IRON POWER

The potential of Iron Power technology in the energy transition

by Roland Berger

Supported by

- TKI Energy
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Iron powder, a promising metal fuel, can serve as a carrier in vessel transport and local distribution and storage, and can be put to direct use

A Metal fuels

Iron powder is a promising metal fuel due to its circular, sustainable, and potentially high-efficiency processes

- Metal fuels are metal powders that can be used as a circular and sustainable energy carrier. Iron powder is the metal fuel with the largest potential, given its abundant atoms, possible sustainable production, and high output temperature replacing fossil solid fuels in current systems
- The Iron Power cycle can carry and store renewable energy by iron powder production through reduction, transport, heat generation through oxidation and return logistics. Iron powder can be used in high-grade process heat, centralized electricity generation, district heating and hydrogen production
- Reduction and oxidation are key and promising technologies, expected to have high energy efficiencies and low energy losses

B Role of Iron Power technology

Iron powder can be an efficient energy carrier in vessel transport, local distribution and (de)central storage, and can be used directly as a fuel in applications such as high-grade industrial heating

- As 2050 approaches, green molecules, especially hydrogen, will play an increasingly important role in decarbonizing non-electrifiable industries
- The Netherlands will likely rely on green molecule import from cost-competitive countries, a hydrogen backbone for local distribution will be developed. However, hydrogen transport and storage is complicated by safety concerns, low volumetric energy density and high infrastructure cost, and is not expected to reach all industrial areas
- Iron powder is a clean, sustainable and efficient energy carrier that can enable the energy transition for industries that are difficult to decarbonize
  - It performs well as a transport carrier due to its high volumetric energy density, high cycle-efficiency, infrastructure simplicity and low overall costs
  - It can be relatively easily locally distributed and stored in (de)central locations beyond the hydrogen backbone, such as Cluster 6
  - The direct oxidation of iron powder can be used in e.g. process heat, district heating, electricity generation, and potentially direct reduced iron (DRI) which can decarbonize the steel industry

! Throughout the document, 'Iron Power' refers to either the specific cycle or the technology, whereas 'iron powder' denotes the substance serving as the energy carrier

Iron powder could complement other energy carriers, and the Netherlands is well positioned to support and capitalize on its potential

- The case study in this document compares 2030 projections for Iron Power technology, with more developed energy carriers and processes, since Iron Power's TRL is currently <6. As all the energy carriers and technologies are currently in various stages of R&D, the results presented here are subject to change
- The case: Hydrogen produced and converted in a low-cost (LCoH) region, transported by vessel to the Netherlands, distributed to decentral locations, then used in process heat applications
- The case demonstrates that iron powder could have potential as an energy carrier for long-haul transport. Its landed energy costs are in line with other energy carriers, especially the carriers reconverted to hydrogen upon arrival
  - The full potential of Iron Power technology, however, is reached when iron powder is used as a carrier along the entire value chain, including direct high-grade heat generation
  - Iron powder's potential is mainly driven by the fact that no reconversion is needed (it can be directly combusted), and that is has low expected energy losses along the value chain
- Moreover, integrating the novel solid oxide electrolysis cell (SOEC) technology with reduction technology is expected to improve the overall efficiency of hydrogen production and reduction by sharing heat among the processes
- Ultimately, direct electrochemical reduction (DER) could even further improve the potential of Iron Power technology, as this innovative technology will eliminate the step to green hydrogen, increasing the overall energy efficiency and decreasing costs

Iron powder has the potential to become a complementary energy carrier, especially when used in combination with high-grade heat generation

C Case study

- The Netherlands is well-positioned, due to large number of potential companies that could play a role within the Iron Power ecosystem, to capitalize on Iron Power technology within the energy transition and initiate technological services to maximize the global market share

The Netherlands is well-positioned to support and capitalize on the full potential of Iron Power technology in the global energy transition

D NL positioning

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A Metal fuels and iron powder

Iron powder is a promising metal fuel due to its circular, sustainable, and potentially high-efficiency processes

Metal fuels are metal powders that can be used as a circular and sustainable energy carrier – Among the metal fuels, iron powder has the most potential

Introduction to metal fuels and key advantages

Metal fuels description

- **Metal fuels are metal powders that are oxidized** (with e.g. oxygen or water vapor) to release their chemical energy
- After oxidation, metal fuels can regain their energy through reduction. This **circular process** allows metal fuels to act as energy carriers
- **A range of metals can be used** as metal fuel, including iron, magnesium and aluminium
- **Iron powder has the most** promise as a metal fuel due to its abundance and the potential to sustainably reduce it
- Metal powders are already **used in several industries and applications,** ranging from machine building to magnetic products

Key advantages of metal fuels

High performance

- High **output temperature** (up to >1500 °C)
- High volumetric **energy density**
- **High power density**

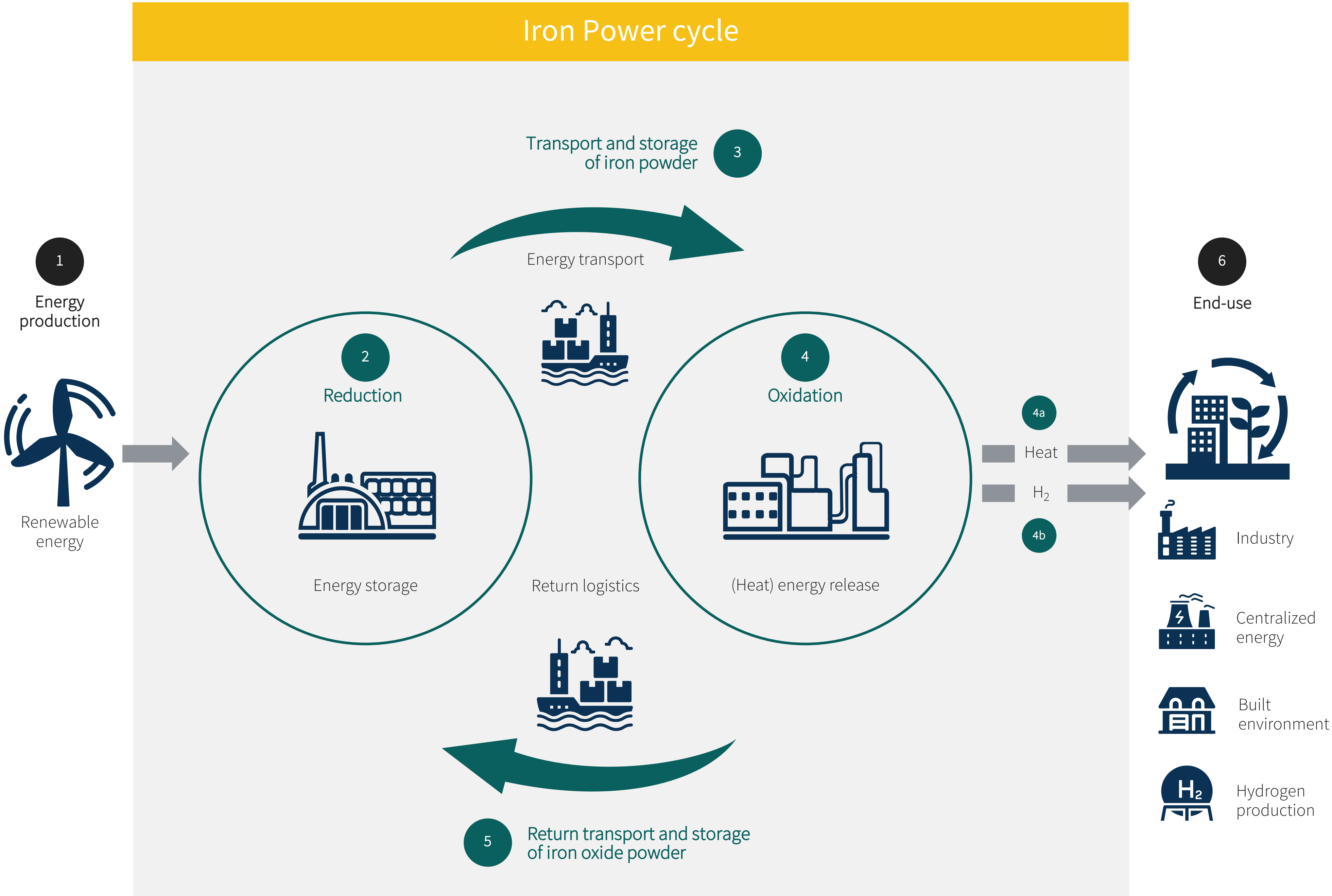
Competitive transport and storage

- High direct **oxidation efficiency** leading to less material needed
- Possibility of **reusing** and **retrofitting** existing transport and storage infrastructures

Sustainable and no emissions

- **No** direct **CO_2** emissions and **low/no** direct emissions of **NO_x and SO_x**
- Full **recyclability** and **circularity**
- **Limited health or environmental** hazard and **no toxicity**

Source: TNO, IRON+



Iron Power cycle
1
Energy production
Renewable energy
2
Reduction
Energy storage
Transport and storage of iron powder
3
Energy transport
Return logistics
4
Oxidation
(Heat) energy release
4a
Heat
H_2
4b
5
Return transport and storage of iron oxide powder
6
End-use
Industry
Centralized energy
Built environment
H_2
Hydrogen production

The Iron Power cycle can carry & store renewable energy by iron powder production through reduction, transport, heat generation through oxidation and return logistics

1. Energy production
   - Energy production using **renewable energy sources**
   - Energy (electricity) producing the hydrogen used for reduction
2. Reduction
   - Reduction of iron oxide powder with hydrogen to **store energy in iron powder**
   - To start the cycle, iron oxide produced at oxidation is reused in reduction, the Iron Power cycle lifetime includes <100 cycles
3. Transport and storage of iron powder
   - Transport and storage of iron powder to **transfer energy**
4. Oxidation
   - a **Release of (heat) energy** through oxidation of iron powder – Produces high output temperature (>1500 °C)
   - b **Produce hydrogen** by oxidation of iron powder pellets using steam
5. Return transport and storage of iron oxide powder
   - **Return flow** of iron oxide powder back to reduction step
6. End-use
   - Potential for high-grade process heat, centralized electricity generation, district heating and hydrogen production

Outlook

(see deep dives on page 25 & 26)

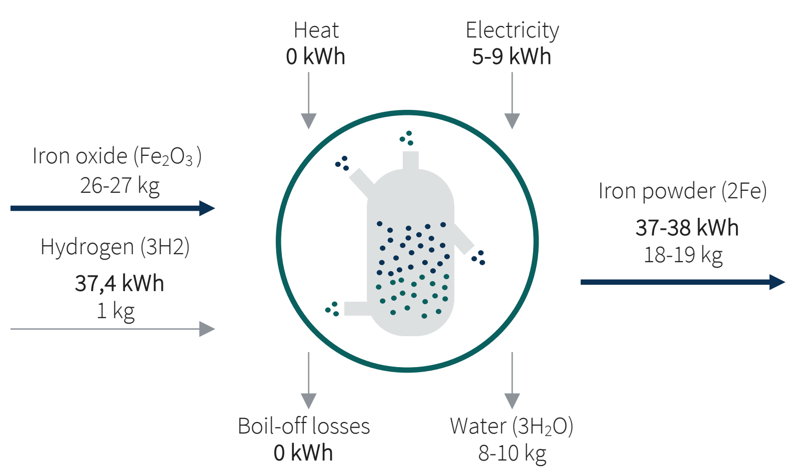
- **Solid oxide electrolysis cell (SOEC) reduction integration** ensures a more efficient process by sharing heat – Will improve hydrogen and iron powder production efficiency
- **Direct electrochemical reduction (DER)** of iron oxide displaces the need for green hydrogen in the reduction process

Source: Technical University of Eindhoven; Iron+; RIFT, Topsoe

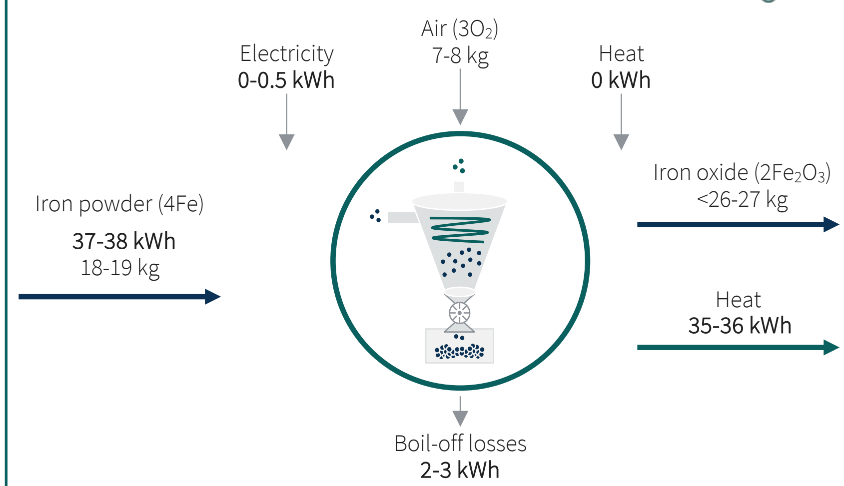
CALCULATIONS ARE BASED ON EXPECTED IRON POWER TECHNOLOGY EFFICIENCIES IN 2030, VALUE CHAIN SET-UP AND SCALE OF OPERATION

Reduction and oxidation are key and promising technologies, expected to have high energy efficiencies and low boil-off losses

Iron oxide reduction



Iron powder oxidation



	Iron oxide reduction	Iron powder oxidation
∑ Energy consumption	8-9 kWh	0 kWh
∑ Energy output	37-38 kWh	35-36 kWh
Energy efficiency[1)]	80-87%	90-99%

➡ Iron oxide and iron powder ➡ High-grade heat ➡ Other inputs and outputs

1) Per step efficiency is calculated by dividing the energy output of the step [kWh] by (electricity and heat [kWh] + energy input into the step [kWh]

Source: RIFT, HyChain, Irena, HyDelta, TNO

B

Role of Iron Power technology

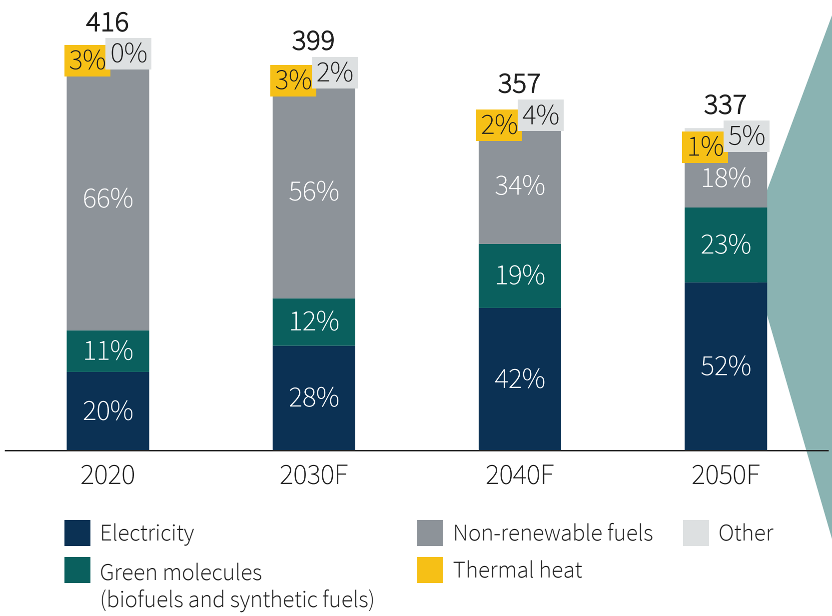
Iron powder can be an energy carrier for vessel transport, local distribution and (de)central storage, and can be used directly as fuel in applications such as high-grade process heat

As 2050 approaches, green molecules, especially hydrogen, will play an increasingly important role in decarbonizing non-electrifiable industries

Global energy outlook

In the energy transition, not all energy consumption is expected to be electrified – Green molecules are expected to play an increasing role in non-electrifiable industries

Total global final energy consumption, NZE[1] scenario [EJ]



Non-electrifiable industries, examples of potential green molecule use cases

Industry
- High-grade heat
- Feedstock

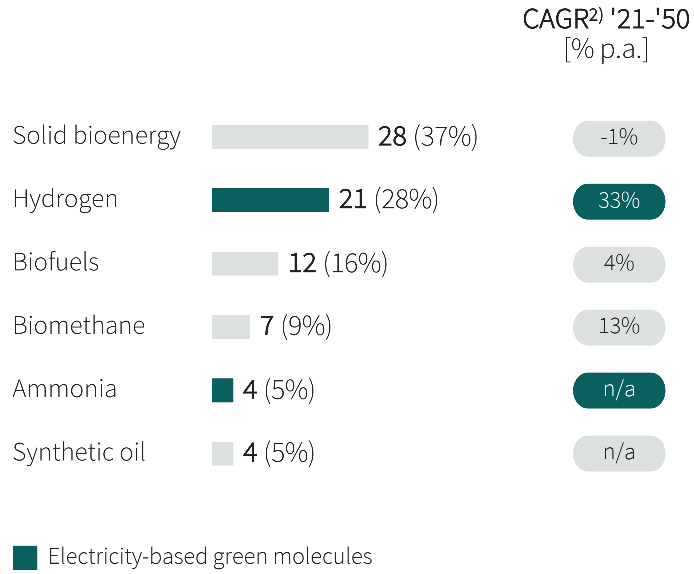
Mobility
- Commercial aviation
- Commercial shipping
- Long-haul heavy ground transport

Centralized energy
- Electricity generation
- Gas generation

Built environment
- District heating
- Heating for older and less insulated buildings

Electricity-based molecules will be among the dominant green molecules after 2050

Global green molecule production, NZE[1] scenario, 2050 [EJ, % of total]



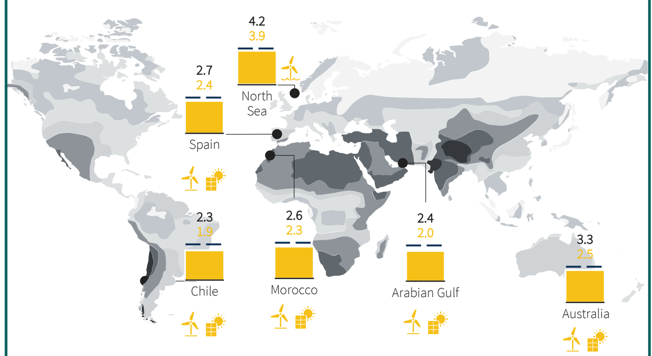
1) Net zero energy; 2) Compound annual growth rate

Source: IEA 2022, Roland Berger research

The Netherlands will likely rely on green molecules from low LCoH regions and local H_2 distribution by backbone, but safety and backbone's accessibility are concerns

NL will rely on green molecule import from low levelized cost of hydrogen (LCoH) hubs …

Indicative



Offshore wind   Onshore wind   Solar photovoltaic (PV)

Est. technical cost range of green H_2 for 250 MW electrolysis plant by 2030 [EUR / kg H_2]

Attractiveness per region for green H_2 production (+ / –)

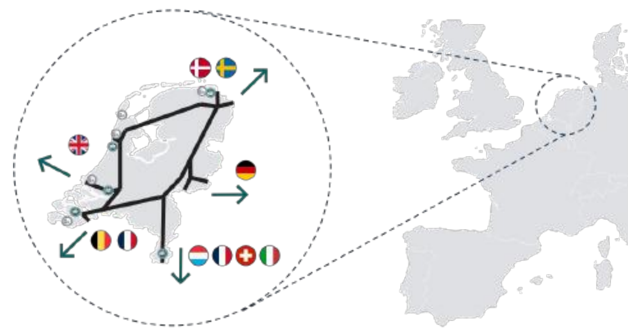
Hydrogen export **raises water scarcity concerns**, especially in dry regions. The **closed-loop Iron Power cycles eliminates this concern by not exporting hydrogen atoms**, thus preventing water exportation

… which requires long-distance pipelines and vessel transport

Vessel transport[1)]   Pipeline transport[1)]

Green H_2 production

NL, and EU are establishing a H_2 backbone to reach large industries and logistical hubs



H_2 backbone H_2 storage   Industry cluster connected to H_2 backbone

!

Hurdles to lang-haul transport, storage, and regional distribution of hydrogen

- Pipeline – expensive, high infrastructure complexity, not all offtakers/ producers will be connected to the network
- Vessel transport – low volumetric energy density requiring large vessels, safety risks, high energy dissipation
- Storage – decentral industries likely not connected to the H_2 backbone, requiring decentral energy storage solutions

1) Pipeline and vessel trajectory based on EHB report "Analyzing future demand, supply and transport of hydrogen"

Source: IEA, Dutch Ministry of Economic Affairs and Climate (EZK), European Hydrogen Backbone

Iron powder is a clean, sustainable and efficient energy carrier that can enable the energy transition for industries that are difficult to decarbonize

Navigation page: Iron Power technology strengths

1

Effective in vessel transport

Iron powder can make use of relatively conventional vessel transport, and has low energy losses during transit

2

Opportunity for local distribution and storage in areas lacking H_2 backbone access (Cluster 6)

Iron powder can make use of relatively conventional local distribution and storage assets, and has low energy losses during operations

3

Suitable for direct applications without harmful emissions

Iron powder can be directly used for process heating in industry without CO_2 and SO_2, and low NO_x emissions

4

Possibility for hydrogen production through wet-cycle technology

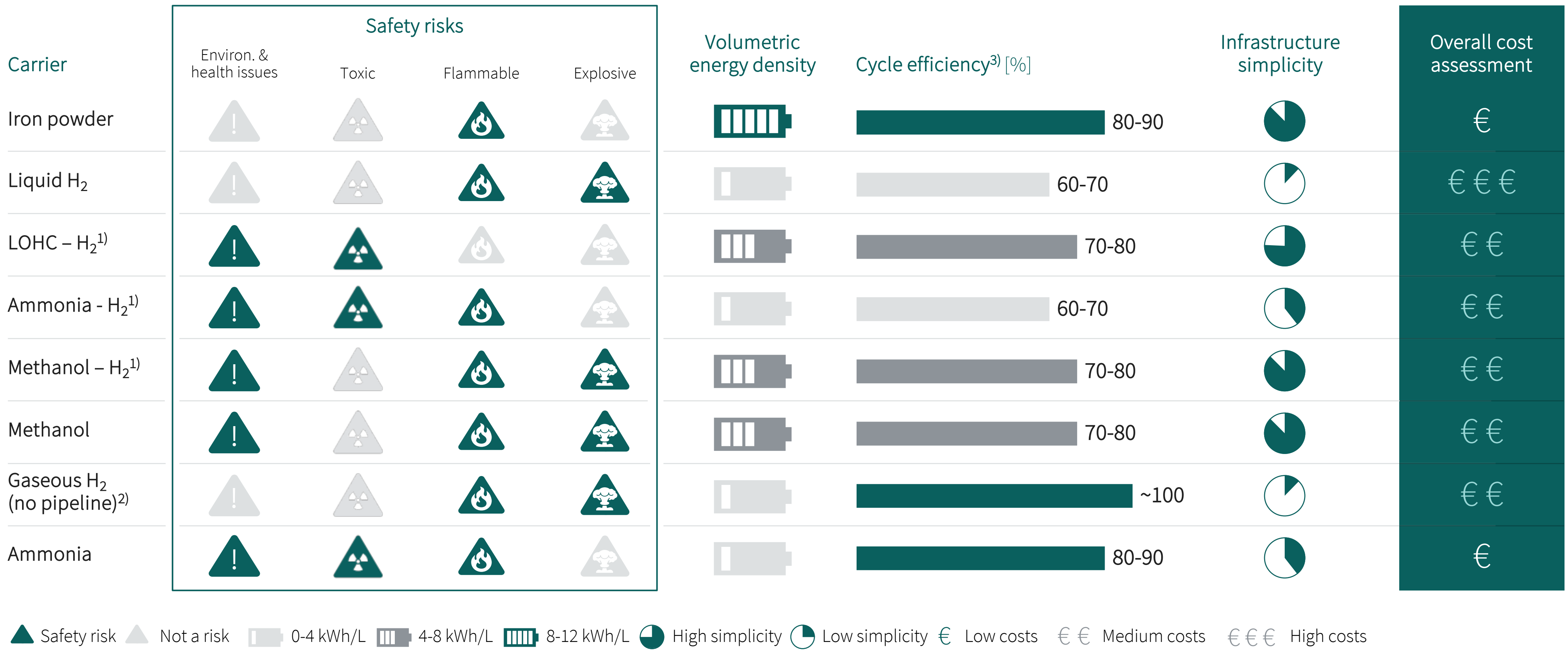
Iron powder pellets can be used to produce high purity, low carbon hydrogen for industries without access to the H_2 backbone

See deep dive on next pages

1 Vessel transport

Iron powder performs well as a transport carrier due to its high volumetric energy density, cycle-efficiency, infrastructure simplicity and lower costs

Back-up: Qualitative assessment of sustainable energy carriers for long-haul vessel transport



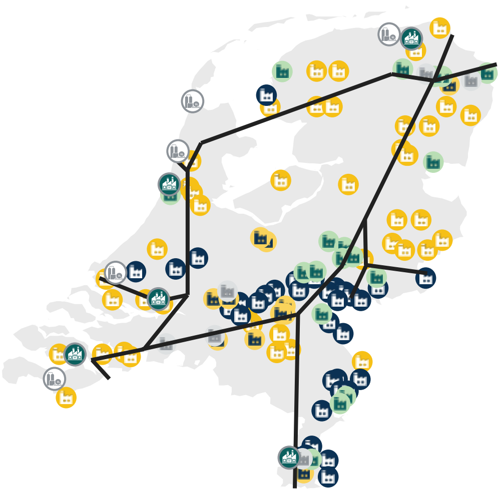
1) Carriers reconverted to hydrogen; 2) Assessment of decentral gaseous hydrogen use - silos instead of pipeline - as defined use case is not connected to hydrogen backbone; 3) Excluding external energy needs

Source: IRENA, IEA, Methanol Institute

Iron powder can be relatively easily locally distributed and stored in locations without access to the hydrogen backbone such as Cluster 6

Back-up: Decentral distribution and storage to local industries without access to the hydrogen backbone

Overview of planned hydrogen backbone in 2030 and current relevant Cluster 6 companies[1)]



- Hydrogen backbone
- Hydrogen storage
- Industry cluster connected to hydrogen backbone

Cluster 6: Industry without access to the hydrogen backbone[1)]

~350 production locations in the Netherlands are not part of a geographical industry cluster – As these locations are scattered, they are **not expected to be connected to the H_2 backbone**

Beyond a 5 km radius from the H_2 backbone, building backbone connections becomes too expensive and noncompetitive for small-scale energy consuming businesses, when compared to the business case of iron powder

- Ceramic industry
- Food industry
- Chemical industry
- Glass industry
- Paper and cardboard industry

Key statistics Cluster 6[1)]

- **5–6 m Mt CO_2** Emissions (25-30% total NL industrial emissions)
- **EUR 7–9 bn** Revenue
- **4.5–5.5 TWh** Heat demand
- **1.5–2.5 TWh** Electricity demand

Majority of Cluster 6 companies difficult to decarbonize as they need **high-grade heat** for their operations, which **excludes electrification** as solution

Due to decentral location, Cluster 6 companies also need **decentral energy storage capacity**

Key advantages of Iron Power technology in relation to distribution and storage

- High volumetric energy density
- Ability to store in bulk and can make use of relatively conventional assets to transport and store
- Possibility of reusing and retrofitting existing infrastructure
- Limited toxicity or environmental and health hazards

1) Only considers the 5 relevant sectors that will potentially employ iron powder. Following industries are excluded: oil & gas exploration, waste & recycling, ICT and metallurgy as these sectors are net producers of energy, will likely be connected to the hydrogen backbone or do not require process heat in their operations

Source: VNCI Cluster 6, European Hydrogen Backbone, Company annual reports, Deloitte iron powder study

3 Direct use in range of applications

The direct oxidation of iron powder can be used in e.g. high-grade process heat, district heating, electricity generation, and potentially direct reduced iron

Back-up: Market potential of Iron Power technology per direct use case (without reconversion)

Key advantages of Iron Power technology in relation to direct use

- High output temperature
- Stable flame
- High oxidation efficiency
- No direct CO_2, and SO_x emissions, low NO_x emissions
- Full circularity and recyclability

	Use case	Electricity	Hydrogen	NH_3	MeOH	Iron powder
Direct industry	Iron & steel[1]	✓	✓	✗	✗	✓
	Synthetic fuels[1]	✗	✓	✓	✓	✗
	Ammonia end-products[1]	✗	✓	✓	✗	✗
	Methanol end-products[1]	✗	✓	✗	✓	✗
	Process heat[2]	✗	✓	~	✗	✓
Mobility	Light duty	✓	✓	~	✓	✗
	Heavy duty	✓	✓	~	✓	✗
	Rail	✓	✓	~	✓	✗
	Inland shipping	~	✓	✓	✓	✗
	Offshore shipping	~	✓	✓	✓	✓
	Aviation	✓	✓	✗	✓	✗
Centralized energy	Rankine cycle	n.a.	✓	✓	✗	✓
	Combined cycle	n.a.	✓	✓	✗	✓
Built environm.	District heating	✓	✓	~	~	✓
	Local boiler/heat pump	✓	~	✗	✗	~
	Other[3]	✓	✗	✗	✗	✗

Iron powder end-uses

Opportunity to produce or import **DRI**, potential to decarbonize steel industry

Process heat for industry

NON-EXHAUSTIVE

Construction

Chemicals

Glass

Food and

Ceramics

Paper & cardboard

Efficient direct oxidation of iron powder for high-grade heating purposes

Power plants

Opportunity to fuel **steam engine** for electricity generation as part of combined cycle turbine

District heating

Use of iron powder **heat**, especially for peak-load applications

✓ Expected viable use case ~ Potentially viable use case ✗ No viable use case

High market potential · Medium market potential · No market potential

1) Uses molecule as feedstock; 2) Only mid- and high-grade heat; 3) Other uses include wood, solar, thermal, electric, oil

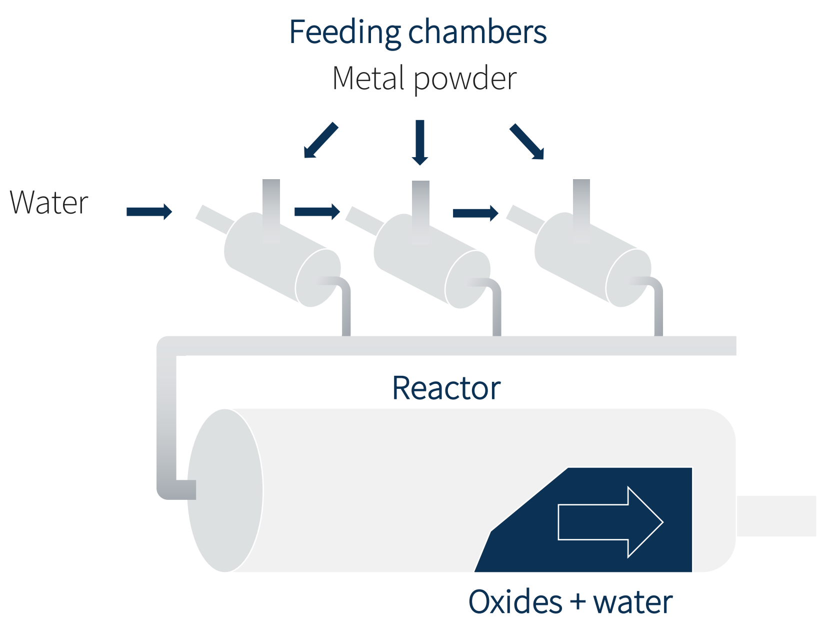
Source: Roland Berger research, European Hydrogen Backbone June 2021

Iron powder can be used to produce high purity, low carbon hydrogen for industries without access to the hydrogen backbone, currently at low TRL (<4)

Back-up: Iron powder reconversion to hydrogen

Introduction to Iron Power wet-cycle technology

- The wet-cycle technology is currently still at **low TRL** (<4), various production methods are currently researched
- The gaseous reactants in the oxidation reaction consists of hydrogen and steam only, **this process generates highly pure hydrogen and heat** through steam reaction
- **Team SOLID** is a yearly student challenge that focusses on Iron power technology development, currently the team is actively researching the Iron Power wet-cycle



Key advantages Iron Power wet-cycle technology in relation to H_2 production

- High purity hydrogen production
- No CO_2 emissions during hydrogen production
- Relatively simple process
- Heat produced during the process

Source: International Journal of Hydrogen Energy

C

Case study of Iron Power technology

Iron powder has the potential to become a complementary energy carrier, especially when used in combination with high-grade heat generation

Case study projects the Iron Power technology future potential (2030) against more developed energy carriers and processes – Iron Power technology now at <6 TRL

Case study background

Results should be interpreted knowing

- **Estimated technology status**[1)]
  - **Iron Power technology**: Expected technology status for 2030 to be at TRL 8-9 (now at TRL <6)
  - **Other carriers**[2)] **– Transport logistics:** Current technology status (now at TRL 8-9)
  - **Other carriers**[2)] **– (Re-)Conversion:** Estimated technology status for 2028-2030 (now at TRL 4-8)
- **Results subject change**
  Results can change over time due to research and development of all energy carrier technologies
- **2023 price levels & discounted future cost**
  Cost levels shown in the document are based on 2023 price levels and future costs are discounted using a 6% discount factor

- In August 2023, the Iron Power consortium (TU/e, TNO, Metalot, RIFT, Iron+) has assessed the competitiveness of iron powder in a case study with the help of Roland Berger
- The goal of the case study is to assess the potential role of Iron Power technology as complementary energy solution in the energy transition and future energy mix
- Assessed carriers within case study include iron powder, liquid hydrogen, ammonia, methanol, and hydrogen reconverted from LOHC, ammonia and methanol
- The potential of all energy carrier technologies is assessed by analyzing the following factors for each value chain step
  - The energy input to each step [kWh];
  - The loss of material when carriers are (re-)converted, and boil-off losses [%];
  - The energy consumption needed for the processes within the step [kWh];
  - The lifetime, capital and operating expenses associated with each step [EUR/MWh]
- The data and information sources used for the case study are public reports and studies, Iron Power consortium input, and sometimes market expert input
- The following pages describe the high-level results of the case study, more background information and deep dives into the case study are presented in the appendix.

1) Technology status refers to both process efficiencies and costs; 2) This includes carriers such as liquid hydrogen, LOHC-hydrogen, ammonia, methanol and carriers reconverted to hydrogen including ammonia and methanol

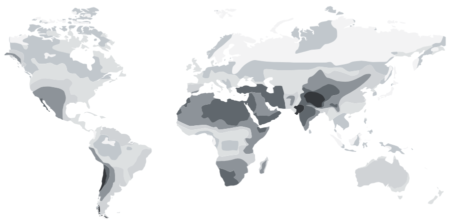
Source: RIFT, Ion+, Roland Berger research, IEA, TNO, HyChain 3, HyDelta, Irena, European Hydrogen Backbone

The case: Hydrogen produced and converted in a low-cost region, transported to the Netherlands, distributed to decentral locations, then used in process heat

Iron Power technology case study

Including return logistics for iron powder

H_2 production and conversion in remote and low-LCoH region



Attractiveness per region for green H_2 production (+ / –)

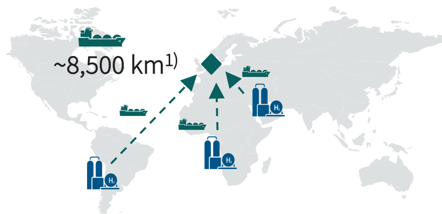
Case description

- Hydrogen purchased from expected LCoH hub
- Conversion to energy carrier in region of origin

Key model assumptions

- H_2 is purchased for **3.0 USD/kg** (**2.77 EUR/kg**)
- CO_2 input price **60 EUR/kg** applied to methanol production
- H_2 storage incurs boil-off losses **0.3 %/d**

Long-haul vessel transport to the Netherlands



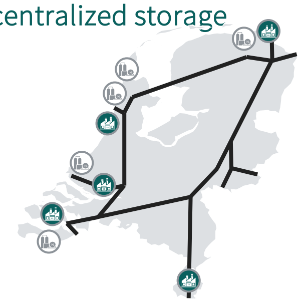
Case description

- Energy carrier is shipped by vessel to Port of Rotterdam
- Use of pipeline is not considered

Key model assumptions

- Vessels are not fueled on transported energy carrier, but use VLSFO[1)]
- Transported distance assumed **8,500 km**
- Iron powder lifetime spans **20 cycles** (reduction to oxidation)

Local distribution & decentralized storage



Case description

- Target end-use for energy carrier is businesses not connected to the hydrogen backbone
- Decentralized short-term storage is required to reach these industries

Key model assumptions

- Local distribution: truck transport over a distance of **100 km**
- Carriers are either reconverted before or after truck transport, depending on which option is less expensive

Oxidation for process heat application

Construction

Glass

Food & beverage

Paper & cardboard

Chemical

Waste management

Case description

- End use: high-grade process heat

Key model assumptions

- Ammonia and methanol are not direct competitors as they are mainly used as fuel or feedstock for industry – direct oxidation of these releases large amount of pollutants

1 (spans H₂ production through long-haul vessel transport)

2 (spans all four steps)

1) Very low sulfur fuel oil

Source: European Hydrogen Backbone, VNCI Cluster 6, RIFT

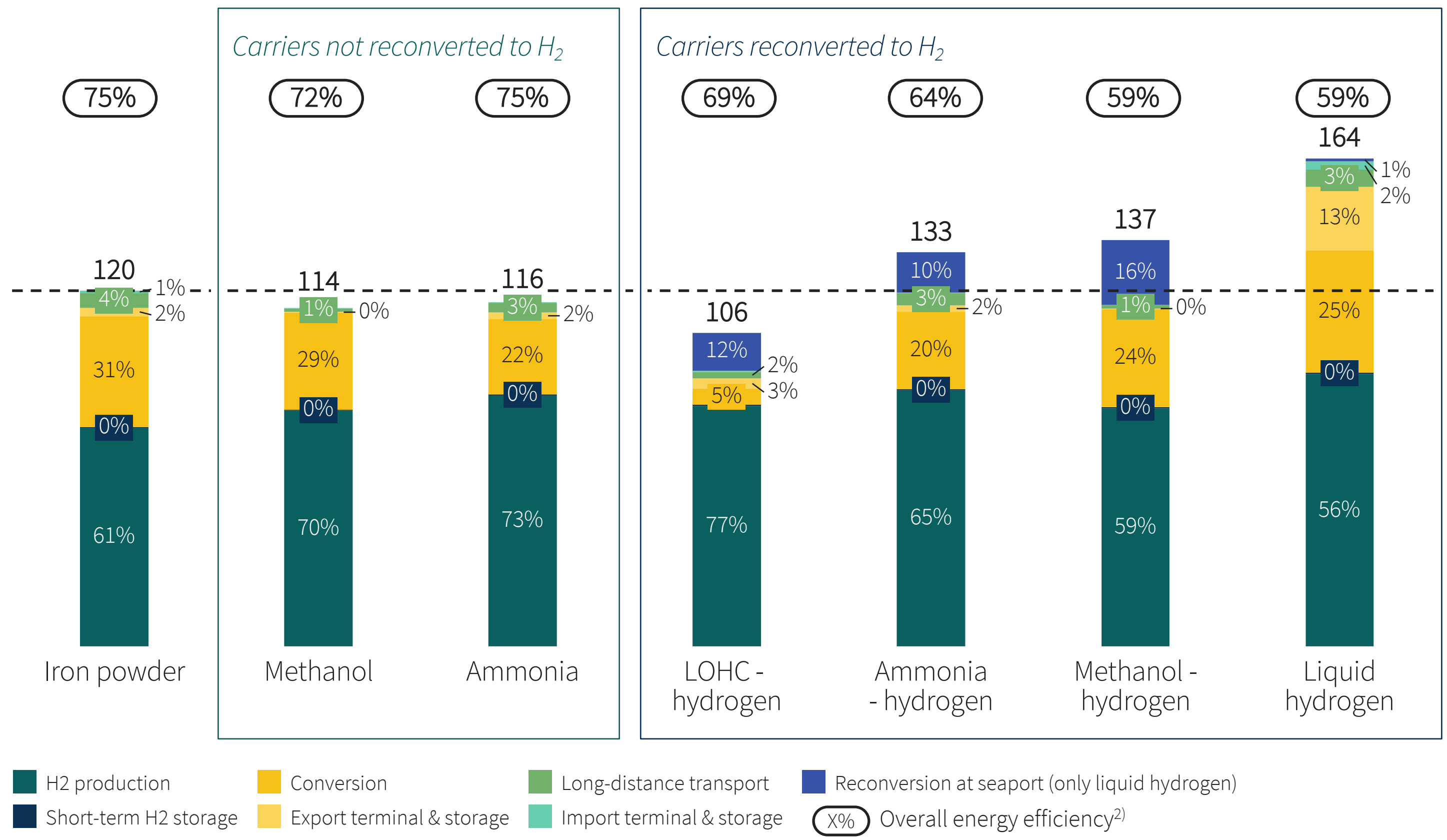
1 Calculations are based on expected iron power technology efficiencies in 2030, value chain set-up and scale of operation

Iron powder could have potential as an energy carrier for long-haul transport – Its landed energy costs are in line with other energy carriers

Discounted[1] cost for 1 MWh of landed energy delivered to Port of Rotterdam [EUR/MWh]

Key takeaways

- Iron powder within landed cost range of ammonia, methanol and reconverted carriers driven by high overall energy efficiency
- Conversion cost of iron oxide to iron powder is less competitive due to high energy inputs and costly iron oxide feedstock



Deep dive in appendix

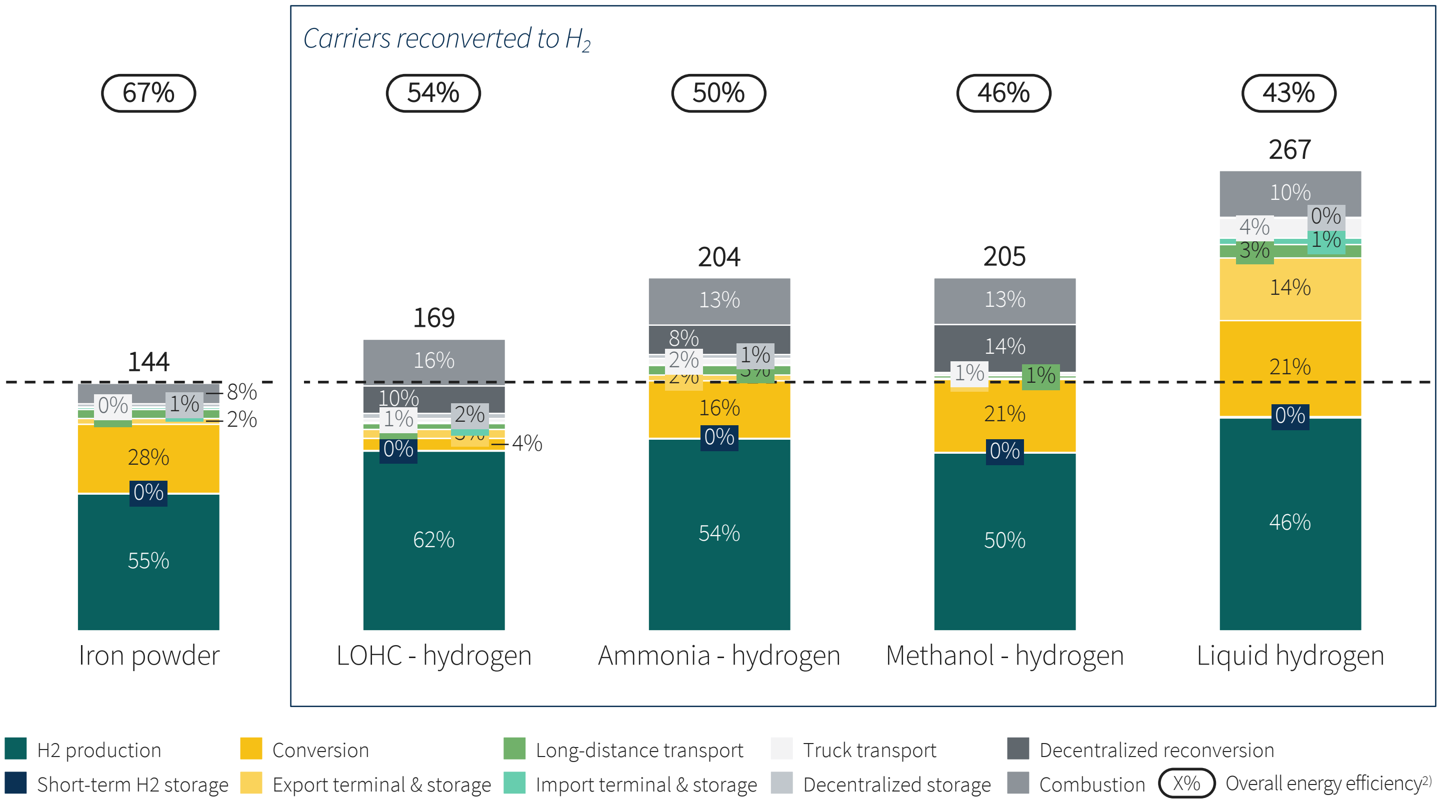
1) In the LCOE calculations, both the total energy and total costs are discounted using the industry-standard 6% discount rate; 2) Overall energy efficiency is calculated as: MWh delivered at final value chain step / (MWh input at H_2 production + energy input during processes MWh)

Source: RIFT, Irena, HyChain, HyDelta, Roland Berger research

2 Calculations are based on expected iron power technology efficiencies in 2030, value chain set-up and scale of operation

The full potential of Iron Power technology is reached when iron powder is used as a carrier along the entire value chain, including direct high-grade heat generation

Discounted[1)] cost for 1 MWh of process heat delivered to industrial company in the Netherlands [EUR/MWh]



Key takeaways

- **Iron powder does not require reconversion,** avoiding a costly process step (additional EUR 14-27/MWh for other carriers)
- **Direct oxidation of iron power is efficient** and approximately 50-60% cheaper than other carriers
- **Iron powder has 20-30% higher remaining energy at combustion** compared to reconverted carriers
- **Iron powder lifetime (number of cycles)** is still being researched; this will impact conversion costs

Deep dive in appendix

1) In the LCOE calculations, both the total energy and total costs are discounted using the industry-standard 6% discount rate; 2) Overall energy efficiency is calculated as: MWh delivered at final value chain step / (MWh input at H_2 production + energy input during processes MWh)

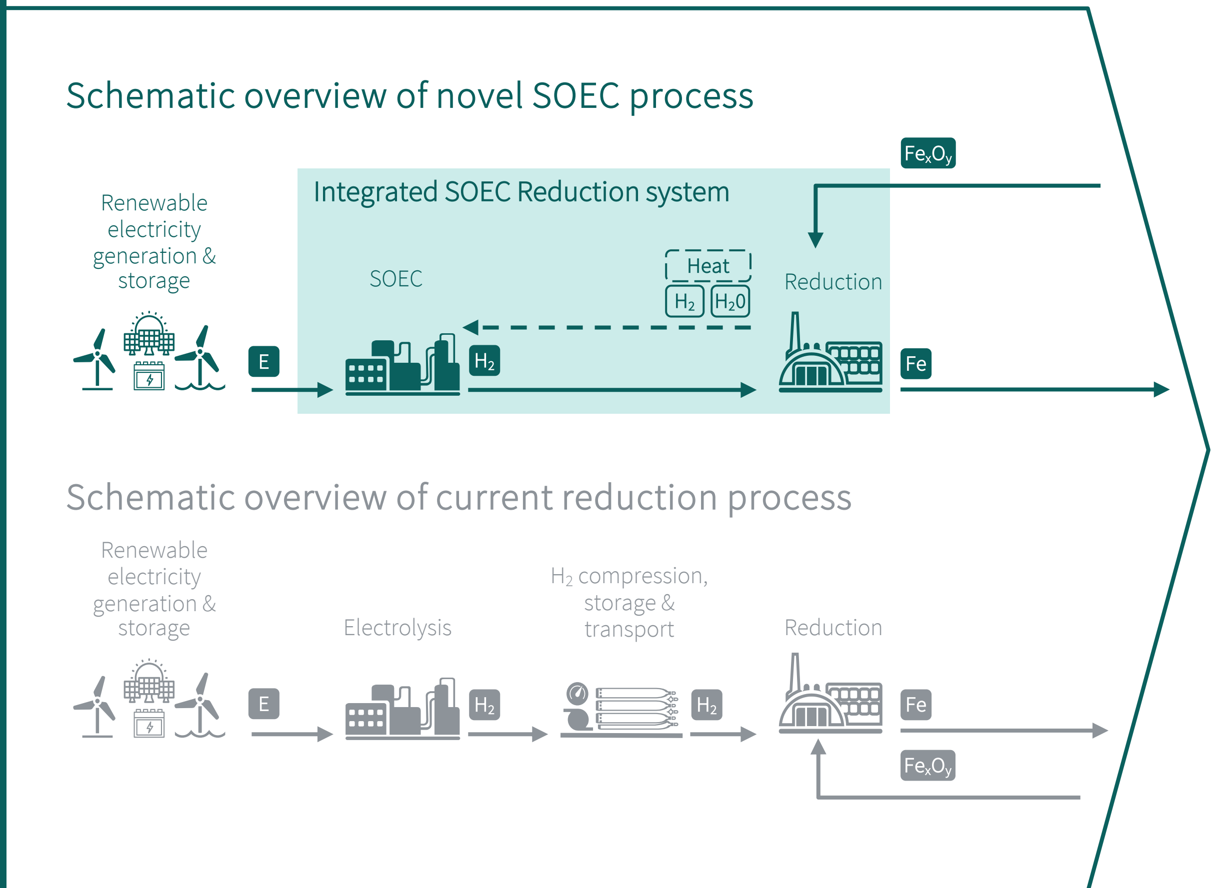
Source: RIFT, Irena, HyChain, HyDelta, Roland Berger research

Moreover, integrating SOEC with reduction technology is expected to improve the overall efficiency of hydrogen production and reduction processes

Future technology: Overview of solid oxide electrolysis cell (SOEC) in the Iron Power cycle

SOEC[1)] technology background

- **SOEC utilizes renewable electricity to produce hydrogen**. The technology has unrivaled conversion efficiencies due to:
  - Favorable thermodynamics and kinetics at higher operating temperatures
  - The ability to be operated in reverse
  - Efficient dynamic load operation under fluctuating power levels
  - Ability to thermally integrate with a range of chemical syntheses
- **Technology still in early stages of development (TRL <6)**
- **Currently, Topsoe has the most advanced SOEC** demo plant – successful demo operating at combined stack power of 350 kW



SOEC technology reduces energy consumption by integrating process heat, thus improving hydrogen and iron powder production efficiency

(Energy) carrier   Value chain step

1) SOEC stands for solid oxide electrolysis cell

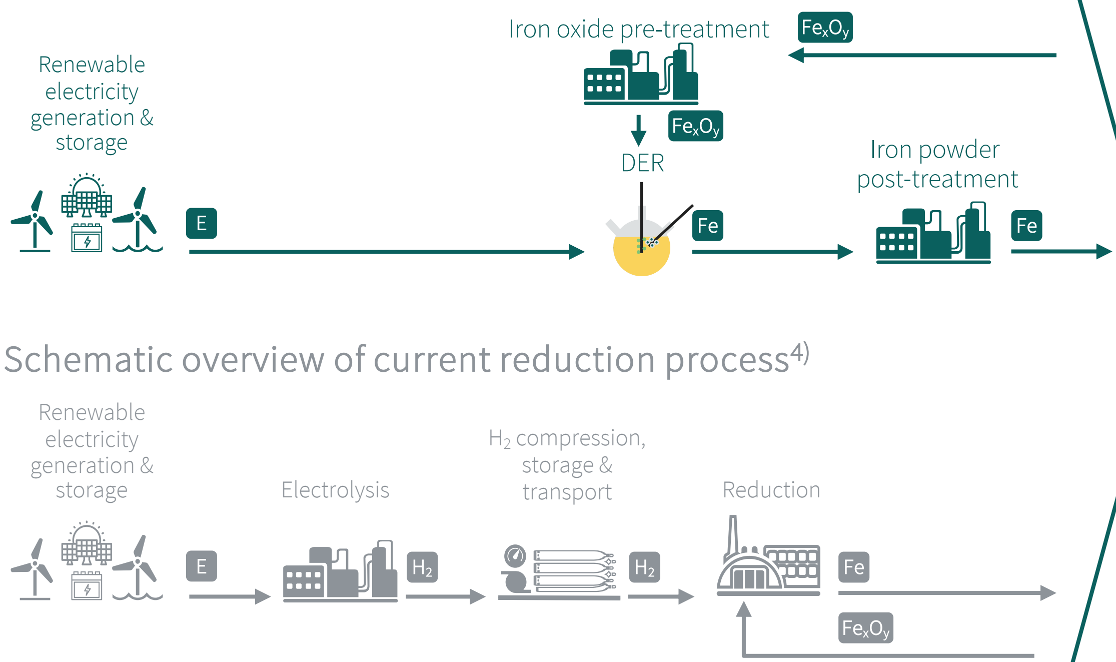
Source: Eindhoven University of Technology, Topsoe, International Journal of Hydrogen Energy

Ultimately, direct electrochemical reduction can further enhance Iron Power technology potential by removing the need for green hydrogen

Future technology: Overview of direct electrochemical reduction (DER) in the Iron Power cycle

Schematic overview of novel SOEC process[4)]

Schematic overview of current reduction process[4)]



DER removes the step for costly and scarce green H2 and its storage and transport – increasing overall energy efficiency and reducing costs

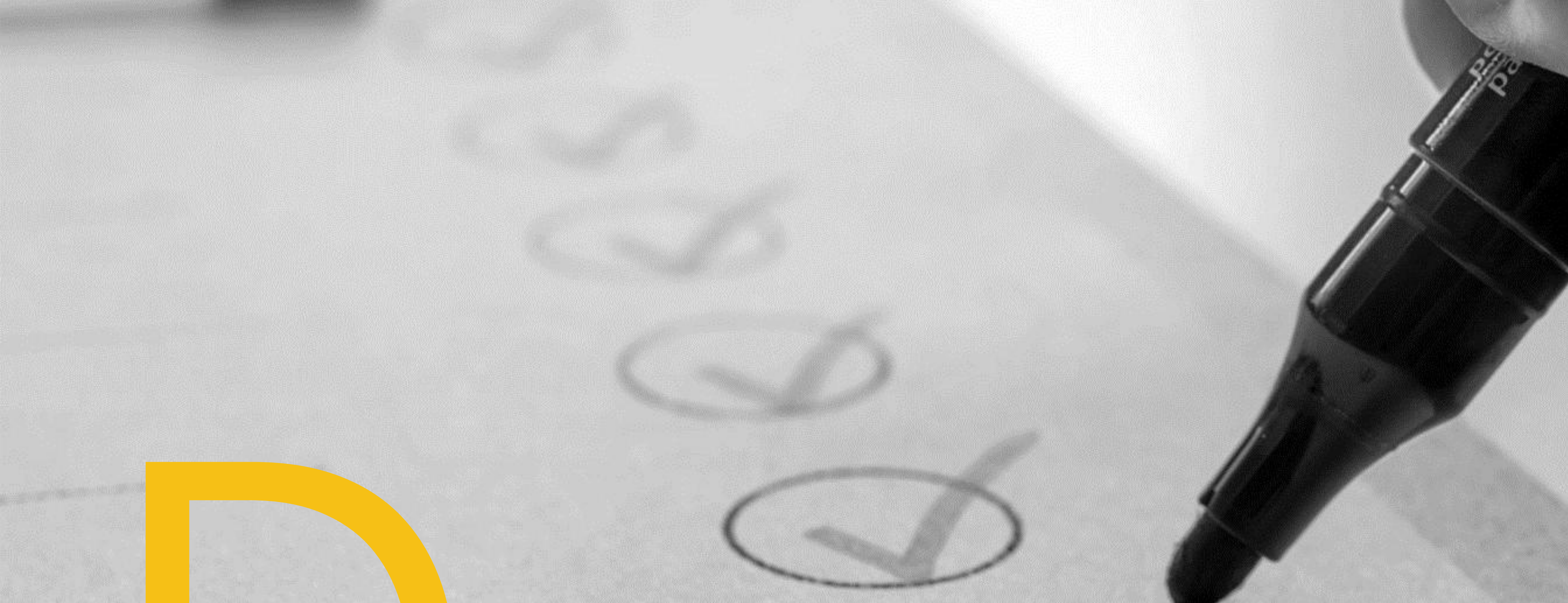
(Energy) carrier   Value chain step

1) Direct electrochemical reduction; 2) Ironoxide may consist of various chemical formulas. Current focus is on Fe_2O_3 , however Fe_3O_4 and FeO are also being researched; 3) Non-exhaustive list; 4) Schematic overview includes return logistics for ironoxide as the Iron Power technology ecosystem is circular

Source: Eindhoven University of Technology, Frontiers in Materials

DER[1)] technology background

- **Direct use of renewable energy** to perform **DER to iron oxide (Fe_xO_y[2)])** to produce iron powder (Fe), reducing the energy consumption of iron production to 3-4 MWh/ton iron
- **Advantages of DER include**[3)]:
  - No costly green hydrogen required
  - Absence of CO_2 emissions, and no polluting by-products
  - No water extraction
  - No sintering/agglomerated powder
  - Lower temperature requirement and lower electric energy consumption vs. current electrolysis and reduction process
- Technology is in **early stages of development, currently at low TRL (<4),** but is gaining attention from steel industry and researchers
- **Companies currently developing DER technology** are focused on iron production (briquettes) for decarbonizing the steel industry



D

NL positioning

The Netherlands is well- positioned to support and capitalize on the full potential of Iron Power technology in the global energy transition

Example company logos[1)]

The Netherlands is well-positioned to capitalize on Iron Power technology within the energy transition and initiate technical services to maximize global market share

Players that could play a potential role within the Iron Power ecosystem

Equipment manufacturing & maintenance providers

Pometon, RIFT, HeatPower, VDL, Iron+, Fenix Energy, Alpha Pro, EMGROUP Energy and Environmental Technologies

National and global offtakers

AsfaltNu, Veolia, Engie, Ennatuurlijk, Tata Steel, Nyrstar, Kingspan, Xirqulate, ArcelorMittal

Research institutes

TU/e Eindhoven University of Technology, TNO innovation for life, Metalot, Maastricht University, RISE, SOLID, Fortescue, TU Delft Delft University of Technology

Logistics providers

Vos Logistics, Port of Amsterdam, Port of Rotterdam, Orient Shipping Rotterdam, SMT Shipping, De Rijke accelerating value

1) Example companies that could play a potential role within the Iron Power ecosystem but are not necessarily currently active in Iron Power technology and value chain

Reach out to one of the Eindhoven University of Technology if you are interested in learning more about Iron Power technology

Iron Power experts and key consortium partners

	TU/e EINDHOVEN UNIVERSITY OF TECHNOLOGY	metalot	RIFT	Iron+	TNO innovation for life
Current Iron Power technology related activities and projects[1]	• R&D projects into the end-to-end value chain technologies of Iron Power (reduction, oxidation, transport and storage) • Research into technologies (SOEC[2] and DER[3]) to enhance Iron Power technology competitiveness	• Bridges gap between knowledge and expertise from scientists, entrepreneurs and the market to accelerate Iron Power technology development • Developing a worldwide ecosystem for Iron Fuel companies	• Development and installation of first operational 1 MW boiler system for district heating • Development of iron powder simulation models	• Development and installation of first 0.5 MW boiler in a brewery • Development of iron powder industrial process equipment	• R&D in application and integration, production, transport and storage of iron powder • Research into direct electrochemical reduction of iron oxide
Contact information TU/e	Philip de Goey L.P.H.d.Goey@tue.nl	Raoul Voeten	Jan Hubers	Guy Willems	Herbert Zondag
Function	Research & Development	Managing director	Manager Non-Dilutive Funding	Director at EMGroup; representing Iron+	Professor Thermal Energy Storage, TU/e and TNO/ECN

1) Non-exhaustive list; 2) Solid oxide electrolysis cell; 3) Direct electrochemical reduction

E Appendix

The entire value chain of each carrier has been considered – For iron powder and LOHC, return logistics are also considered

Value chains of carriers in case study

Comments

- **End-to-end model** includes all value chain steps
- **No reconversion included for iron powder** as direct use of material is assumed
- **Transport of iron powder and LOHC** include return logistics (A) of iron oxide powder and LOHC as value chain of both carriers is circular
- **For all considered carriers,** local reconversion after distribution is modeled, except for **liquid H_2** (B) where **reconversion** is done before distribution as this is the less expensive option

A Including return logistics for iron powder and LOHC

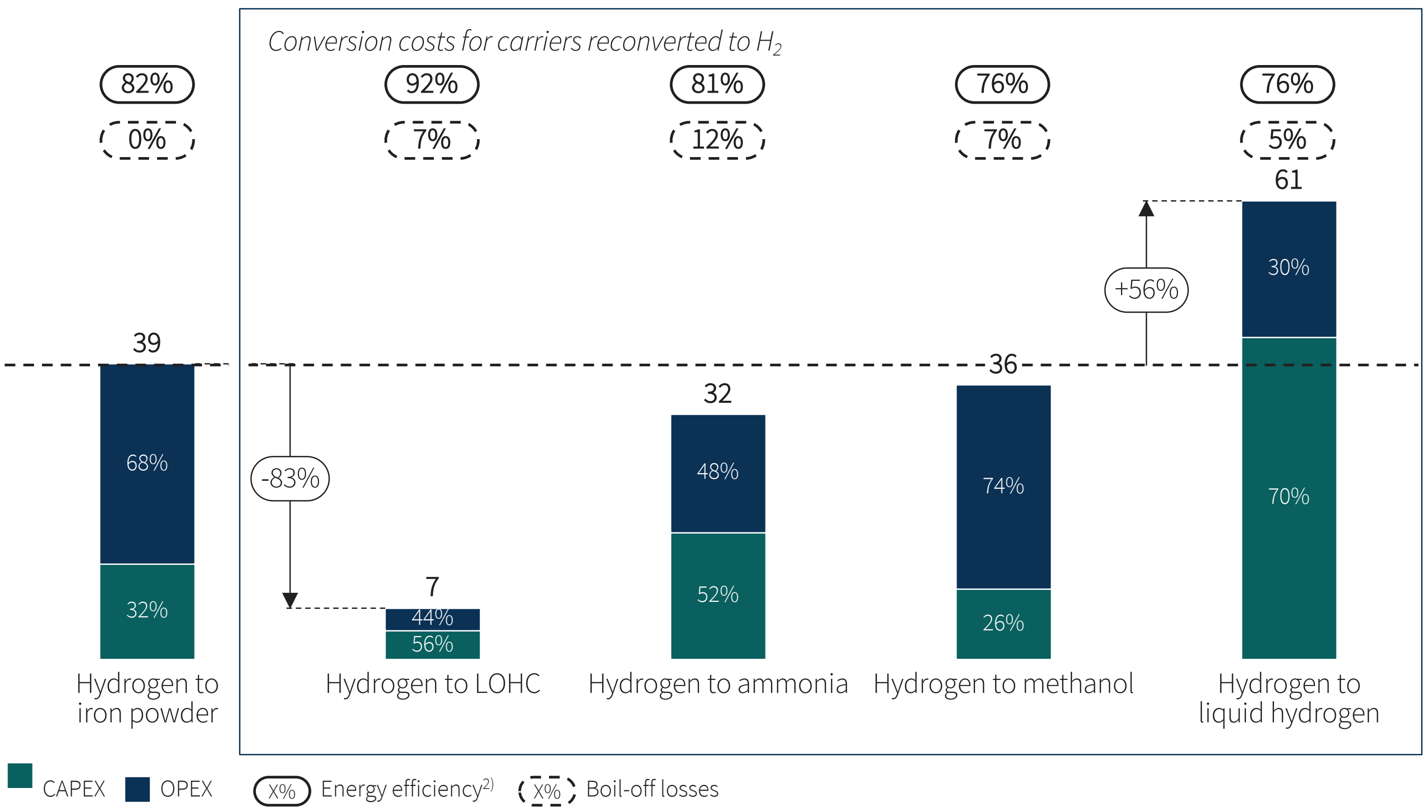
	H_2 input		Conversion	Transportation			Short-term storage		Local reconversion	End-use
Case	H_2 production	Short-term H_2 storage	Conversion	Export terminal	Long-haul transport	Import terminal	Distribution	Storage	Reconversion	Application
Iron powder	Purchase of green H_2	Pressurized H_2 tank	Reduction into iron powder	Solid bulk storage	Solid bulk carrier	Solid bulk storage	Solid bulk trucks	Solid bulk storage	-	High-grade heat
Liquid H_2	Purchase of green H_2	Pressurized H_2 tank	Liquefaction into liquid H_2	Liquid H_2 tank	Liquid H_2 vessel	Liquid H_2 tank	Fuel trucks (B)	Gaseous H_2 tank	Vaporization into H_2	High-grade heat
LOHC - hydrogen	Purchase of green H_2	Pressurized H_2 tank	Hydrogenation into LOHC	LOHC tank	Oil tanker	LOHC tank	Fuel trucks	LOHC tank	Dehydrogenation into H_2	High-grade heat
Ammonia - hydrogen	Purchase of green H_2	Pressurized H_2 tank	Synthesis into ammonia	Ammonia tank	LPG tanker	Ammonia tank	Fuel trucks	Ammonia tank	Ammonia cracking into H_2	High-grade heat
Methanol - hydrogen	Purchase of green H_2	Pressurized H_2 tank	Synthesis into methanol	Methanol tank	Oil tanker	Methanol tank	Fuel trucks	Methanol tank	Methanol reforming into H_2	High-grade heat

Source: Roland Berger research

CALCULATIONS ARE BASED ON EXPECTED IRON POWER TECHNOLOGY EFFICIENCIES IN 2030, VALUE CHAIN SET-UP AND SCALE OF OPERATION

Iron oxide conversion to iron powder is less competitive than other carriers – Costs are mainly driven by large OPEX (electricity input and iron oxide feedstock)

Conversion H_2 to carrier: Levelized[1)] cost comparison [EUR/MWh]



Key takeaways

- **Iron oxide conversion cost** driven by electricity input and iron oxide feedstock
- **Iron Power technology can become more competitive** by improving iron powder lifetime (number of cycles re-used)
- **Hydrogen conversion to methanol costs are largely OPEX driven** due to costly CO_2 input prices
- **Hydrogen conversion to LOHC is an exothermic and circular process**, as a result, the process requires low energy inputs and low DBT feedstock costs
- Hydrogen conversion to LOHC, ammonia, methanol and liquid hydrogen is associated with large **boil-off losses –** these carriers could potentially become even more competitive if boil-off losses are reduced

1) Levelized costs considers the costs per MWh output of the step; 2) Per step energy efficiency is calculated as MWh delivered after conversion step divided by (MWh input to conversion + energy input during process MWh)

Source: Irena, HyChain, HyDelta, International Journal of Hydrogen Energy, Roland Berger research

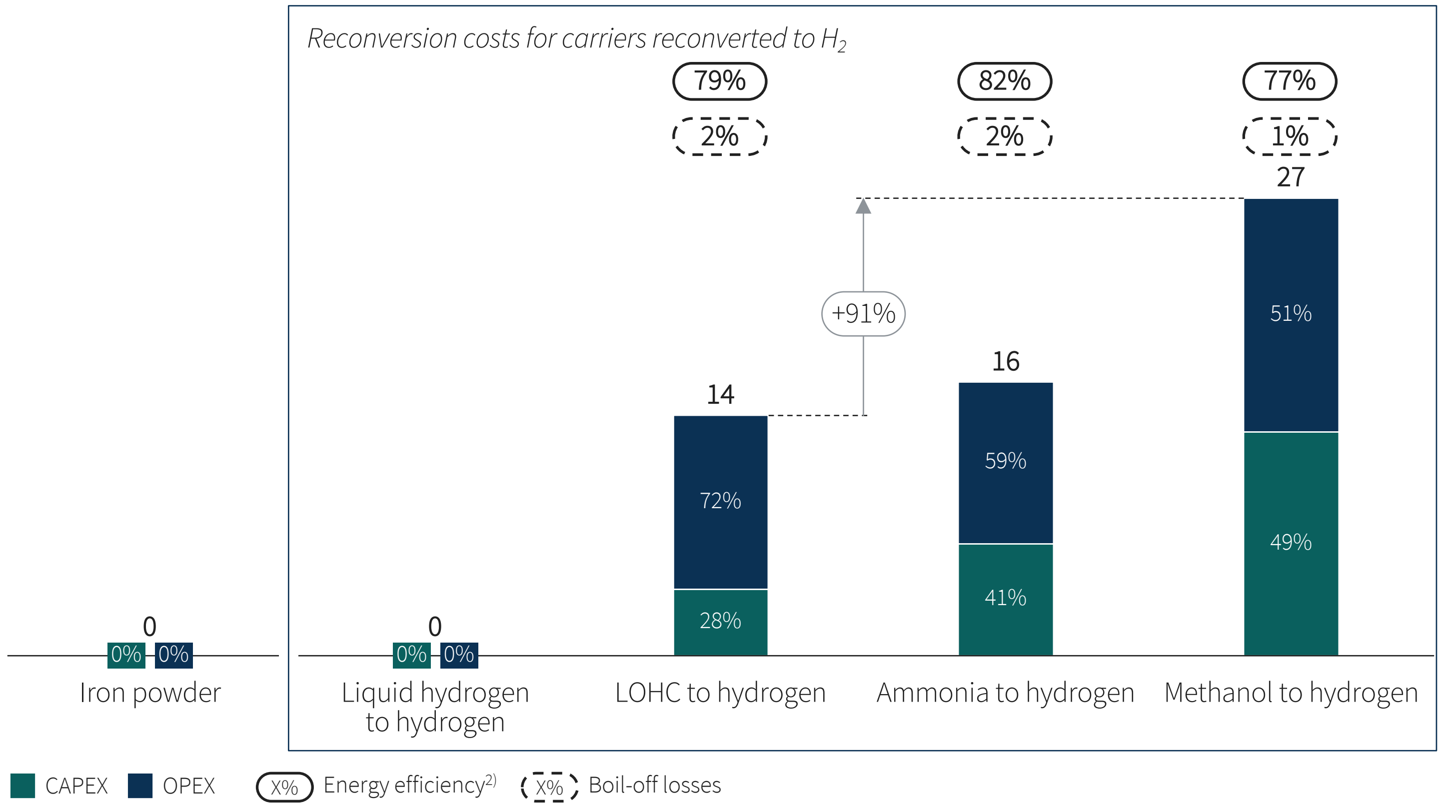
CALCULATIONS ARE BASED ON EXPECTED IRON POWER TECHNOLOGY EFFICIENCIES IN 2030, VALUE CHAIN SET-UP AND SCALE OF OPERATION

Iron powder does not require reconversion for process heat, avoiding a costly step (additional EUR 14-27/MWH for other carriers)

Reconversion carrier to H_2: Levelized[1)] cost comparison [EUR/MWh]

Key takeaways

- **Direct oxidation of iron powder** for process heat applications eliminates need for reconversion
- **Carrier reconversion to hydrogen is largely OPEX driven** due to large energy input requirements



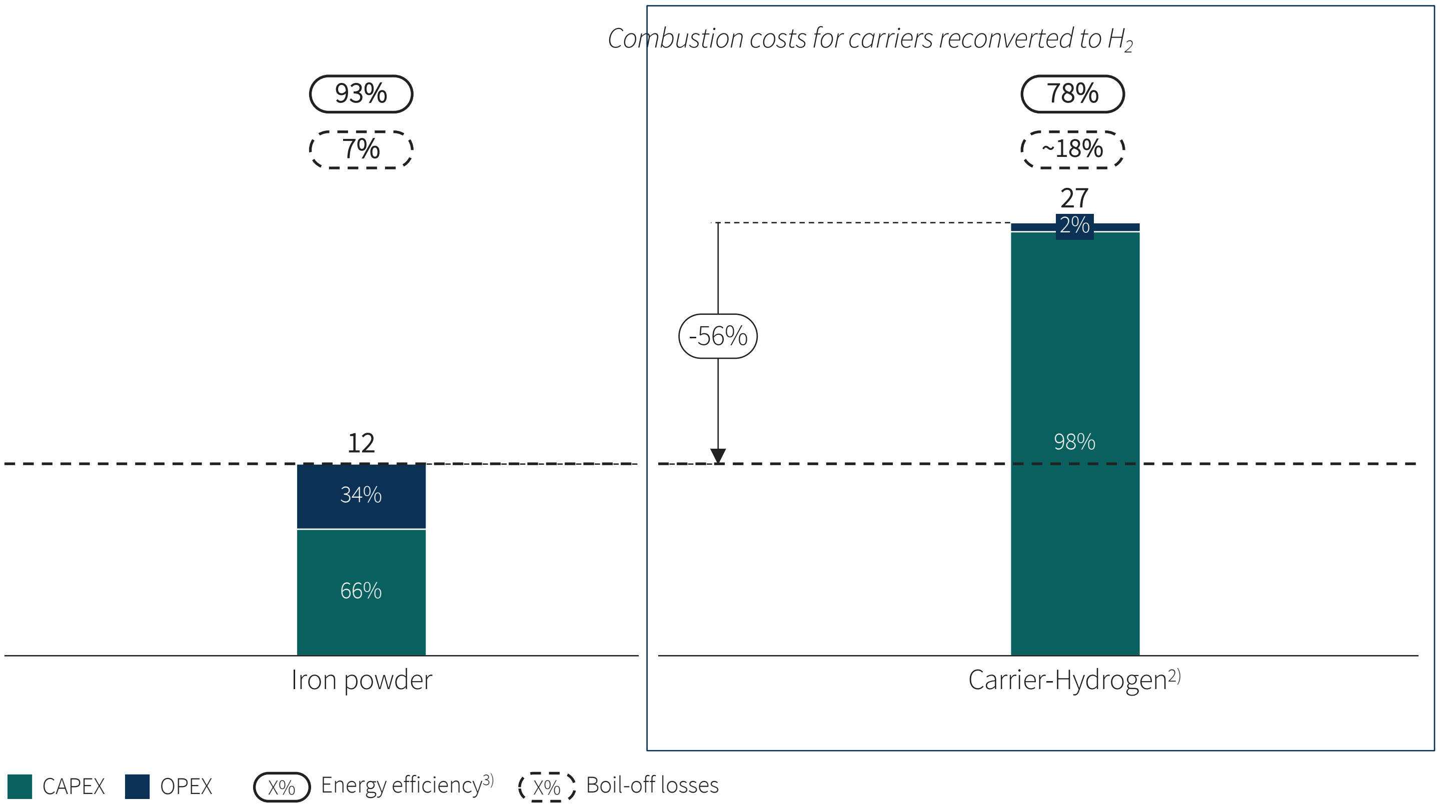
1) Levelized costs considers the costs per MWh output of the step; 2) Per step energy efficiency is calculated as MWh delivered after conversion step divided by (MWh input to conversion + energy input during process MWh)

Source: Irena, HyChain, HyDelta, Roland Berger research

CALCULATIONS ARE BASED ON EXPECTED IRON POWER TECHNOLOGY EFFICIENCIES IN 2030, VALUE CHAIN SET-UP AND SCALE OF OPERATION

Direct oxidation of iron powder is efficient and approximately 50-60% cheaper than carriers reconverted to hydrogen

Combustion: Levelized[1)] cost comparison [EUR/MWh]



Key takeaways

- **Hydrogen combustion is CAPEX driven** due to investment in retrofitting of existing boilers
- **Hydrogen combustion has low energy efficiency** due to large boil-off losses

1) Levelized costs considers the costs per MWh output of the step; 2) Includes carriers reconverted to hydrogen: LOHC, ammonia, methanol, liquid hydrogen; 3) Per step energy efficiency is calculated as MWh delivered after combustion step divided by (MWh input to combustion + energy input during process MWh)

Source: Irena, HyChain, HyDelta, Roland Berger research

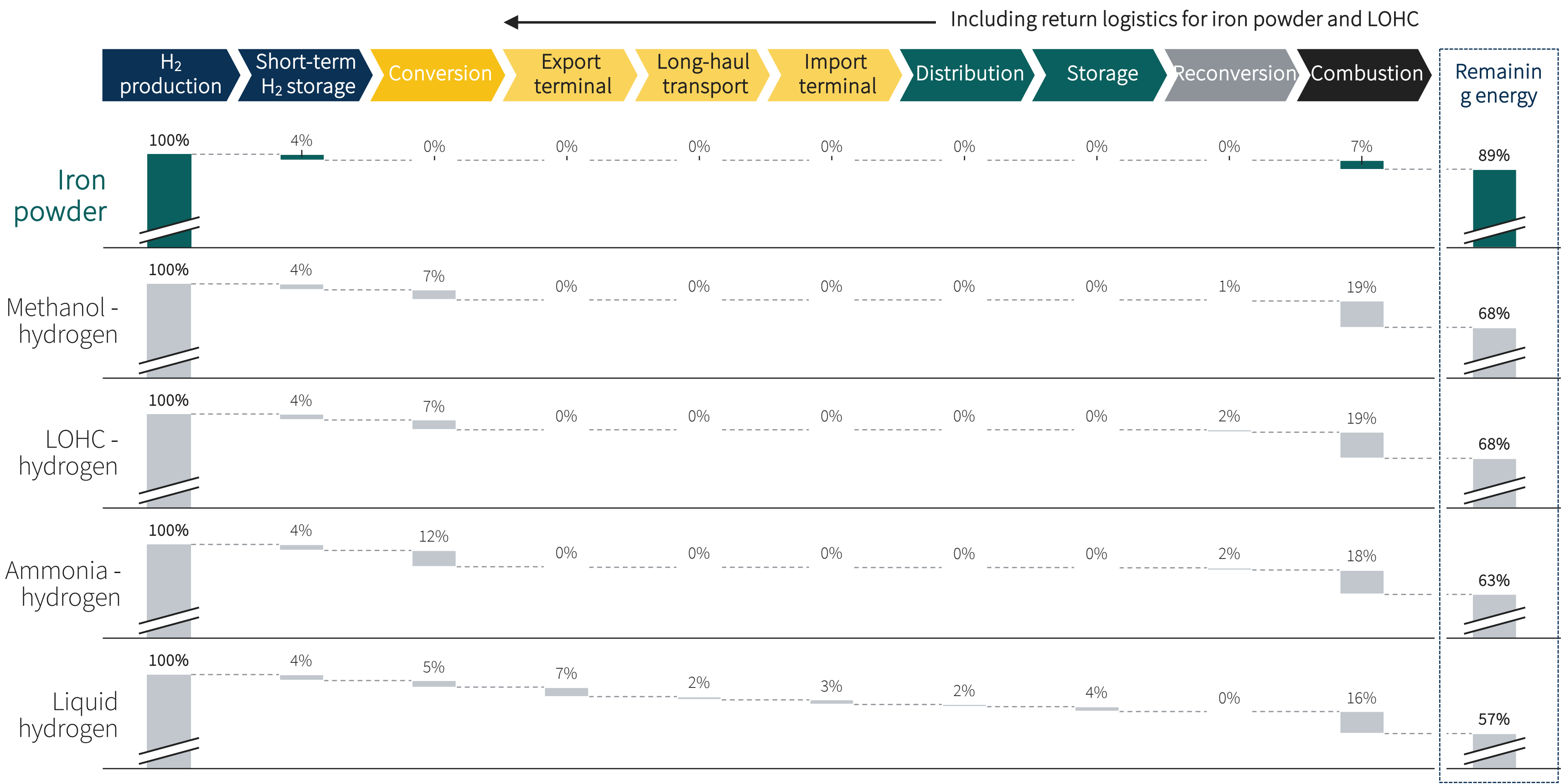
CALCULATIONS ARE BASED ON EXPECTED IRON POWER TECHNOLOGY EFFICIENCIES IN 2030, VALUE CHAIN SET-UP AND SCALE OF OPERATION

Iron powder has 20-30% higher remaining energy at combustion compared to reconverted carriers that have high boil-off losses at conversion and combustion

Boil-off losses [%] per value chain step

Key takeaways

- **Iron Power technology logistics** minimize energy losses, ensuring high energy retention in the value chain
- **Carrier conversion to H_2** results in substantial boil-off losses, especially for ammonia due to low efficiency
- **Combustion** of hydrogen associated with highest boil-off losses



Source: RIFT, HyChain 3, Irena

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