Direct reduction of steel with electrolytically produced green hydrogen – The Green Steel Route

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This is the contents

- Introduction: Motivation and solution approach
- State-of-the-art in science and technology
- Market analysis and plant concepts
- Characteristics of educts and products
- Process developmet
- Cost estimation and ecological assessment
- Evaluation of the procedure and outlook

Steel has a wide range of applications. There is a constantly growing demand for steel worldwíde

- According to the World Steel Association steel demand in 2021 was:

  Germany about 426 kg/person

  Russia about 306 kg/person

  China about 667 kg/person

- Decarbonization of all industrial branches required
- EU Green Deal: 55 % less CO_2 emissions until 2030
  - Traffic, industry, buildings
- Shut-down of coal and nuclear power plants
- Expansion of renewable energy plants: increasing the share of renewable electricity in the energy sector
- Promotion of hydrogen production and implementation in different sectors

There is a huge market potential for steel

Market 2020 -

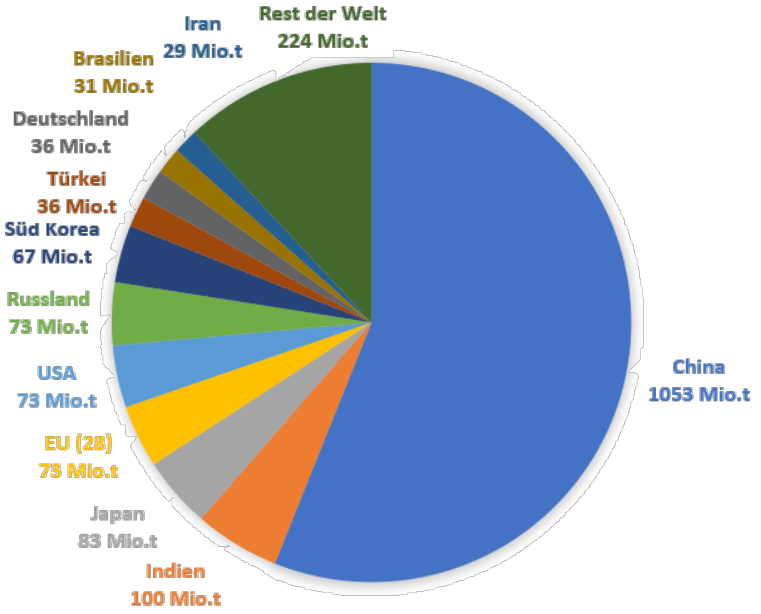
- Worldwide Produktion – 1.9 billion t/a
- Nowadays, most of the production takes place in China (57%)

  Total Asia – 75%

Global Players 2020

- China Baowu Group (CN)
- ArcelorMittal (NL)
- Nippon Steel & Sumitomo Metal Corporation (Japan)
- Shagang Group (CN)
- POSCO (South Korea)
- Mitsubishi Corp. (Japan)

Steel producing countries 2020



Raw steel production worldwide in 2020 [5]

But there is a problem…

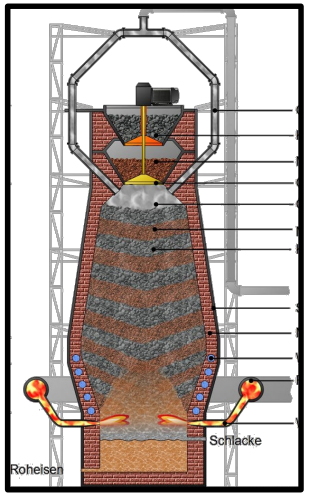
Approximately 70% of the steel produced in the EU comes from the blast furnace route that is based on coke

More than 80 percent of greenhouse gas emissions in the steel industry are caused in the primary stage during hot metal production

The remainder is mainly recycled from scrap in electric arc furnaces.

Blast furnace route:

- Emissions about 2-2.2 t CO_2 per ton steel (incl. agglomeration, iron and steel production, casting and hot rolling) = ca. 7% of the yearly global emissions.
- Release of harmful furnace gases: N_2 (45-60%), CO_2 (20-25%), CO (20-30%), and H_2 (2-4%)
- Energy intensive process → ca. 5-5.5 MWh/t raw steel



Höfler, A.: Direktreduktionsverfahren: Eisenwerk - tec-science, (17.09.2022)

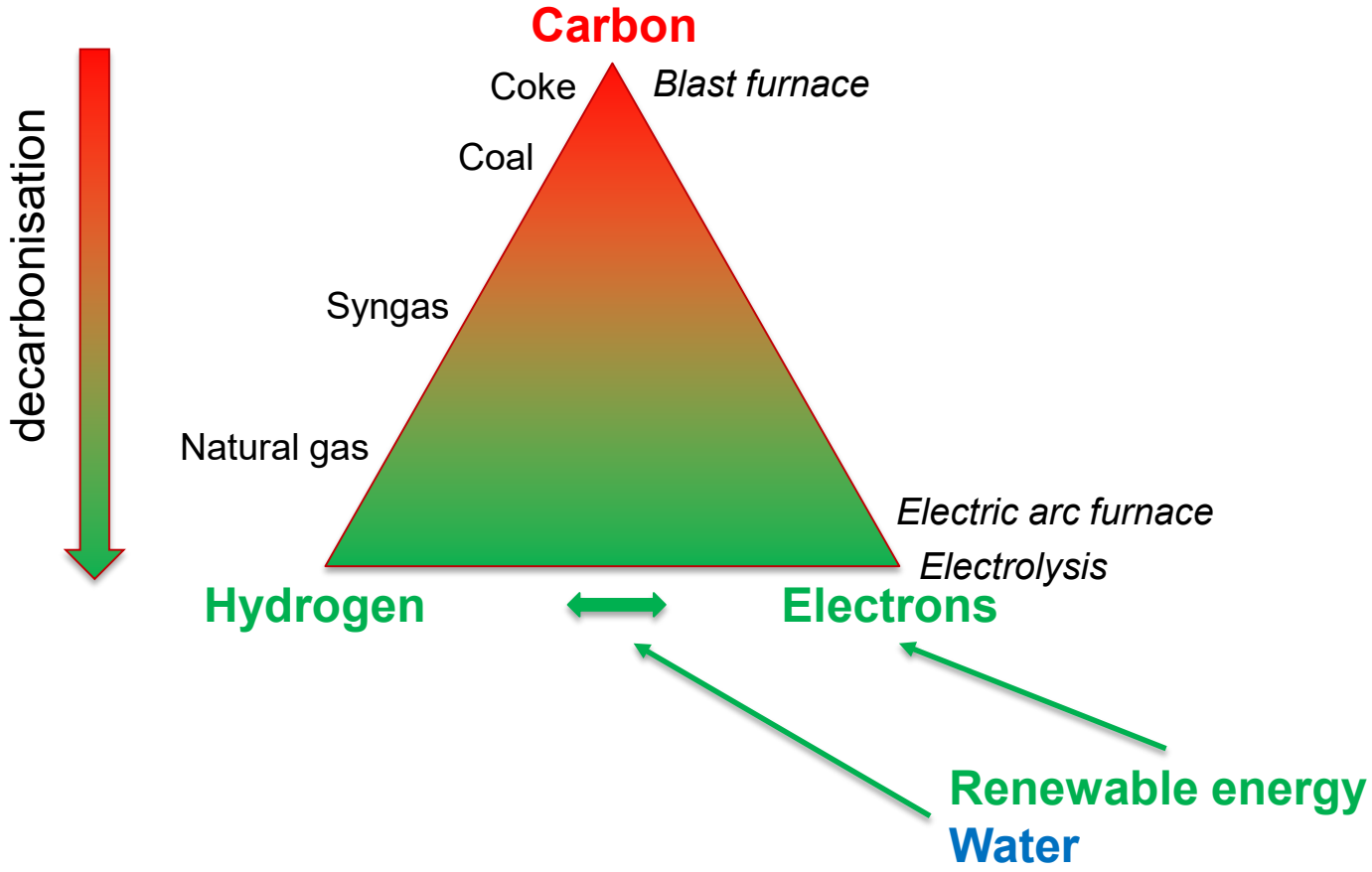
Solution approaches:

→ Smart Carbon Usage (SCU)

→ Carbon Capture and Storage (CCS)

→ **Carbon Direct Avoidance (CDA)**

Decarbonisation of the steel industry involves several options



modified: www.ulcos.org

In direct reduction, green hydrogen – instead of carbon - can be used as a reducing agent

Blast furnace

Coke as carbon source

CO as reducing agent

$C + O_2 \rightarrow CO_2 \qquad C + CO_2 \rightarrow 2\,CO$

$Fe_2O_3 + 3\,CO \rightarrow 2\,Fe + 3\,CO_2$

Direct reduction with green hydrogen

$0{,}5\,Fe_2O_3 + 0{,}5\,H_2 \rightarrow FeO + 0{,}5\,H_2O$

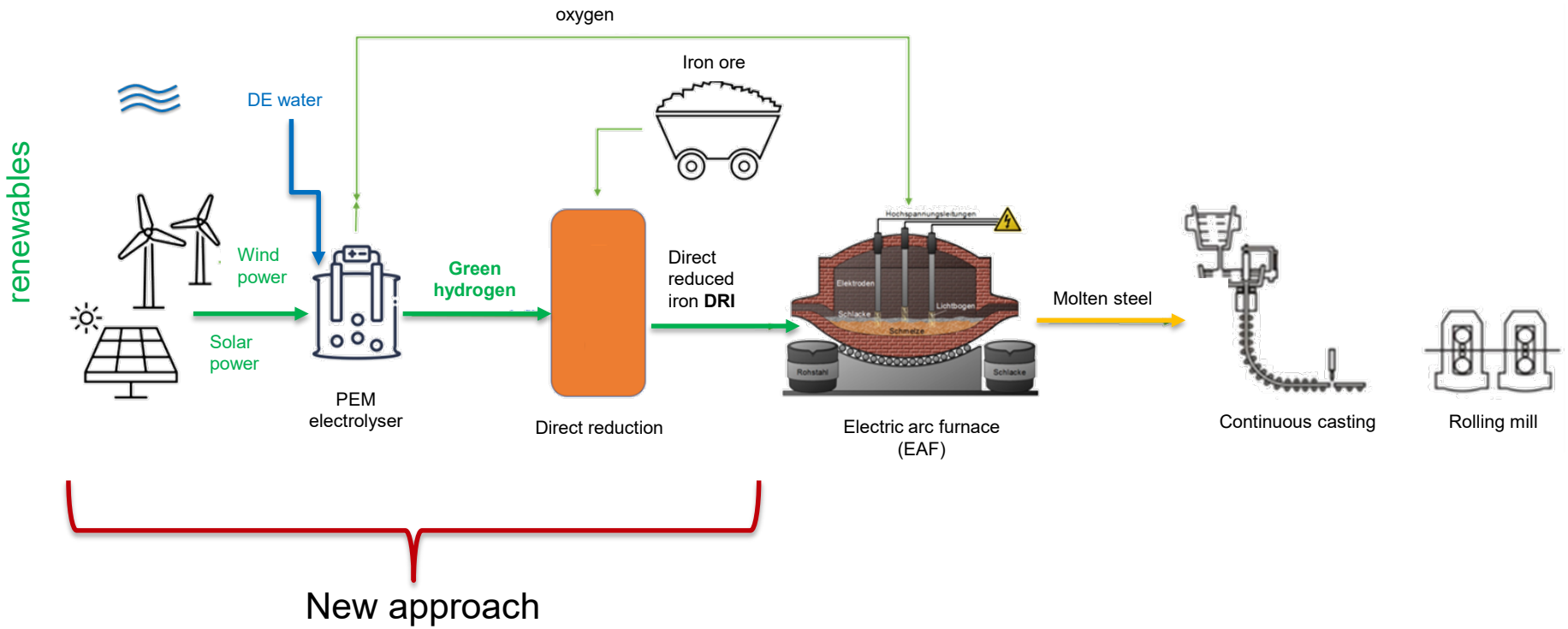
$FeO + H_2 \rightarrow Fe + H_2O$

Direct reduced iron (**DRI**)

Nearly no CO_2 emissions

$\Rightarrow$ Reduction of greenhouse gas emissions: ca. 97%

A new green steel approach that is being investigated on industrial scale is the direct reduction of iron ore with green hydrogen



Modified after: Höfler, A.: Direktreduktionsverfahren. [Online]: https://www.tec-science.com/de/werkstofftechnik/stahl- erzeugung-herstellung/direktreduktionsverfahren/, (12.09.2022).

Some projects are beeing implemented in Western Europe

- Planned plants for the production of green steel/DRI:

Company	Site	Planned capacity [Mio. t/a]	Investment [Mio. €]
ArcelorMittal	Bremen / G	2.4	1
Thyssenkrupp	Duisburg / G	1.2	7
Salzgitter	Salzgitter / G	1.0	3 - 4
Stahl-Holding-Staar	Saarland / G	2.0	3 - 4
H2 Green Steel / SMS	Boden / Sweden	2.1 (+2.1)	3 - 4
Voestalpine	Linz & Donawitz / A	-	-
Tata Steel	Ijmuiden (NL)	-	-

→ Production in Europe, initially starting in Germany

→ Competition weak - limited renewables capacities

The concepts are based on a combination of Power-to-Gas systems and direct reduction processes

- **Green energy production by PV & wind power:**

  Coverage of electricity demand (450 GWh/a) with 20% from PV systems and 80% from wind turbines

  Weather conditions in Germany: availability of wind power > than sun power

- **Water treatment systems:**

  Filtration, reverse osmosis, ion exchange, and UV disinfection

- **Application of an PEM electrolyser**

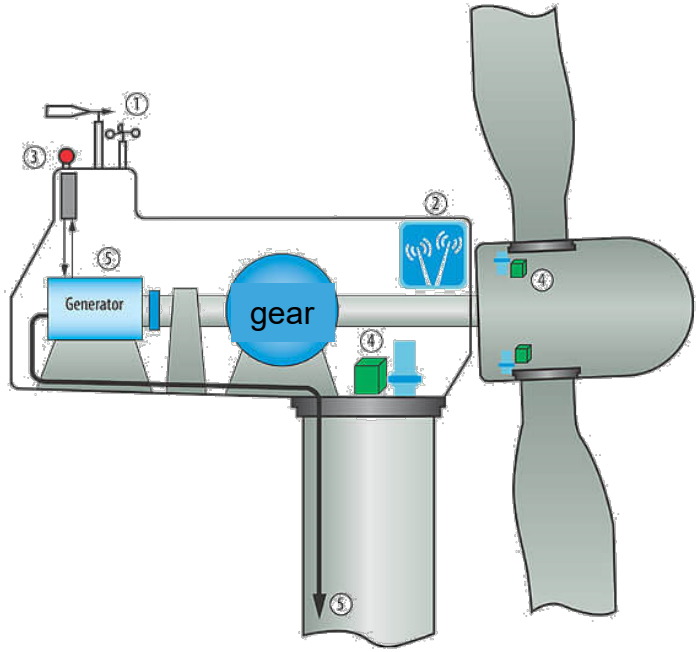
  Approx. 70 - 74 % efficiency, current density of 2 A/cm², power up to 10 MW

- **Direct reduction**

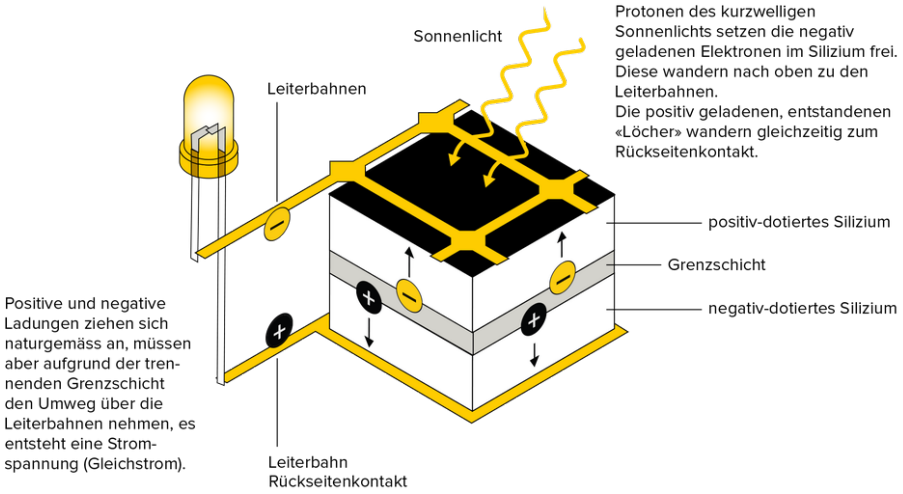
  Reduction of hematite pellets (Fe_2O_3) with hydrogen in a shaft furnace

  → Plant capacity initially set at 100,000 t/a

Function of renewable energy supply - integral parts of a wind power plant



Umweltretter: Wie funktioniert eine Windkraftanlage? [Online]: https://umweltretter.net/windkraftanlage/, (15.09.2022)



https://www.solarspar.ch/wie-funktioniert-photovoltaik/,

In **DE** 2020: **104.8 TWh wind energy**

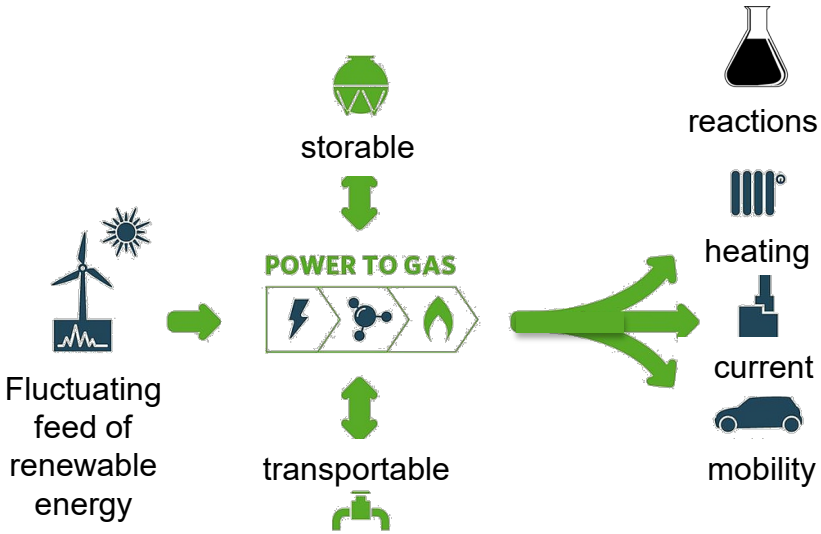
In **DE** 2020: **48.6 TWh PV electricity**

Renewable or climate-neutral green hydrogen is expected to be a key factor in the decarbonisation of different sectors

Power-to-Gas (PtG) is the central coupling element between electricity and gas infrastructure

PtG: Gases, such as hydrogen or methane are generated from electricity-based and CO_2 free processes

- **Integration** of renewable energy sources to optimize energy supply systems, whereby economic efficiency, sustainability and security of supply can be ensured
- **balancing** of the volatile generation capacity of renewable power generation plants



Ways to use a power-to-gas system

Zukunft Erdgas e.V.: Was versteht man unter Power-to-Gas (PtG)? [Online]: https://www.energie-experten.org/erneuerbare-energien/oekostrom/sektorkopplung/power-to-gas, (10.09.2022)

Up to now, the production of green hydrogen has not been economically competitive with hydrogen, which is produced from fossil fuels by means of steam reforming

The main reasons for this situation are

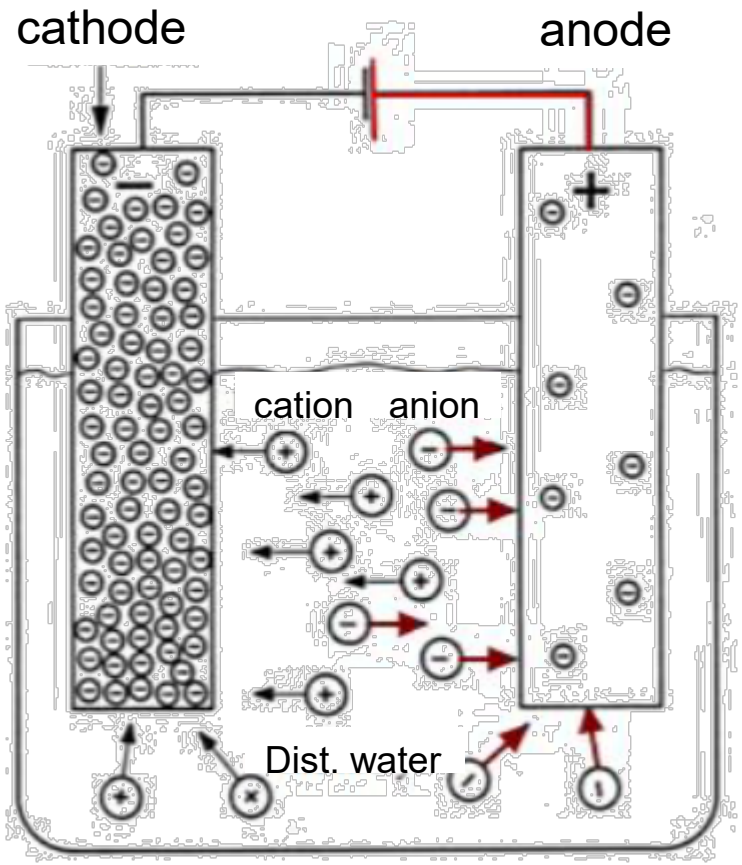
- the **high cost of electricity** from renewable energy sources,
- **low efficiency** of commercial electrolyzers.

Current state-of-the-art electrolyzers have an electricity requirement of about **53 kWh** for the production of 1 kg of hydrogen.

- about 47.5 kWh required by the actual conversion process,
- about 5.5 kWh required to supply the technical systems.
- ⇒ The energy efficiency achievable through these processes is around 83% [Hodges, 2022].

The stated goal of the International Renewable Energy Agency (IRENA) is to achieve an energy consumption for the production of **< 42 kWh** / 1 kg of hydrogen by 2050 [IRENA, 2020]

This graph depicts the function of an electrolyser for water splitting



- **Water splitting**

$$H_2O\ (l) \rightarrow H_2\ (g) + \frac{1}{2}\ O_2\ (g)$$

$$\Delta H = 285\ \mathrm{kJ/mol}$$

- **Minimum voltage [V]**

$$U_0 = \frac{\Delta G^0}{F \cdot z}$$

Minimum voltage U_0= 1.23 V required, as the water molecule can only be split up at 4.700 K

Kurzweil, P.: Polymerelektrolyt-Brennstoffzelle, Brennstoffzellentechnik, in: Kurzweil, P. (edit.): Angewandte Elektrochemie. Grundlagen, Messtechnik, Elektroanalytik, Energiewandlung, Technische Verfahren. Amberg: Springer Vieweg, S. 77–143, 2020b

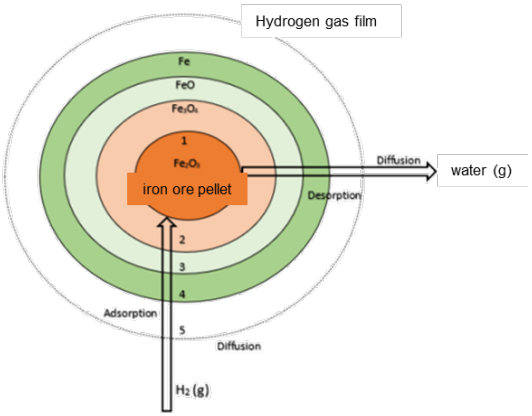
Reaction system

- Non catalytic gas / solid phase reaction:

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

$$\Delta_R H = +96{,}2\ \mathrm{kJ/mol}$$

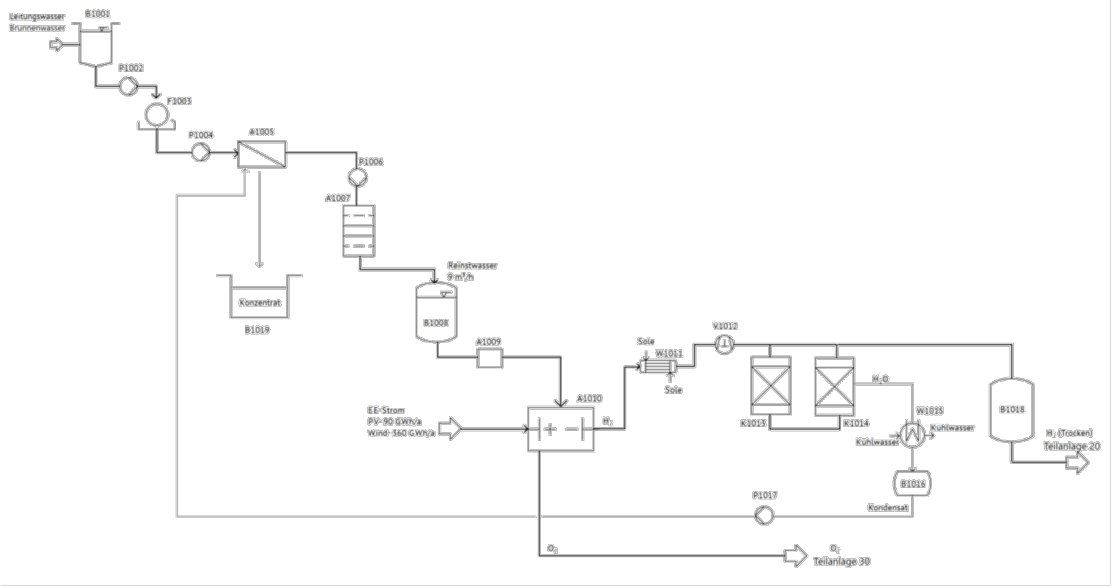
$$\Delta_R G = +87{,}1\ \mathrm{kJ/mol}$$



- Reactor design: Isothermal fixed bed reactor with conical discharge
  - → Reactor number / diameter: 1 / 5 m
  - → Reaction temperature / ΔT_{ad}: 900 °C / 2.000 K
  - → Reactor pressure: 5 bar

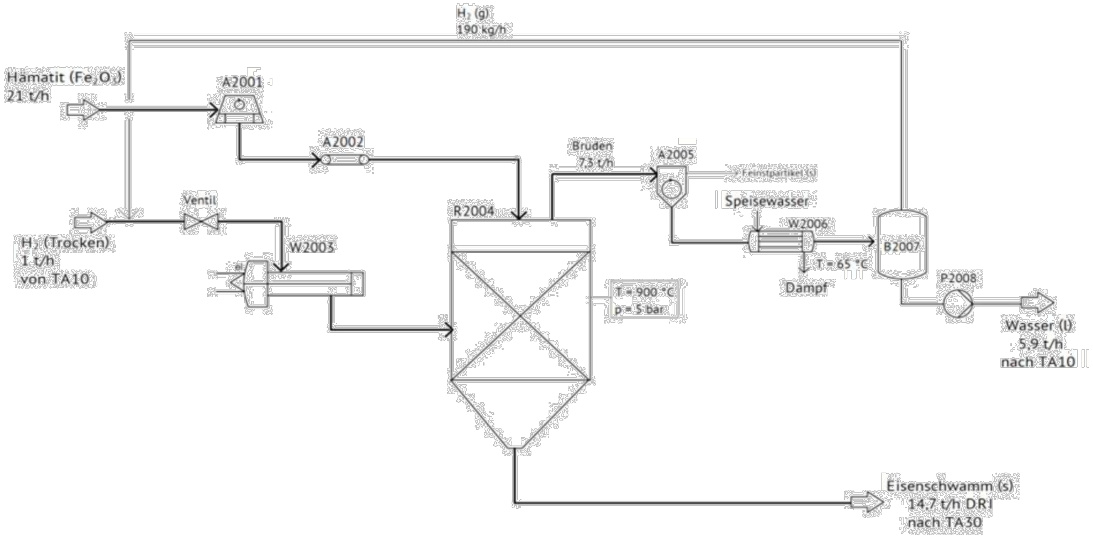
Bhaskar, A.; Assadi, M., Nikpey Somehsaraei, H.: Decarbonization of the Iron and Steel Industry with Direct Reduction of Iron Ore with Green Hydrogen: Energies, Vol. 13, No. 3, S. 1–23, 2020

We calculated the process



periphery

DRI reactor



Final balance

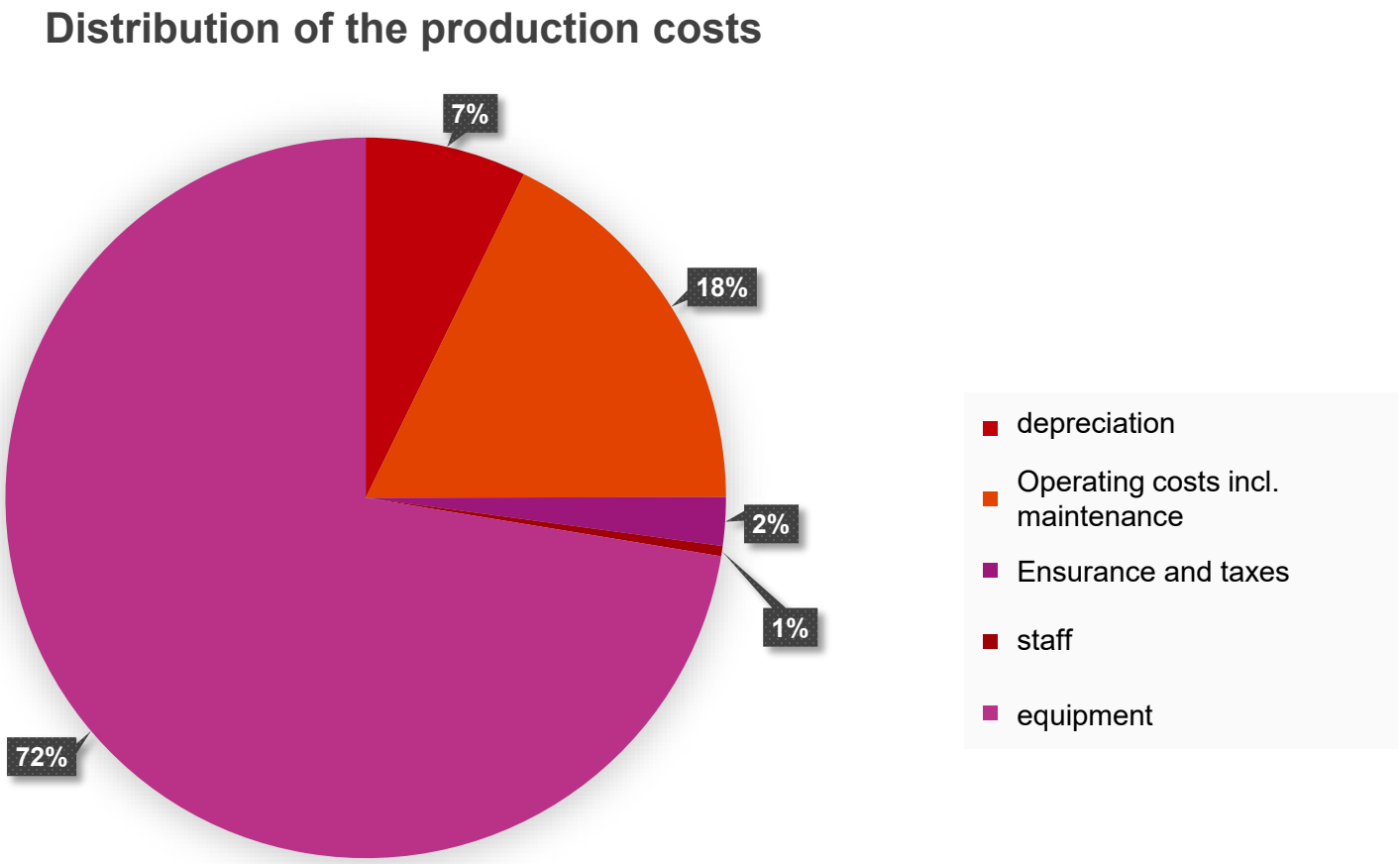


Abb. 19 – Ermittlung der Produktionskostenverteilung für die Teilanlage 10 und 20

The evaluation of the process showed following data

Parameter	Unit	Blast furnace	Natural gas DRI	H_2 DRI
Reducing agent	-	Coal / coke	Syn gas (CO/H_2)	Hydrogen (H_2)
Energy demand	GJ/t_{steel}	20 - 31	10 - 11	12.5 - 14
Production costs	$€/t_{steel}$	800 – 1,000	700 – 1,000	4,000-7,000
CO_2 emission	tCO_2/t_{steel}	1.8 - 2	1.2	0.25

Comparison of reduction processes with direct reduction by hydrogen or natural gas

Revenue 2022: 700 €/t Stahl
Emission allowances
- 2021 25 €/t CO_2
- 2022 30 €/t CO_2
- 2023 30 €/t CO_2
- 2024 35 €/t CO_2

The Green steel route...

- ✓ Generates a product of high purity (99%)
- ✓ Allows the production and exploitation of green energy and green hydrogen
- ✓ Coupling of different industrial sector– Decentralisation of production steps and more flexible reduction possible
- – Production costs very high (min. 4.000 €/t)

Further investigations

- Influence of raw material composition and reaction time
- Influence of pellet particle size on the reduction grade
- Evaluation of the potentials of hydrogen production on EU level and formation of international partnerships
- Integrative concepts, like seawater electrolysis and application of powdery ores
- Ecological footprint?

Thank you for your attention!

Do you have any questions?

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