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Soroush Basirat || Energy Finance Analyst, Global Steel

Electrifying ironmaking: The potential of direct electrolysis for iron ore

- *Direct electrolysis of iron ore could establish a niche role in smaller-scale green iron production by utilising lower-grade iron ores without extensive ore preparation, lower infrastructure needs and, particularly in low-temperature processes, by operating more effectively with intermittent renewable electricity.*
- *While the energy consumed in the electrochemical process rivals conventional ironmaking, the scale of clean electricity required presents a challenge for its widespread adoption.*
- *The scaleability of electrochemical ironmaking remains uncertain as the process must be demonstrated at a commercial scale due to the fundamental changes it introduces to conventional iron production methods.*
- *Regardless of whether renewable electricity is used to produce green hydrogen or directly reduce iron through electrolysis, greater investment in firmed renewable electricity will be essential to decarbonise primary steel production.*

Introduction

Iron has been produced for thousands of years using carbon-intensive processes in which fossil fuels generate carbon monoxide and hydrogen to remove oxygen from iron ore. An alternative approach is direct iron electrolysis, an electrochemical process that uses electrons rather than fossil fuel-derived reducing agents to produce metallic iron directly.

This approach has long been used to produce other metals, such as aluminium, copper and zinc. Although iron production via electrolysis was patented in 1906, it has never been deployed at commercial scale because more cost-effective and scaleable technologies for producing iron and steel have been available. However, ironmaking via electrolysis has recently gained attention in the steel industry as a potential pathway for deep decarbonisation.

Theoretically, electrolysis, when powered by clean electricity, has the potential to produce near-zero-emissions iron, and has been identified as a potential solution to the global steel

decarbonisation challenge. However, significant technical and commercial challenges remain before the technology can be deployed at scale.

Technological pathways

One way to classify direct electrolysis technologies is according to the reaction environment (electrolyte type) and the operating temperature (Table 1).

- **Low-temperature electrowinning**
- **Molten salt electrolysis (MSE)**
- **Molten oxide electrolysis (MOE)**

Among these pathways, MOE and electrowinning in aqueous solution with real world initiatives are better understood, whereas MSE remains less advanced and less well characterised.

Low-temperature electrowinning

In the low-temperature electrochemical process, from room temperature to 120°C, various aqueous electrolytes, including alkaline, acidic, as well as some ionic liquids, could be used. Once iron is present in the electrolyte, either as dissolved iron ions or in suspended ore particles, an electric current is passed through the electrolyte, causing iron ions to be deposited as metallic iron at the cathode while oxygen evolved at the anode.

Aqueous electrowinning systems benefit from a low operating temperature and relatively simple cell configuration. However, the low-temperature environment also introduces several challenges, most notably the limited solubility of iron ore in aqueous electrolytes. Another major concern is the competing hydrogen evolution reaction (HER), which reduces faradaic efficiency.

In general, aqueous acidic electrolysis (AAE) provides higher iron solubility, making it more suitable for iron oxide decomposition than aqueous hydroxide electrolysis (AHE), which uses alkaline electrolytes to dissolve iron ore. Operating at moderately elevated temperatures can further increase iron solubility, improve reaction kinetics, and enhance the overall efficiency of the process.

In addition to aqueous systems, several studies have also investigated non-aqueous electrolytes as an alternative approach to overcoming the limitations of conventional low-temperature electrowinning.

Molten salt electrolysis (MSE)

MSE is sometimes presented as an approach that combines some of the advantages of both very high- and low-temperature electrolysis. Operating at high temperatures between 400°C and 900°C, it addresses one of the key limitations of aqueous electrolysis by enabling rapid electrochemical reduction without the slow dissolution of iron ore in electrolytes. For example, according to Electra's chief technology officer, the entire process takes three to five days. The MSE process typically uses molten carbonate, chloride, fluoride or mixed-salt electrolytes to directly reduce metal oxides into high-purity metals with high current efficiency.

Aluminium production through MSE is the most commercially established example of this technology. While aluminium oxide (alumina) can only be melted at approximately 2,050°C, in the Hall–Heroult process (~660°C) , alumina is dissolved in molten cryolite (Na3AlF6), which serves as the electrolyte. This process consumes almost 13 megawatt hours (MWh) per tonne of aluminium produced, making it nearly four times more electricity-intensive than ironmaking via electrolysis.

Another pathway under investigation is molten salt hydrogen electrolysis, which introduces water into a molten salt reactor to generate hydrogen in situ. The hydrogen produced can then act as a reducing agent for iron ore within the reactor. This approach is being investigated in Japan by I'MSEP.

Both electrowinning and MSE can be carried out using either dissolved iron or solid iron oxide feedstocks, and several studies have demonstrated the direct electrochemical reduction of solid iron ores, including pellets. Using dissolved iron offers the advantage of facilitating impurity removal, as gangue minerals that are insoluble in the electrolyte can be separated before electrolysis. In contrast, direct reduction of solid iron ore bypasses the challenge of limited iron oxide solubility, eliminating the need for a dissolution step. However, this approach introduces other technical challenges, including sluggish mass transfer, limited contact between the electrolyte and the solid feed, and the formation of non-conductive intermediate phases on the cathode, which hinder current distribution and reduce process efficiency.

Molten oxide electrolysis (MOE)

The ultra-high temperature electrolytes contain oxide compounds, operating above the melting point of iron (1,538°C), which enables the generation of molten/liquid iron, ranging from 1,400°C to 1,600°C.

One of the key technical challenges of this pathway is the extremely high operating temperature, which significantly limits the choice of suitable electrolytes. The electrolyte must remain stable and resist decomposition under these harsh conditions while having a lower density than molten iron to enable effective separation and tapping of the produced metal from the bottom of the electrolytic cell. Similar to the MSE pathway, developing an anode material that can operate efficiently while maintaining structural stability under oxygen-rich, high-temperature conditions remains challenging.

In MOE, most gangue oxides remain in the molten oxide electrolyte, which forms slag, allowing impurities to be separated from the liquid iron in a manner similar to conventional ironmaking.

Table 1: Direct electrolysis of iron ore pathways

Technology	Subcategory	Electrolyte		Temperature (°C)	Advantages	Challenges
Electrowinning	Aqueous acidic (AAE)	HCL, H_2SO_4		20–90	High solubility, mature electrochemistry	HER, corrosion, low current efficiency
	Aqueous hydroxide (AHE)	NaOH, KOH, LiOH		22–120	Suppresses HER, Lower corrosion, stable electrolyte	Poor iron oxide solubility
	Non-aqueous	$AlCl_3$-based		<100	Suppresses HER, lower temperature, higher faradaic efficiency	High cost, very early stage, poor iron oxide solubility
Molten salt electrolysis (MSE)	Carbonate-based	Li_2CO_3, Na_2CO_3, K_2CO_3, $CaCO_3$		<900	Good conductivity, good dissolution	Carbonate decomposition, corrosion
	Chloride-based	LiCl, NaCl, KCl, $CaCl_2$, $MgCl_2$	Mixture AlF_3, $AlCl_3$	800–1,000	High current density, rapid kinetics, lower cost	Corrosion, chlorine management, poor dissolution
	Fluoride-based	LiF, NaF, AlF_3		-	-	Very low solubility
Molten oxide electrolysis (MOE)	Oxide melt	CaO, Al2O_3, MgO, B_2O_3, Na_2O, SiO_2, NaF, CaF_2		<1,600	Direct liquid iron production	Extreme temperature, refractory and inert anode challenges

Sources: Electrochimica Acta, IEEFA. Note: In many studies, particularly those on MOE and MSE, the electrolyte consists of a mixture of multiple components rather than a single compound.

Key technology developers

Beyond academic research and laboratory-scale experiments, several companies are actively developing iron electrolysis technologies and progressing towards pilot- and demonstration-scale facilities. These companies are working to validate the technical and economic feasibility of direct electrolysis, with the aim of scaling the technology for commercial iron production.

Boston Metal

Boston Metal is one of the most established initiatives in the iron electrochemistry field, with decades of research behind it and backing from major steelmakers and iron ore producers. The MOE process was patented in 1991 by Professor Donald Sadoway at MIT while he was researching inert anodes for aluminium production. In 2013, Boston Metal was spun out from MIT with the aim of advancing the technology from laboratory research towards commercial-scale iron production.

The company has raised more than USD500 million in equity funding to develop the technology, one of the largest funding amounts secured by any company in electrochemical ironmaking.

Many companies have invested in Boston Metal, including major iron ore producers such as BHP and Vale, steelmakers such as ArcelorMittal and Tata Steel, and others including Microsoft's Climate Innovation Fund.

Boston Metal is pursuing projects in the US and Brazil to derisk its technology before commercialisation. In March 2025, the company announced the commissioning of its first-of-a-kind (FOAK) multi-inert anode MOE industrial cell at its facility in Woburn, Massachusetts. In this 10-anode cell, new anodes made from a chromium–iron alloy were tested and demonstrated the ability to remain stable for more than 30 days of operation.

Anode durability is one of the major challenges to the development of the MOE pathway. Boston Metal has reported it is developing anodes with improved durability and stable operation.

While Boston Metal has been trialling the technology at various scales, it seems the company is pivoting towards processing critical metals as "strongest near-term opportunity for MOE" instead of iron and steel.

In 2022, the company founded Boston Metal do Brasil, its first facility in Brazil, to extract critical metals from mining and metallurgical waste, with production capacity of 10,000t of ferro alloys targeted to begin in 2026. However, an incident at the Brazil facility caused it to miss a key milestone and lose a finance option, with 71 US employees consequently laid off.

The technical equipment failure was related to the refractory materials inside the cell wearing out due to the highly corrosive slag at around 1,600°C, which resulted in material leakage. This failure, which Boston Metal described as an "unforeseen industrial accident", highlights that the technology still requires further improvements.

Electra

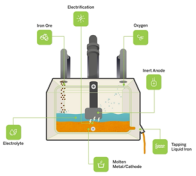
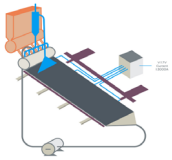
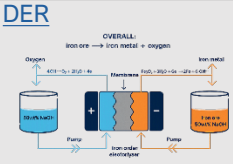
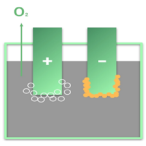
Among the companies developing direct electrolysis technologies, Electra — founded in 2020 — has emerged as one of the leading contenders. Its AAE-based process has attracted substantial investor support from Rio Tino, BHP, Nucor and POSCO. Electra raised USD85 million in Series A funding in October 2022 and USD186m in Series B funding in April 2025. Most recently, Electra secured an additional USD30m in venture debt financing from JP Morgan.

In addition, the company secured a USD50m grant from Breakthrough Energy Catalyst and about USD8m in tax credits through the Colorado Industrial Tax Credit Offering, further strengthening its funding for technology development and commercialisation.

Electra commissioned its first pilot plant in Boulder, Colorado, in 2024. The plant produces iron plates about 1m², and its modular design enables production capacity to be increased by adding more electrolysis cells. In late 2025, the company announced plans to build its first demonstration plant — a 12,000m² facility in Jefferson County, Colorado — with an annual production capacity of 500t.

Unlike Boston Metal, Electra's process produces solid iron plates rather than molten iron. These plates must be remelted before being used for steel production. Producing iron at low temperatures provides greater operational flexibility, allowing the process to better utilise intermittent renewable electricity. The relatively simple process design has also enabled Electra to accelerate technology development, progressing from the initial concept to a pilot plant in less than 3½ years.

Table 2: Developers of electrochemical ironmaking

Company	Technology	Capacity (ktpa)	Temp. (C°)	Electrolytes	TRL*	Challenges
Boston Metal	MOE 	0.012–0.024 from one cell	1,600	Oxide mixes	5	Very high temperature to keep the molten phase. Specialised chromium-iron alloy anode is needed.
Electra	AAE 	60kg per cathode (Pilot) Next step: demonstration-scale 0.5ktpa	60	Acidic solution	4–5	Operating at low current densities, requiring more cells to achieve the desired production capacity
Volteron by ArcelorMittal and John Cockerill (former SIDERWIN project)	AHE 	Multi-kg Plans include commissioning a new 40–80ktpa plant.	110	Solution with suspended particles ($NaOH–H_2O$)	5–6 at pilot scale. Aiming for 7.	Dendrite forming Electrochemical efficiency Needs very fine, high-grade ores as the iron ore doesn't dissolve.
Fortescue	DER 	Goalà establishing a plant with 100kg feed capacity	<130	Alkaline (NaOH)	≥2 in December 2025 . Aiming for 6.	Needs specialised electrolyser membrane (uses Agfa Zirfon)
Element Zero	MSE 	0.05 (continuous production plant)	250–300	Alkaline eutectic	-	Electrolyte (salt) recovery

*Sources: Company reports, IEEFA. Notes: *TRL = technological readiness level. As part of the ULCOS initiative, the European Union previously supported an MOE project known as the Molten Iron by Direct Electrolysis of Iron Ore (MIDEIO) project. However, there have been no significant public updates on the project in recent years. The EU-funded ZEROSTEEL initiative is supporting the development of four innovative steel decarbonisation pathways, one of which is based on MOE. The final product of MOE process is molten iron while other technologies produce solid iron.*

Volteron (former SIDERWIN project)

Building on the outcomes of the SIDERWIN (ΣIDERWIN) project — funded by the EU to develop an electrowinning-based ironmaking process — ArcelorMittal and John Cockerill announced in 2023 plans to construct a plant with initial production capacity of 40–80ktpa iron plates by 2027. The Volteron plant is expected to be expanded in later phases to a capacity of 0.3–1MTPA.

Volteron commissioned a pilot plant with an electrode area of 1m² in April 2025. The company states that the technology has reached technological readiness level (TRL) 5–6, and plans to advance it to TRL 7 at the new pilot plant.

Preliminary studies estimate the FOAK commercial plant, with a production capacity of 0.8MTPA of iron, has a capital expenditure (capex) share of approximately USD165/t of final product (iron plate). With further design optimisation, this is expected to decrease to about USD123/t Fe.

The process requires a highly refined iron ore feedstock consisting of very fine, high-grade hematite with a particle size of 10–20µm and a silica content of approximately 1%.

John Cockerill also appears to be exploring potential co-operation with China's Shougang Group to develop this technology.

Fortescue (low-temperature DER)

Fortescue is also developing a low-temperature direct electrochemical reduction (DER) process in collaboration with Deakin and Curtin universities through a project supported by the Australian Renewable Energy Agency (ARENA). The technology is based on a solid-state slurry electrolyser with an alkaline electrolyte, and is designed to operate using intermittent renewable electricity. Unlike other electrolysis pathways, the process incorporates a specialised membrane, making it distinct from other technologies under development. DER technology remains at a very early stage of development, with both its TRL and commercial readiness level (CRL) estimated to be more than 2.

Element Zero

Element Zero is an Australian company developing a MSE pathway for iron production. While limited public information is available on its technology, the company has demonstrated its process in a batch production system at the kilogram scale. In 2025, it opened a new facility in Malaga, Western Australia, to establish its first continuous trial plant.

The company says it can completely dissolve a wide range of iron ores, from low- to high-grade, in less than an hour. Compared with conventional methods, it is reported to reduce energy consumption by 30–40%, is compatible with renewable electricity, and can operate effectively with intermittent power supplies.

Although Element Zero remains at an earlier stage of development than several other companies pursuing direct electrolysis technologies, it has outlined long-term plans to commercialise the process through large-scale plants in Australia and the US. The company raised USD10 million in seed funding in 2024, led by Playground Global, to advance the development of its technology.

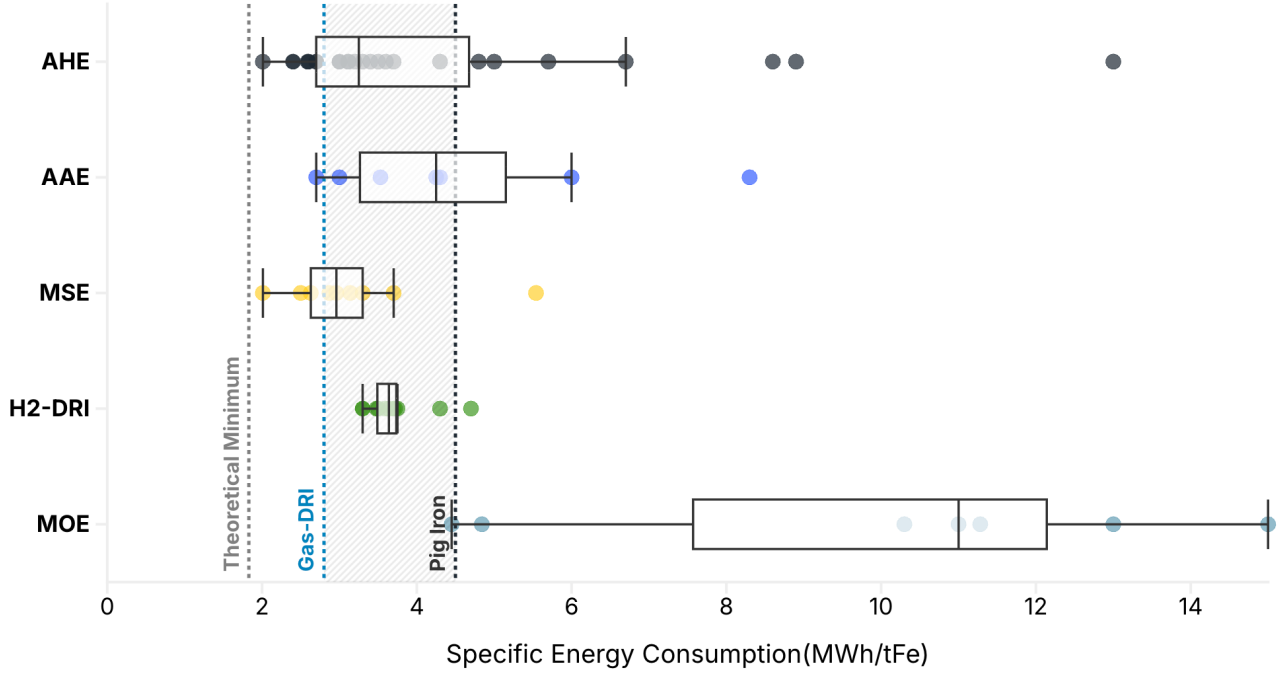
Energy consumption

Theoretical calculations indicate the minimum energy required to decompose hematite (Fe_2O_3) into iron (Fe) and oxygen (O_2) at 25°C is 1.83MWh per tonne of iron produced. Some studies also estimate the thermodynamic energy requirement based on the enthalpy change, which is

about 2MWh/t Fe. However, the practical energy consumption of electrolysis processes is higher than the theoretical minimum due to process inefficiencies, including heat losses, particularly in high-temperature pathways such as MOE. The SIDERWIN pilot reported a specific electricity consumption of as low as 2.7MWh/t Fe under ideal operating conditions.

Estimates of electricity consumption for the various electrolysis pathways remain conceptual and require further validation through larger pilot and commercial-scale operation to better understand their real-world energy requirements. A University of Newcastle study assessed the specific energy consumption of various electrolysis pathways (Figure 1). Reported electricity consumption ranges from 2.7–6.0MWh/t Fe for AHE/AAE, 4–5MWh/t Fe for MSE, and 4.5–6.0MWh/t Fe for MOE. Most of these figures are based on experimental data from small-scale laboratory tests. Although they remain subject to considerable uncertainty, they provide a useful indication of the potential energy consumption range of each technology pathway. (Results for MOE span an even wider range.)

Figure 1: Specific energy consumption of direct electrolysis vs conventional ironmaking



Sources: Green Electrolytic Iron Production, IEEFA. Note: Every data point represents a different temperature and experimental condition.

In general, many studies based on the results from pilot facilities suggest that electricity consumption for direct electrolysis is likely to fall within the range of 3–4MWh per tonne of crude steel (CS), assuming continued improvements in process efficiency. This is broadly consistent with estimates from Agora Industry of 3.7–4.1MWh/t CS and the Energy Transitions Commission's estimate of 4.0–4.2MWh/t CS.

Volteron says its technology can achieve an energy consumption of less than 3.74MWh/t, with approximately 3.22MWh/t (~85%) used for iron production through electrolysis (at the reported Faradaic efficiency), 0.31MWh/t consumed by electrolyser-related auxiliaries, and the remainder used for other purposes.

While the theoretical energy consumption of electrochemical ironmaking is close to that of conventional ironmaking routes, including gas-DRI (~2.8MWh/t DRI), pig iron production in BF (~4.5MWh/t hot metal) and hydrogen-based DRI pathways, the amount of electricity required at commercial scale remains substantial.

Firmed renewable electricity cost

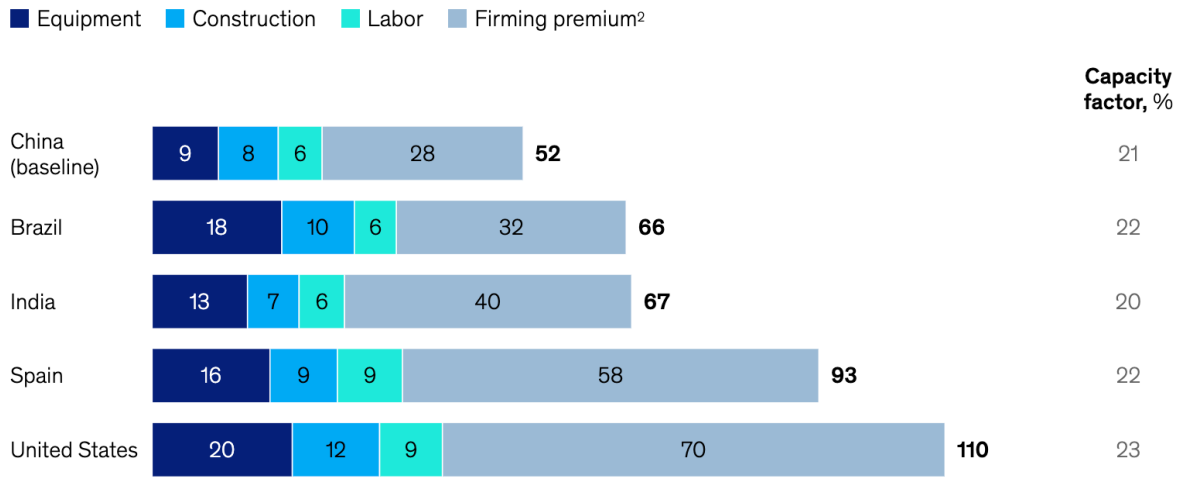
Electrochemical ironmaking relies on clean electricity to decarbonise the iron and steel value chain. While electricity generated from renewable sources is the lowest-cost form of power generation, ensuring a reliable supply by firming these variable energy sources with energy storage systems, such as batteries, still requires significant investment.

A Lazard July 2026 levellised cost of energy (LCOE) report estimates the cost of firming intermittent electricity generated from wind, solar, and solar/wind + battery energy storage systems (BESS) across different US regions ranges from USD8–62/MWh . As a result, the total levellised cost of firmed renewable electricity is estimated to range from USD70–167/MWh .

An Ember report also found that providing 24/7 carbon-free electricity from solar PV was already achievable in locations with high solar irradiation at an average cost of approximately USD104/MWh. It estimates that delivering 1kW of continuous firmed solar power requires approximately 5kW of installed solar PV capacity and 17kWh of battery energy storage.

A McKinsey report indicates that the levellised cost of utility-scale firmed solar PV could be as low as USD52/MWh in China and USD67/MWh in India. In almost all locations, the cost of firming accounts for more than half of the total cost.

Figure 2: LCOE for utility-scale solar PV + BESS (USD/MWh*)



*Sources: McKinsey Global Institute, International Renewable Energy Agency. Notes: *Levellised costs are before taxes and subsidies. Based on 24/7 renewable economics for firm solar and wind; firming premium calibrated to 95% reliability. Firming premium is the extra cost of converting variable solar output into 24/7 power, covering the additional battery storage and overbuilt solar capacity required to meet a 95% reliability level. Numbers may not sum due to rounding.*

Battery technology is evolving, and the cost of lithium-Ion batteries has declined from USD827/kWh in 2013 to USD108/kWh in 2025. Outside China and the US, Ember reported the October 2025 cost of utility-scale battery storage was about USD125/kWh in countries such as Italy, India and Saudi Arabia. As a result, the cost of firming renewable electricity is on a downward trajectory, and is expected to continue falling, improving the economic outlook for technologies highly dependent on low-cost electricity.

Modelling by the International Renewable Energy Agency shows a 31% cost reduction for firmed solar PV + BESS at 95% reliability between 2020 and 2025. A further reduction of about 30% is expected by 2030 and 40% by 2035 — bringing the LCOE below USD50/MWh at best-performing sites worldwide. Additionally, lowering the reliability target to 85% could significantly reduce the firmed LCOE.

Electricity is the primary cost driver in iron production via electrolysis. Therefore, access to abundant, low-cost clean electricity will be a key factor in the commercial viability and widespread deployment of electrochemical ironmaking.

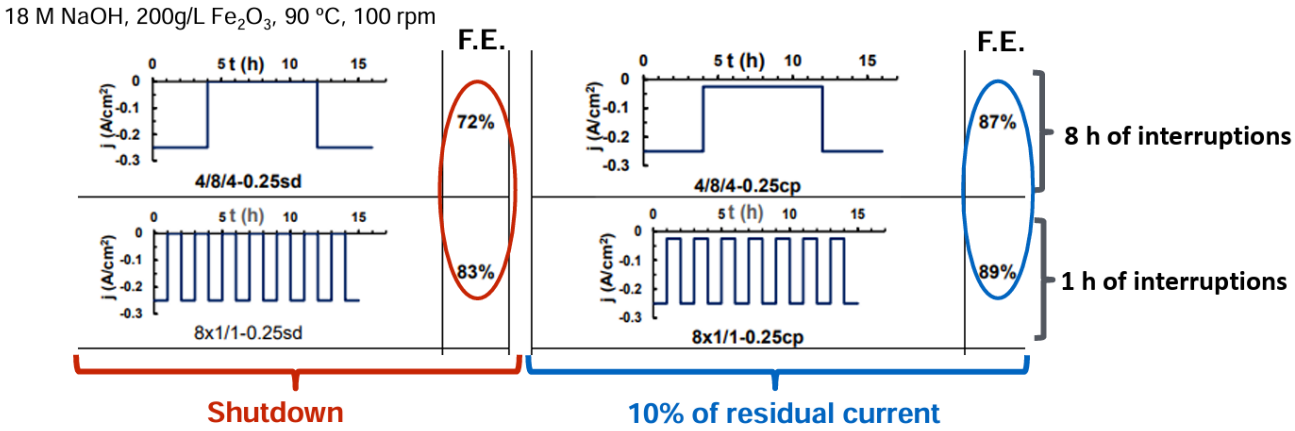
Investing in firming up renewables has already been adopted in other electrochemical metal production industries, particularly aluminium and copper. For example, Rio Tinto has signed an agreement with Edify Energy to develop 600MW of solar PV and 2,400MWh of BESS to support its aluminium operations. Similarly, BHP's copper mining and processing operations in Chile have partnered with Sungrow to deploy 195MW of solar PV and 960MWh of BESS.

Process flexibility and consumption management

Beyond the availability of firmed renewable electricity, some electrochemical ironmaking technologies may offer greater operational flexibility in electricity consumption. Some studies identify the ability to operate directly on renewables as a potential advantage of direct iron electrolysis, suggesting some processes may be more tolerant of intermittent power supply. However, this advantage is not guaranteed to high-temperature electrolysis processes, particularly MOE, which operates with molten iron. Power interruptions could damage the electrolytic cell.

In contrast, aqueous electrowinning operates at much lower temperatures, and is therefore better suited to integration with variable renewable electricity. It can ramp down during periods of high electricity prices, allowing it to respond flexibly to market conditions. Experimental testing by SIDERWIN demonstrates the process can tolerate intermittent electricity supply with minimal loss of efficiency. Notably, this applies when the cell is in cathodic protection mode and maintained at approximately 10% of its operating current during power interruptions rather than undergoing a complete shutdown. The faradaic efficiency was 89% in this scenario (Figure 3).

Figure 3: Effect of electricity interruptions on alkaline aqueous electrolysis

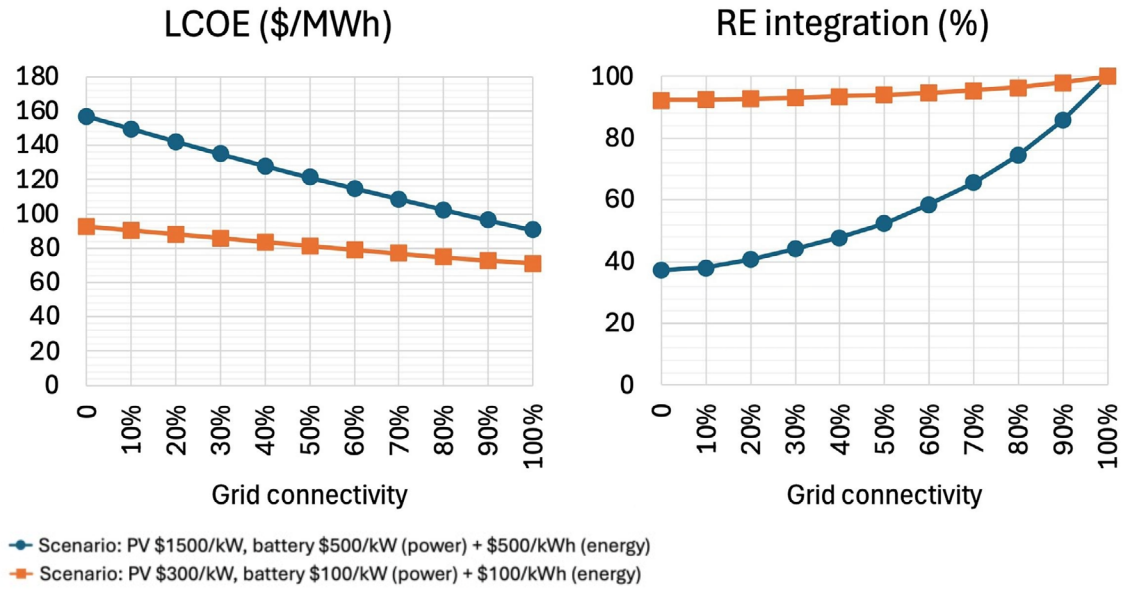


Source: SIDERWIN, Iron Electrowinning – lessons learned, Webinar 23 March 2023. Notes: Cycles with shutdown interruptions or cathodic protection (10% of residual current) for iron electrowinning from Fe2O3 suspensions. The feasible faradaic efficiency (FE) of the system was reported at >90%. Faradaic efficiency (FE) is defined as the amount (moles) of collected product relative to the amount that could be produced from the total charge passed, expressed as a fraction or a percent.

The technology can shift electricity consumption away from peak-price periods and participate in demand-side response (DSR) programs and maximising negative hourly wholesale electricity prices. This flexibility can help balance electricity supply and demand in the grids with a high share of renewables, reducing the need for additional peak generation capacity — often fossil fuel-based — or significant investment in firming renewables. Furthermore, it opens the option to firm up the system with a lower reliability target, which significantly reduces the cost.

One study by the Australian National University showed load flexibility can reduce the LCOE significantly regardless of solar PV + BESS capex. The sensitivity analysis shows that under scenarios of high capex for PV and battery, the LCOE decreases by 57% from AUD157/MWh to AUD68/MWh. Under the lowest-cost PV + BESS scenarios, the LCOE decreases by 80% from AUD92/MWh to AUD19/MWh while maintaining a high share of renewables in the mix.

Figure 4: Load flexibility and LCOE



Source: Solar Energy. Note: All Figures are in AUD; AUD1 = USD 0.7168.

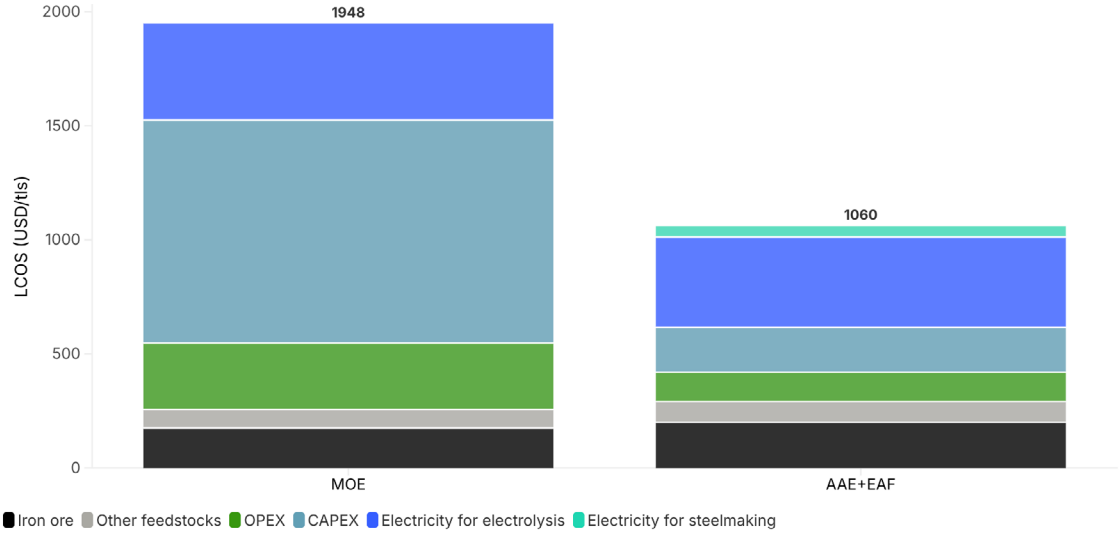
In addition to electrolysis flexibility, melting iron produced through direct electrolysis is expected to require less electricity than melting DRI in an electric arc furnace (EAF). DRI typically has a metallisation rate of about 95%, meaning it still contains residual iron oxide (FeO). The reduction of this remaining FeO in the EAF is an endothermic process that requires additional energy. In addition, gangue and other impurities present in DRI increase slag formation, further increasing electricity consumption during steelmaking. Electricity consumption is typically about 340–390kWh/t when using 100% scrap as feedstock. In comparison, electricity consumption increases to approximately 530–680kWh/t when the charge consists of 80–95% DRI. These values are likely to be even higher under real-world operating conditions.

Economics of electrochemical ironmaking

Limited techno-economic analysis has been conducted on direct iron electrolysis, and the available studies provide only indicative estimates of the capex and operating expenditure (opex) due to the lack of reliable experimental and real-world data. Capex estimates are generally derived from analogous electrochemical metal production processes, with adjustments to account for the specific requirements of iron ore electrolysis. As with most electrochemical processes, the primary cost drivers are electricity, iron ore and capex.

Figure 5 presents the estimated levellised cost of steel (LCOS) for FOAK commercial plants using two electrochemical ironmaking pathways.

Figure 5: Levellised cost of steel for FOAK electrochemical steel production

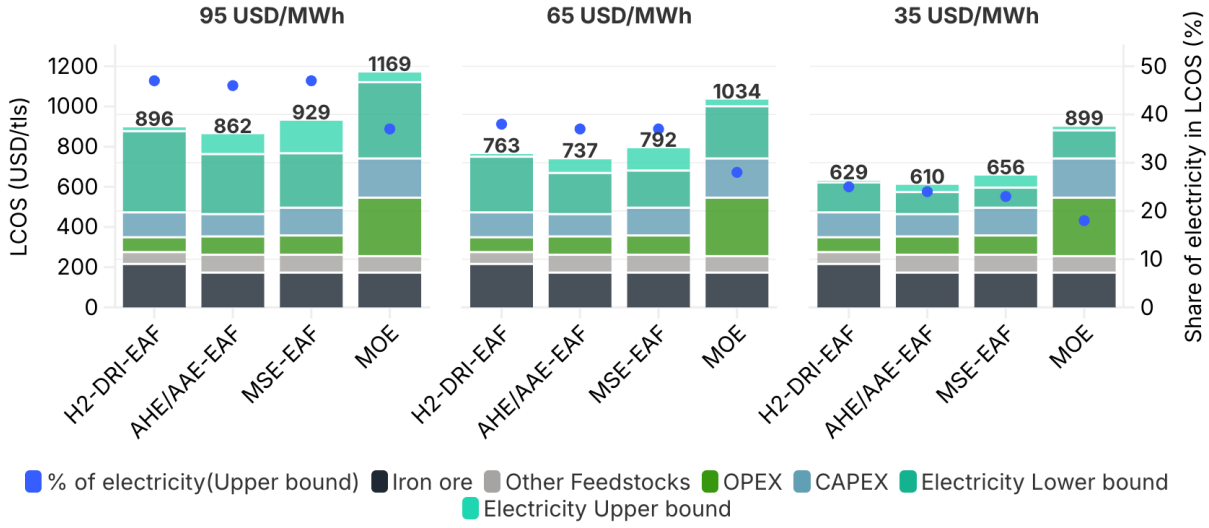


Sources: IEEFA calculations, BNEF Steel Production Valuation Model, Volteron. Note: See Appendix 1 for more information. Click here to see the interactive chart.

Longer term, these technologies are expected to mature, leading to reductions in both capex and opex costs, while improvements in process efficiency are likely to reduce electricity consumption.

Figure 6 shows a comparison of the estimated nth-of-a-kind (NOAK) LCOS for various electrochemical ironmaking pathways with the H²–DRI–EAF route, which is considered the leading decarbonisation pathway for primary iron and steel production. The economics of all electrochemical pathways are highly sensitive to electricity prices. Lower-cost firmed renewable electricity is expected to significantly reduce production costs in the future, improving the competitiveness of these technologies.

Figure 6: LCOS for NOAK by production pathway at different electricity prices



Source: IEEFA calculations. Note: See Appendix 2 for more information. Click here to see the interactive chart.

Under a scenario assuming an electricity price of USD95/MWh, electricity accounts for 40–50% of the total production cost. Aqueous electrowinning processes have the potential to be among the lowest-cost electrochemical ironmaking pathways, and could be cost-competitive with alternative low-emissions technologies, particularly H2–DRI.

In the long run, direct electrolysis of iron ore could become more economical than the H– DRI pathway if the technology reaches maturity and continues to improve over time. However, hydrogen production through electrolysis is also undergoing continuous development, with many companies working to improve electrolyser efficiency and reduce the electricity required to produce each unit of hydrogen.

Technical and commercial challenges of electrochemical ironmaking

The technology readiness level (TRL) of electrochemical ironmaking remains low, with most projects about TRL 4 on a scale of 1 to 9. As a result, these technologies are still in the early stages of development, and are unlikely to be available at commercial scale in the near future.

In addition, technology readiness alone does not determine whether a new process will succeed. Manufacturing readiness level (MRL) and adoption readiness level (ARL) are equally important in assessing a technology's potential for large-scale deployment. Transforming a mature industry such as iron and steel requires more than technical innovation; it involves establishing new manufacturing capabilities, developing viable business models, and building market acceptance. Such transitions typically take decades, and require close collaboration across the entire value chain, from technology developers and equipment manufacturers to mining companies, steel producers, customers and policymakers.

Scaleability is another big barrier to the electrochemical pathways. For example, Boston Metal's recently commissioned multi-inert anode MOE cell has a production capacity of only 1–2 tonnes a month. Electra's recently announced demonstration plant has capacity of 500 tonnes a year. Scaling the technology to commercial iron production would require thousands of similar cells operating simultaneously. In addition, the production capacity of each individual cell would need to increase significantly. By comparison, Al Taweelah aluminium smelter operates 1,262 electrolysis cells, each producing approximately 3.3t of aluminium a day. Daily production per cell at the UAE's Jebel Ali and Australia's Tomago smelters is approximately 1.8 and 1.95 tonnes, respectively.

In electrochemical processes, cell capacity is closely linked to the electrical current that can be passed through the cell, with higher current generally enabling higher production rates, assuming comparable current efficiency and operating conditions. Boston Metal envisions developing cells capable of operating at up to 600 kiloamperes (kA), with 300 cells operating in parallel potentially supporting approximately 1MTPA of molten iron production. The company has reportedly reached 25kA with its multi-anode cell, and plans to scale this to 200kA (first commercial scale) as an intermediate step towards the 600kA target. In the 200kA cell, the target production rate is approximately 3t a day, compared with 1–2 tonnes a month in the previous cell.

Bridging this gap in production scale will be one of the key challenges for the commercialisation of this technology.

There are still several technical and fundamental challenges developers and researchers must overcome to improve production efficiency. These include:

- The low solubility of iron oxide.
- Maintaining the chemical stability of the electrolyte and molten iron.
- Minimising the hydrogen evolution reaction (HER) to improve current efficiency.
- Developing suitable anode materials.

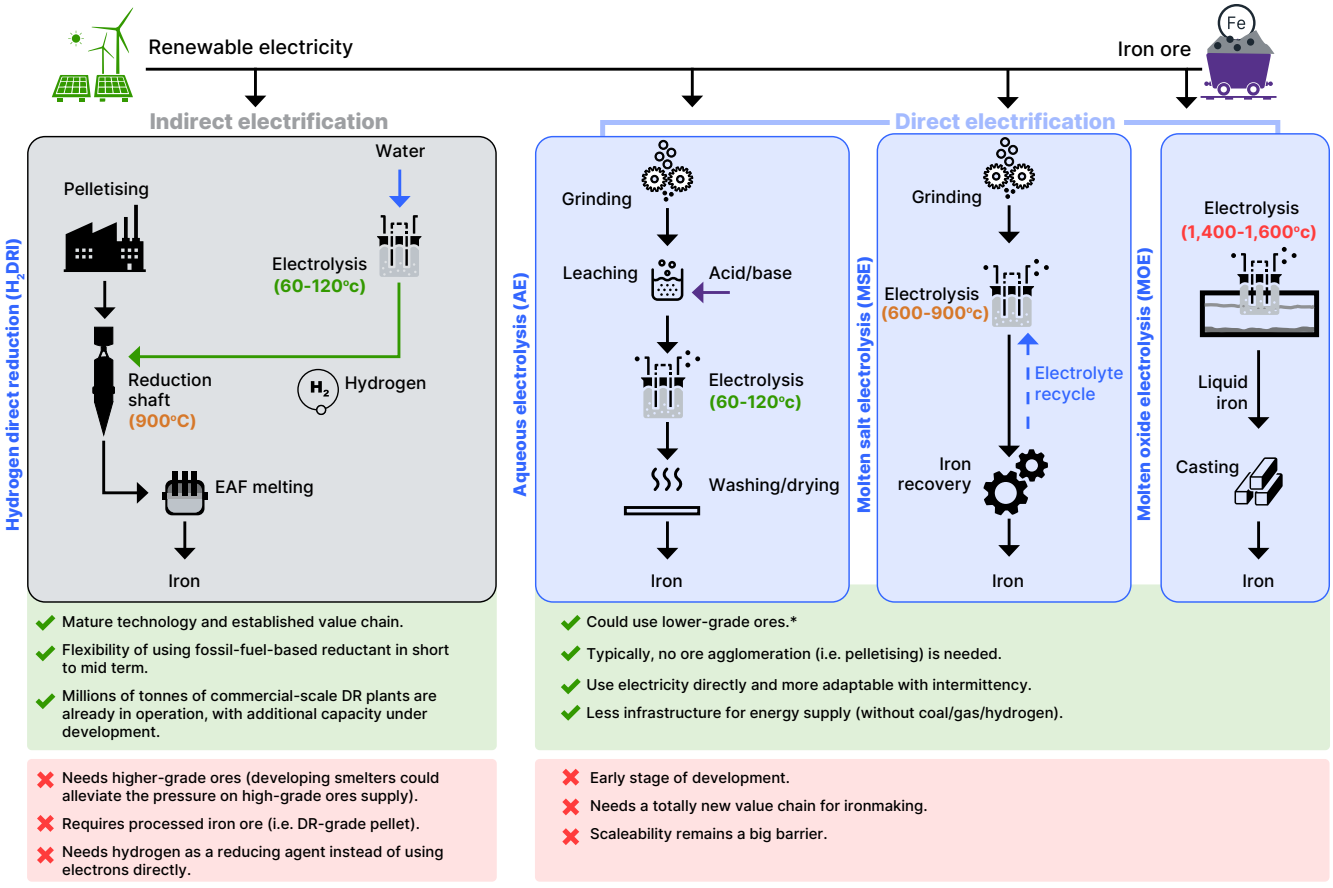
Addressing corrosion under highly reactive operating conditions. High-temperature processes appear to face greater and more distinctive technical challenges due to the harsh operating environment.

Electrochemical ironmaking future

Among primary steel decarbonisation solutions, direct electrolysis is likely to lag hydrogen-based steelmaking in terms of scaleability, commercial readiness and industry adoption. At the same time, its projected electricity consumption and production costs may be broadly comparable to those of hydrogen-based steelmaking.

Overcoming the technical challenges associated with direct electrolysis is only part of the transition. The adoption of entirely new system would require a fundamentally different ironmaking value chain, one that is largely unfamiliar to the steel industry. Unlike conventional blast furnaces or direct reduction processes, electrochemical ironmaking relies on completely different process configurations, equipment and operational expertise, which could significantly slow industrial adoption.

Figure 7: Decarbonising steelmaking, direct electrification vs indirect electrification



*Sources: Redfern, IEEFA. Note: *This may not apply to all direct electrolysis pathways. For example, the Volteron (formerly SIDERWIN) project reports the process requires very fine, high-grade hematite (<1% silica) with a particle size of 10–20µm.*

Furthermore, most net-zero emissions studies for the iron and steel sector do not envisage a significant contribution from direct electrolysis technologies by 2050.

This suggests that while direct electrolysis is likely to become part of the future mix of ironmaking technologies, it is unlikely to become the dominant production route in the coming decades. Consequently, countries seeking to establish green iron industries, such as Australia, cannot

rely solely on these emerging technologies while more mature, low-emissions pathways are already available for commercial deployment.

However, it has unique advantages that differentiate it from other pathways. In particular, the ability to use lower-grade iron ores with minimal or no processing (even magnetite ore as low as 35% Fe) and, in the case of low-temperature processes, greater compatibility with intermittent renewable electricity.

Electrolysis also requires less energy-related infrastructure at the steel plant. By eliminating the need for coal, gas and even hydrogen as reducing agents, it reduces the requirement for associated infrastructure such as bulk material handling systems for coal, gas pipelines, hydrogen storage and distribution facilities, and related port infrastructure. In addition, the overall process configuration is simpler, as it removes the need for several upstream processing steps, including cokemaking and agglomeration processes such as sintering and pelletising. A Wuppertal Institute study estimated the electrowinning process requires approximately 1 tonne (~28%) less raw material per tonne of steel produced than the conventional, coal-based, blast furnace–basic oxygen furnace (BF–BOF) route.

These characteristics could enable direct electrolysis to establish a niche role in smaller-scale green iron production, particularly in regions with abundant renewable energy resources and access to lower-grade iron ores, even in the absence of an existing steelmaking industry.

Appendix 1

Assumptions	Unit	Volteron (AAE–EAF)	MOE
Iron ore	USD/t	130*	100
Electricity (firmed renewables)	USD/MWh	106	106
Electrolysis feedstock (electrolyte, anode**)	USD/t steel	32	83
Other feedstock steelmaking (EAF)	USD/t steel	59	-
Opex (labour, maintenance)	USD/t steel	239	291
Capex: Electrolysis***	USD/t capacity	1,858	11,000
Capex: Steelmaking	USD/t capacity	350	-
Ironmaking electricity	MWh/t iron	3.74	4
Steelmaking electricity	MWh/t steel	0.45	-
Production capacity	ktpa	800	20

*Sources: BNEF Val March 2026, Volteron, IEEFA. Notes: *The Zanaga iron ore specification appears to be close to the feedstock requirements reported for the Volteron process, with a hematite grade of 68.5% Fe and approximately 1.05% SiO. **Volteron estimates a fresh caustic soda consumption of 92kg NaOH per tonne of iron produced, assuming a 50% NaOH solution at USD0.35/kg. For molten oxide electrolysis (MOE), electrolyte costs have been estimated at USD50.75/t of molten iron, with anode costs of ~USD31.6/t of molten iron. Other EAF consumables (including ferroalloys, industrial gases, fluxes, electrodes and refractories) are estimated at USD59/t of steel for the Volteron pathway. ***BloombergNEF estimates the capital cost MOE technology at USD11,000 per annual tonne of capacity for a 20,000TPA plant. In 2021, it estimated capital costs of USD8,360 for a 10,000TPA facility (FOAK) and USD1,672 per annual tonne for a 1MTPA commercial-scale plant in the US by 2050.*

Appendix 2

Assumptions	Unit	H_2–DRI–EAF	AHE/AAE–EAF	EAF	MOE
Iron ore (67% pellet or 61% fines)	USD/t	140	100	100	100
Electricity (firmed renewables)	USD/MWh	35, 65, 95			
Other feedstock (electrolysis + EAF)	USD/t steel	59	89	89	82
Opex (labour, maintenance)	USD/t steel	74	91	96	291
Capex (ironmaking/electrolysis)	USD/t capacity	650	900	1200	2200
Capex (steelmaking)	USD/t capacity	350	350	350	-
Ironmaking electricity (low)	MWh/t iron	0.3	2.7	2.4	4
Ironmaking electricity (high)	MWh/t iron	0.5	3.74	4.1	4.5
Steelmaking electricity	MWh/t steel	0.75	0.45	0.45	-
Hydrogen delivered	USD/kg	2.8, 4.4, 6	-	-	-
Hydrogen electricity	MWh/kg H_2	53	-	-	-
Hydrogen consumption	Kg H_2/t DRI	55	-	-	-

Notes: For most of the key assumptions, values were drawn from multiple references and adjusted where necessary for the purposes of this study. Production period: 30 years; discount rate: 8%.

About IEEFA

The Institute for Energy Economics and Financial Analysis (IEEFA) examines issues related to energy markets, trends and policies. The Institute's mission is to accelerate the transition to a diverse, sustainable and profitable energy economy. www.ieefa.org

About the Author

Soroush Basirat

Soroush Basirat is an Energy Finance Analyst with IEEFA Australia, examining the global steel sector with particular focus on green technology transition and the opportunities and barriers for different nations and companies.