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Renewable Metal: Iron

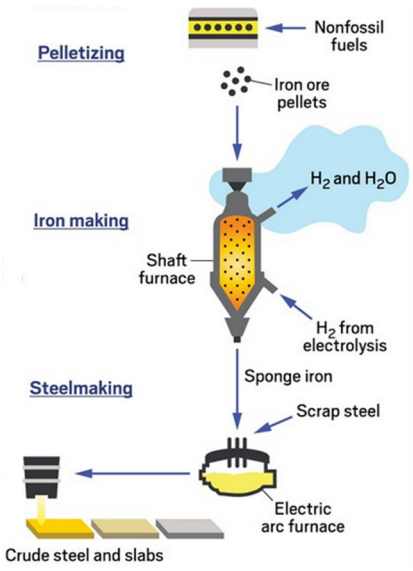
Seasonal energy carrier – Power-to-X technology

The Direct Reduction of Iron via hydrogen (DRI-H2) uses hydrogen to reduce iron oxide pellets at 700–900°C, eliminating CO_2 emissions typical of conventional ironmaking. The feedstock is regenerated iron oxide collected after combustion cycles, formed into uniform pellets via agglomeration and sintering.

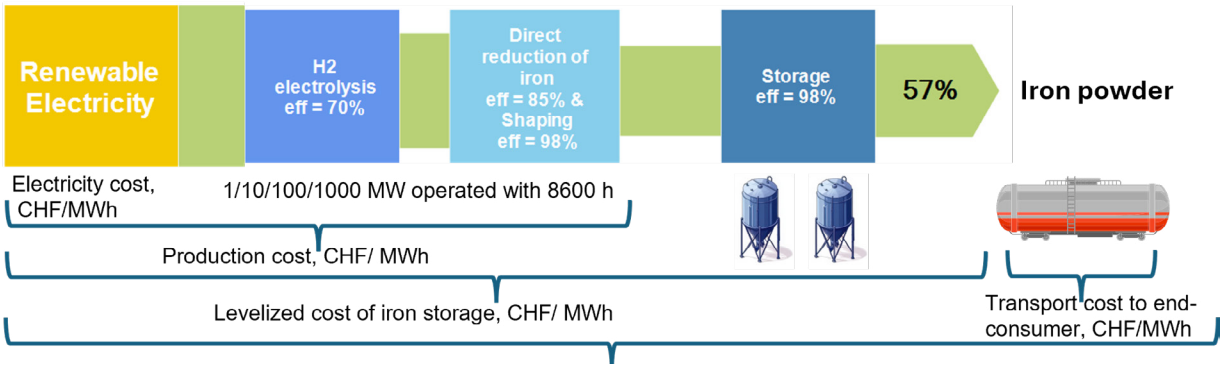
In hydrogen direct reduction, the chemical reaction $Fe_2O_3 + 3\ H_2 \rightarrow 2\ Fe + 3\ H_2O$ occurs within shaft furnaces or fluidised bed reactors, producing metallic iron (sponge iron) and water vapour. The resulting sponge iron retains its pellet shape but becomes porous because oxygen atoms are removed from the iron oxide lattice during reduction, leaving voids and cavities where they were previously located. This porosity (typically 85–95% metallic iron) increases surface area, making sponge iron suitable for further processing into iron powder via grinding or milling for energy storage applications.

Production can be scaled as needed, and by reusing regenerated iron oxide, virgin iron ore extraction is avoided. To produce steel, sponge iron (direct reduced iron, DRI) is melted in an electric arc furnace (EAF) together with scrap steel to form crude steel and steel slabs. The EAF process uses electricity as its primary energy source, meaning no direct CO_2 emissions are generated during melting, unlike traditional blast furnace routes that rely on coal-based reduction. In terms of technology development, hydrogen-based direct reduction is already at an advanced stage, with technology readiness level (TRL) 6–8. Major industrial initiatives, such as HYBRIT in Sweden (SSAB, LKAB, Vattenfall), currently at TRL 7, are demonstrating pilot and demonstration plants, with full industrial deployment expected by 2030 to enable fossil-free iron and steel production.

Considering iron production via hydrogen-based direct reduction, a Power-to-Iron-to-Storage efficiency of approximately 57% can be achieved.



Process steps of steel production with DRI-H_2 to produce sponge iron in the iron-making process step [1].



Availability

Abundance / World reserves	Fourth most abundant element / 85 000 Mio. tonne iron content [1]
Global production of iron in 2024	2500 Mio. tonne [1]
Total cumulative global production	68 831 Mio. tonne [2]
CH production of renewable iron in 2024	-

Chemical properties

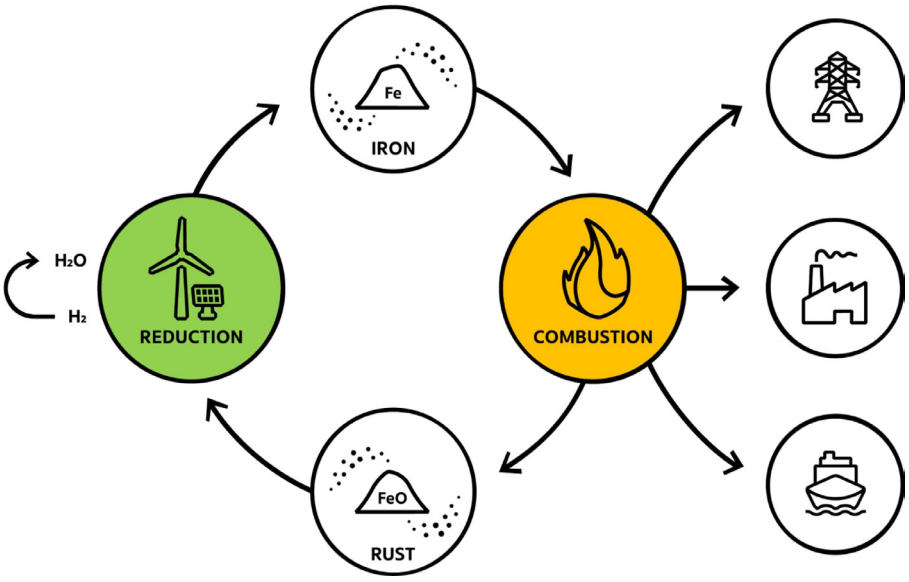
Volumetric bulk energy density	14 900 kWh/m³ for bulk material / ~7000 kWh/m³ for powder [3]
Gravimetric energy density	~2 kWh/kg
Melting point / Boiling point	1538 / 2862 °C
Auto ignition	Varies by form: bulk solid ion is not self-igniting, but fine powder can ignite at 350-500 °C depending on particle size [4]
Flammability in air as bulk	Non-flammable in bulk solid or coarse granules
Flammability in air as powder	Combustible as fine powder (<100 um); dust explosion risk class St1-St2 depending on fineness

Circular economy concept

Iron powder serves as an energy carrier in a circular Power-to-Iron system. Iron oxide undergoes direct reduction using hydrogen generated via electrolysis from renewable electricity, converting electrical energy into chemical energy stored within iron powder without any direct CO_2 emissions.

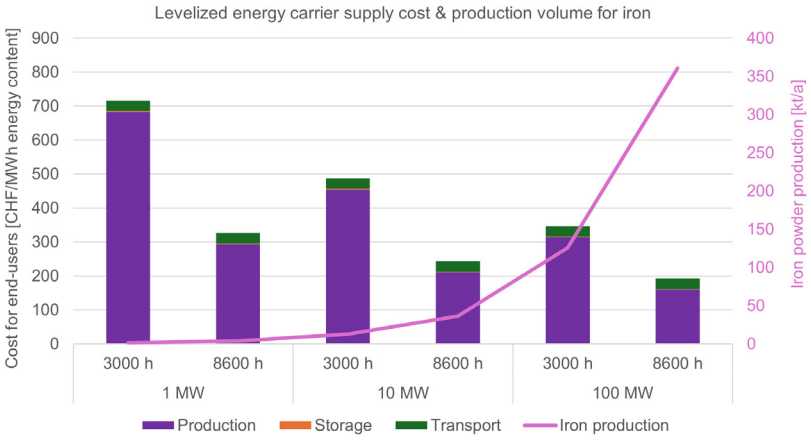
The iron powder provides high volumetric energy density with stable, non-toxic properties for safe transport and storage. Energy release occurs through combustion, producing high-temperature heat for power generation, industrial processes, and district heating. Iron powder can also be applied as a CO_2-free fuel in ships, particularly for short-sea or service vessels, though its high mass requirement limits use to weighttolerant applications. Iron oxide (rust) is the sole byproduct. Additionally, oxidation with water or steam is a current focus of R&D.

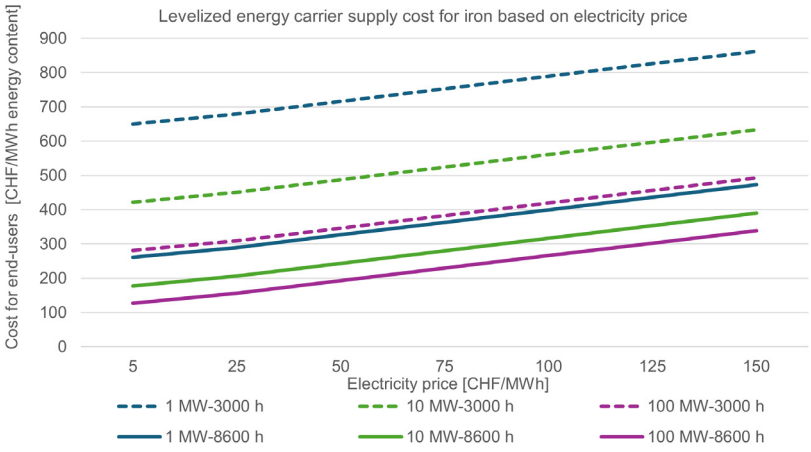
The circular system is completed by collecting the iron oxide and returning it to the Power-to-Iron facility for regeneration. This creates a closed-loop material cycle with complete recyclability. Iron powder's high volumetric energy density exceeds that of ammonia or compressed hydrogen, while offering minimal NOx and particle emissions when combusted, making it a safe, low-cost, and environmentally friendly solution for large-scale, long-term energy storage.



Simplified concept of iron powder ReMeC storage cycle [3].

Cost analysis





The two graphs illustrate iron's cost dynamics as an energy carrier, focusing on levelized supply cost structure and electricity price sensitivity. The upper left graph compares supply costs for three system sizes – 1 MW, 10 MW, and 100 MW – at two utilization levels: 3000 and 8600 full-load hours per year. Calculations are based on an electricity price of 50 CHF/MWh, a 5% interest rate, and a 25-year economic lifetime.

Costs decline substantially with increasing system size and operational hours: a 1 MW plant operating 3000 hours an-nually exceeds 700 CHF/MWh, while a 100 MW plant at 8600 hours delivers energy at below 200 CHF/MWh. Production accounts for most total supply costs, with storage and transportation contributing only marginally. This underscores that securing low-cost renewable electricity is the key lever for competitiveness.

The lower left graph shows a near-linear relationship between electricity price and levelized supply cost for each system. Smaller, low-utilization plants face steep cost increases with rising electricity prices, making them more exposed to market volatility. In contrast, larger, highly utilized plants maintain lower base costs and flatter cost curves, reflecting greater resilience.

At an electricity price of around 100 CHF/MWh, supply costs range from roughly 800 CHF/MWh for a 1 MW plant operating at 3000 hours to around 250 CHF/MWh for a 100 MW plant operating at 8600 hours, highlighting the substantial benefits of scale and high utilization. Still, these estimates are subject to high uncertainty, as they rely on assumptions and literature values, and reflect a market that is only at an early stage, with few operational projects worldwide.

Sources / additional information

[1] M. Shababuddin et al., «Hydrogen-based iron production: techno-economic and environmental analysis,» Journal of Cleaner Production, vol. 395, 2023, Art. no. 136391. doi: 10.1016/j.jclepro.2023.136391.
[2] USGS, «Iron Ore Historical Statistics Data Series 140,» U.S. Geological Survey. [Online]. Available: https://www.usgs.gov/media/files/iron-ore-historical-statistics-data-series-140
[3] Iron-Power: Enabling Large-Scale Green Energy Storage Using Iron Powder, Hydrogen Tech World, [Online]. Available: https://hydrogentechworld.com/iron-power-enabling-large-scale-green-energy-storage-using-iron-powder.
[4] Penta Chemicals, «Iron powder Safety Data Sheet,» ver. 3.0: https://www.pentachemi-cals.eu/data/Bezpecnostni_listy/en/Iron%20powder_1727_3.0.pdf

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Prepared as part of the ReWAX research project, funded by the Swiss Federal Office of Energy (SFOE), Buildings and Cities Program – Version 1.0, November 2025.