Proposal for the Inclusion of Metal Energy Carrier Technologies in the Net-Zero Industry Act[1]

Relevance of Metal Energy Carriers for the Net-Zero Industry Act

Metal energy carriers (e.g., iron or aluminum) represent a complementary solution for large-scale renewable energy storage and transport, directly aligning with the SET Plan and Net-Zero Industry Act objectives. These carbon-free carriers enable:

- On-demand production of heat, power and hydrogen through oxidation and reduction processes.
- Efficient storage of intermittent renewable energy, supporting grid stability and energy security.
- Decarbonized industrial heat applications in sectors like steel and cement production, and also food processing, paper.
- A circular energy system, as metal energy carriers can be infinitely recycled without degradation, reducing reliance on raw material extraction.

As complementary solutions to hydrogen, metal energy carriers enhance system resilience by diversifying energy storage, transport options and enabling retrofitting of existing combustion infrastructure. Their inclusion in the Act is vital to accelerate commercialization and preserve Europe's competitive edge in this emerging field, where EU companies and institutions currently lead.

European Ecosystem

Europe's leadership in metal energy carriers is underpinned by a robust network of stakeholders, among them:

Technology Developers

- Startups: Ambartec (DE), apricot366 (CH), Fenix Energy (FR), HyIron (DE), Iron+ (NL), IronEnergy (CH), nacompex (DE), RIFT (NL), Swiss Nanomaterials (CH)
- Industrial Stakeholders:
  - Manufacturing: Doosan Lentjes (DE), Hans Henning (DE), SPIE (NL), Steinmüller Engineering (DE), TS Elino (DE)
  - Steel sector: ArcelorMittal (LU), TATA STEEL (NL)
  - Cement sector: Holcim (CH)
  - Feedstock utilities: Höganäs (DE), Pometon (IT)

Energy and Infrastructure Partners

- Utilities: BTB Berlin (DE), Engie (FR), Ennatuurlijk (NL), Uniper (DE)

[1] This proposal was initiated by TU/e, metalot and the project Clean Circles (TU Darmstadt, KIT) and is supported by various stakeholders of the European metal energy carrier ecosystem.

Research Institutions

- Belgium: UCL (Université catholique de Louvain)
- France: UO (Université de Orléans)
- Germany: DLR (German Aerospace Center), KIT (Karlsruhe Institute of Technology), MPI SusMat (Max Planck Institute for Sustainable Materials), PTB (Physikalisch-Technische Bundesanstalt), RUB (Ruhr-University Bochum), TUDa (Technical University of Darmstadt), UDE (University of Duisburg-Essen)
- The Netherlands: ESA (European Space Agency), Metalot, TNO (Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek), TU/e (Eindhoven University of Technology)
- Slovenia: NIC (National Institute of Chemistry)
- Sweden: LU (Lund University), RISE (Research Institutes of Sweden)
- Switzerland: ETH (Swiss Federal Institute of Technology Zurich), OST (Eastern Switzerland University of Applied Sciences)

Supporting Evidence and Market Validation

- EU Projects:
  - EFRE/JTF: HyCS storage power plant
  - Interreg Flanders-Netherlands: MP2H
  - Eurostars 3 - Call 7, #6873: INSPIRE
  - RFCS: CORAL
  - EU Horizon Europe: REVEAL
  - ERC AdvG: MetalFuel
  - ERC PoC: ICONIC
  - ERC AdvG A-STEAM
  - ERC MefiX
- Market Study: *The Potential of Iron Power Technology in the Energy Transition* by Roland Berger highlights iron powder's scalability and cost-effectiveness for decarbonization.
- Technology Portal: Metalot's Knowledge Hub aggregates peer-reviewed research, pilot projects, and industry partnerships, validating metal energy carriers technical and commercial readiness.
- Key Scientific Studies:
  - The peer-reviewed study *The Potential of Retrofitting Existing Coal Power Plants: A Case Study for Operation with Green Iron* demonstrates that converting coal plants to operate on iron powder achieves 1–2% higher net efficiency than coal combustion while reusing the majority of core infrastructure components.
  - The peer-reviewed study on *Recyclable metal fuels for clean and compact zero-carbon power* analyzes the viability of metal fuels (e.g., iron, aluminum) as zero-carbon energy carriers.
  - The peer-reviewed study Techno-Economic Assessment of Long-Distance Supply Chains of Energy Carriers compares hydrogen and iron as carbon-free energy carriers for global trade.
  - Peak Metal - Covering winter peaks of heat and electricity demand by «renewable metal fuels» shows large potential for the use of metal energy carriers in decentralized systems for heat and electricity.
  - The peer-reviewed paper Seasonal energy storage in aluminium for 100 percent solar heat and electricity supply shows that metal fuels may complete solar energy synergistically.

Proposed Classification within the Net-Zero Industry Act Framework

New Category: Metal energy carrier technologies (details see table below)

Alternative Categorization Pathways:

1. Classification under Battery and energy storage technologies
2. Classification under RFNBO (Renewable Fuels of Non-Biological Origin)

	Sub-categories of net-zero technologies	**Final products**	**Primarily used components**
Metal energy carrier technologies	Metal energy carrier oxidation technologies	Metal-powder combustion system	- Metal-powder combustor - Gas injection and recirculation system with swirl generator - Intra-combustor heat exchanger - particulate filtration systems (e.g. cyclones, aerosol filters)
		Metal-steam and -water reaction and in-situ hydrogen generation system	- Metal (powder or pellet)-steam or -water reactor - Steam injection and recirculation system - H_2 separation membrane - Intra-reactor heat exchanger - particulate filtration systems (e.g. cyclones, aerosol filters)
	Metal-oxide reduction technologies	Low-temperature electro-deposition cell	- Electrolyte and electrodes - Metal deposition removal and collection system - By-product gas ventilation and recirculation system
		Intermediate-temperature fluidized-bed H_2-reduction system	- fluidized-bed reactor (e.g. rotating drum) - H_2 separation and recirculation system - Electric heating elements - H_2 burner systems
		High-temperature entrained-flow H_2-reduction system	- Entrain-flow reactor - H_2 separation membrane - H_2 injection and recirculation system - Electric, combustion-assisted system

	Metal energy storage and transport technologies	Metal particle storage	- Atmosphere controlled silos - Transport container
		Metal powder logistics, transshipment and in- and near-plant logistics	- Particulate conveyor belts - Pneumatic conveying systems - Powder conveying and dispersion system