Fossil-free steel production ready for industrialisation

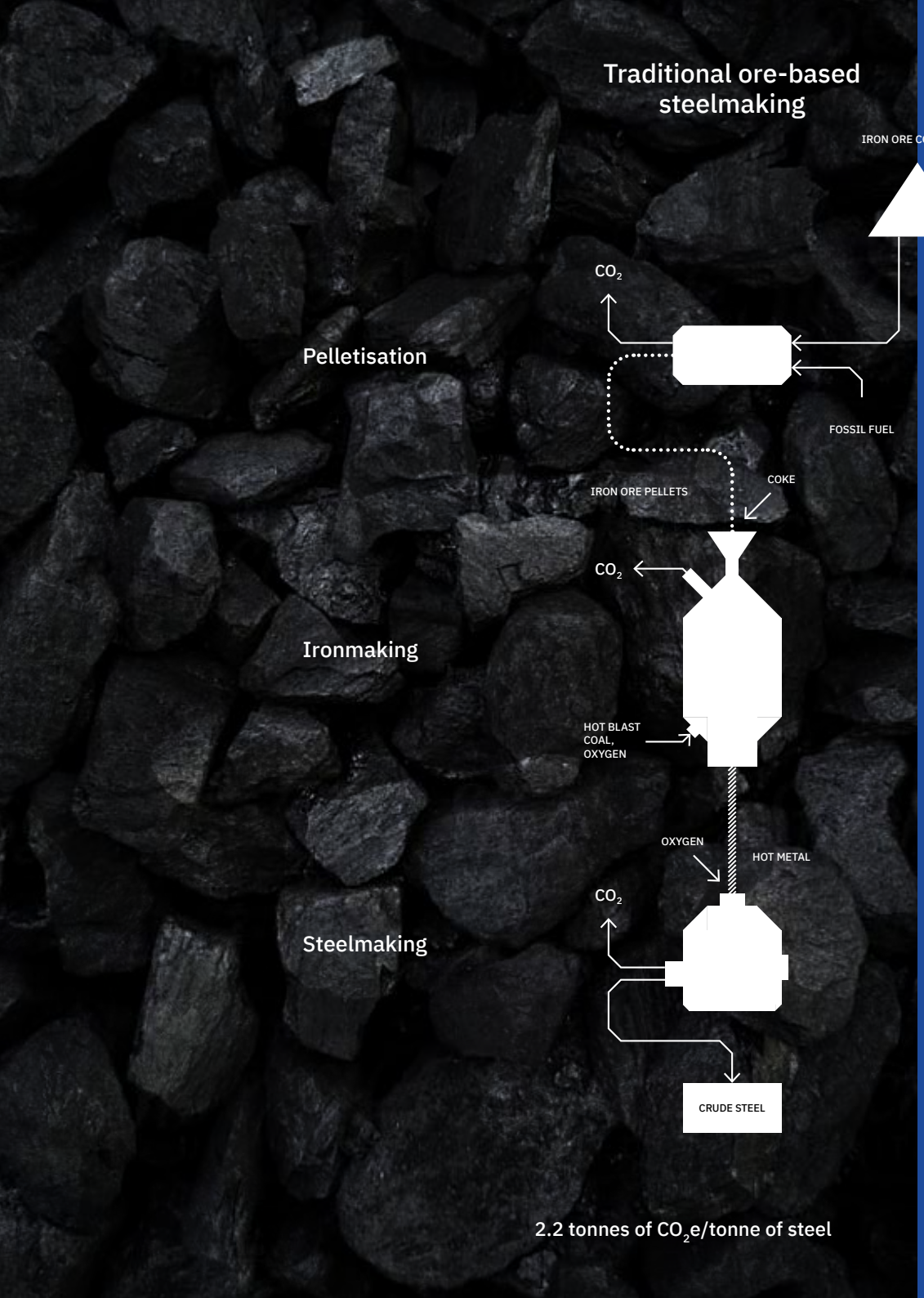
The technology to eliminate more than 10% of Sweden's CO_2 emissions is now available.

HYBRIT

SSAB LKAB VATTENFALL

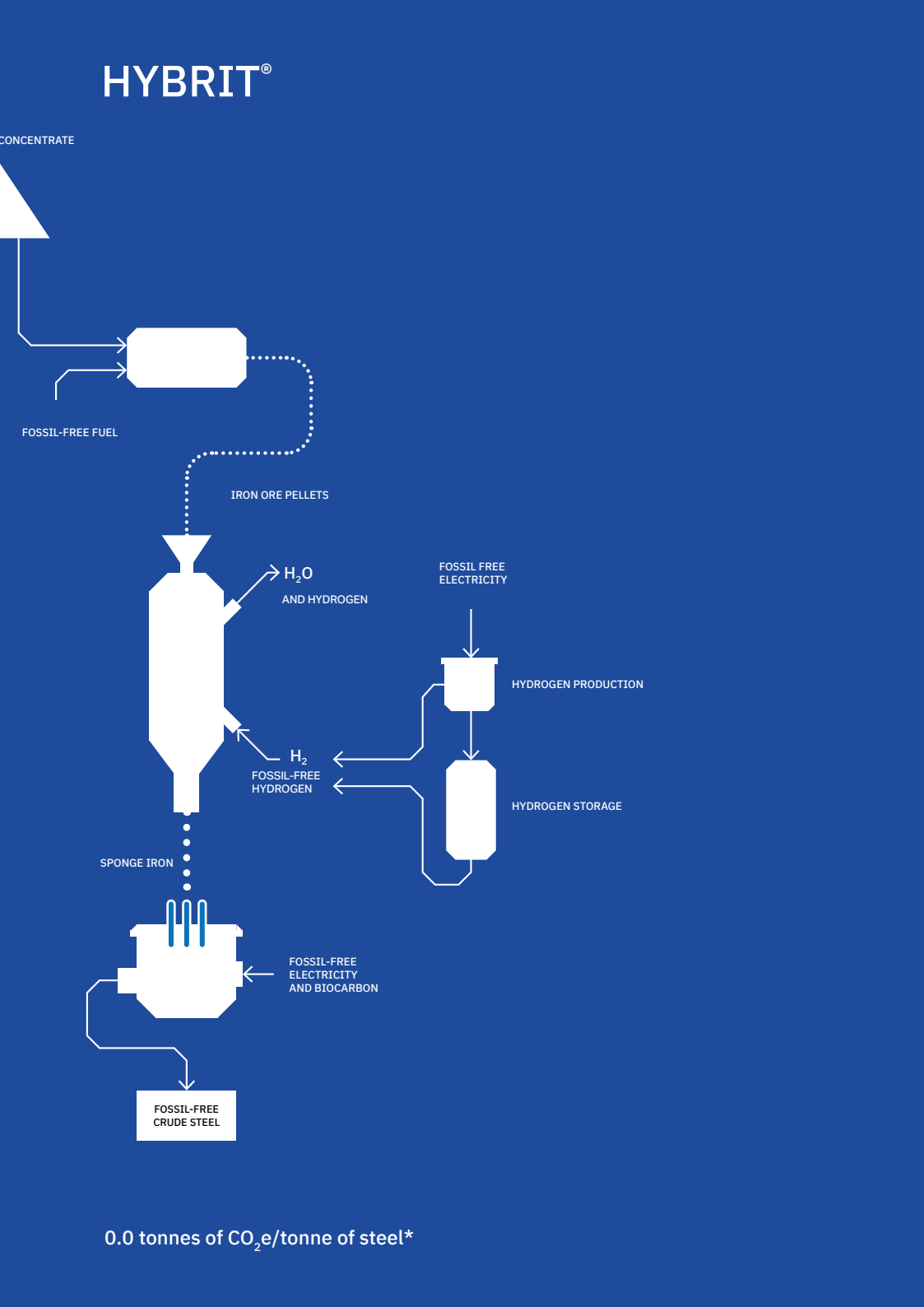
August 2024
Hybritdevelopment.se

Traditional ore-based steelmaking



2.2 tonnes of CO_2e/tonne of steel

HYBRIT®



0.0 tonnes of CO_2e/tonne of steel*

HYBRIT® eliminates CO_2 from the iron and steel industry

The steel industry accounts for a large share of industrial carbon dioxide emissions, equivalent to 7% of global emissions and at least 10% of Swedish emissions. Europe's and Sweden's national climate targets clearly show the way – a transition of the industry is needed to reach net zero greenhouse gas emissions by 2045.

Today's steelmaking in blast furnaces relies on fossil coal to provide energy and to reduce iron oxide to pure iron. The blast furnace process accounts for around 85-90% of total carbon dioxide emissions in ore-based steelmaking.

In the HYBRIT process, iron ore pellets are reduced to iron using only hydrogen gas without the use of fossil carbon. The iron has a porous structure and is known as sponge iron, direct reduced iron or DRI (Direct Reduced Iron). The residual product from the process is water.

0.0

tonne CO_2e/tonne of steel*

* The process produces small emissions of carbon dioxide from the consumption of graphite electrodes and the addition of slag formers in the electric arc furnace. These emissions are less than 0.05 tonnes of CO_2e/tonne of steel which is rounded to 0.0 tonnes of CO_2e/tonne of steel. Typical value for ore-based steelmaking with blast furnace technology is 2.2 tonnes CO_2e/tonne of steel.

Focus on technology development for industrial scale

The most extensive of HYBRIT's pilot projects is now coming to an end. The project has run from 2018 until summer 2024 and included hydrogen-based direct reduction of iron ore, hydrogen production by electrolysis of water and production of crude steel by melting sponge iron in an electric arc furnace.

HYBRIT's process concept is founded on research results linked to existing technologies for iron and steel production. At the same time, a new hydrogen-based value chain requires new knowledge of process principles that can lead to changes in current technology solutions.

The focus of HYBRIT's technical development has been to build up expertise and to set the technical prerequisites in place for implementing HYBRIT's fossil-free process in full-scale production.

Development and testing on a semi-industrial scale – so-called pilot development – have played a central role. Large parts of the development work have been carried out in facilities that correspond to full-scale industrial production environments in terms of both equipment and process control, but with lower production capacity. The development has had a broad scope where each process step in HYBRIT's process chain has been investigated.

Main results:

- HYBRIT has developed technology that enables efficient fossil-free steel production – 0.0* tonnes of CO_2e/tonne of steel (Scope 1 and Scope 2). *See footnote on page 3.
- The choice of process settings and technologies has been validated through pilot scale trials throughout the value chain from ore to steel.
- The value chain is based on a new sponge iron product with unique properties.
- No new technical obstacles have been identified. The results pave the way for further development and implementation of the HYBRIT technology on an industrial scale.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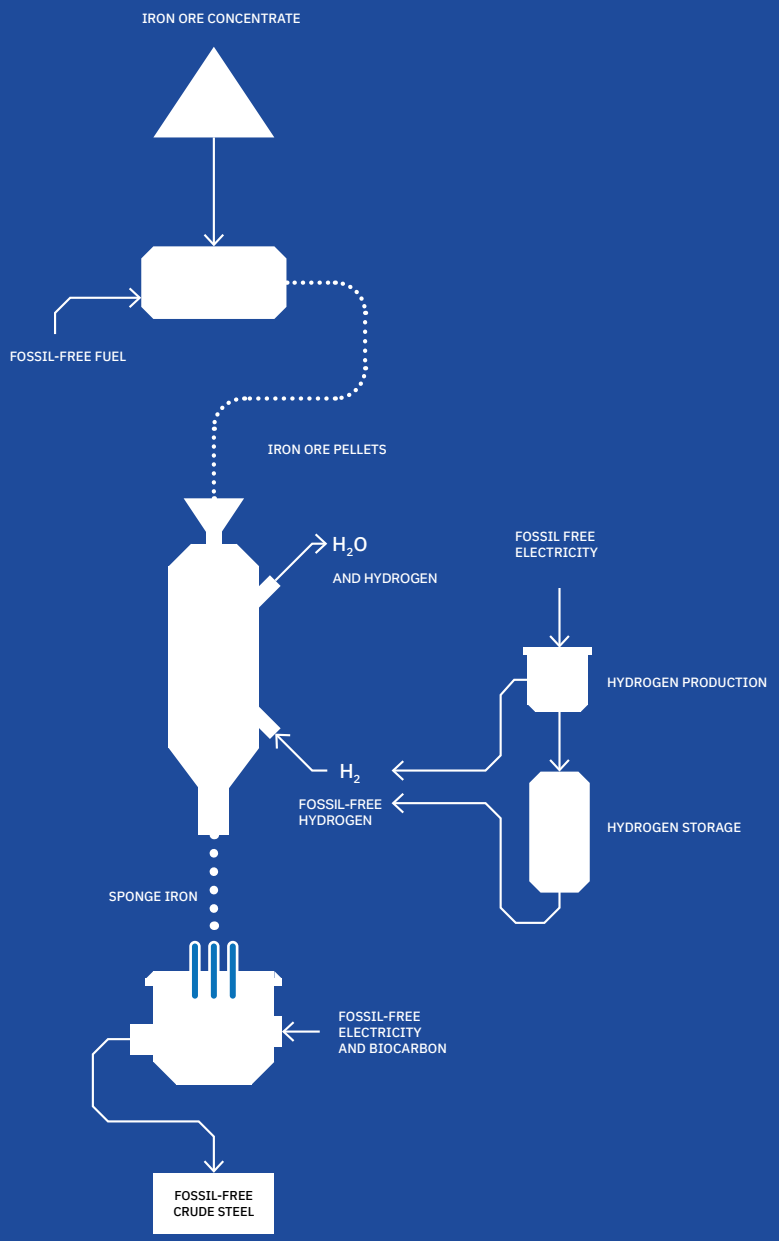
HYBRIT®


IRON ORE CONCENTRATE
FOSSIL-FREE FUEL
IRON ORE PELLETS
H_2O
AND HYDROGEN
FOSSIL FREE
ELECTRICITY
HYDROGEN PRODUCTION
H_2
FOSSIL-FREE
HYDROGEN
HYDROGEN STORAGE
SPONGE IRON
FOSSIL-FREE
ELECTRICITY
AND BIOCARBON
FOSSIL-FREE
CRUDE STEEL

Verified development at each step

Fossil-free production of iron ore pellets

The manufacturing process for fossil-free iron ore pellets has been developed at LKAB's pellet plant in Malmberget during 2020-2021. The fossil fuels have been replaced with bio-oil, which is 100% renewable. See page 16 for more information.

Hydrogen-based direct reduction on a semi-industrial scale

A pilot plant for the direct reduction of iron ore with hydrogen was commissioned in Luleå in the autumn of 2020. In the spring of 2021, the first fossil-free sponge iron was produced where iron ore was reduced with pure hydrogen as reduction agent. See page 8 for more information.

A carbon-free iron product provides a competitive iron and steel value chain

Developing a competitive value chain from ore to steel has been a central focus of HYBRIT's work. This has been achieved by consolidating and integrating results from the various process steps in the chain. The analysis shows that carbon-free direct reduced iron is well suited for industrial application in SSAB's and LKAB's production systems. See page 10 for more information.

Melting of fossil-free iron raw material in an electric arc furnace in co-operation with Swerim

HYBRIT, in collaboration with the research institute Swerim, has developed an efficient and fossil-free process for melting fossil-free iron raw material into crude steel in an electric arc furnace. The experiments show that the fossil-free melting process produces steel that is of the same quality as today's fossil ore-based steel. See page 14 for more information.

Hydrogen production and storage

HYBRIT's pilot plant in Luleå has electrolysers for the production of hydrogen for the reduction process. The electrolysers also supply hydrogen to the hydrogen storage pilot plant at Svartöberget in Luleå. The pilot storage facility was commissioned in the summer of 2022 and is used to validate the process and technology for a large-scale storage of hydrogen in an underground steel-enclosed rock cavern. See more on page 19.

Industrial process practice established

Efficient use of raw materials and energy has been a key development focus for HYBRIT. During the pilot phase, an optimised process practice has been established, confirming that the process is equal or better in terms of energy efficiency, resource utilisation and safety compared to the iron and steel industry's standards. See more on page 20.

Innovation on time and within budget

Within a relatively short period of time, HYBRIT has developed extensive technical expertise and knowledge regarding the HYBRIT process and fossil-free technology. The pilot project has delivered development results in accordance with high expectations, on time and within budget. The cooperation between different organisations has been crucial to the success.

From iron ore pellets to iron with hydrogen

In HYBRIT's direct reduction process, iron ore pellets are converted into iron using only hydrogen.

- Iron ore pellets are fed into the top of a shaft furnace and the bed of pellets slowly moves downwards. An upward stream of hot hydrogen gas reacts with the oxygen in the pellets and leaves the shaft at the top as water vapour.
- The reduced iron does not melt but remains in its solid original pellet form.
- The product leaves the shaft in either hot or cold condition. Hot sponge iron can be compacted into briquettes.

Direct Reduced Iron (DRI) pellets and Hot Briquetted Iron (HBI) briquettes.

Pilot trials for direct reduction

- Tests in the pilot plant are run around the clock for periods of 6-8 weeks at a time. The total time for testing until 2024 is 61 weeks.
- Reduction of iron ore pellets using only hydrogen has accounted for 75% of the operating time in the pilot so far.
- The mechanisms of the process have been characterised by testing 175 different process states.
- Sponge iron has been produced for extended periods under stable process conditions. More than 5000 tonnes of fossil-free sponge iron have been produced so far.

A validated process concept has been delivered to LKAB and SSAB for full-scale implementation.

The technology behind direct reduction

Hydrogen reduction differs from reduction based on natural gas, for example in terms of the reduction chemistry and the heat conversion (thermodynamics) of the process. The knowledge gained from HYBRIT's development work has led to a process that is fossil-free, energy-efficient and produces sponge iron of very high quality – 98-99% degree of metallisation and 0% carbon.

In the pilot scale trials, different process conditions have been evaluated. Different composition and temperatures of the reducing gas have been tested. The pressure and residence time in the shaft have also been varied.

Process steps linked to hydrogen-reduced iron have been developed and compared with the corresponding steps for natural gas-based products. Examples include passivation of DRI and briquetting to HBI to make the product less reactive. Different methods for fossil-free heating of the reduction gas have been evaluated, with tests of gas-fired and electric heaters and partial combustion with oxygen.

Sampling of the sponge iron can also be done from the inside of the reduction shaft when the plant is in a safe state.

HYBRIT makes fossil-free iron and steel a reality

Our results on a semi-industrial scale show that HYBRIT enables a radical step towards eliminating CO_2 emissions from iron and steel production.

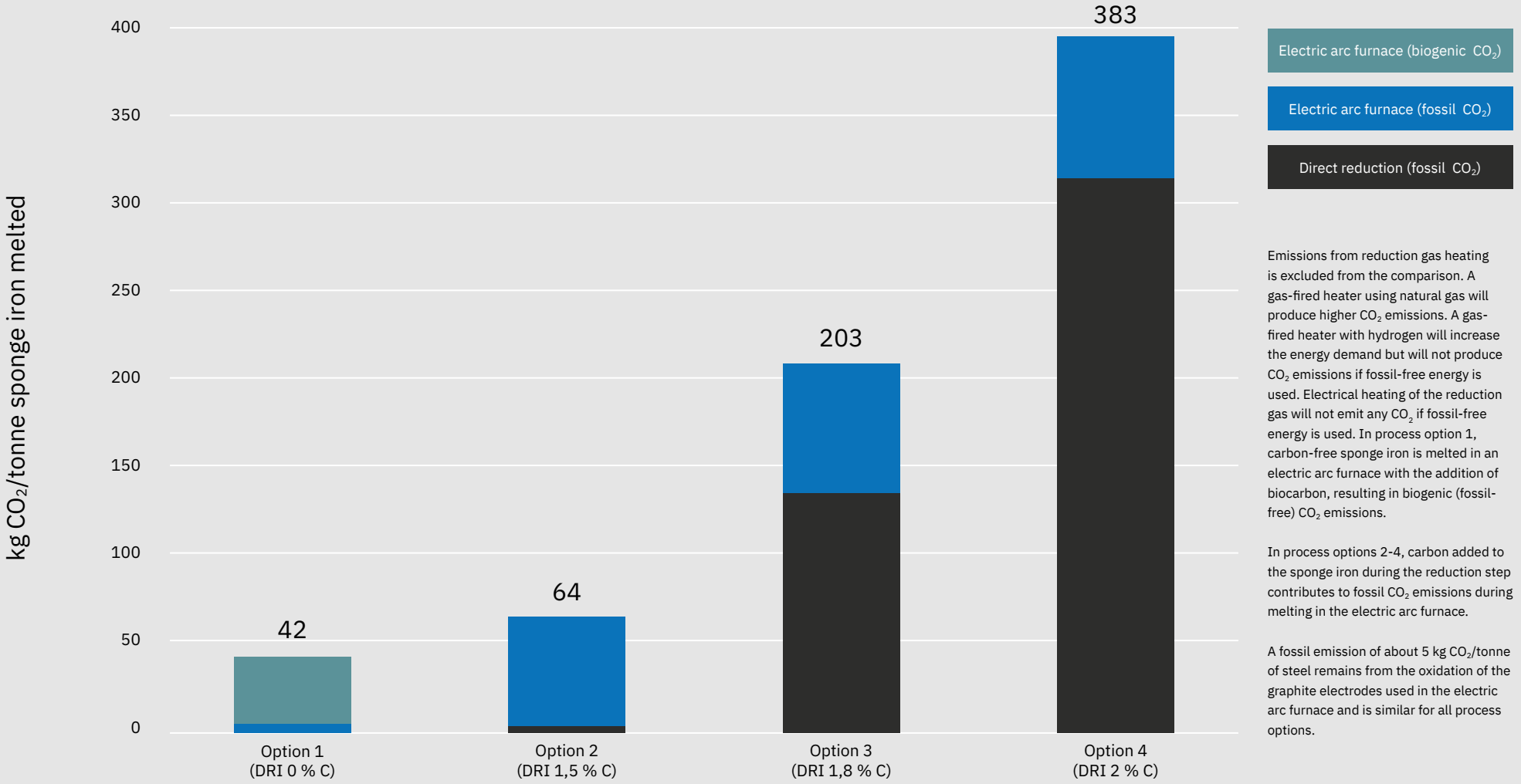
A large number of trials at the pilot plants for direct reduction and electrical arc furnace melting have provided experimental results so that CO_2 emissions for different process options can be compared in a selected area of the value chain (direct reduction to melting in EAF). Representative examples are the following:

1. Direct reduction of iron ore pellets using hydrogen only. Biocarbon is fed to the electric arc furnace during the melting of the sponge iron. **This is the main option of the HYBRIT process.**
2. Direct reduction of iron ore pellets using hydrogen only, but the sponge iron is carburised after the reduction step using, for example, natural gas.
3. Direct reduction of iron ore pellets using mainly hydrogen, but the sponge iron is carburised during the reduction process as a small amount of natural gas is added to the hydrogen.
4. Direct reduction of iron ore pellets using conventional technology based on natural gas.

The overall value chain analysis shows that the best overall efficiency is achieved when the iron ore is reduced with hydrogen in the reduction step and then melted into crude steel together with a minimal biocarbon addition in the electric arc furnace (process option 1).

The diagram shows results for the biogenic and fossil carbon dioxide emissions of the process options broken down into the direct reduction step and melting in an electric arc furnace. The typical value for ore-based steel production using blast furnace technology is 2200 kg CO_2e/tonne of steel.

CO_2 emissons from trials in pilot scale for direct reduction and melting in EAF.



Emissions from reduction gas heating is excluded from the comparison. A gas-fired heater using natural gas will produce higher CO_2 emissions. A gas-fired heater with hydrogen will increase the energy demand but will not produce CO_2 emissions if fossil-free energy is used. Electrical heating of the reduction gas will not emit any CO_2 if fossil-free energy is used. In process option 1, carbon-free sponge iron is melted in an electric arc furnace with the addition of biocarbon, resulting in biogenic (fossil-free) CO_2 emissions.

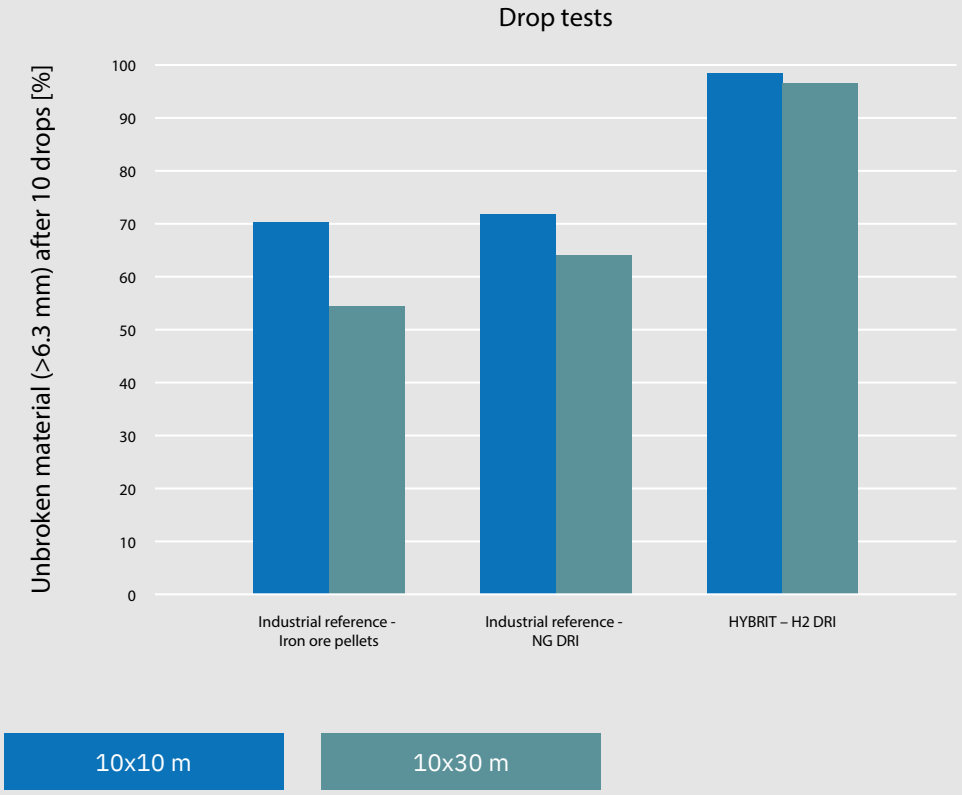
In process options 2-4, carbon added to the sponge iron during the reduction step contributes to fossil CO_2 emissions during melting in the electric arc furnace.

A fossil emission of about 5 kg CO_2/tonne of steel remains from the oxidation of the graphite electrodes used in the electric arc furnace and is similar for all process options.

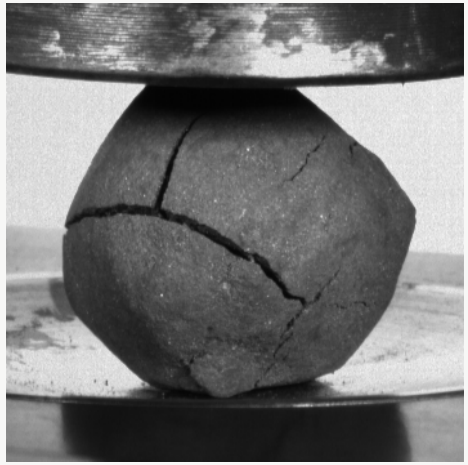
New sponge iron product with unique properties

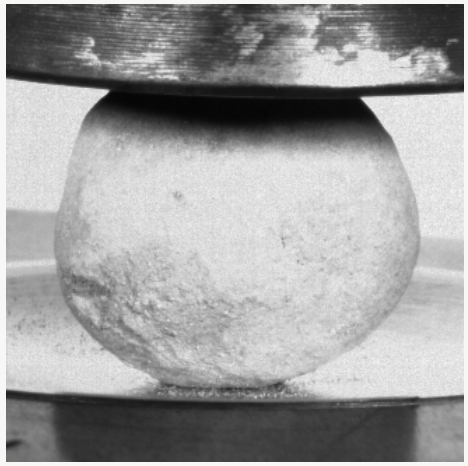
Sponge iron pellets reduced with hydrogen have significantly better transport, storage and melting properties compared to sponge iron reduced with conventional natural gas-based processes.

- Low iron oxide content and 0% carbon give the sponge iron robust mechanical properties. The product is resistant to mechanical pressure, abrasion and drops. Therefore, losses during handling and transport of the product are minimised.
- Tests also show that the product has very good and stable chemical properties. The material ages very slowly when handled properly and can therefore easily be stored for a longer time.
- A high degree of metallisation (98-99%) means that there is very little iron oxide remaining. This implies reduced losses in the value chain and results in lower energy consumption in the melting step.



Drop tests have been developed and the results have turned out to be good indicators for mechanical strength. Sponge iron reduced with only hydrogen performs better in drop tests from 10 and 30 meters compared to industrial refence material.





Sponge iron pellets reduced with hydrogen have a high degree of metallisation (98-99%) and 0% carbon. Measurements show that they have higher compressive strength than pellets produced with natural gas.

Melting of carbon-free sponge iron into fossil-free steel

HYBRIT has developed a safe, robust, productive and energy-efficient fossil-free process for the production of high-quality crude steel. The process has been verified on a pilot scale by melting HYBRIT's sponge iron in Swerim's 10-tonne electric arc furnace in Luleå.

The sponge iron is fed into the furnace along with slag formers, biocarbon and oxygen gas and is melted by heat generated with fossil-free electricity via electrodes dipped in the slag.

Slag formers are added both to purify the steel and to form an insulating 'blanket' that maximises energy efficiency and protects the liquid steel from contamination.

To minimise electrode consumption and maximise energy efficiency and productivity, biocarbon and oxygen are added, which together with the slag form an emulsion, a so-called foaming slag.

The development has been carried out by testing a variety of raw material properties, additive methods, process configurations and process settings.

Pilot trials in Swerim's electric arc furnace

- Continuous weekly operation
- 12 weeks total testing time
- More than 400 trial melts
- More than 1000 tonnes of steel have been produced

A fossil-free process for melting carbon-free sponge iron has been developed and is ready for full-scale implementation.

Varied parameters

Iron carriers

- Type: Sponge iron (DRI) and hot compacted sponge iron (HBI)
- Adding method: Continuous feeding and batchwise
- Chemical properties: Carbon content and degree of metallisation

Carbon carriers

- Type: Biocarbon and compacted biocarbon with different size fractions
- Addition method: Batch, injection, top feeding
- Chemical properties: Volatile fraction, carbon content

Process parameters

- Oxygen content
- Amount of carbon
- Productivity
- Slag composition

Iron ore pellets for direct reduction

Pellets for direct reduction are an enriched iron ore product made primarily from high-grade magnetite. The manufacturing process for fossil-free iron ore pellets has been developed at LKAB's pelletising plant in Malmberget. In the pelletisation process, the pellets are heated to such an extent that the iron ore particles partially fuse together but retain their porosity.

The fossil fuels of the conventional process have been replaced by bio-oil, which is 100% renewable. Other alternative heating technologies have also been tested such as hydrogen combustion and electric heating technologies.

- The world's first fossil-free pellet plant is located in Malmberget and has been in operation since HYBRIT's fossil-free pellet project ended in 2021.
- In 2023, the plant produced 3.6 million tonnes of pellets, and 50,000 tonnes of fossil CO_2 emissions were eliminated.

In LKAB's pelletising plant in Malmberget, bio-oil is used as fuel in the pelletisation process.

Alkaline electrolysers using fossil-free energy produce all the hydrogen used in the direct reduction and hydrogen storage pilot plants.

Hydrogen production and storage

Fossil-free hydrogen is central to the HYBRIT process. The pilot plant in Luleå includes electrolysers, which use fossil-free electricity to split water into hydrogen and oxygen, for producing hydrogen.

Electrolysers

- Commercial alkaline electrolysers were installed in Luleå in 2021.
- The nominal production capacity is 910 Nm^3/h which corresponds to an electrical power supply of approximately 4.5 MW.
- The electrolysers have been in operation for more than 9000 hours.
- The plant produces all the hydrogen used for direct reduction and hydrogen storage.

Hydrogen storage

HYBRIT's pilot plant for testing the storage of fossil-free hydrogen began construction in May 2021, and became operational after the summer of 2022. It is located adjacent to the direct reduction pilot plant, 30 metres below the ground surface in Svartöberget in Luleå. The hydrogen is stored in a Lined Rock Cavern (LRC). It has a volume of 100 m^3 and contains hydrogen pressurised up to 25 MPa. Hydrogen storage testing and development is still ongoing.

A hydrogen storage facility opens up the possibility to adapt hydrogen production to the price of electricity while meeting the hydrogen needs of the reduction process. This creates the conditions for cost-effectively managing fluctuations in the supply of renewable electricity based on, for example, wind and solar power.

Results from trials at the pilot plant show that storage can reduce the variable cost of hydrogen production by up to 40%. The conclusions will be summarised when the project ends at the end of 2024, but the hydrogen storage facility is planned to continue operating until 2026.

Competitive production verified

During the pilot phase, all parts of HYBRIT's fossil-free value chain have been evaluated.
The technical and economic potential of the steps has been confirmed with regard to:

Security and safety

HYBRIT's pilot plants were designed with safety as the first and highest priority right from the planning phase. During the operation of the plants, safety has permeated all work. The pilot plants have been in operation since autumn 2020, and during this time no incidents have occurred that have compromised the safety of staff or the plant.

Environmentally friendly production

The focus is on fossil-free production in all process steps. Extensive measurements and sampling have been carried out at pilot scale to understand differences in residual gases and residual material compared to today's conventional processes and how this can be handled in the best possible way for future environmentally friendly production. One example of this is monitoring the amount and composition of dust leaving the direct reduction shaft and evaluating how this material can be best utilised in the value chain.

Intermediate commodities

Energy, raw material and additive requirements have been optimised. By exploring the impact of a range of process parameters on product quality, a process window for direct reduction has been defined.

Productivity

Productivity has been maximised for a competitive production cost. By exploring direct reduction and melting in a large process window, the unique properties of the hydrogen reduced sponge iron have been defined and optimised.

Stability

The process has proven to be robust, with only small variations in results and implementation.

Product quality

The final fossil-free crude steel product meets or exceeds the applicable quality requirements.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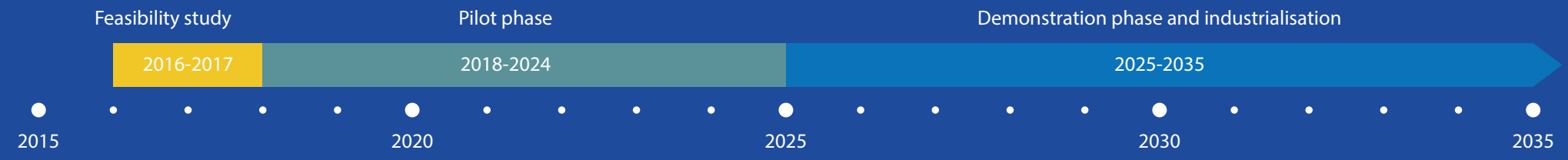
The road to fossil-free steel is open

The work of the HYBRIT initiative is progressing according to plan. In the next phase, the HYBRIT process will be implemented on an industrial scale. The results and specifications of the pilot project apply to Swedish conditions and have laid a solid foundation for industrialisation. The road is now open for the transformation of SSAB's and LKAB's production facilities.

Conditions for a transformation to a fossil-free iron and steel value chain and implementation of the HYBRIT process may be different for other geographies and steel companies.

HYBRIT's pilot-scale technological development continues – to further contribute to fossil-free steelmaking and to a major reduction in CO_2 emissions.



The HYBRIT initiative was launched in 2016 by SSAB, LKAB and Vattenfall with the aim of creating a completely fossil-free value chain from mine to fossil-free steel, with fossil-free pellets, fossil-free electricity and hydrogen. The aim of the initiative is to phase out the use of coal and to virtually eliminate carbon dioxide emissions for the steel industry, corresponding to about 10% of Sweden's total CO_2 emissions. On 31 August 2020, the pilot plant for the direct reduction of iron ore with hydrogen was commissioned and in August 2022, the pilot plant for the storage of fossil-free hydrogen was commissioned. The HYBRIT technology, validated and optimised over several years of development with very promising results, will now be used and further developed in industrial applications.

HYBRIT is mainly funded by SSAB, LKAB and Vattenfall with support from the Swedish Energy Agency and the European Union.

SSAB LKAB VATTENFALL

Swedish Energy Agency

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