Fossil-free hydrogen storage in lined rock caverns ready for industrialization

The technology to make industrial hydrogen production and usage more flexible and profitable is now available.

HYBRIT

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hybritdevelopment.se

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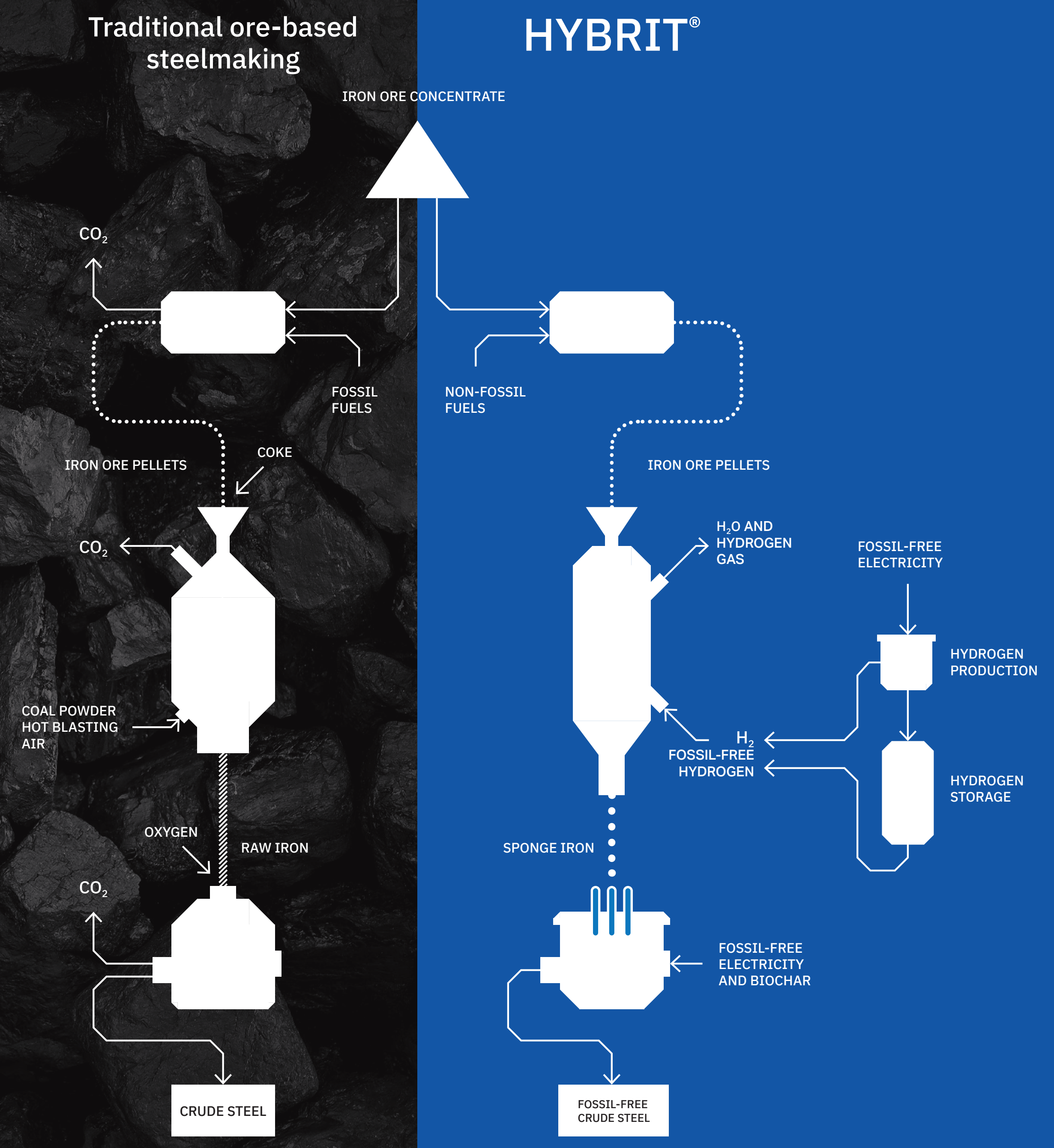


2.2 tons CO_2e/tonne steel*

0.0 tons CO_2e/tonne steel*

HYBRIT® - the world's first fossil-free steel production

Europe´s and Sweden's climate goals are paving the way towards a fossil-free society. To mitigate global warming and achieve net-zero greenhouse gas emissions by 2045, an industrial transformation is essential.

Currently, the steel industry is responsible for a significant portion of industrial carbon dioxide emissions, accounting for 7% globally and over 10% in Sweden. Current steel production relies on fossil coal, primarily to reduce ore (iron oxide) to pure iron in blast furnaces. This process accounts for approximately 85-90% of the total carbon dioxide emissions in ore-based steel production.

The HYBRIT process utilizes fossil-free hydrogen to reduce iron ore pellets to iron, producing sponge iron (direct reduced iron) and water as a by-product. The sponge iron is subsequently melted in an electric arc furnace powered by fossil-free electricity to create fossil-free 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 steel production using blast furnace technology is 2.2 tonnes CO_2e/tonne of steel.

HYBRIT pilot project: Hydrogen storage in rock caverns with LRC technology

HYBRIT has now developed the technology for hydrogen storage in rock caverns through a project carried out during the period 2019-2024. The project entailed the design, construction, and operation of a pilot-scale hydrogen storage facility with a capacity of 100 cubic meters, situated 30 meters below the ground surface in Svartöberget, Luleå.

Adapted concept for hydrogen

LRC stands for Lined Rock Cavern. The basic concept of LRC storage has already been demonstrated on an industrial scale for natural gas in Skallen, outside Halmstad, and the technical development work has therefore been based on this existing knowledge.

However, the concept needs to be adapted for hydrogen storage, especially in terms of material selection.

To cope with the fluctuations in the electricity market, it is expected that a commercial hydrogen storage facility needs to be filled and emptied with higher frequency and speed compared to a natural gas LRC. This also implies different requirements for the design and operation of the facility. This has been successfully tested in the pilot plant.

The value of a pilot project

A pilot-scale storage facility has allowed the project to update existing knowledge and experience of LRC storage – to now store hydrogen. A pilot-scale storage was also well suited for conducting tests of flexible operation and integration with the electricity market.

- LRC stands for Lined Rock Cavern.
- The basic concept has been demonstrated for natural gas.
- The design needs to be adapted for hydrogen storage, in particular in terms of material selection and higher frequency and rate of filling and emptying the storage.
- Through the project, knowledge and experience on LRC storage has been updated. Flexible operation and integration with the electricity market have been tested in the pilot plant.

Storage reduces variable cost of hydrogen production

Challenges for industrial production of hydrogen

The challenge of large-scale industrial production of fossil-free steel using hydrogen lies in the substantial electricity requirements. Hydrogen is generated through the electrolysis of water using fossil-free electricity. In today's electricity system both production and demand for electricity varies over the day, between the days of the week and between seasons.

These variations in the balance between electricity supply and demand lead to variations in electricity prices. In the future electricity system the magnitude of the variations in particulary the production are expected to increase – as the share of weather-dependent power production, such as wind and solar, increases in the electricity grid. This is also expected to increase the variability of electricity prices and thus the demand for flexibility.

25-40%

in reduced operating costs*

Hydrogen storage creates flexibility

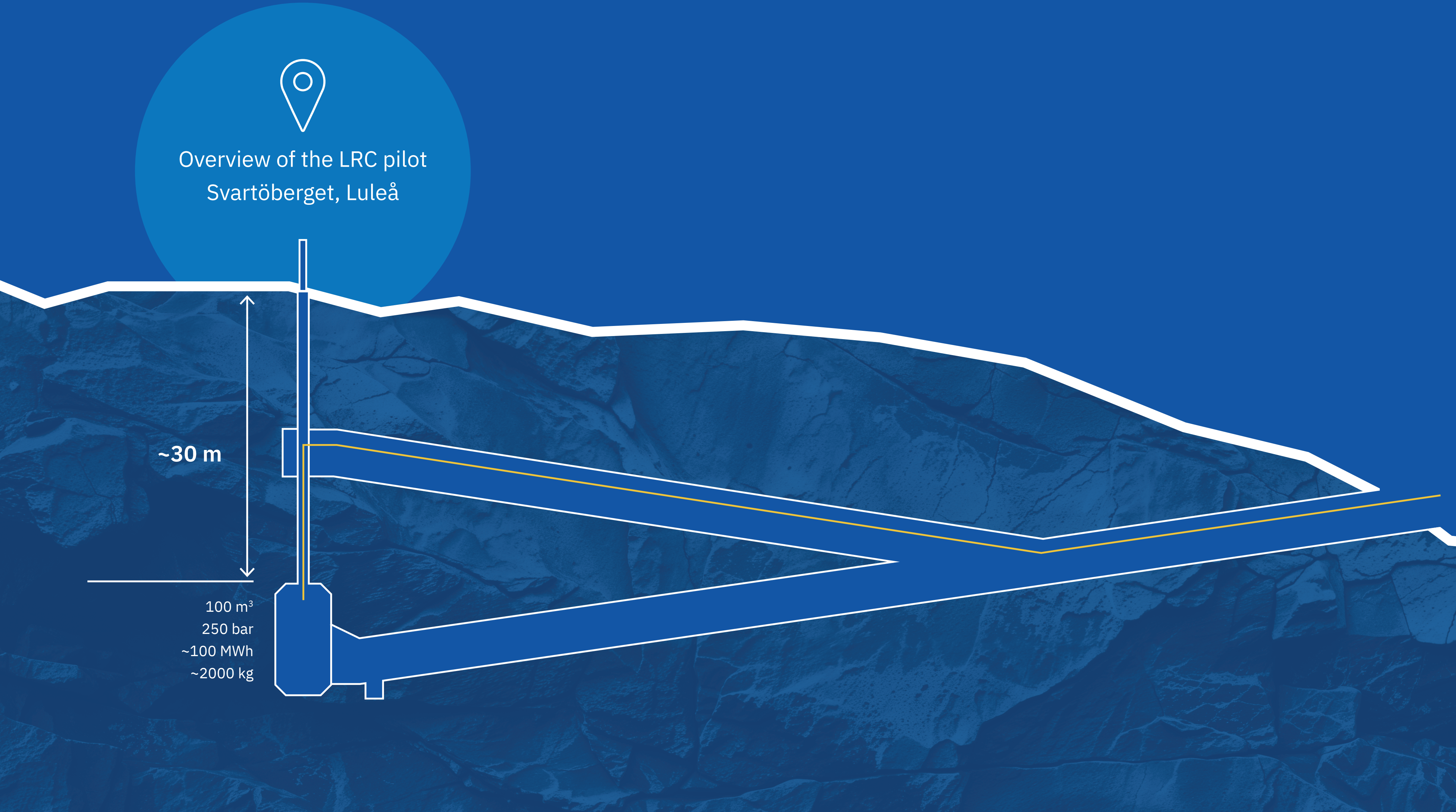
To address this, hydrogen storage is included as part of the HYBRIT value chain. By investing in a hydrogen storage facility and some excess hydrogen production capacity, periods of low electricity prices can be used to produce a surplus of hydrogen that is then stored. During periods of high electricity prices, the hydrogen in storage can then be used in the process, thereby reducing electricity demand.

Reducing operating costs and stabilizing the electricity grid

A large-scale hydrogen storage facility can thus reduce the operating costs of fossil-free steel production by taking advantage of electricity price fluctuations. The project's simulations of future electricity market scenarios show that hydrogen storage can reduce the variable operating costs of industrial hydrogen production by 25-40%. It can also smooth out the differences in supply and demand in the electricity grid.

* The potential for variable operational cost savings with storage compared to without storage has been estimated to be in the range of 25-40% based on simulations of various future scenarios in the electricity market.

Design of a Lined Rock Cavern storage



Building up the LRC

A LRC storage consists of an excavated rock cavity, shaped as a vertical cylinder with a rounded top and bottom. The rock cavern is fitted with a gas-tight liner consisting of:

1. a steel liner (toward the gas)
2. a force-transmitting reinforced concrete layer (between steel liner and rock)
3. a sliding layer (between steel lining and concrete to reduce friction)

The forces from the high storage pressure are transferred via the liner to the rock mass, which has the strength to withstand very high loads. Around the facility, there is a drainage system that removes water during the construction phase and monitors gas tightness during operation.

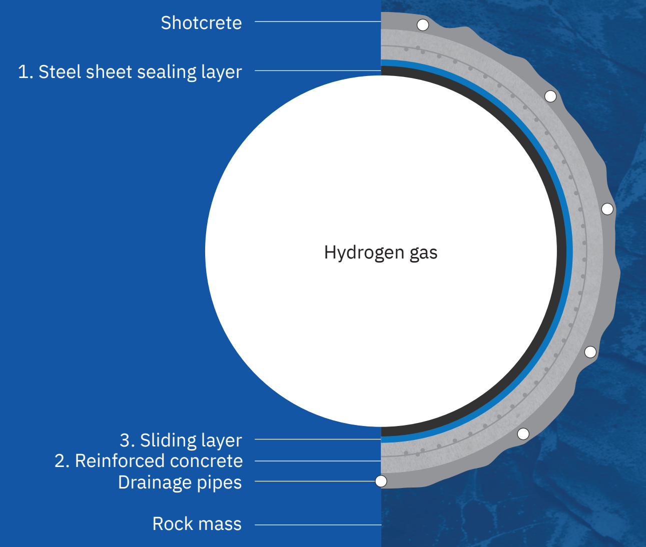
Material choice is important

The choice of material for the storage's steel lining has been one of main issues during the design phase. A steel material has been selected based on existing research and specific laboratory tests, conducted on behalf of HYBRIT. The material is resistant to the effects of hydrogen on the material and can withstand the cyclical load of frequent emptying and filling of the storage.

Above ground connection

The hydrogen is conveyed through a pipeline approximately 3 km long from the hydrogen production site (electrolyzers) to the storage compressor station. At the station, the pressure is increased from 7-9 bar to a maximum of 250 bar by compressing the gas.

The hydrogen is further transported in a high-pressure pipeline that connects to the storage for filling. During emptying, the gas is sent back to a depressurization station located in the same building as the compressor, and the hydrogen is transported back in the pipeline to the consumer.



Successful testing of the pilot storage

Tests at the pilot plant in Luleå have demonstrated that large-scale storage of hydrogen using LRC technology is technically feasible.

Results in brief:

- Over more than two years of operation with hydrogen, the safety, functionality and performance of the plant have been successfully demonstrated.
- Approximately 3 800 hours of hydrogen operation with 94% availability have been achieved.
- The maximum pressure level is 250 bar (corresponding to 2 500 m water depth).
- The maximum amount of hydrogen stored is about 2 tonnes.
- The design of the storage facility, including the rock mass and the lining, has been successfully tested together with the process equipment of the storage system.
- The storage can be emptied and filled at the frequency and rate required to match the fluctuations in the electricity system.
- The storage has been shown to be completely gas tight throughout the period.

Design of the test campaigns

Four hydrogen test campaigns of six weeks each have been conducted within the project. Initial campaigns focused on demonstrating the safety, functionality and performance of the storage at system and component level, testing operational strategies and generating data for validation of models for simulation of the storage facility. This was followed by test campaigns that tested the commercial potential of the storage by integrating its operation in real time with the electricity market.

The pilot storage facility has also been subjected to accelerated mechanical tests through frequent variations between high and low storage pressure. The tests performed correspond to the same mechanical load as during an expected lifetime of at least 50 years of a commercial large-scale storage facility.

3 800

hours of operation
with 94% availability

250 bar

maximum pressure in the
hydrogen storage during
normal operation

Compressor station with high pressure pipeline
to tunnel system and hydrogen storage

Bringing security of supply and savings to industries

The pilot storage has been integrated with hydrogen production from electrolyzers and delivered hydrogen from the storage to two facilities. These are HYBRIT's own pilot plant for direct reduction and SSAB's industrial coke oven gas network, both located on Svartön's industrial area in Luleå.

- The project's tests have shown that hydrogen storage functions effectively within the value chain, supporting large-scale hydrogen users with a reliable supply. Additionally, the storage can serve as a backup system in the event of hydrogen production failures or if the consumer cannot receive the full amount of available hydrogen.
- The storage can also act as a back-up system, in case hydrogen production fails or the consumer cannot receive the full amount of hydrogen available.

Reducing operating costs for hydrogen production

Tests conducted in collaboration with Vattenfall have demonstrated the integration of hydrogen production and storage into the electricity system, specifically Nordpool's spot and intraday market. A hydrogen storage facility allows for flexible hydrogen production based on electricity market conditions. In the long run, large-scale hydrogen storage supports the electricity system and potentially facilitates new electricity production from all fossil-free power sources.

The tests against the electricity market show the following:

- The operation and control of the hydrogen storage system is fully automated and integrated in real time with Nordpool, in the same way as a commercial plant.
- Savings of 26-31% of variable operating costs have been demonstrated in practice.
- Simulations carried out on future scenarios for the Swedish electricity market show likely savings of around 25-40% of the variable operating cost, as the first commercial facilities become operational.
- The extent of the savings will depend on the development of the electricity market, both in terms of the expansion of power generation and the electricity transmission system, and on the development of the general demand for electricity.

Safety in hydrogen storage

An important aspect of hydrogen storage is safety, as hydrogen in contact with oxygen produces a highly flammable gas.

- The advantage of storing hydrogen in rock caverns is that there can be no ignition or explosions inside a cavern filled with 100% hydrogen gas.
- The depth of the storage is adapted so that the rock mass can withstand the upward force from the pressurized storage with a satisfactory degree of safety. The storage is well protected from external influences.
- To prevent weaknesses in the construction, the material for the storage has been carefully selected and thorough quality controls have been conducted during the construction.

Safety systems

The storage facility is designed with a system for rapid detection of leaking hydrogen, as well as collection and diversion to a safe location – in the unlikely event of a hydrogen leak.

- The storage has been shown to be gas tight throughout the test period.
- When testing the safety system with simulated gas leaks, even very small amounts of leakage could be detected within a short time, as fast as 10 seconds.
- The tests have also verified that the leaking hydrogen is collected in the system and can be diverted to a safe location.

Ventilation mast, Svartöberget

Hydrogen storage supports the transition to a fossil-free society

There are several benefits of large-scale hydrogen storage, both for industrial operations and for the electricity grid in general. The main advantage is that hydrogen storage supports the transition to a fossil-free society, by:

1. Lowering the variable operating cost of hydrogen production

By taking advantage of variations in electricity prices, hydrogen storage allows electricity to be stored as hydrogen when electricity prices are lower – and the stored hydrogen to be used in the industrial process when electricity prices are higher. Savings of up 40% of variable operating costs are possible through large-scale hydrogen storage.

2. Creating flexibility

A hydrogen storage facility creates flexibility for industrial operations that use hydrogen. It also creates resilience against disruptions in hydrogen production, as there is always hydrogen available in the storage to supply the production.

3. Stabilizing the electricity grid

Large-scale hydrogen storage stabilizes the electricity grid, by balancing electricity both when supply is good and when demand is high.

4. Stabilizing fluctuations in the electricity market

Large-scale hydrogen storage makes the power system more robust by balancing the grid both when supply is abundant and when demand is high. By redistributing electricity supply and demand on both an hourly and weekly basis, hydrogen storage can allow more variability from weather-dependent electricity generation to be balanced in the electricity system.

- Variable operating costs for hydrogen production can be reduced by taking advantage of fluctuations in the electricity market.
- Creates robustness against disruptions in production. Hydrogen is always available.
- Balances the electrical grid and evens out electricity price variations when deployed on a large scale.
- Favors investments in new electricity generation from all fossil-free power sources.

Ready for the next step

With the HYBRIT pilot project, LRC technology has now been tested for the first time for hydrogen storage. Technology development – with design, construction, and testing with validation at pilot scale – has been successfully carried out.

The project demonstrates that LRC technology for large-scale hydrogen storage:

- is available, tested, and safe
- reduces variable operating costs for fossil-free steel production
- has significant potential in industrial processes using hydrogen
- is an important piece of the puzzle for the transition to a fossil-free society
- can enhance system resilience and increase renewable energy in the electricity grid
- is ready for the next step.

With the knowledge and experience generated by the project the technology is proven and ready for industrialization. This allows for the further development of large-scale commercial storage facilities in the range of 50,000 to 100,000 m³.

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 in the steel industry, corresponding to about 10% of Sweden's total CO2 emissions. On August 31, 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 optimized over several years of development with very promising results, will now be used and further developed in industrial applications.

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FOSSIL-FREE STEEL