Clean Circles

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TECHNISCHE UNIVERSITÄT DARMSTADT

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MAX PLANCK INSTITUTE FOR SUSTAINABLE MATERIALS

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Iron as energy carrier in a carbon-free circular energy economy

Cluster Project Clean Circles

IRON IS THE NEW COAL

IRON AS ENERGY CARRIER IN A CARBON-FREE CIRCULAR ENERGY ECONOMY

KEY MESSAGES

1 The energy system of the future needs different **energy storage systems**.

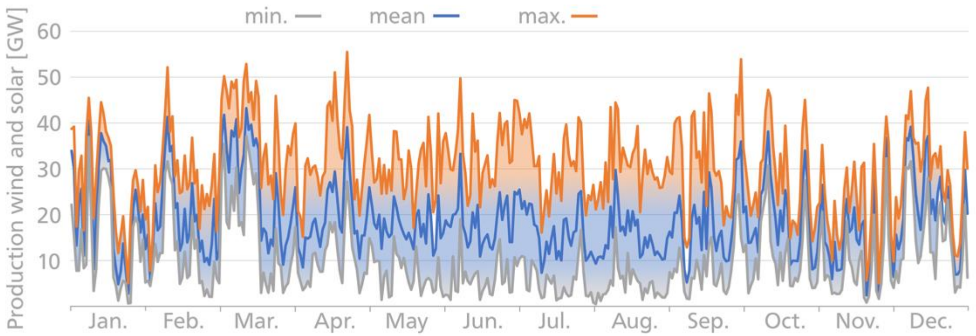
2 **Metals** are suitable for the long-term storage of large amounts of energy.

3 **Climate-neutral retrofitting** of infrastructure is important for the energy transition.

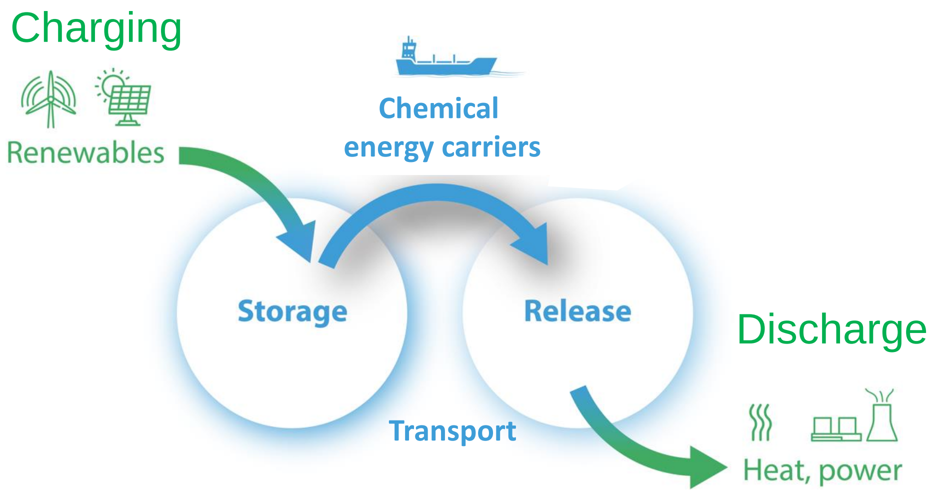
4 **Basic research and demonstrators** work together to drive progress. Scale-up and transfer through collaboration.

WHY DO WE NEED ENERGY STORAGES?

- Renewable energies are very volatile and the potential is unevenly distributed around the world.
- Many countries, including Germany, will continue to be dependent on energy imports in the future.
- Storage, transportation and on-demand use in another location are necessary.
- Direct long-term (seasonal) storage of electricity is not possible on a TWh scale.
- **CONCLUSION:** "Molecules instead of electrons", chemical energy carriers are of crucial importance.



Quelle: **Dreizler,** A. et al., *Applications in Energy and Combustion Science,* **2021**, *7*:100040



STORING – BUT HOW?

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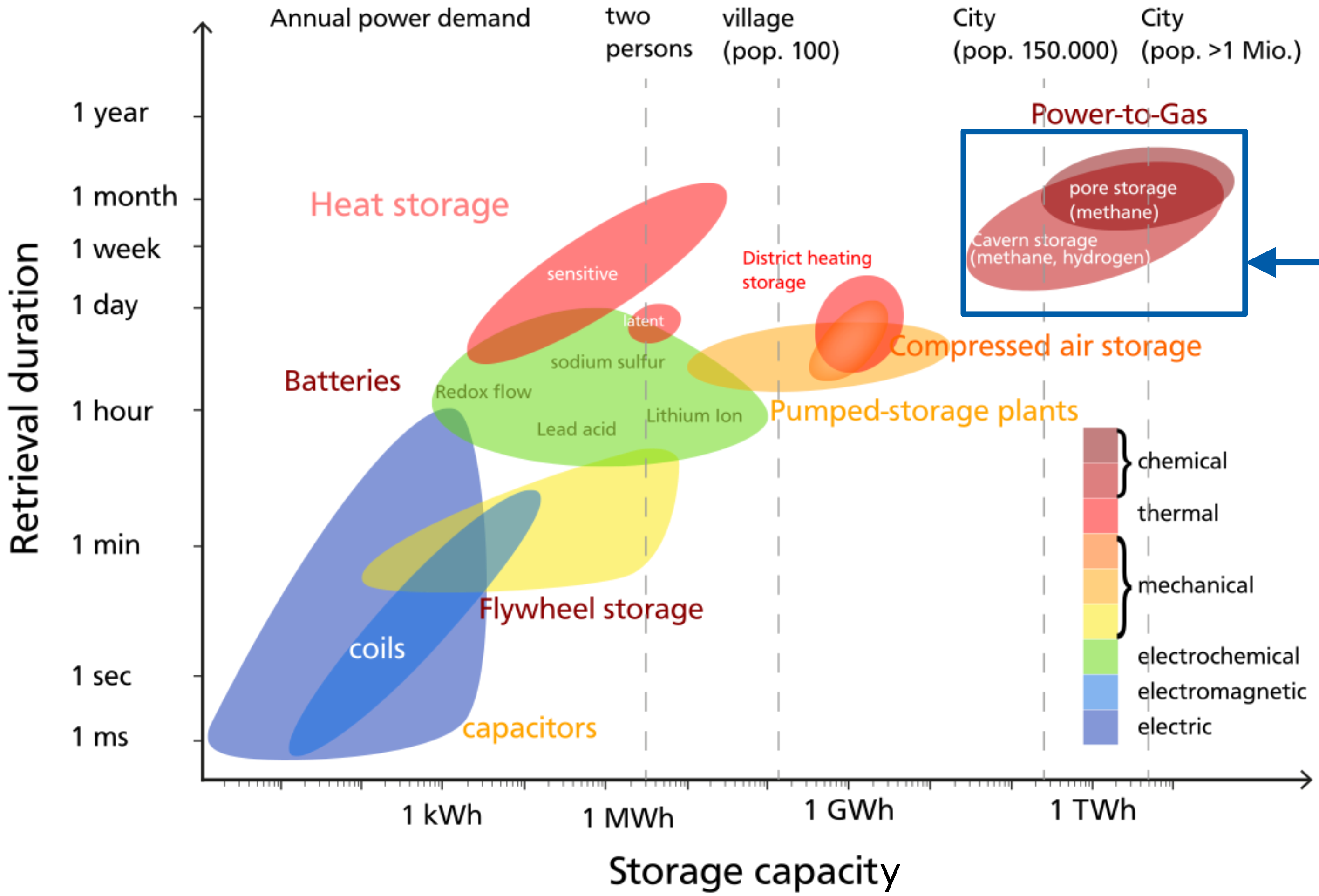

CHEMICAL ENERGY CARRIERS

- High storage capacity
- High duration of retrieval

Dreizler, A. et al., *Applications in Energy and Combustion Science*, **2021**; adapted from Sterner and Stadler 2014/ 2019 (EN)

CHEMICAL ENERGY CARRIERS

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1 litre bottles

*depending on origin: 0.7–0.9 kg, 1.9–5.0 kWh

**depending on origin: 1.2–1.6 kg, 8.3–15.8 kWh

CHEMICAL ENERGY CARRIERS

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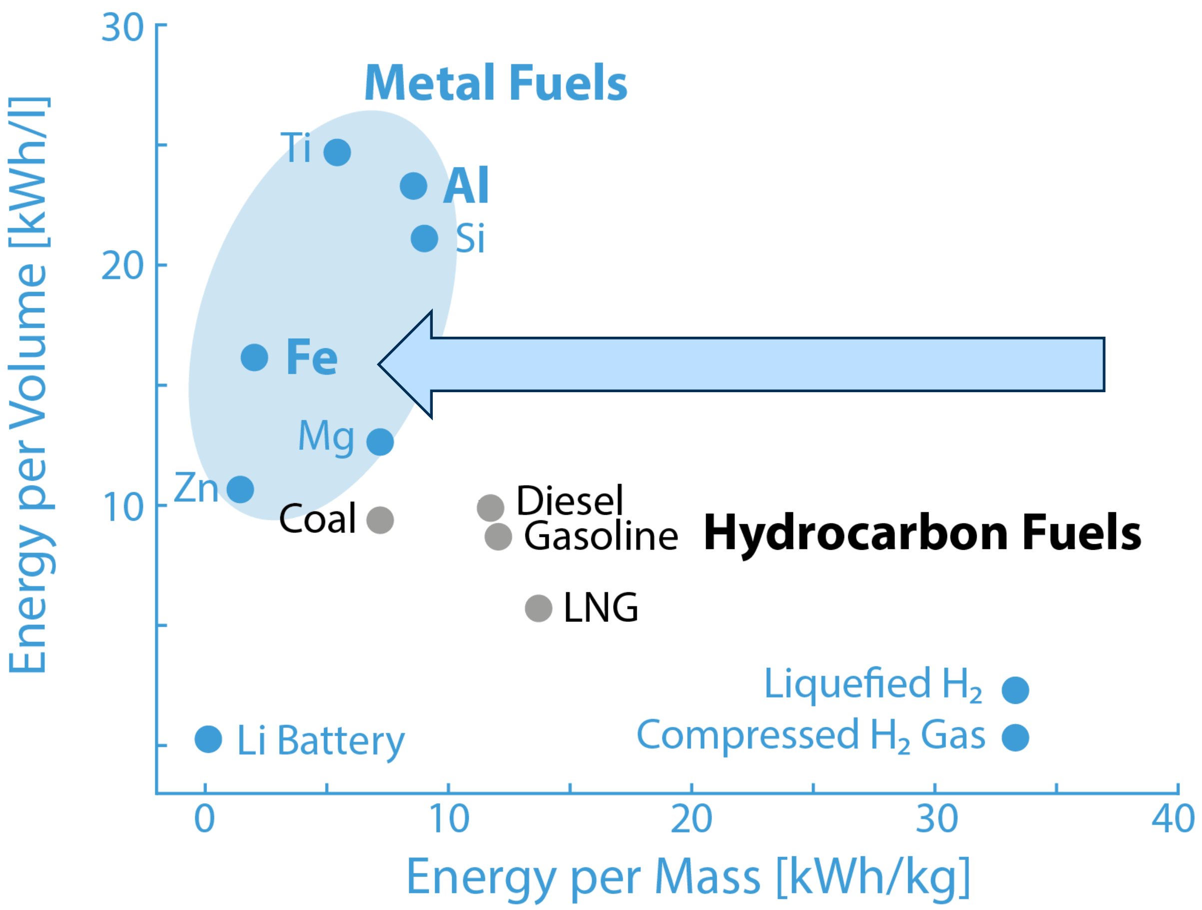

IRON

- High specific energy
- Controlled conversion with air and water
- Non-toxic
- Not a critical resource
- Highly available and mineable
- Scalable into the TWh range

CIRCULAR ENERGY STORAGE

- Energy storage must be able to be charged and discharged like a battery.
- No consumption, 100% recycling
- Discharge: CO_2-free oxidation
- Charging: CO_2-free chemical reduction

Debiagi, P., Rocha, R.C., Scholtissek, A., Janicka, J., Hasse, C. 2022: *Iron as a sustainable chemical carrier of renewable energy: Analysis of opportunities and challenges for retrofitting coal-fired power plants*, Renewable and Sustainable Energy Reviews, 165:112579

CO_2-FREE – CIRCULAR ECONOMY

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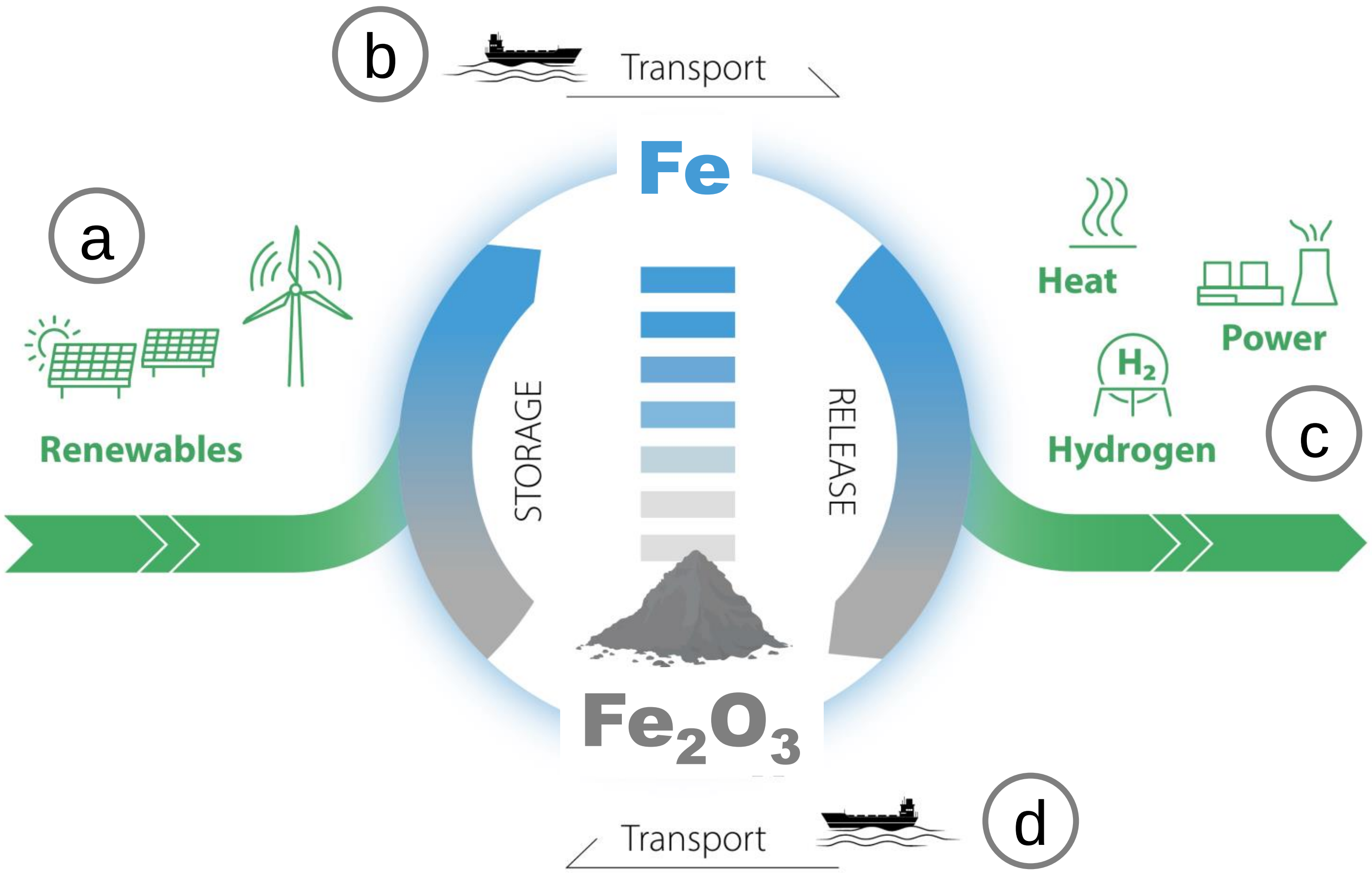


CO_2-free circular economy:

a. **Charging**
   Renewable energy is stored by reducing iron oxide (Fe_2O_3) to iron (Fe).

b. **Storage**/ Transport
   The high-energy iron is transported to its destination.

c. **Release**
   The energy is released as required through oxidation for the generation of electricity, heat and H_2.

d. **Recycling**
   The product is solid iron oxide, which is transported back for recycling, i.e. reduction.

1. REDUCTION

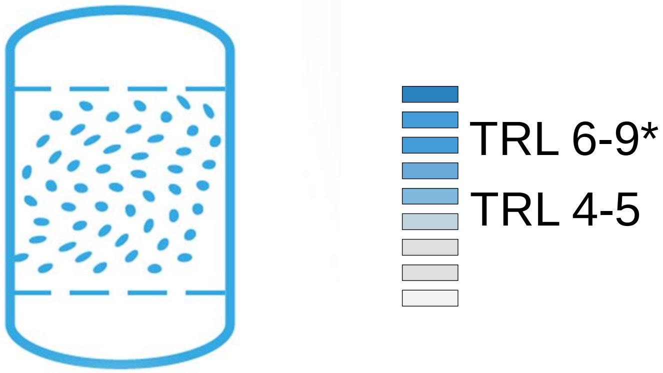
THERMOCHEMICAL REDUCTION

- Reduction with green hydrogen (from electrolysis)
- In flow and fluidized bed reactors

→ H_2 is recycled locally, no export of H_2/water

→ Synergies with green steel production

$Fe_2O_3 + 3H_2 \rightarrow 2Fe + 3H_2O$



ELECTROCHEMICAL REDUCTION

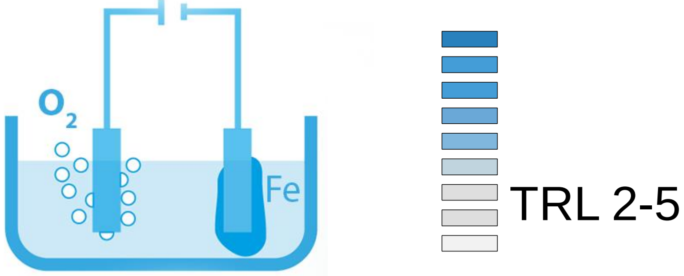
- Dissolved iron oxides
- Direct reduction through electrolysis

→ Using electricity from renewable sources

→ Possibly higher efficiency

→ „Higher risk, high gain“

$2Fe_2O_3 + 6e^- \rightarrow 4Fe + 3O_2 + 6e^-$



*Technology in commercial use for non-“Iron Power“ applications.
Roland Berger: *Iron Power* 09.2023

2. TRANSPORT

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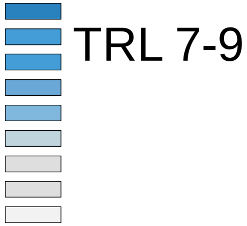
MARINE AND RAIL TRANSPORT

- Established transport technologies for bulk metal powders

- Safety guidelines for reduced iron exist
  - Intertization in N_2-atmosphere
  - Thin nitride passivation layers with NH_3 [1]

→ Further research on safety and standardization ongoing



*Pilotship *Suiso Frontier*, performance will increase

[1] Ma, Y., Bae, J. W., Kim, S.-H., Jovičević-Klug, M., Li, K., Vogel, D., Ponge, D., Rohwerder, M., Gault, B., Raabe, D., *Reducing Iron Oxide with Ammonia: A Sustainable Path to Green Steel*. Adv. Sci. 2023, 10, 2300111. https://doi.org/10.1002/advs.202300111

3. OXIDATION – DRY-CYCLE

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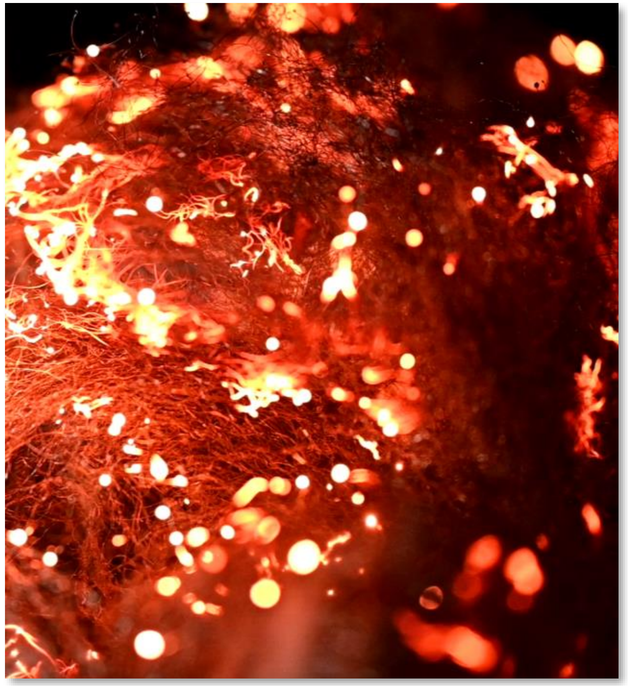
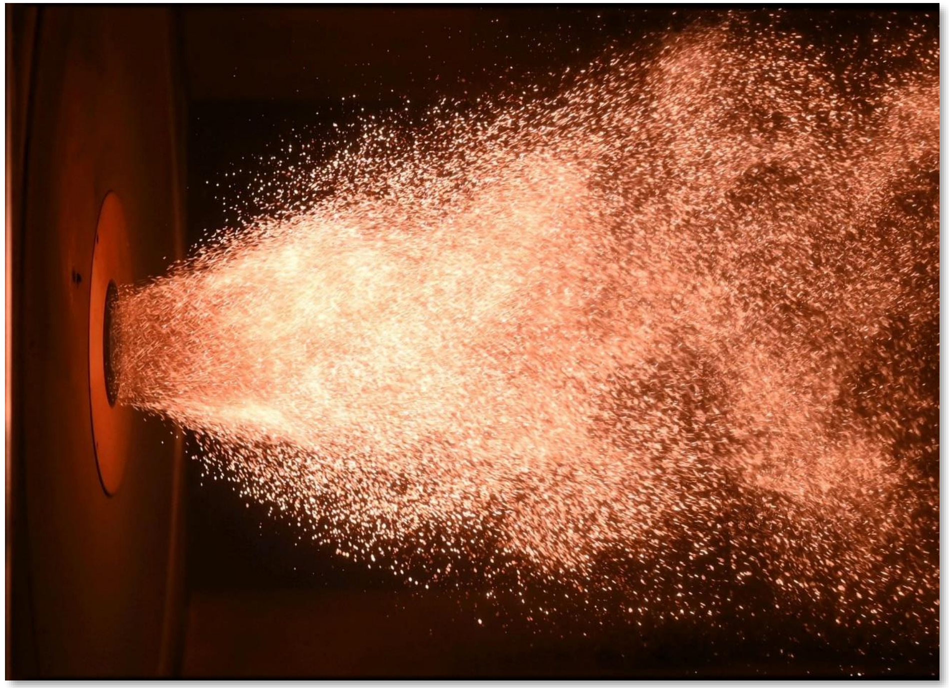
IRON BURNS – CO_2 FREE!





YouTube

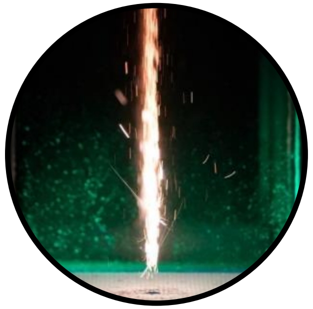
3. OXIDATION – DRY-CYCLE

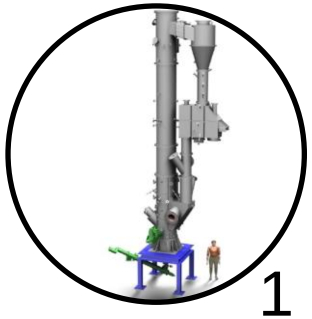
Clean Circles

IRON BURNS – CO_2 FREE!

$4Fe + 3O_2 \rightarrow 2Fe_2O_3$ + Heat

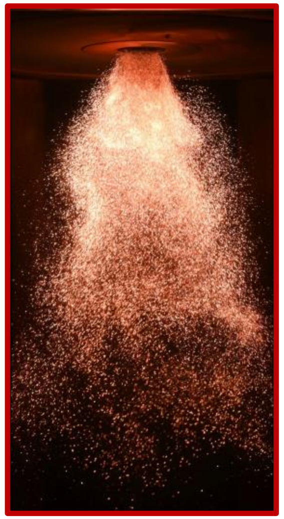
- Iron powder < 50 µm
- Stored energy released by turbulent dust flame
- Powers high-temperature processes or steam turbine for electricity generation





1 MW_{th}

Particle flames | **Laminar flames** | **Turbulent flames** | **Semi-industrial**



TRL 6-9*

TRL 4-5

*Technology in commercial use for non-“Iron Power“ applications. Roland Berger: *Iron Power* 09.2023

3. OXIDATION – WET-CYCLE

- Low- and high-temperature oxidation of metals in water/steam

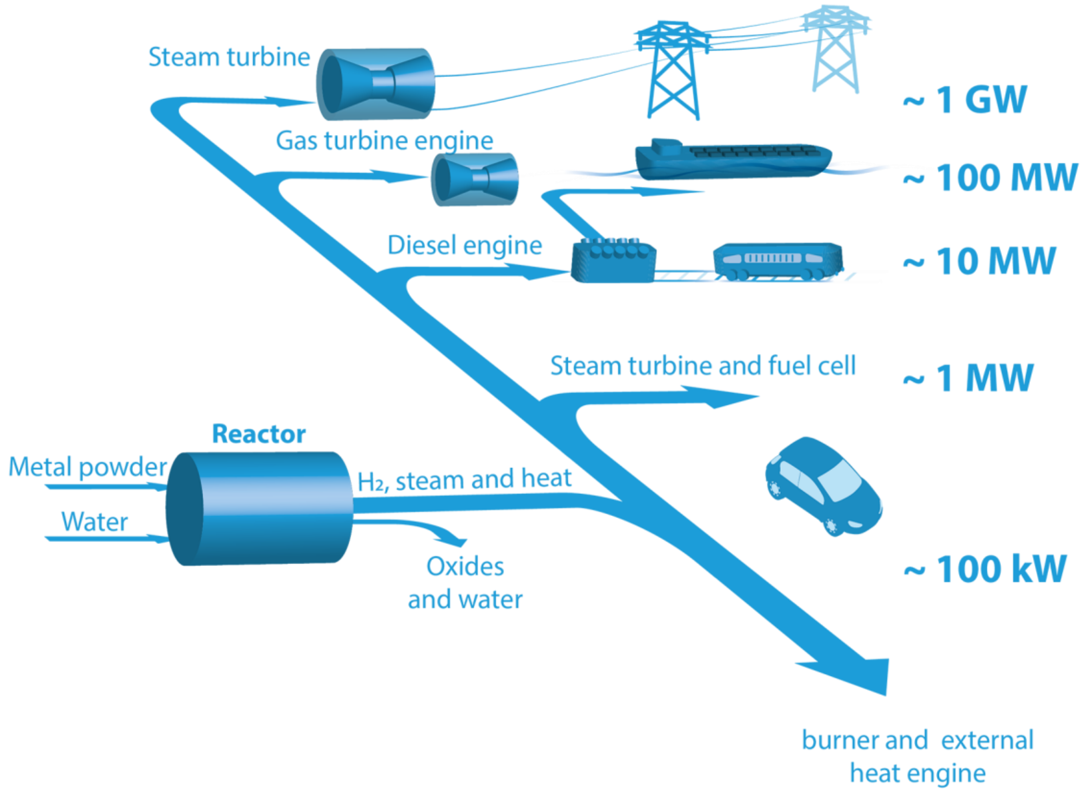
- Potential for high efficiencies: production of heat and H_2

$$Me + H_2O \rightarrow MeO_x + H_2 + heat$$

- Suitable metals: *Al, Mg, Si, Fe*

TRL 2-3

$$3Fe + 4H_2O \rightarrow Fe_3O_4 + 4H_2 + heat$$

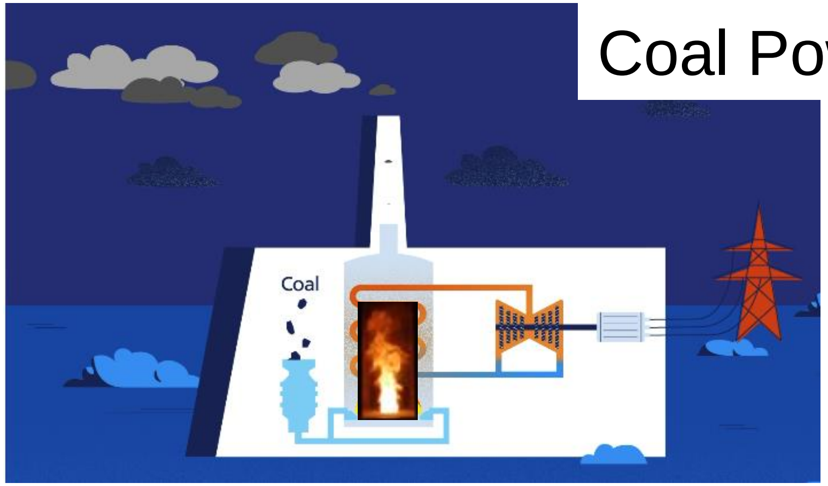


adapted from Bergthorson PECS 2018

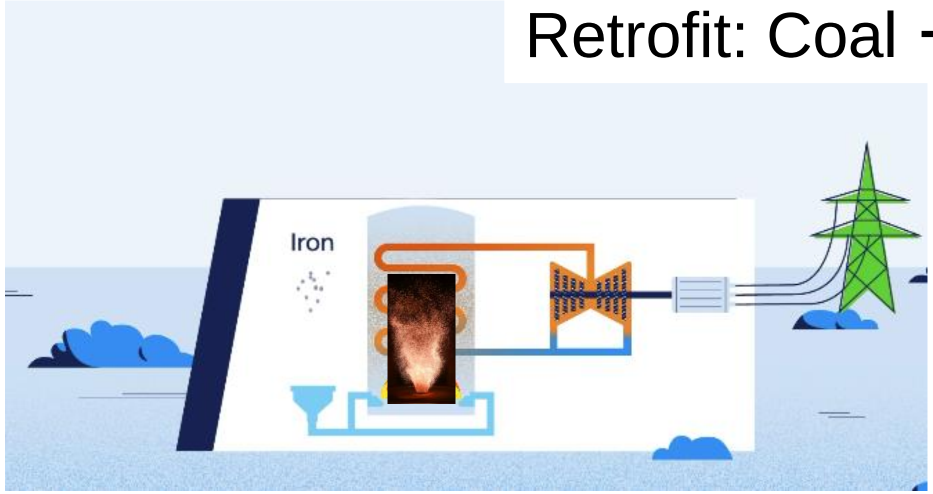
CLIMATE-NEUTRAL RETROFITTING

CO_2-free power plants for the base load after the coal phase-out

Coal Power Plant



Retrofit: Coal → Iron



- Continued use of existing power plants and transportation infrastructure is possible.
- Iron can be burned in turbulent dust flames.
- Adaptations for fuel supply, boiler and exhaust gas cleaning/dust removal are necessary.
- Steam generators and turbines can continue to be used.
- Thermal efficiencies are comparable to coal – with higher potential for optimization.

J. Janicka , P. Debiagi, A. Scholtissek, A. Dreizler, B. Epple, R. Pawellek, A. Maltsev, C. Hasse: *The potential of retrofitting existing coal power plants: A case study for operation with green iron*, Applied Energy 339 (2023) 120950

RETROFIT DETAILS

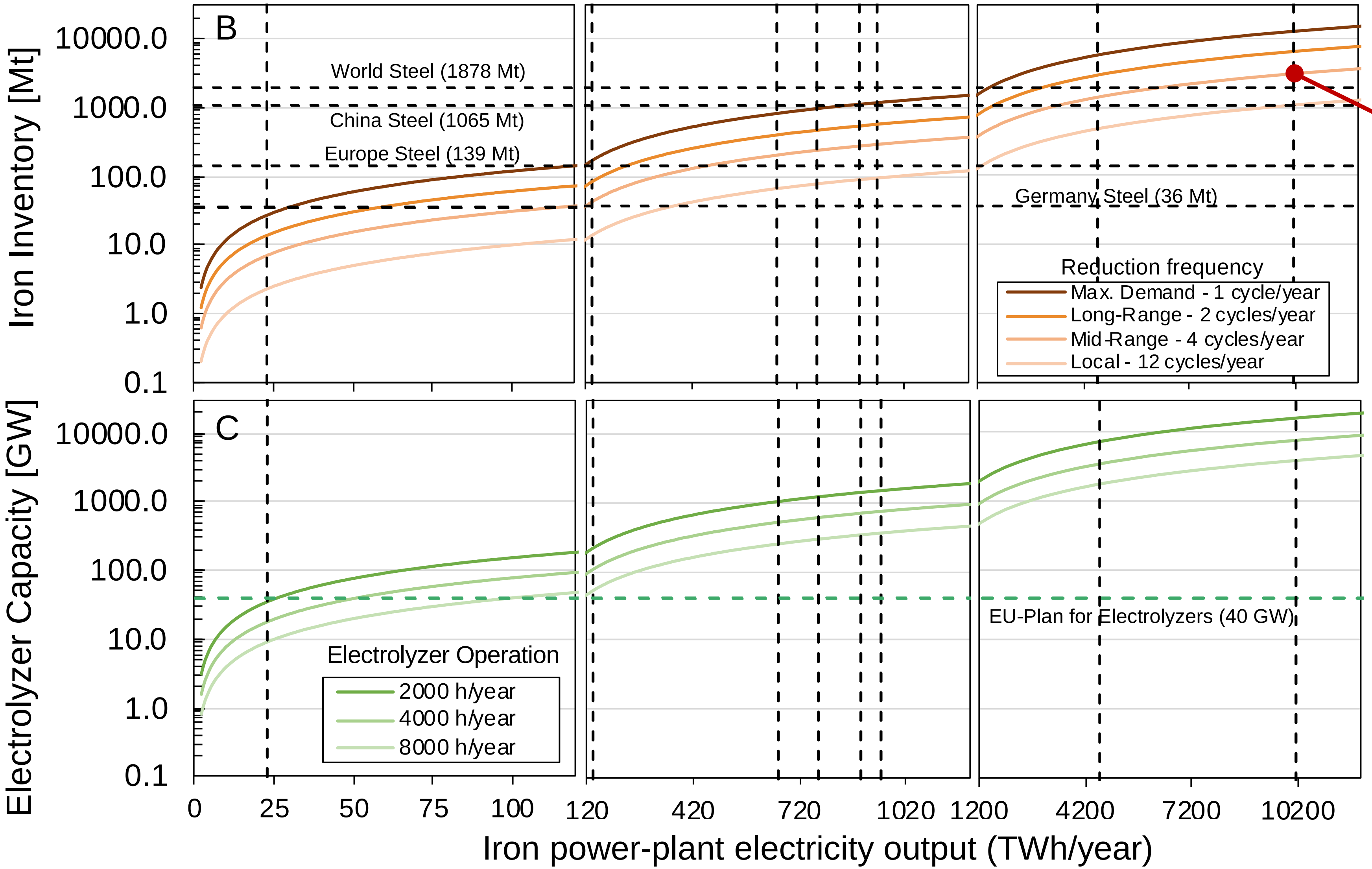
Component reusability:
Our analysis demonstrates the feasibility of reusing major components like the steam generator and steam cycle with moderate modifications. However, certain elements, such as the fuel feeding system, burners, and dedusting system, necessitate redesign.

Efficiency gains: The retrofitted power plant showcases an efficiency improvement of approximately 1–2% when compared to its coal-fired counterpart. This enhancement is primarily attributed to reduced internal energy consumption from auxiliary systems. We have eliminated the need for equipment like mills and desulphurisation systems, and the possibility of omitting the denitrification system exists. Additionally, we have achieved significantly higher heat transfer coefficients due to enhanced thermal radiation of the particles. As a result, exhaust gas temperatures decrease, leading to increased boiler efficiency.

Overcoming limitations: Our design modifications enable us to circumvent previous constraints, such as addressing sulfur-related dew point undershoots in the flue gas segment and adhering to maximum temperatures at the mills in the air segment. Consequently, we can consider higher air preheating temperatures, contributing to the plant's overall efficiency.

J. Janicka , P. Debiagi, A. Scholtissek, A. Dreizler, B. Epple, R. Pawellek, A. Maltsev, C. Hasse: *The potential of retrofitting existing coal power plants: A case study for operation with green iron*, Applied Energy 339 (2023) 120950 https://doi.org/10.1016/j.rser.2022.112579

HOW MUCH IRON DO WE NEED?



Worldwide retrofit of all coal power plants:

- ~2.5 Gt iron inventory needed (4 cycles/year)

P. Debiagi, R. C. Rocha, A. Scholtissek, J. Janicka, and C. Hasse, “Iron as a sustainable chemical carrier of renewable energy: Analysis of opportunities and challenges for retrofitting coal-fired power plants,” *Renewable and Sustainable Energy Reviews*, vol. 165, p. 112579, Sep. 2022, [10.1016/j.rser.2022.112579](https://doi.org/10.1016/j.rser.2022.112579).

WE MINE ENOUGH IRON

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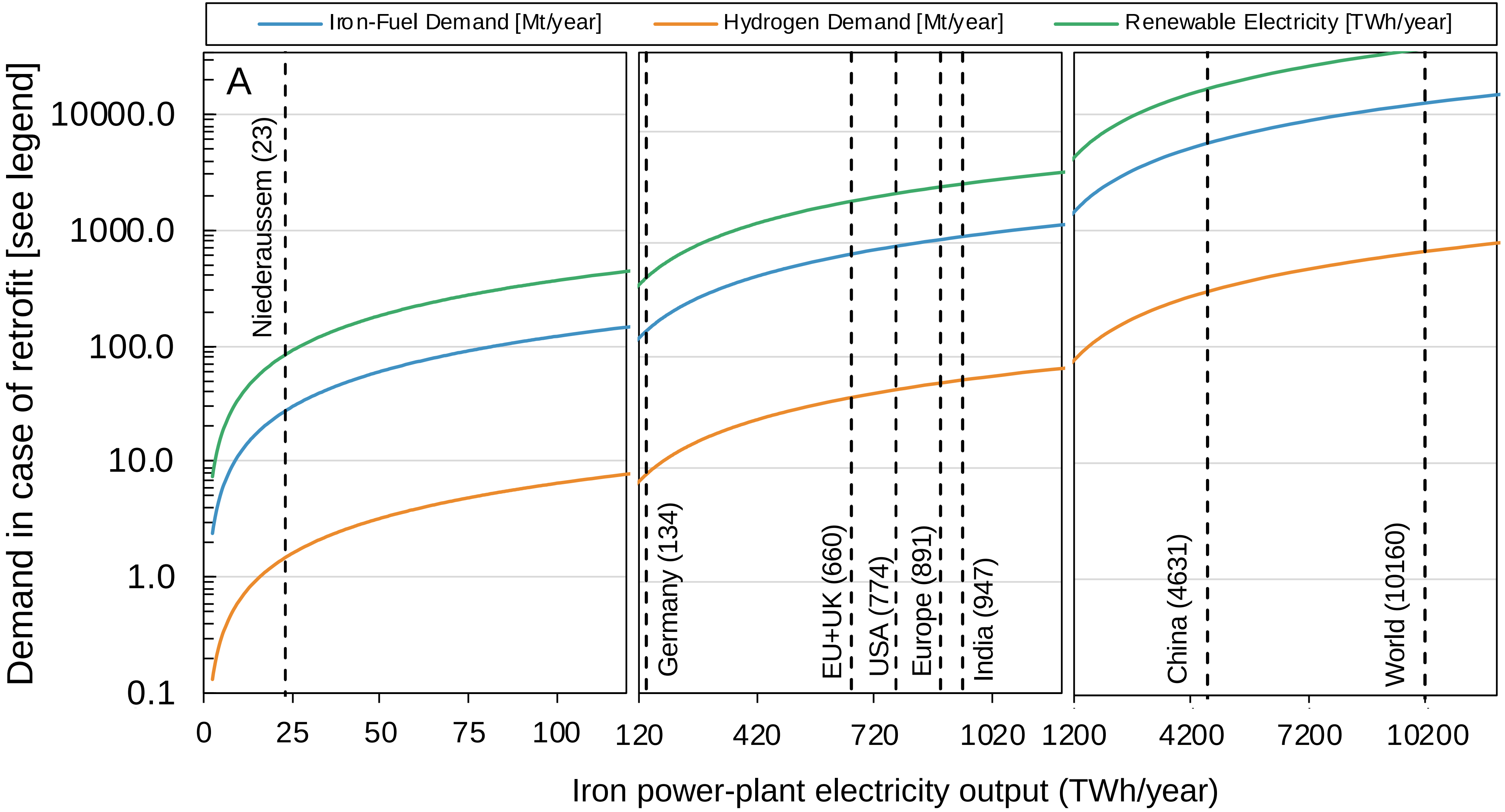
Calculating the iron demand for a worldwide retrofit of coal power plants

- ~2.5 Gt iron inventory needed (4 cycles/year)
- 20 year transition period
- Iron production capacity increase by +5-6 % (and then constant level) required

https://www.visualcapitalist.com/wp-content/uploads/2022/10/all-the-metals-mined-2021-full.html

DEMAND FOR HYDROGEN, RENEWABLES, AND IRON IN AN IRON ENERGY SYSTEM

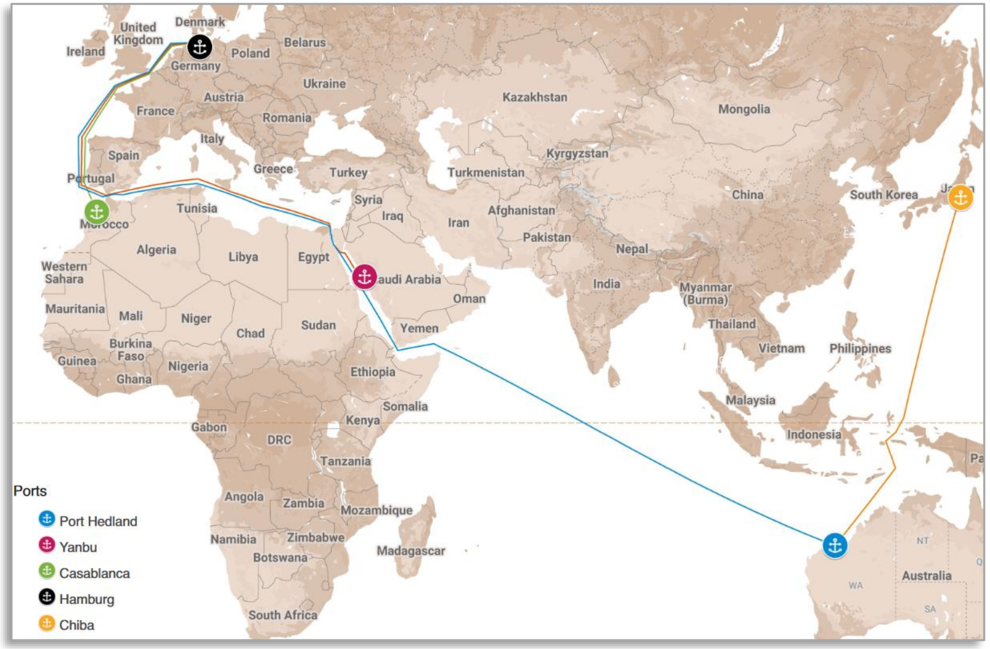
Clean Circles

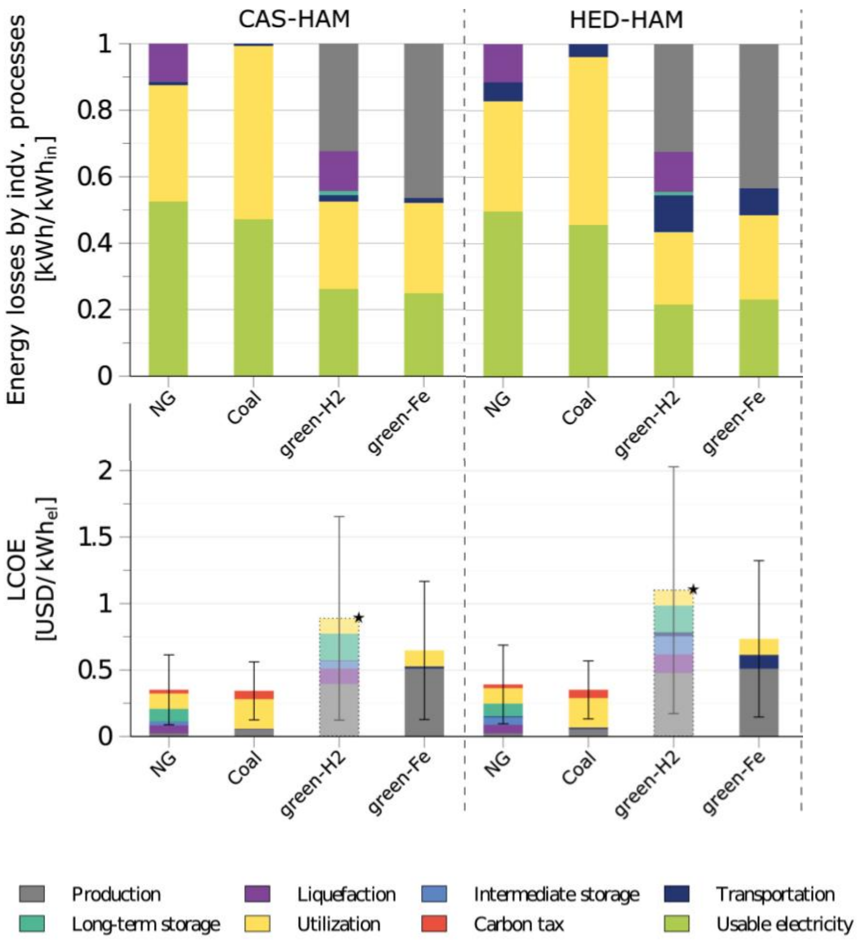


P. Debiagi, R. C. Rocha, A. Scholtissek, J. Janicka, and C. Hasse, "Iron as a sustainable chemical carrier of renewable energy: Analysis of opportunities and challenges for retrofitting coal-fired power plants," *Renewable and Sustainable Energy Reviews*, vol. 165, p. 112579, Sep. 2022, 10.1016/j.rser.2022.112579.

EFFICIENCIES & COSTS

Clean Circles





REACTIVE METALS COMPLEMENT H_2

- Better for long-term storage
- Better for long-distance transport
- Retrofit and reuse of existing infrastructure for base load provision

HIGHER UNCERTAINTIES FOR H_2

- Technology less mature
- Well suited for transportation by pipeline

Neumann, Rocha, Debiagi, Scholtissek, Dammel, Stephan, Hasse:
Applications in Energy and Combustion Science 14 (2023) 100128

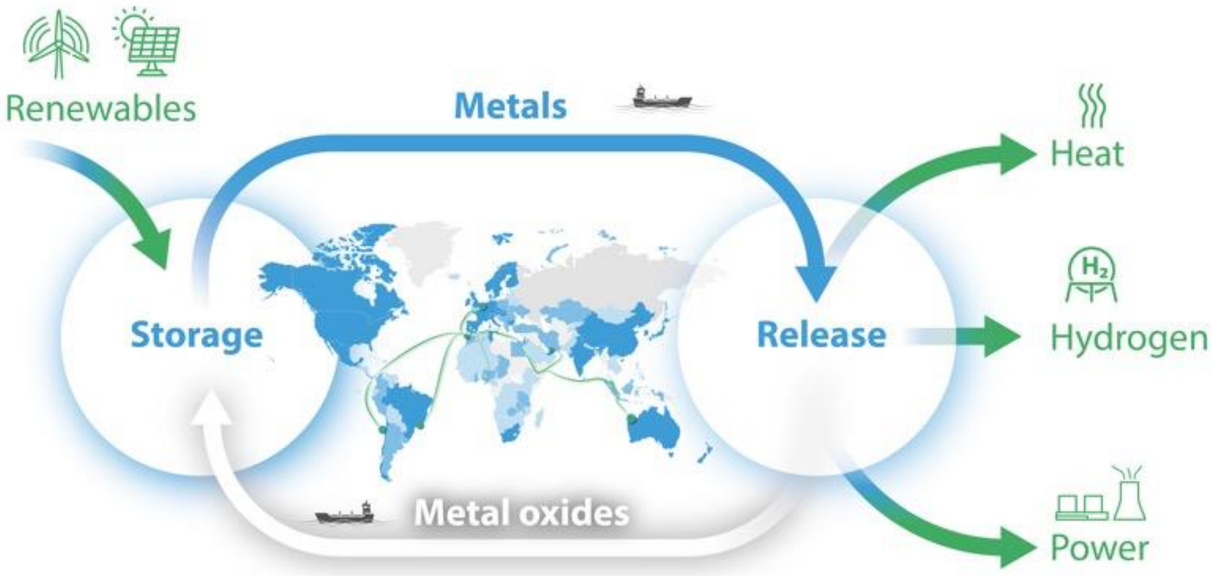
DEMANDS IN A CIRCULAR ECONOMY

Constructing the iron cycle is challenging, but possible

Retrofit example:

- Niederaußem coal power plant: 3.6 GW | 23 TWh/a
- H_2 demand: 1.5 Mt/a
- Electrolyzer capacity: 17.9 GW
- Renewable energy demand: 71.6 TWh/a

EU 2030 target: 100GW

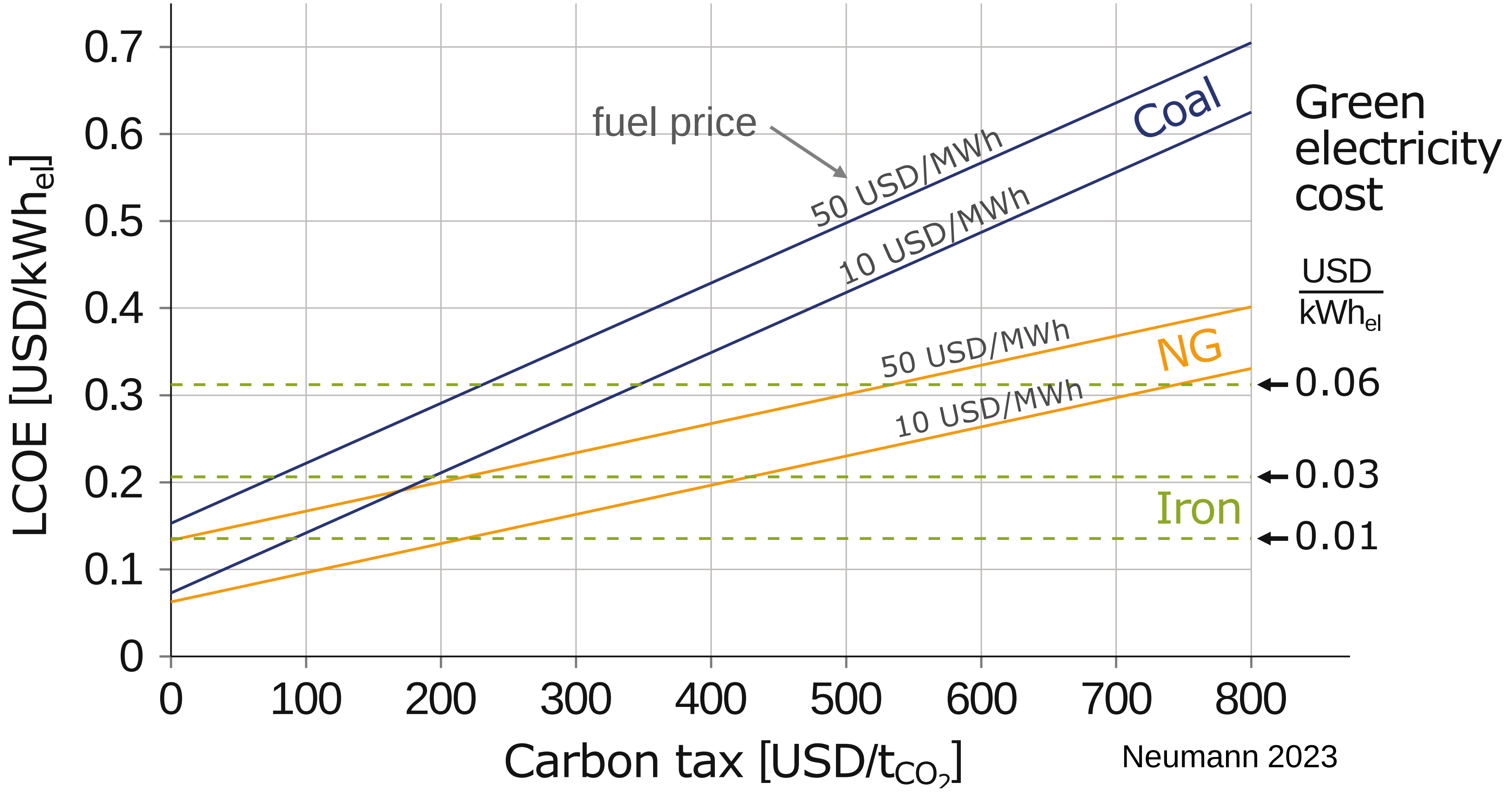


Transport is not a barrier

- Transporting iron from Morocco to central Europe requires ~3% of its stored energy
- Iron can be cost-competitive with H_2
  → higher production costs and energy requirements are overcompensated by favorable storage, transport, and retrofit potentials.

INFLUENCE OF CO_2-PRICES

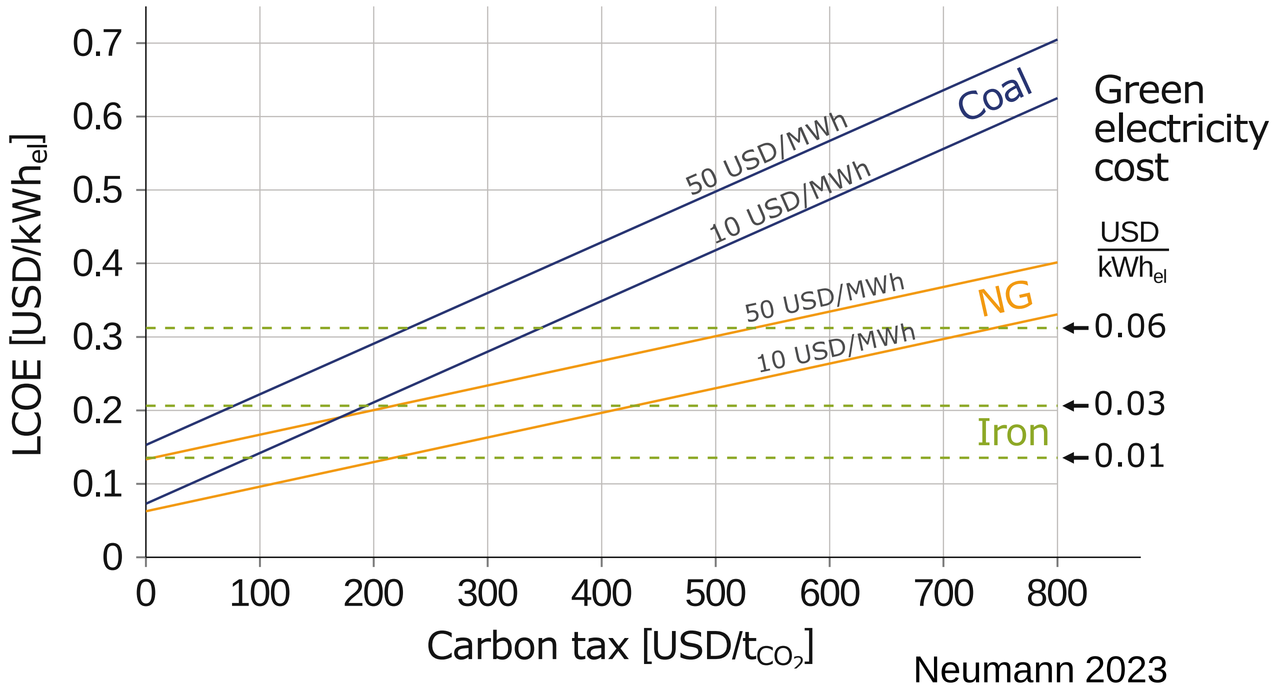
Clean Circles



Assumptions:

- Evaluated for 8000 km transport distance
- Fully developed, mature iron energy technology assumed
- Current price of coal and natural gas: 15-20 USD/MWh

INFLUENCE OF CO_2-PRICES



Neumann 2023

CONCLUSION

1. Cost of renewable energy is crucial
2. At very competitive prices (0.01 USD/kWh, e.g. Saudi Arabia), iron gains the advantage compared to coal at ~100 USD/t_{CO2}
3. At moderate prices (0.03 USD/kWh_{el}), at ~200 USD/t_{CO2}
4. Competitiveness compared to Natural Gas requires a doubled CO_2-price, respectively.

FURTHER REFERENCES

clean-circles.de - Circular Economy

Debiagi et al. *Iron as a sustainable chemical carrier of renewable energy: Analysis of opportunities and challenges for retrofitting coal-fired power plants*, 2022.

→ **Analysis of the (global) retrofit and key demands**

Neumann et al. Techno-economic assessment of long-distance supply chains of energy carriers: Comparing hydrogen and iron for carbon-free electricity generation, 2023

→ **Comparison and analysis of transport and levelized cost of electricity**

Janicka et al. The potential of retrofitting existing coal power plants: A case study for operation with green iron, 2023

→ **Detailed analysis of an exemplary retrofit of an 800 MW coal power plant**

SUMMARY – IRON AS ENERGY CARRIER

ADVANTAGES

- Long-term storage and transport of energy
- Ease of storage and transport
- High-temperature heat provider (up to >1500°C)
- No direct CO_2, low/no NO_x and SO_x emissions
- Use of existing infrastructure (retrofit)
- Competitive efficiencies
- Additional process coupling possible (Wet Cycle: hydrogen + heat production)
- No export of water (H atoms) from arid regions required
- Non-toxic, no environmental hazard

DISADVANTAGES

- (H_2) elektrolyzer capacity is the main bottleneck for the green thermochemical reduction
- Global energy economy with an international network of partners needed

OPEN RESEARCH QUESTIONS

- Combustion design and implementation in power plants
- Influences on cyclability of iron
- Realization of electrochemical reduction
- Safety concerns along the cycle at industrial scales (explosiveness, nanoparticle production)
- Policy advice: best practise & consulting

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Clean Circles

Funded by the Hessian Ministry of Science and Art (HMWK), the Karlsruhe Institute of Technology (KIT), and the Deutsche Zentrum für Luft- und Raumfahrt (DLR)

- Total funding volume EUR 15 million
- 4 years duration 04/2021-03/2025
- 30 subprojects & PIs
- 60 PhD candidates & PostDocs
- 7 locations & institutions

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FUTURE FUNDING

- Public funded project for *semi-technical demonstration* (1 MW thermal)
  - Potential support by Hessisches Ministerium für Wirtschaft, Energie, Verkehr und Wohnen (HMWEVW), Bundesministerium für Wirtschaft und Klimaschutz (BMWK) and Projektträger Jülich (PtJ)
  - Additionally searching for industrial partners and expertise
  - Funding requirement: about EUR 5 Mio.

CLEAN CIRCLES: NEXT STEPS

Clean Circles

TOWARDS THE APPLICATION

until 2027
1 MW Demonstrator

until 2031
> 10 MW Demonstrator

until 2035
Retrofit of coal power-plant

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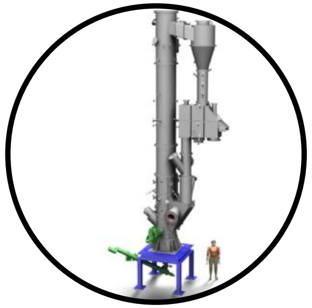
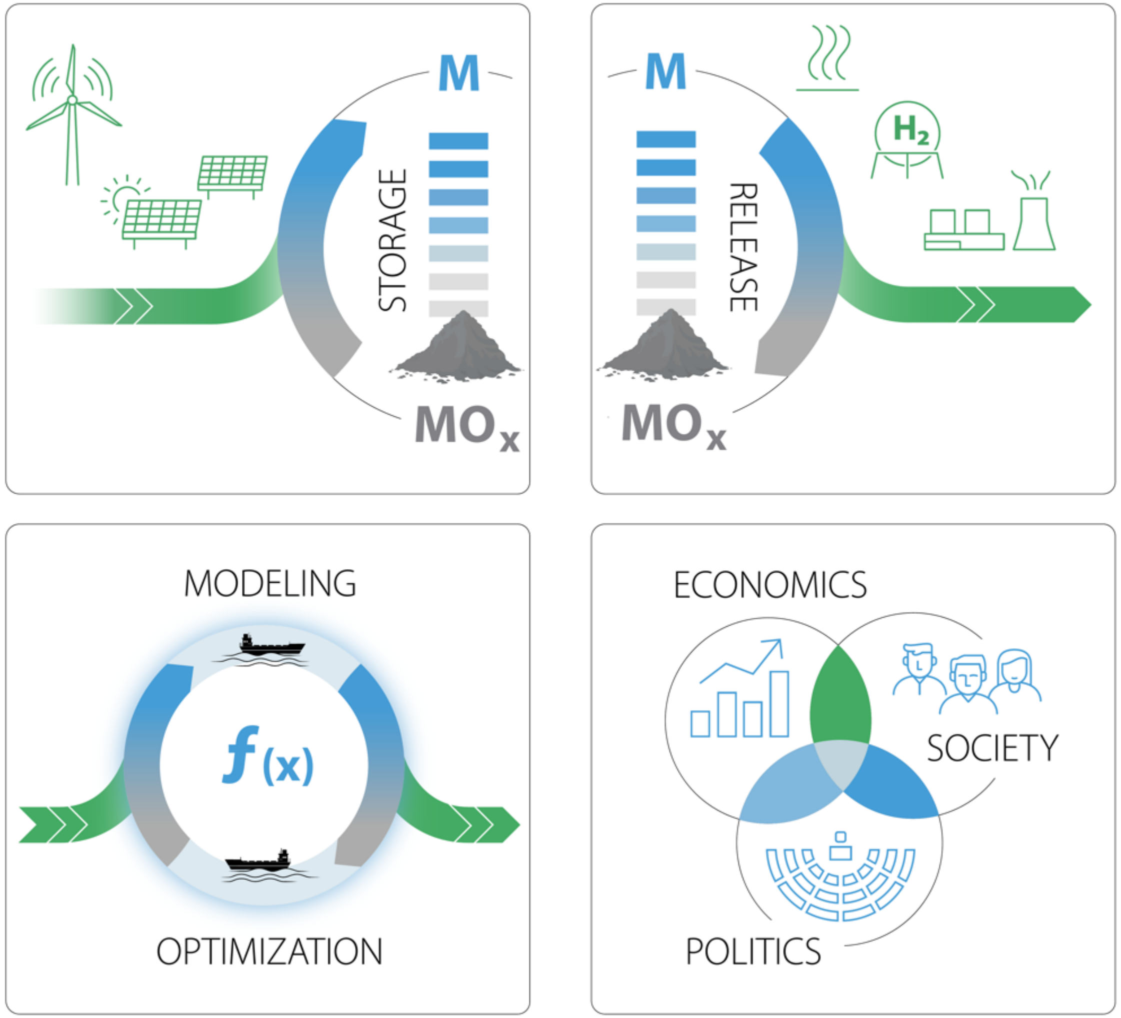


→ Speed of transformation strongly influenced by industrial and political interest (see National Hydrogen Strategy)
→ In parallel: Basic research, for the increasingly knowledge-based design of iron-fired power plants

INTERDISCLINARY APPROACH

FOUR RESEARCH AREAS

1. Reduction processes
2. Oxidation processes
3. Thermodynamic-mathematical and techno-economic modeling
4. Governance and socio-economic modeling



GLOBAL ACTIVITIES

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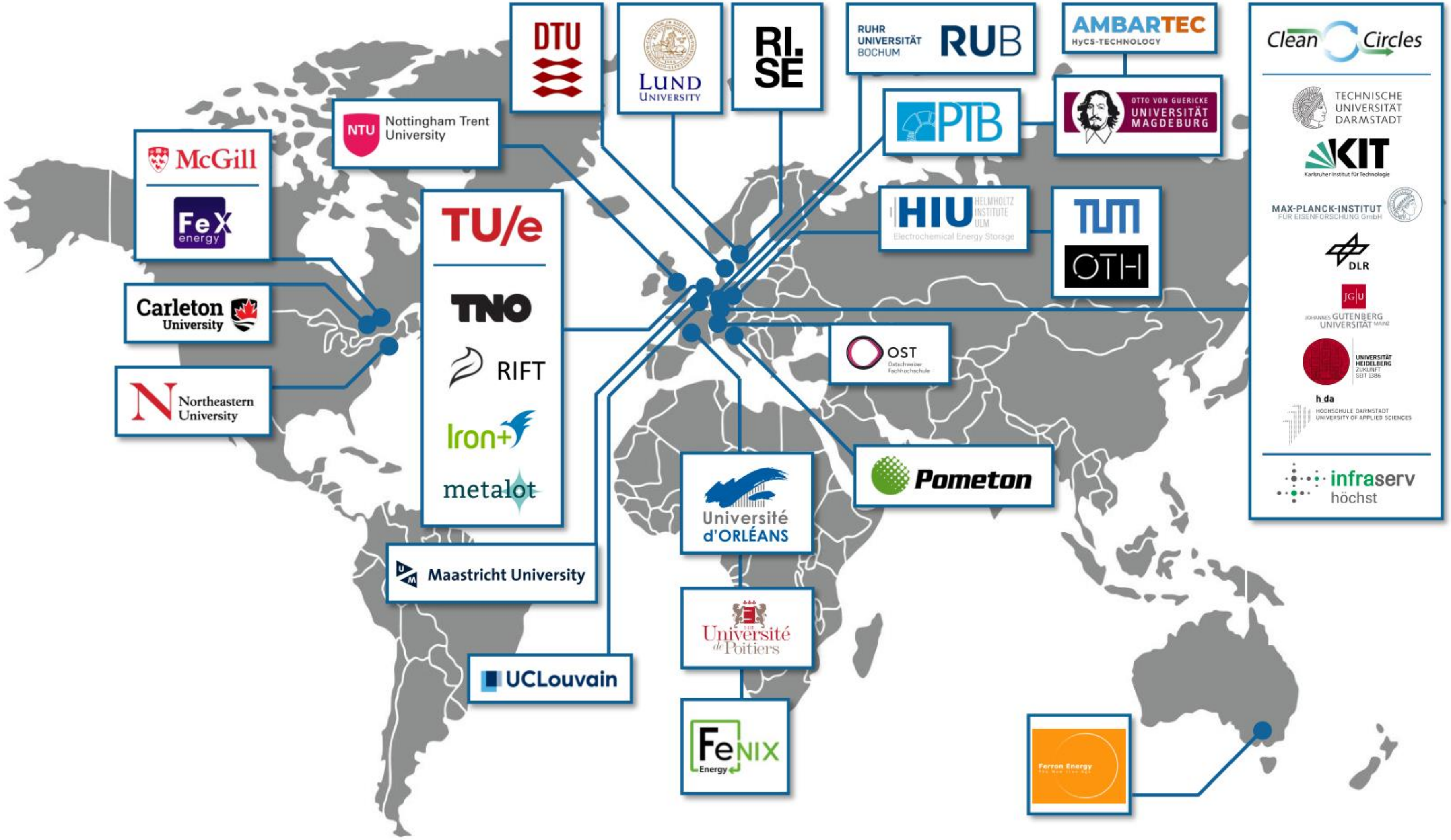

NEXT STEPS – TU/e, NETHERLANDS

metalot

2020

Lighthouse MP

Swinkels

0.1 MW

2023

OPZuid MP

LaTrappe

1.0 MW

2024

MF & City Plants

Uniper

5 MW

2028

MF International

Uniper & Swinkels

5+5 MW

>2030

MF on large scales

Industry & Energy

10-2000 MW

CLEAN CIRCLES IN THE MEDIA

- Handelsblatt 14.05.2024 - Eisen statt Kohle - So lässt sich in Zukunft Energie speichern (DE)
- Niklas Kolorz 31.03.2024 - Energy storage of the future: Is iron the new coal? (EN CC)
- Breaking Lab 15.02.2024 - Energy storage revolution: chemical storage with iron (EN CC)
- hr “alles Wissen” 30.11.2023 – Climate and energy: storing electricity in iron (EN CC)
- hr “alle Wetter!” 04.10.2023 – Clean Circles (DE)
- Durchblick N – Magazin für Nachhaltigkeit 06/2023 (DE)
- FAZ 04.04.2023 – Eisen statt Kohle verbrennen? (DE)
- ZDFheute “Good News” 02.03.2023 – CO2-freies Bier dank Rost (DE)
- FAZ 29.11.2022 – Heißes Eisen für das Klima (DE)

Excerpt International

- TU/e, metalot & Roland Berger 05.07.2024 – Vision Document *Iron Power* (EN)
- IEEE Spectrum 22.06.2023 – Iron Fuel Shows Its Mettle (TU/e) (EN)

Homepage

Transfer & Outreach

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