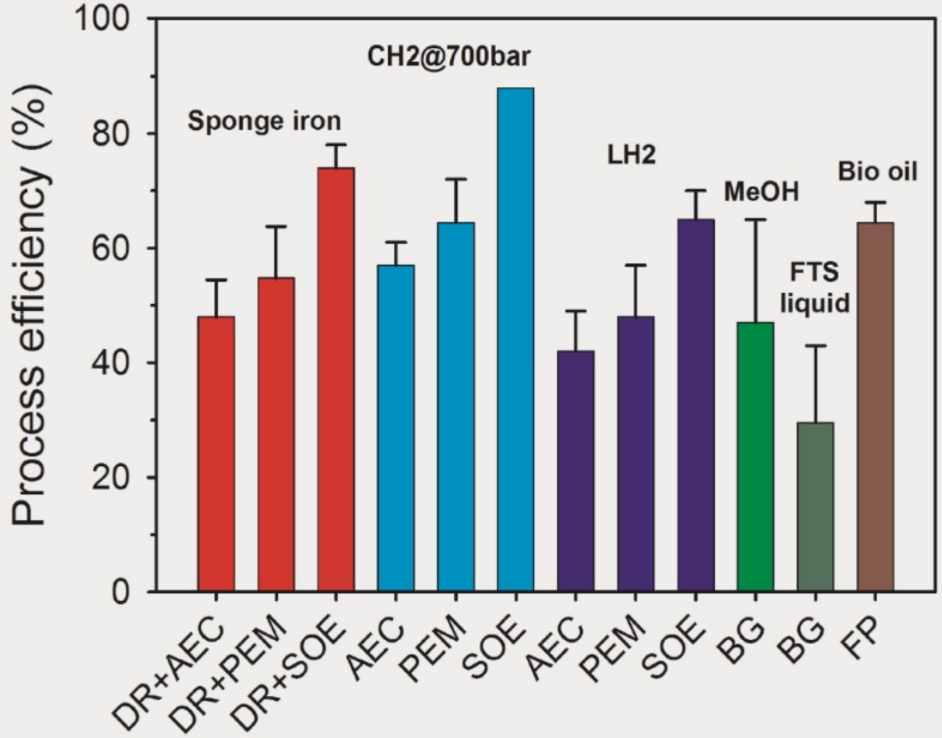
Iron Fuel: Cycle structure



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