Green Hydrogen Advantage ™

TOWARDS FOSSIL-FUEL FREE STEEL & TITANIA

Aiming to replace coal with hydrogen inthe steelmaking process.

A ground breaking industry effort to reduce CO_2 emissions and de-carbonise the steel industry.

This requires high grade iron ore with 67% plus iron oxide content.

Which is rare, or Ilmenites with close to 50% iron oxide.

Which are unique to New Zealand.



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Growing Global Demand for Steel

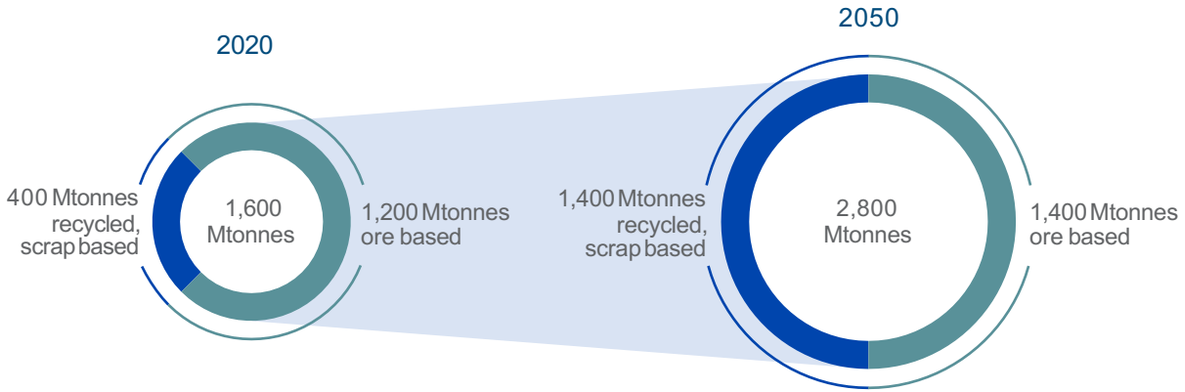
Steel is an important enabler for building the modern society, including industry, innovation and infrastructure. Steel helps to fight poverty and raise living standards throughout the world.

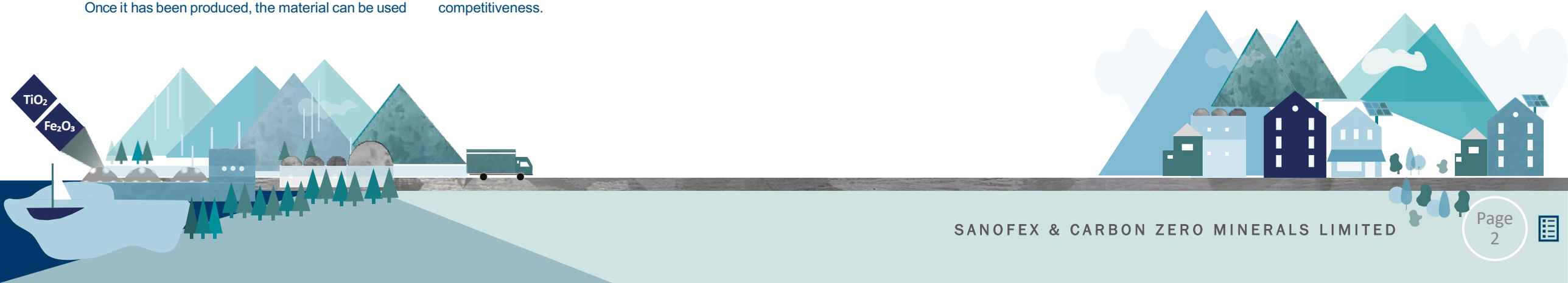
The steel industry is one of the highest carbon dioxide emitting industries, accounting for up to 7% of global, and 5% of New Zealand CO_2 emissions. New Zealand has set a national target to reach zero net emissions of carbon dioxide by the year 2050, defining the future pathway for the country's steel industry. New Zealand offers favourable conditions for hydrogen to contribute to these national targets, such as high-quality niche production of iron-ore pellets, a specialised and innovative steel industry, and an abundant supply of fossil-free electricity.

Steel is one of the world's most recycled materials. Once it has been produced, the material can be used repeatedly via the scrap-based production route. Even though steelmaking from recycled scrap has been estimated to increase drastically, the overall demand for steel in the next few decades can only be met by utilising ore-based virgin iron as well.

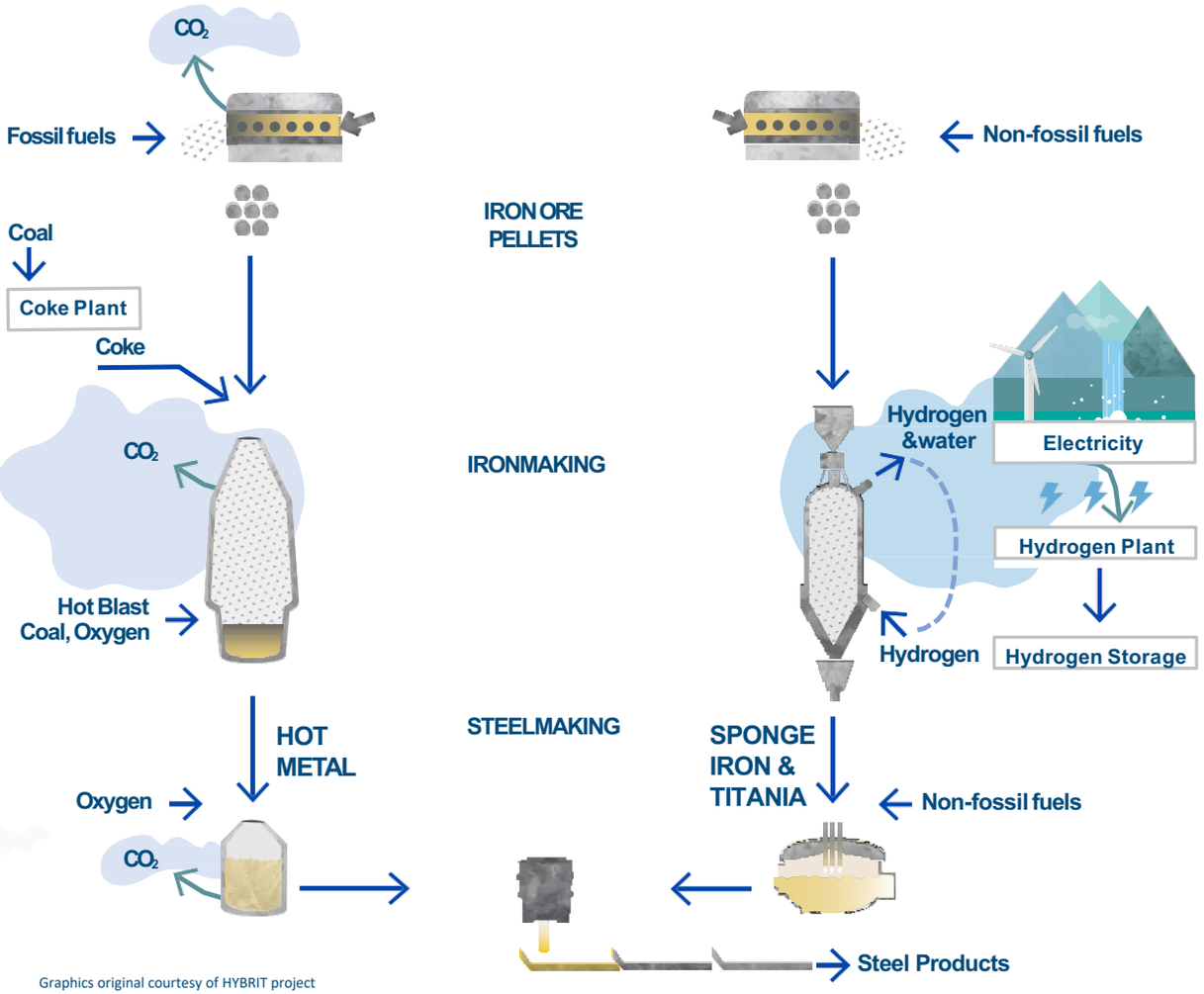
Although the hydrogen reduction route of fossil-free industrial production will face challenges, it offers a great opportunity to reach new global markets for green technology and products. As a demonstration of science and innovation, hydrogen reduction has the potential to sustain New Zealand's leading position in fighting climate change while strengthening competitiveness.

Steel demand – today and forecast 2050





Decoupling of Carbon Dioxide & Energy

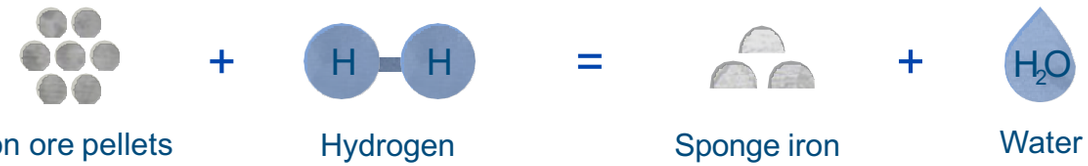


Graphics original courtesy of HYBRIT project

WATER INSTEAD OF CARBON DIOXIDE

The reduction reactions in ironmaking represent around 85 to 90 per cent of the total carbon dioxide emissions in the ore-based steelmaking value chain. In addition, the energy-containing gas from coke ovens and blast furnaces has an important role as the main energy source for heating furnaces and materials. Fossil-free steel production will eliminate the formation of CO_2 by using fossil-free reductants and energy sources.

In the case of HYDROGEN, iron metal is produced by using hydrogen gas as the main reductant. The production route is similar to existing direct reduction processes, except for the carbon dioxide emissions: hydrogen reacts with iron oxides to form water instead of carbon dioxide. Hydrogen gas (H_2) is produced by electrolysis of water using fossil-free electricity, which is already the standard in New Zealand.



The ore-based steelmaking value chain starts at the iron ore mine. After mining, the iron ore is processed, and a product rich in iron oxides is produced in the form of pellets, or fines. At the steelmaking site, iron ore is converted to metallic iron by reduction of the iron ore pellets with coke in a blast furnace. The iron oxide and carbon then react to form CO and CO_2 gases, as well as metallic iron. Now in liquid form, the iron is further processed before a semi-finished steel product is cast.



Taking the Green Route

Future Emission Reduction Solutions have to be Technically and Economically Viable.

When calculating initial emissions of the current dominant production process, both direct and indirect emissions were included. Sweden, as a technological base case represents best in class. The carbon dioxide emissions using current technology are 1.6–1.7 tonnes of CO_2 per tonne of crude steel, compared to the estimated 2.0–2.1 tonnes of CO_2 for a typical integrated steel plant in Western Europe.

The result can be explained by differences in the electricity mix, with more renewable sources available in Sweden. Another factor is the high level of energy efficiency in the Swedish industry, where LKAB and SSAB are leading operators in terms of energy and CO_2 efficiency. New Zealand is on target to follow in Sweden's footsteps with renewable energy sources set to replace fossil-fuels.

Assessment of Capital and Operating Expenses

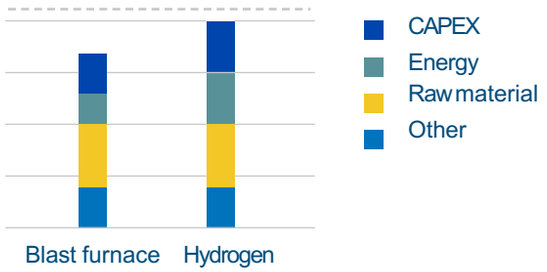
Capital costs have been estimated for the construction of respective production systems in greenfield conditions. This is, however, a generalisation and therefore, careful planning is important.

The estimated total cost per tonne of crude steel has been calculated based on current commodity and energy prices.

The indication is that the production cost for steel via the hydrogen route is approximately 20 to 30 per cent higher than for the reference case.

In the steel industry, commodity and energy prices may fluctuate considerably over time, and there are several factors indicating that the relative cost level can change during the hydrogen planning horizon.

Cost comparison –
COPEX increases 20-30%



Estimated crude steel production costs at greenfield conditions.

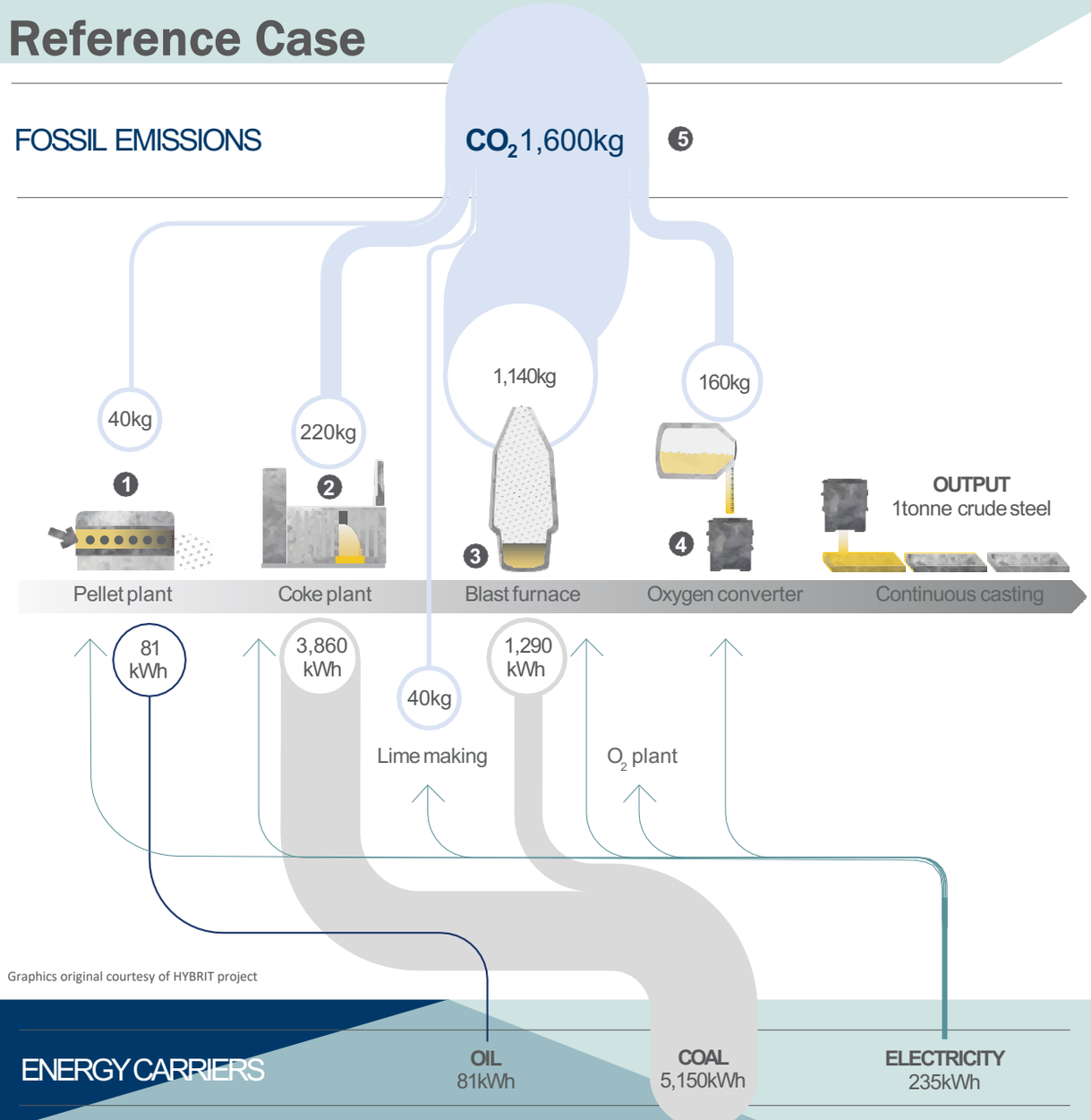
The main factors affecting viability of the hydrogen process in the long run are mainly price developments for coking coal, electricity and emission allowances. If coking coal prices increase, it will benefit the hydrogen business case, while increasing electricity prices will weaken the case for hydrogen. Also, future developments of the emission trading system (NZ ETS) will have an impact.

Although a complete replacement of carbon by renewable energy will result in an increase in material costs, the impact on the end-user product is neglible. Predictions of future costs are highly uncertain, but anticipated shifts in prices and market demands make the fossil-free hydrogen concept a commercially attractive option.





Reference Case



Graphics original courtesy of HYBRIT project

ILMENITE ORE

Typically, the fine Ilmenite ore concentrate contains approximately 48% iron and 48% titania.

PELLETISING 1

In the pelletising plant, the fine ore concentrate is dewatered, and a binding agent is added before the concentrate is rolled into 10-millimetre pellets. The pellets are dried, preheated, sintered, and cooled down before storage and transportation to the steel plant. The ilmenite ores in New Zealand are especially suitable for such processing.

COKE PRODUCTION 2

Coke is a stable fuel and reducing agent with a high carbon content, made from coal. Parts of the volatile matter in coal are used as energy for the high temperature baking process in coke production.

PRINCIPLE SYSTEM DESCRIPTION

Numbers do not reflect a specific production site or time period. All numbers per tonne of crude steel.

BLAST FURNACE 3

The iron ore and coke is added to a process designed to release oxygen from the ore according to the simplified reaction: ore + carbon => titania + iron + carbon dioxide. This takes place in a shaft furnace where the solids are charged to the top of the furnace, and preheated air is injected in the lower parts to enable an efficient heat transfer. The result is a molten hot metal consisting of iron, with 5% of dissolved carbon and a titania rich slag.

OXYGEN CONVERTER 4

The hot metal is treated with oxygen gas to lower the carbon content and form molten steel. The reaction releases heat, which is utilised to melt an additional 10-20% of steel scrap, before the liquid steel is tapped into a ladle, where the final chemical composition and the temperature of the steel is adjusted. After this, the steel is cast into crude steel slabs in a continuous caster.

CO_2 5

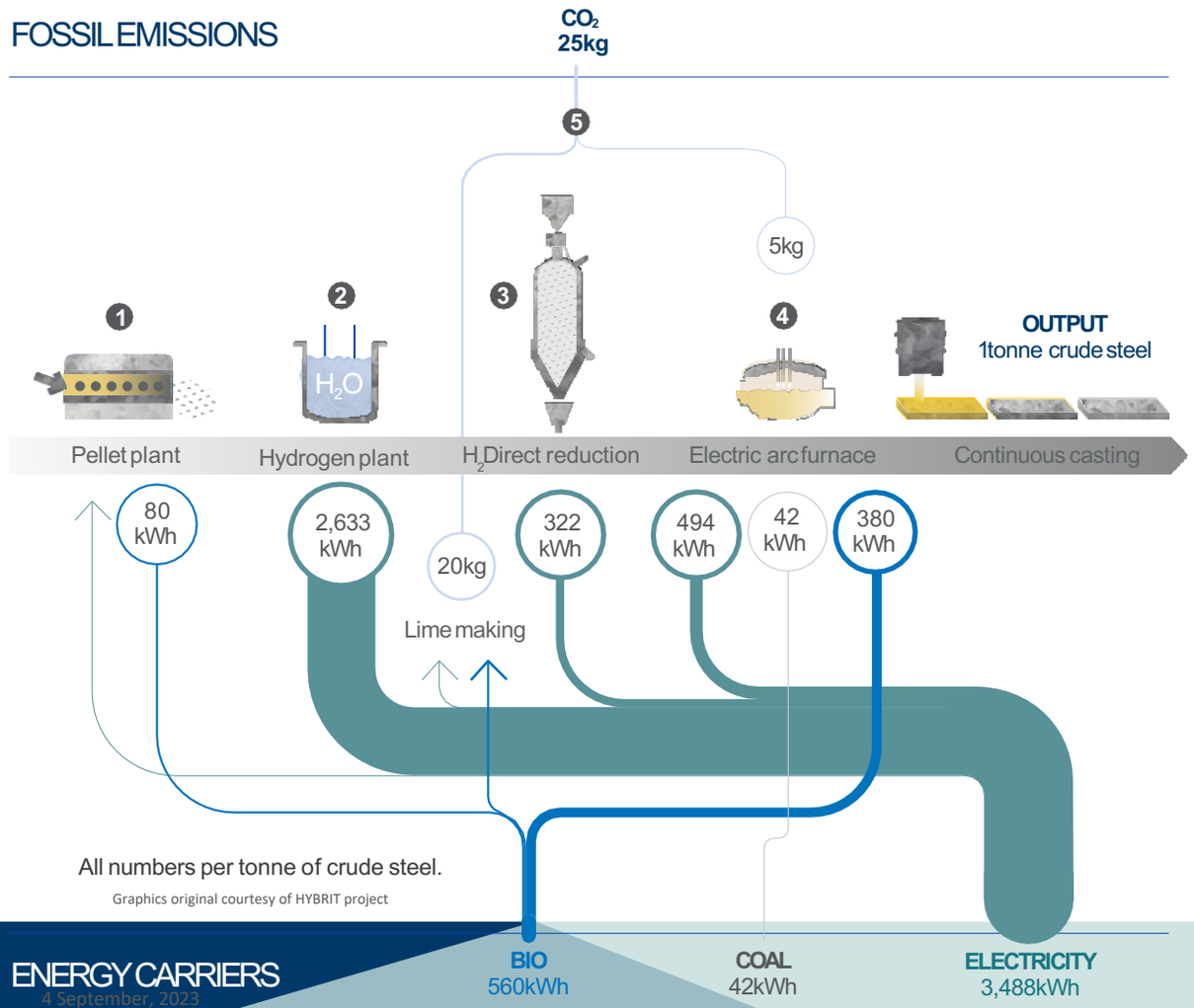
Carbon dioxide originates from the blast furnace, coke making, decarburisation of hot metal in the converter process, and fossil fuels used in the pelletising process.



Implementation

HYDROGEN REDUCTION

FOSSIL EMISSIONS



PELLETISING 1

The fossil fuel in ore processing will be eliminated with an increased level of energy efficiency and by switching to fossil-free sources of energy.

HYDROGEN PLANT 2

Hydrogen production takes place by electrolysis of water into hydrogen gas and oxygen. Renewable electricity is the primary energy source. Electrolysis is a mature technology, and principally, there are no barriers to building a large-scale plant.

DIRECT REDUCTION 3

The existing direct reduction method needs to be adapted to reduction with hydrogen to eliminate carbon dioxide emissions. The off-gas of the reduction process would be water, according to the simplified reaction: ore + hydrogen => titania + iron + water. The result is a solid porous sponge iron, suitable for steelmaking and chloride grade titania suitable for pigment production or titanium metal.

ELECTRIC ARC FURNACE 4

The Electric Arc Furnace (EAF) is used for heating and melting charged materials by means of electric current. The use of EAFs allows steel to be made from up to 100% scrap metal, or as in the hydrogen concept, from a mix of direct reduced iron and scrap if desired. Similar to the reference process, the liquid steel is tapped into a ladle where the final chemical composition and the temperature of the steel is adjusted, before it is cast into crude steel slabs in the continuous caster.

CO_2 5

CO_2 emissions will be reduced dramatically, although minor emissions can still arise because of the use of certain process equipment, and because small amounts of coal must be used in the manufacturing process.



Renewable Electricity Substitutes Coal

The figure below shows the summation of the carbon dioxide reduction roadmap for emissions in New Zealand.

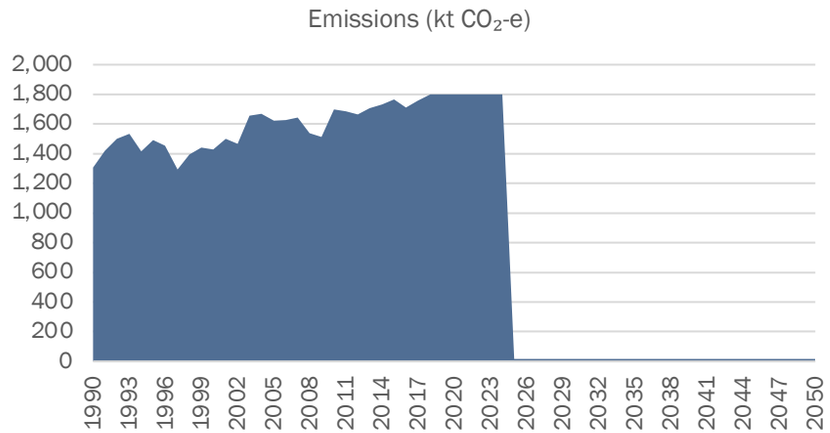
The most significant steps with regards to CO_2 reduction are associated with the phasing out of blast furnaces, substituted by hydrogen-based direct reduction plants and electric arc furnaces. The primary iron source in steel plants will then shift from blast furnace iron to hydrogen-based direct reduced iron, using the hydrogen production principle.

After this development, electricity from renewable sources will be the primary energy carrier and consumption will increase in the order of 8 TWh, primarily to be used for hydrogen electrolysis and steel melting processes.

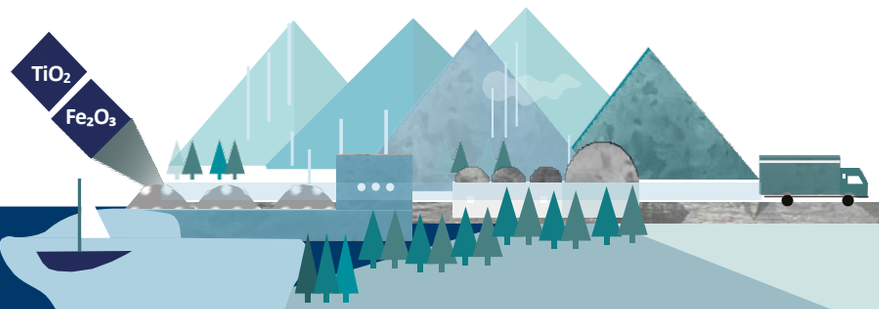


Implementing de-carbonised ore-based steel production before the year 2050 will both directly and indirectly (materials for renewable energy technology) contribute significantly to the target of a fossil-free New Zealand.

Contribution to territorial Carbon footprint in New Zealand
(Mtonnes/year)



Data from New Zealand's Greenhouse Gas Inventory published in 2019





Focus on Future Development

PROMISING TECHNOLOGICAL POTENTIAL
The prefeasibility study results underline that no major, previously unknown technical obstacles have been identified. Nevertheless, considerable future development efforts will be required to realise and verify the concept, and to handle risks. These include fundamental research projects using models and laboratory scale experiments, as well as trials in pilot and demonstration plants.

PRODUCTION COSTS SEEM VIABLE
Considering current cost levels, a titania, iron and steelmaking value chain based on the hydrogen concept would result in a 20 to 30 per cent increase in the cost of producing crude steel. The cost structures of fossil and fossil-free value chains are strongly dependent on the prices of coking coal, electricity and emission rights. An expected future shift in costs and market demands makes the fossil-free hydrogen concept an attractive alternative.

HYDROGEN AS WIND AND SOLAR BUFFER
Large-scale hydrogen production and storage will allow for flexibility in power consumption on a large scale, which will favour the implementation of intermittent renewable energy sources for electricity production.

PROMOTION OF HYDROGEN TECHNOLOGIES
Large-scale hydrogen production will boost the transition to other hydrogen-based technologies and spur innovation and business spin-offs associated to the hydrogen society.

SOCIETAL SUPPORT NEEDED
Electrical infrastructure expansions and regional transformation support are fundamental requirements for the concept. Competence and capacity building will support the future value chain production systems and business models. A viable business case may be dependent on carbon dioxide instruments, as well as development of niche markets for fossil-free iron and steel.

LOW COST INFRASTRUCTURE SPENDING
With interest rates at historic lows there has never been a better time to support large scale infrastructure projects.

> Support from society will be required to make the transition manageable.

CLIMATE CHANGE RESPONSE ACT 2002 NZ
The Climate Change Response Act 2002 contains the legal framework which enables New Zealand to meet its international climate change obligations.

NEW ZEALANDS EMISSIONS TRADING SCHEME
The Act was amended in 2008 to encompass the New Zealand Emissions Trading Scheme (NZ ETS) which is New Zealand's principal response for reducing domestic emissions and its primary mechanism to meet international emissions reduction commitments.

ENVIRONMENTAL PROTECTION AUTHORITY
is responsible for the day-to-day administration of the ETS as well as compliance and enforcement.

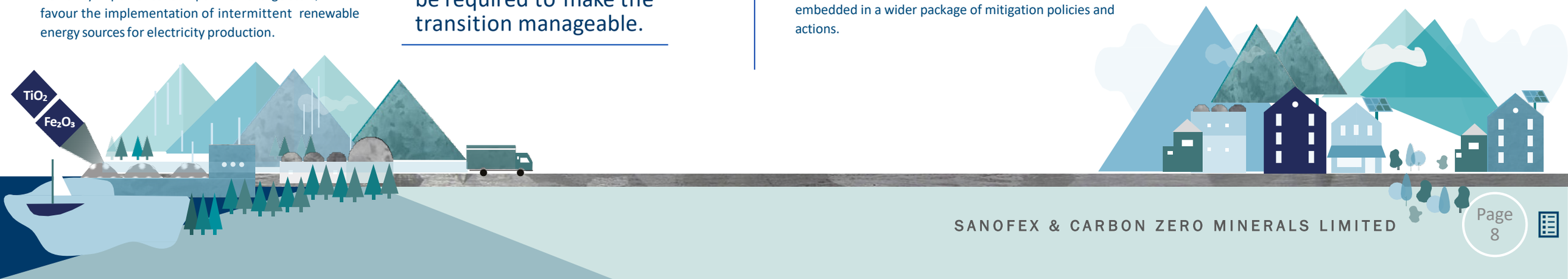
LIMITS
There is no fixed cap on total emissions (and no stated plans to do so), which implies that there is no restriction on the supply of emission units, and hence no strong enough price to constrain the overall level of emissions. It is important to recognise emissions pricing has an important role but to be effective it needs to be embedded in a wider package of mitigation policies and actions.

INDUSTRIAL PROCESSES
Industrial process participants include producers of iron, steel, vanadium, aluminium, clinker, burnt lime, glass and gold.

PARTICIPANTS
Industrial process participants have obligations to report their emissions and surrender NZUs under the NZ ETS. In the future they may trade their NZUs.

TRADING
Industry participants are currently required to surrender only one NZU for every two tonnes of emissions. This was intended to be a transitional measure ending in December 2012 but has been extended indefinitely to allow households and businesses to manage the effects of the global financial crisis.

BUYING CREDITS
Participants can also buy NZUs from the Government at a fixed price of $25 per NZU.



Identified Main Challenges

To obtain a viable fossil-free industry, certain issues remain, with major challenges in various areas.

THE EFFECT OF CARBON-FREE PROCESSING must be clarified. Carbon is arguably the most important element in traditional iron and steelmaking. Without carbon added in any substantial amount, there is a need to understand mechanisms and define process principles. Niobium and Vanadium strengthen steel.

HYDROGEN PRODUCTION will be based on existing commercial technology, yet to be proven on a large scale. Controlling scale effects will thus be important for process functionality and economics.

HYDROGEN STORAGE plays an important role in the value chain economics and integration. Technology for large-scale hydrogen storage is still untested.

FOSSIL- FREE FUELS AND TECHNOLOGIES FOR PROCESS HEAT will be required to replace existing fossil heat sources in the production system.

AN OPERATING PRACTICE needs to be established in the new process to function as a stand-alone unit, and as part of a value chain technically and economically optimised on the system level.

THE ELECTRICITY SUPPLY AND TRANSMISSION from renewable sources to the future production sites plays an important role to secure the foreseen increased demand of electricity.

REGIONAL EFFECTS ON SOCIETY will be considerable in the areas where transition will take place, requiring further consideration.

POLITICAL INSTRUMENTS, e.g. emission trading, will affect the industrial transition period and the likelihood of a viable business case.

THE FUTURE BUSINESS CASE for fossil-free titania, iron and steel product requires further in-depth studies to find the most likely future scenario and related business model.

THE INDUSTRIAL TRANSITION STAGES and associated technological and economic effects represent considerable risks and costs for the companies involved, which need to be resolved.



The Climate Change Response Act 2002 New Zealand – Paris Agreement Update 2017

INDUSTRIAL ALLOCATIONS to prevent NZ businesses being unfairly disadvantaged when their competitors overseas don't face a carbon cost, entities engaged in the production of emission intensive and trade exposed goods may receive an allocation of NZUs.

Industry sectors carrying out 'Eligible Industrial Activities' (activities considered emission intensive and trade exposed) can apply for an allocation of NZUs. These include Iron and Steel production.

OBLIGATIONS of participants include a requirement to monitor and report on their own activities. They must collect prescribed data, calculate emissions and removals in accordance with prescribed methodologies, and retain records of data and calculations. Data and calculations may be required to be verified.

Participants must submit an annual emissions return recording the participant's activities, emissions and removals, and an assessment of the participant's emission unit liability or entitlement. Non-forestry participants are required to surrender one emission unit for every two tonnes of greenhouse gas emissions that the participant is responsible for.

ALLOCATIONS

The Government provides assistance to some sectors by providing them with NZUs free of charge to compensate for the loss of asset value resulting from the ETS or mitigate ETS-related costs increases for eligible business. Firms whose activities are emissions intensive, who are exposed to international trade and cannot recover costs from customers receive the allocation (e.g. international steel sales).

PARIS AGREEMENT UPDATE

NZ is currently out of the international emission units trading scheme (X-Kyoto, Doha 2012) but plans to reopen the NZ ETS to international carbon markets (auction trading) in 2021. The NZ$25 ETU price is approximately half the price of current European carbon pricing.



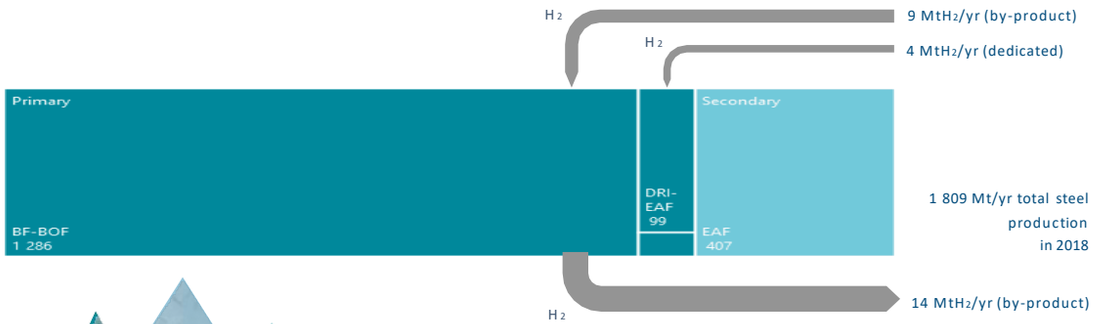
Hydrogen in Iron & Steel Production

HYDROGEN IN IRON AND STEEL PRODUCTION

DRI is a method for producing steel from iron ore. This process constitutes the fourth-largest single source of hydrogen demand today (4 MtH_2/yr, or around 3% of total hydrogen used in both pure and mixed forms), after oil refining, ammonia and methanol. Based on current trends, global steel demand is set to increase by around 6% by 2030, with demand for infrastructure and a growing population in developing regions compensating for declines elsewhere.

The iron and steel sector produces a large quantity of hydrogen mixed with other gases as a by-product (e.g. coke oven gas), some of which is consumed within the sector and some of which is distributed for use elsewhere. Virtually all of this hydrogen is generated from coal and other fossil fuels. To reduce emissions, efforts are underway to test steel production using hydrogen as the key reduction agent (as opposed to carbon monoxide derived from fossil fuels), with the first commercial-scale designs expected in the 2030s. In the meantime, low-carbon hydrogen could be blended into existing processes that are currently based on natural gas and coal to lower their overall CO_2 intensity.

Hydrogen consumption and production in the iron and steel sector today



Today the iron and steel sector accounts for 4 MtH_2/yr of dedicated hydrogen production. Of the 14 MtH_2/yr it produces as a by-product in hydrogen-containing gases, it consumes roughly 9 MtH_2/yr, with the remainder exported for use in other sectors.

HOW DOES THE IRON AND STEEL SECTOR USE HYDROGEN TODAY?

More than three-quarters of global steel demand today is met using primary production methods that convert iron ore to steel, as opposed to the secondary production route, which utilises limited supplies of recycled scrap steel. The remaining demand is met by re-melting steel scrap in an electric arc furnace (EAF). The two main primary production routes already involve some production and consumption of hydrogen.

The **blast furnace-basic oxygen furnace** (BF-BOF) route accounts for about 90% of primary steel production globally. It produces hydrogen as a by-product of coal use. This hydrogen, contained in so-called "works-arising gases" (WAG), is produced in a mixture with other gases such as carbon monoxide. WAG is used for various purposes on site, but also transferred for use in other sectors including power generation and, in China, methanol production. The portion utilised within the iron and steel sector is estimated at 9 MtH_2/yr today, or around 20% of the global use of hydrogen in mixed forms (i.e. not as pure hydrogen).

The **direct reduction of iron-electric arc furnace** (DRI-EAF) route accounts for 7% of primary steel production globally. It uses a mixture of hydrogen and carbon monoxide as a reducing agent. The hydrogen is produced in dedicated facilities, not as a by-product. Around three-quarters of it is produced using natural gas (reforming) and the rest using coal (gasification). It accounts for around 4 MtH_2/yr in 2018, or 10% of the use of hydrogen consumed in mixed forms globally.



4 September, 2023 - Source: IEA 2019

Using Hydrogen To Meet Growing Steel Demand While Reducing CO_2 Emissions

On average, producing one tonne of crude steel currently results in around 1.4 tonnes of direct CO2 emissions. Several cleaner pathways are under development that would significantly reduce CO2 emissions for primary iron and steel production. Various projects are underway around the world to develop these processes towards commercialisation. These can be divided into two categories:

- **CO_2 avoidance** pathways seek to avoid most of the CO_2 emissions entirely by adopting low-carbon sources of energy and reduction agents, usually using hydrogen.
- **CO_2 management** pathways aim to recover and manage the CO_2 associated with traditional fossil fuel-based routes, usually via the direct application of CCUS (carbon capture, utilisation & storage).

CO_2 AVOIDANCE PATHWAYS

HYBRIT. In Sweden SSAB (a steel producer), LKAB (an iron ore pellet manufacturer) and Vattenfall (a power company) formed the HYBRIT joint venture to explore the feasibility of hydrogen-based steelmaking, using a modified DRI-EAF process design (HYBRIT, 2019). Currently at pilot phase, the first commercial plant is expected in 2036. Of the SEK 1.4 billion (USD 147 m) estimated cost of the pilot plant, the Swedish Energy Agency will provide SEK 528 m (USD 56 m), with the joint venture partners contributing the rest.

SALCOS. Like the HYBRIT project, this collaboration between Salzgitter AG and the Fraunhofer Institute aims to partially implement hydrogen-based reduction of iron ore using the DRI-EAF route. While HYBRIT is aiming at virtually 100% hydrogen reduction from the outset, SALCOS will utilise a natural gas-fed process design and gradually increase the proportion of hydrogen.

GrInHy and **H2FUTURE.** These initiatives, both funded by the European Union's Fuel Cell and Hydrogen Joint Undertaking, aim to scale up emerging electrolyser designs to ensure that variable sources of renewable electricity can be utilised effectively in steel production and other industrial operations. The H2FUTURE project, co-ordinated by the Austrian utility VERBUND, is employing a 6 MW proton exchange membrane design, while GrInHy comprises a new reversible solid oxide cell unit. These projects started in 2016/17 and will conclude in the early 2020s.

Σiderwin and Boston Metal. Σiderwin is a research project initially funded by the European Union and now being taken forward by ArcelorMittal to pilot stage. It employs electrowinning to produce steel (SIDERWIN, 2019). Boston Metal is a start-up venture that has recently attracted USD 20 million of investment to continue developing its molten oxide electrolysis process for producing a variety of metals. Both of these processes utilise electricity directly for reduction, avoiding the need to produce hydrogen.



Source: IEA 2019.

CO_2 MANAGEMENT PATHWAYS

HIsarna. Developed during the Ultra-Low Carbon Dioxide Steelmaking (ULCOS) research project funded by the European Union and several large steel producers, HIsarna is a demonstration-phase process for producing steel with significant potential for emissions reductions, especially if equipped with CCUS. The technology employs an upgraded smelt reduction process that processes iron ore in a single step, negating the need for coke ovens and agglomeration processes. Greenfield commercial plants could be available within 10 years of the completion of the current demonstration project.

DRI with CCUS. Al Reyadah, a wholly-owned subsidiary of Abu Dhabi National Oil Company, is capturing CO_2 from a commercial-scale DRI-EAF plant operated by Emirates Steel. This post-combustion capture approach involves a chemical separation process that is more energy-intensive than that employed in the HIsarna process design, but benefits from the fact that the technology can be applied to existing equipment.

Chemicals from WAG. Several large pilot projects utilise the H_2, CO and CO_2 in WAG for various purposes. The climate benefit of these initiatives depends on the counterfactual considered, were they not to be used. The projects offer a variety of avenues to utilise a vast stock of existing steelmaking assets. Key examples include the public-private Carbon2Chem and Steelanol projects in Europe.

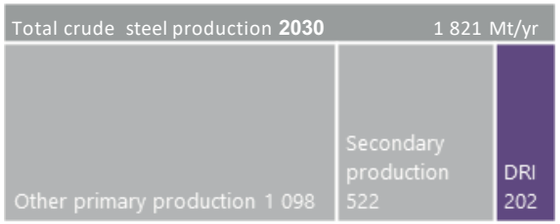
COURSE 50. This Japanese Iron and Steel Federation initiative seeks to raise the proportion of hydrogen used as a reduction agent in the BF-BOF route and to capture CO2 streams from blast furnace gas, with a full-scale demonstration planned in the 2030's. The hydrogen is sourced from enriched and treated WAG streams. Together these modifications could lead to a 30% reduction in CO2 emissions per unit of steel produced.

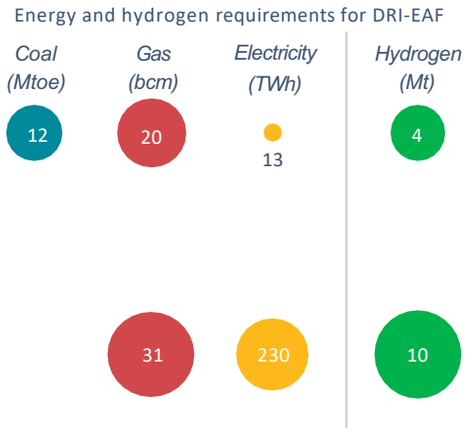


Energy Implications

Energy implications of fulfilling hydrogen demand via the DRI-EAF route







While the role of hydrogen could expand dramatically in the medium to long term, gas would continue to play an important role even after 2030, while the shift took place.

In the long term a **Paris-compatible pathway** would seek to drastically reduce CO_2 emissions from primary steel production. Using the 100% hydrogen DRI-EAF route for all primary steel production would largely eliminate CO_2 emissions, provided the electricity was sourced from renewables. This would require 47–67 MtH_2/yr. More than 2,500 TWh/yr of electricity would be needed to produce this much hydrogen, or roughly the combined electricity consumption of India, Japan and Korea today. A substantial but manageable amount of water would also be required as feedstock for electrolysers: around 0.6 bcm/yr, which is about 1% of total water consumption in the energy sector today. Some 500 Mt/yr of oxygen would be produced as a by-product; this could be put to use elsewhere in industry.

Notes: Only the energy and hydrogen requirements for the commercial coal/gas-based and 100% hydrogen-based DRI-EAF routes are included. Demand figures are consistent with a scenario in which the goals of the Paris Agreement are achieved, including the implementation of materials efficiency strategies and maximum deployment of the secondary production route. Average hydrogen requirements for both the gas and 100% hydrogen-based DRI-EAF routes are assumed in calculating the hydrogen requirements and energy inputs. Bubbles denoting energy and hydrogen requirements are sized on an LHV (lower heating value) energy content basis. The hydrogen and energy quantities are equivalent and not additive. 95% DRI charge to the EAF is assumed in all cases. Current DRI-EAF facilities often operate with a higher share of scrap, as this lowers costs. More information on the assumptions is available at iea.org/hydrogen2019.





4 September, 2023 - Source: IEA 2019

Cost Competitiveness of Cleaner Pathways

In the absence of sufficiently high CO_2 prices, replacing natural gas with renewable hydrogen in the DRI-EAF route would widen the difference in cost between the commercial DRI-EAF and BF-BOF routes. Energy and other raw material input costs represent upwards of about 45% of production costs for the DRI-EAF routes, so small price differences can make a big difference to cost competitiveness. Whereas the range of gas prices today makes the commercial DRI-EAF route competitive with the BF-BOF route in specific instances, the hydrogen-based DRI-EAF route, based on current estimates, would only be competitive in those places with the lowest electricity prices. It would also be significantly more expensive than its natural gas-based counterpart (>15–90%), even if natural gas production involved CCUS (>10–85%).

Among the other low-emissions pathways for steel production currently being explored, the "oxygen-rich smelt reduction BOF with CCUS" (HIsarna) route appears to have the lowest overall production costs in most regions in the current energy price context. It is less capital-intensive even than today's commercial BF-BOF route, and could reduce direct CO_2 emissions by around 80–90%. In most regions, the family of **CO_2 management** pathways tends to be at a more advanced stage of development today. However, in the context of a long-term **Paris-compatible** pathway the HIsarna design would have to be deployed in conjunction with a widespread CO_2 transport and geological CO_2 storage infrastructure.

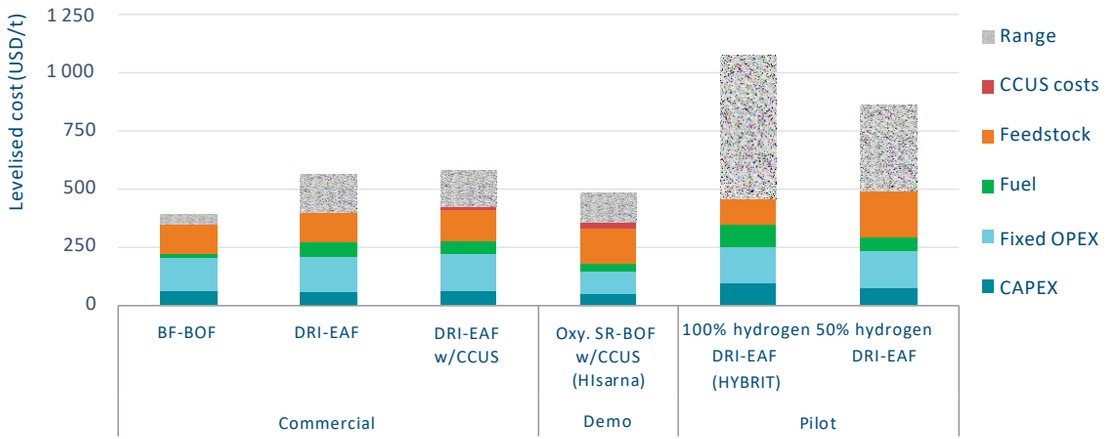
The BF-BOF route accounts for around 90% of existing primary capacity, an asset class in which steel producers are generally not anticipating substantial greenfield investments in the coming years. With many facilities utilising this technology having been constructed in the past 10–20 years, it is going to be difficult for new alternative production routes to outcompete them without policy intervention. These dynamics underpin the development of CO_2 management pathways, which generally seek to reduce emissions while making use of existing integrated steel facilities. HIsarna is an exception to this as it requires greenfield investment.

To compete in the long term with its natural gas-based counterpart equipped with CCUS, the 100% hydrogen-based pathway currently looks likely to need low-carbon electricity prices in the range of USD 5–35/MWh. This translates into hydrogen costs of USD 0.7– 2.0/kgH_2, assuming electrolysers with high efficiencies and low CAPEX requirements. These costs may be realistic in certain regions when using dedicated low-cost renewable resources, but are challenging to achieve elsewhere.



Source: IEA 2019

Estimated costs of steel for selected greenfield production routes in 2020

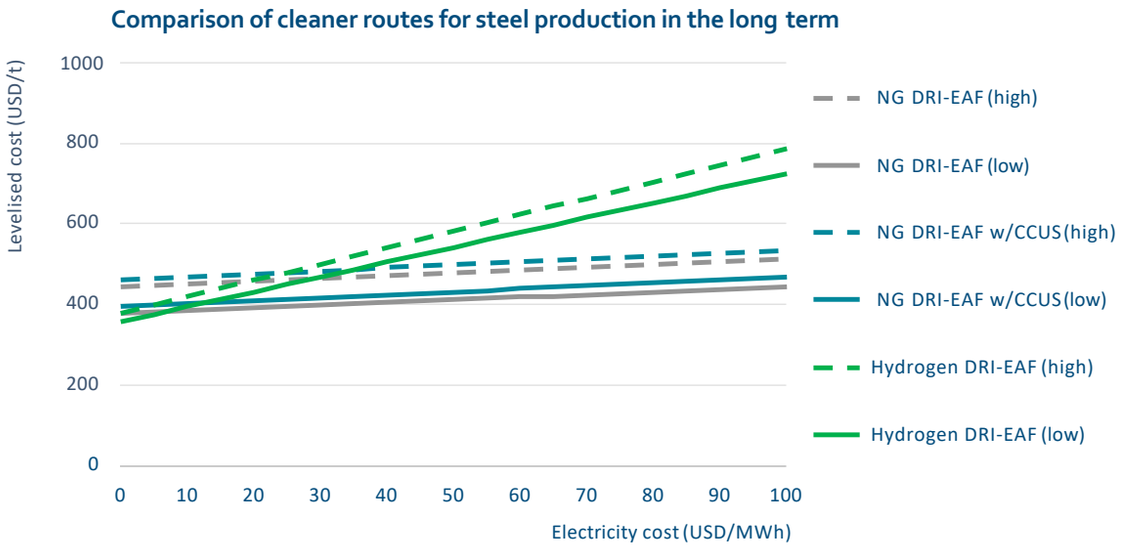


The hydrogen-based DRI-EAF route is between 10% and 90% more costly than its natural gas-based counterpart, and is highly sensitive to the cost of electricity.

From a policy perspective, there are two key areas where support is needed to bolster the sustainable adoption of hydrogen. First, support is needed for demonstration projects that seek to scale up the 100% hydrogen-based DRI-EAF process. Second, **differentiated markets** must be established to support the increased costs faced by steel producers introducing renewable hydrogen into their operations.



Hydrogen Steelmaking Plus Titania & Zircon



Notes: The *levelised cost* includes the cost of CAPEX on core process equipment, fixed OPEX, fuel and feedstock costs, and the cost of capturing, transporting and storing CO_2. Best practice energy performance is assumed for natural gas-based routes. Electrolyser CAPEX range = USD 455–894/kWe. Electrolyser efficiency range = 64–74%. 95% DRI charge to the EAF is assumed in all cases. More information on the assumptions is available at iea.org/hydrogen2019.



4 September, 2023 - Source: IEA 2019

Electrolytic hydrogen-based routes start to compete with their natural gas-based counterpart equipped with CCUS at electricity prices of USD 5–35/MWh. Cost in New Zealand is US$75/MWh resulting in a levelised cost for steel production with hydrogen reduction estimated around US$600/t. A 50% increase over the expected price of circa US$400/t for NG DRI-EAF. Applying an extra US$200/t of hot iron produced (considered a worst case scenario), results in the outcome shown below.

Key project metrics	Hydrogen	Carbon	Units
NPV of Cash Flows	$2,177,448,328	$2,741,955,059	$ US
DCF	6.18%	6.18%	Percentage
IRR	24.48%	33.44%	Percentage
Payback period	2.57	1.77	Years
Life of mine (LOM)	169.37	169.37	Years
LOM Operating Costs + Royalties US$/t ore mined (cash cost)	$14.09	$9.53	$ US/t
LOM Operating Costs + Royalties (A) US$/t produced (ROM)	$202.62	$137.11	$ US/t
LOM Revenue (B) US$/t produced	$623.63	$623.63	$ US/t
LOM Cash Margin (B-A) US$/t produced	$421.01	$486.53	$ US/t
LOM Revenue : Cost of Sales Ratio (B/A) Ratio : 1	3.08	4.55	ratio:1
LOM Free Cash Flow US$ millions (25-year project - 23-year LOM)	$5,844,691,803	$6,853,123,897	$ US LOM

SANOFEX is able to enter the hydrogen reduction steelmaking space effectively due to the production of **three key products** (Steel, Titania & Zircon) **simultaneously**. The project metrics presented above include a ***30% increase*** in iron making CAPEX and an 86***% increase*** in overall OPEX ($200/tonne of hot iron) for the project. Net profits are reduced by US$35.7 million pa or 10.5% after NZUs of CO_2-e are accounted for at NZ$25/t. This may be recovered by the provision of **advantageous financing** for **Green Steel**.



Green Hydrogen & Minerals for Export

Green hydrogen

The Concept Consulting Group is a specialist energy and economics consultancy that provides services to clients in New Zealand, Australia and the wider Asia-Pacific region. In January 2019 they released a report on Hydrogen in New Zealand. The data in this presentation is derived from Concept's public data set and developed within the context of the SANOFEX and Carbon Zero Minerals model for generating **green hydrogen** to reduce ilmenite ores originating in our tenements. The process will be used to produce a carbon zero steel and excess hydrogen for return to the grid or export.

Estimates for producing hydrogen in New Zealand today are $8.91 per kg, including the cost of storage in a tank. For comparison with other fuels, $8.91 per kg translates to $63 per GJ or $0.23 per kWh. For reference, the wholesale cost of natural gas is currently $6/GJ and the wholesale cost of electricity is approximately $0.075/kWh. The components contributing to the hydrogen cost estimate are:

- Wholesale electricity and commercial network connection costs for a large-scale facility (up to 75% of the cost of production);
- COPEX for the electrolyser, storage equipment, on-site bulk storage;
- Efficient sustained production (85% capacity factor);
- Equipment costs make up to a quarter of the cost of production (up to 25% CAPEX);
- Process losses during electrolysis (30%) and compression (10%) for storage add to production costs.

Export

Export would require steady, large-scale production to be viable (pilot plant required). The associated electricity demand could be material on a New Zealand scale such that export would need to be coordinated with new supply (SANOFEX greenfield clean plant). The estimate for the delivered cost of green hydrogen produced in New Zealand and shipped to Japan could be around *$44 per GJ by 2040. This compares to liquified natural gas (LNG) prices of approximately $14 per GJ.

If international hydrogen proof-of-concept trials look to extend in future beyond hydrocarbon-based hydrogen, New Zealand could be an attractive location due to our existing high penetration of renewable electricity production and if an overseas company wishes to invest in a hydrogen production facility in New Zealand, there does not appear to be any market failure or other factor which would prevent such a commercial development. **Internal modelling estimates the cost of liquid hydrogen at US$3.36/kgLH2 including storage at our port side transit station, based on a 1 TWh clean plant modular design.**



*Excess H_2 off-gas from the H_2 reduction furnace may be exothermically combined with O_2 off-gas from the electrolyser and cooled with recycled water to produce super heated steam at a temperature suitable to drive an electrical steam turbine. The electricity generated may be used in a primary EAF circuit to form semi-finished steel from sponge iron or recycled to produce further H_2 from electrolysis. In this manner, the cost to deliver *green hydrogen* may be considerably reduced to meet export targets.

Using MBIE figures for 'Real" 2020 current year electricity costs for *minerals extraction* of 11.66 cents/**kWh and the Concept Consulting Group modelled hydrogen price** of 23 cents/kWh (inclusive of COPEX) or 17.25 cents/kWh (inclusive of operating expenses alone) for analysis, provides the following **actual** comparison between Hydrogen & Carbon-based reduction (**base case**).

Resource	Hydrogen	Carbon	Units
Total bulk sand resource - 10m depth slice	2,214,000,000	2,214,000,000	metric tonnes (t)
Total heavy mineral resource - 10m depth slice	664,200,000	664,200,000	t
Total in-situ ilmenite resource - 10m depth slice	332,100,000	332,100,000	t

Mine	Hydrogen	Carbon	Units
Tonnes of ore mined	13,072,174	13,072,174	tpa
Tonnes of products produced	926,655	926,655	tpa
Iron produced	335,710	335,710	tpa
Synthetic rutile produced	573,171	573,171	tpa
Zircon produced	17,774	17,774	tpa

Costs	Hydrogen	Carbon	Units
Cost to inferred/indicated resource (JORC 2012)	$1,126,020	$1,126,020	$ US
Cost to JORC, PFS, EIA	$2,209,581	$2,209,581	$ US
Cost to extraction permit and resource consent	$7,166,107	$7,166,107	$ US
Cost to produce ilmenite concentrate	$20.28	$20.28	$ US/t
Cost to produce iron & synthetic rutile & zircon	$114.85	$92.50	$ US/t
Operating costs	$104,387,658	$84,071,503	$ US pa
Capital costs	$1,061,894,396	$873,644,396	$ US pa
Capital intensity	$1,169.59	$962.47	$ US/tpa

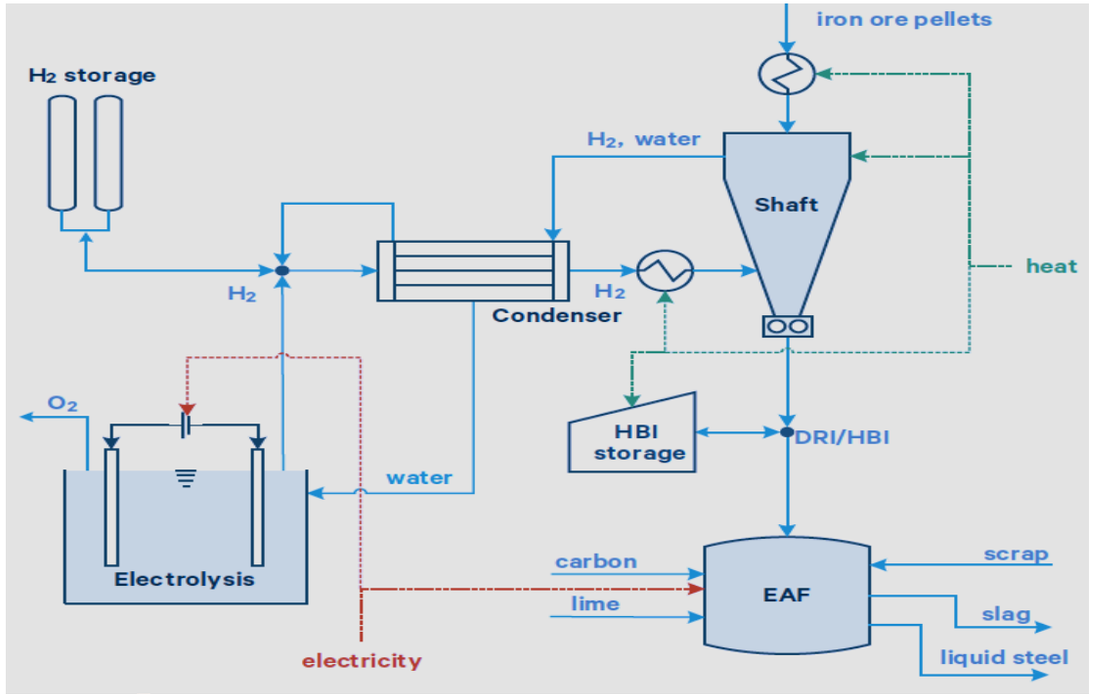
Hydrogen reduction requires more CAPEX and increases operating expense, but these costs are recovered in government or auction traded NZUs of CO_2-e emission. An importer of renewable energy might seek to provide advantageous financing to secure supply, whilst cutting their domestic emissions of CO_2-e by importing semi-finished Steel and Titania products.



4 September, 2023: *Source - concept.co.nz

Process Heat Recovery for Cost Reduction

Original Design Before Process Heat Recovery

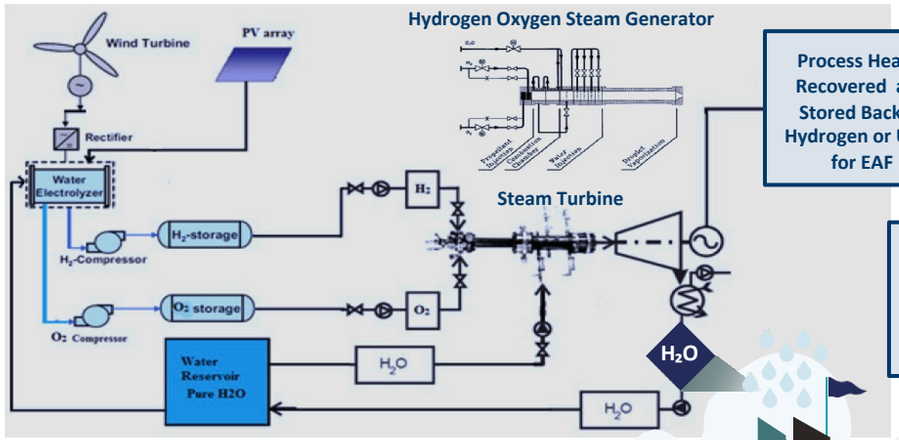


Process Heat Recycling

Oxygen off-gas from the electrolyser is condensed and stored in a tank at very low temperatures and recombined with unused hot hydrogen gas (saving the energy required to condense back to liquid) and heated water from the direct reduction shaft furnace to recapture process heat energy as superheated steam.

$2H_2 + O_2 \rightarrow 2H_2O$ + heat

This reaction is highly exothermic therefore, liquid water is added to the reaction to reduce the steam temperature, so it can be utilized in a steam turbine. The steam generator is a device to burn a stoichiometric mixture of hydrogen and oxygen in a combustion chamber to produce a high temperature superheated steam. Diagram below shows the hydrogen oxygen steam generator device. The mixture of hydrogen and oxygen are ignited in the ignition chamber, then the combustion takes place in the combustion chamber, the temperature in the combustion chamber is controlled by liquid water injection, after that the steam composes in the evaporation chamber. The steam generator efficiency is 100% since there are no emissions and no thermal losses.







Hydrogen & Minerals Partnership

Industrial process heat

Industrial process heat has overtaken electricity generation to be New Zealand's second largest source of energy-related emissions. Further, to the extent that large-scale hydrogen production drives the need for new renewable generation, this will increase the wholesale electricity component of hydrogen production. The relative economics of green hydrogen as an industrial process heat fuel will become more challenging, unless costs can be contained in a super-profits mineral processing plant and exported to a partner who desires both the mineral end products and the processed renewable energy units as liquid hydrogen.

The challenges for green hydrogen are the process losses and capital costs associated with producing and storing hydrogen from electricity. Twice as much primary renewable electricity is required to power a hydrogen-electrolyser-fueled boiler as an electric boiler. So, renewable energy derived green hydrogen must be used in an energy efficient process to produce high value products. SANOFEX is uniquely positioned to deliver such a value proposition to an overseas purchaser, requiring renewable energy units, Iron, Titania and Zircon.

Japan and South Korea's desire to move towards a hydrogen-based power supply

Key drivers:

- The Fukushima nuclear disaster;
    - a strong desire in much of Japanese society to move away from nuclear power;
    - Consequently, many of Japan's nuclear reactors were decommissioned.
- A shortage of domestic renewable energy potential;
    - densely populated islands, mountainous and complex electricity grid;
    - opportunities to build renewable generation are limited.

For Japan, South Korea and others, renewable energy must be imported to meet Paris agreement obligations.

Japan-Australia hydrogen partnership

Kawasaki Heavy Industries (KHI) is working in Australia to set up a brown coal gasification and reformation plant to produce hydrogen, which will then be liquefied and sent by ship to Japan. In Japan, the hydrogen will be burned in special turbines to produce electricity or used in fuel cells. Kawasaki is the major participant at every stage of the process after the coal has been mined, providing hydrogen infrastructure, port facilities, transport ships and electricity generation turbines. Construction of the plant is expected to be completed by late 2021.

KHI anticipates Japan becoming a major hydrogen importer, operating a fleet of 80 hydrogen transport ships by the year 2050. KHI anticipate that they will eventually be able to import hydrogen for a 'landed' price of around $35/GJ or approximately US$4/kg$LH_2$, and at this price point the project will be commercially viable.



The base case plant can be built with a renewable energy feed producing excess green hydrogen for export as liquid H_2 or return to the grid:

Sales of products	Hydrogen	Carbon	Units
Iron sale price (96% iron)	$292.00	$292.00	$ US/t FOB
Chloride grade synthetic rutile sale price (85%+ TiO2)	$800.00	$800.00	$ US/t FOB
Zircon concentrate sale price	$1,200.00	$1,200.00	$ US/t FOB
Basket sale price	$623.63	$623.63	$ US/t FOB

Carbon emissions	Hydrogen	Carbon	Units
CO2-e emission price traded in NZ$ on world markets	$25.00	$25.00	$NZ/t CO2-e
NZ-ETUs (NZUs)	$17,121,409	$12,508,124	$ US pa

Project financials	Hydrogen	Carbon	Units
Revenue	$577,892,920	$577,892,920	$ US pa
EBITDA	$473,505,262	$493,821,417	$ US pa
Depreciation	$41,552,389	$34,186,085	$ US pa
EBIT (operating profit)	$431,952,872	$459,635,332	$ US pa
Royalty (10% EBIT)	$43,195,287	$45,963,533	$ US pa
Tax (28% EBIT)	$105,694,180	$112,670,160	$ US pa
NZ-ETUs (NZUs)	$17,121,409	$12,508,124	$ US pa
Profit	$313,337,423	$323,909,352	$ US pa
Net Profit after NZUs added back	$330,458,831	$336,417,476	$ US pa

Key project metrics	Hydrogen	Carbon	Units
NPV of Cash Flows	$2,484,611,520	$2,579,800,944	$ US
DCF	6.18%	6.18%	Percentage
IRR	27.43%	32.16%	Percentage
Payback period	2.26	1.78	Years
Life of mine (LOM)	169.37	169.37	Years
LOM Operating Costs + Royalties US$/t ore mined (cash cost)	$11.29	$9.95	$ US/t
LOM Operating Costs + Royalties (A) US$/t produced (ROM)	$162.38	$143.07	$ US/t
LOM Revenue (B) US$/t produced	$623.63	$623.63	$ US/t
LOM Cash Margin (B-A) US$/t produced	$461.25	$480.56	$ US/t
LOM Revenue : Cost of Sales Ratio (B/A) Ratio : 1	3.84	4.36	ratio:1
LOM Free Cash Flow US$ millions (25 year project - 23 year LOM)	$6,472,452,641	$6,494,514,365	$ US LOM

This example compares hydrogen and carbon-based reduction of ore without any excess hydrogen production. It will be quickly realized by the reader that adding excess hydrogen capacity will lead to further profits in the hydrogen reduction model compared to the fossil fuel derived reduction stream. This example also incorporates SANOFEX submersible, remotely operated dredge technology, further reducing the project COPEX.

