Innovations for net-zero energy and materials systems

MARCH 2026

Innovation Brief Series

Molten Oxide Electrolysis and Electrowinning

Electrifying steel production

Reduce carbon use

Energy Transitions Commission

SYSTEMIQ

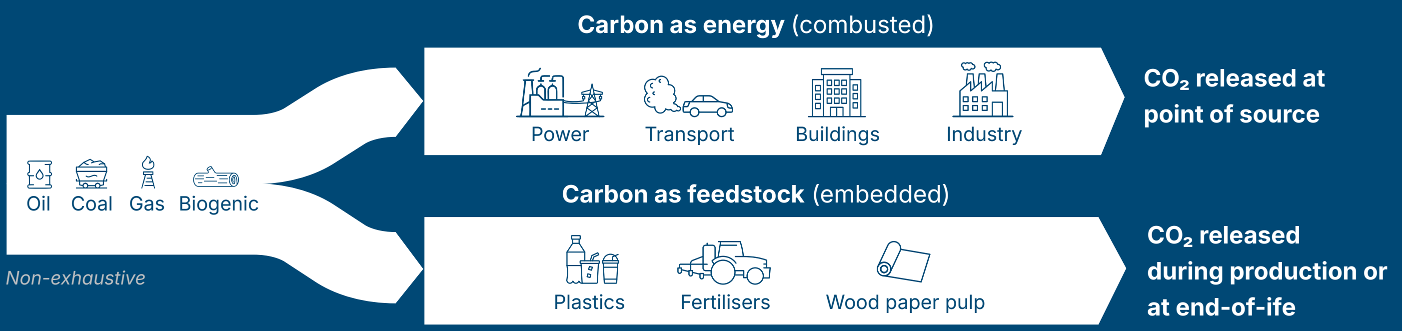
This innovation brief was created by Systemiq and the Energy Transitions Commission as part of the *Carbon in an electrified future* series. Each brief highlights a key technological innovation that can drive electrification, circularity, or carbon sourcing.

Learn more at www.energy-transitions.org/publications/carbon-in-an-electrified-future
www.systemiq.earth/resource-category/carbon-in-an-electrified-future

Molten Oxide Electrolysis and Electrowinning

Carbon sits at the centre of today's energy and materials systems

Carbon is the core component of the fossil fuels and material feedstocks that underpin today's energy and materials systems. When these carbon-based resources are combusted or transformed to produce energy, heat, mobility, and materials, they release carbon dioxide (CO_2). Achieving net zero requires both reducing the carbon entering the system and actively managing the residual carbon that remains.



Three steps towards net-zero energy and materials systems

1 Reduce carbon use
- Increase supply of clean electricity
- Switch to electrification where possible
- Use clean hydrogen when not possible to electrify

2 Recycle and reuse carbon
- Increase durability and reuse of carbon products
- Scale recycling of carbon products
- Capture and reuse carbon emissions

3 Source sustainably and manage end-of-life
- Prioritise non-fossil carbon inputs and capture of unavoidable emissions
- Secure permanent storage for residual carbon

Molten Oxide Electrolysis and Electrowinning

What is Molten Oxide Electrolysis and Electrowinning?

Molten oxide electrolysis (MOE) and electrowinning use electricity as the primary driver of iron ore conversion for steelmaking, providing an alternative decarbonisation pathway alongside hydrogen-based routes and CO_2 capture. MOE uses high temperatures to convert iron ore into liquid iron, while electrowinning uses lower temperatures to convert iron ore into solid iron.

Key takeaways

A **Molten oxide electrolysis (MOE) and electrowinning offer complementary alternatives to existing steel decarbonisation routes,** decoupling depenence upon the global scale-up and cost reductions of CCUS and electrolysers. This can help de-risk the transition, particularly in regions where CO_2 storage is unavailable.

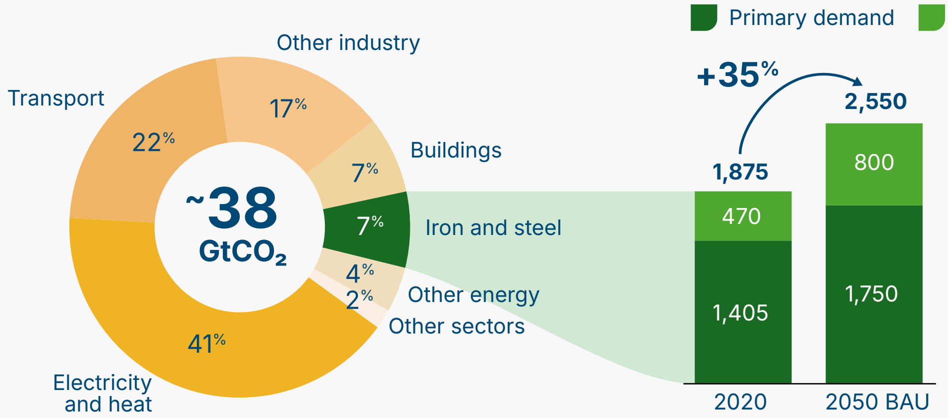
B **Molten oxide electrolysis (MOE) and electrowinning can potentially outperform existing decarbonisation routes** where clean electricity reaches prices below $65/MWh.

C **Deployment remains early-stage,** with projects still at pilot scale and widespread commercialisation unlikely before the early-to-mid 2030s, with further innovation required.

A MOE and electrowinning offer complementary alternatives to existing steel decarbonisation routes

Steel accounts for ~7% of global emissions, and demand is projected to grow ~35% by 2050

Global CO_2 emissions by sector[1] (2024) | **Steel demand outlook (Mt/y)**[2]



Drivers of demand growth:[3]

- Infrastructure construction in emerging-markets
- Deployment of clean energy infrastructure
- Manufacturing of machinery, automotive, and consumer durable goods

Steel production remains predominantly fossil-based[4]; low-carbon alternatives are emerging of which MOE and Electrowinning are an electrified alternative to the iron-making step decoupled from the need for clean hydrogen and CCUS.

		Ironmaking	Steelmaking	
1	Fossil	Blast furnace (Coal)	Basic Oxygen Furnace	~70% of all global steel production[5]
	Lower carbon	Blast furnace (Coal) + CCUS	Basic Oxygen Furnace + CCUS	
2	Fossil	Direct Reduced Iron (DRI) natural gas	Electric Arc Furnace (EAF)	~30% of all global steel production via EAF[6]
	Lower carbon	Scrap	Electric Arc Furnace (EAF)	
		Direct Reduced Iron (DRI) natural gas + CCUS	Electric Arc Furnace + Renewable Energy	
		Direct Reduced Iron (DRI) clean hydrogen/bioenergy	Electric Arc Furnace + Renewable Energy	
3	Lower carbon (fully electrified)	Molten Oxide Electrolysis (High temperature electrolysis)	Electric Arc Furnace + Renewable Energy	
		Electrowinning (Low temperature electrolysis)	Electric Arc Furnace + Renewable Energy	

MOE and electrowinning have high performance on energy intensity and emissions, but are still at a low technology readiness level.[7,8]

Most favourable | Least favourable

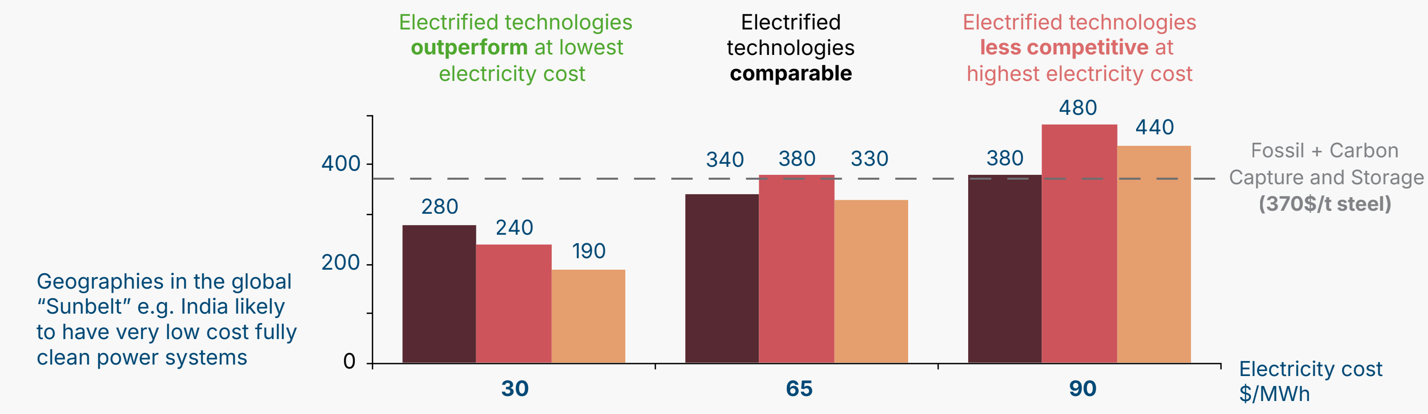
	Energy intensity	Emissions intensity	Technology readiness level[9]
BF-BOF carbon capture with CCUS	**17 GJ/t** (12 GJ/t fossil + 5 GJ/t electricity)	**0.25** (CCS) tCO_2/t steel	**5**
DRI-EAF with green hydrogen	**15 GJ/t** (9 GJ/t H_2 + 6 GJ/t electricity)	**0.08** tCO_2/t steel	**6**
MOE/ Electrowinning	**14-15 GJ/t** (steel)	**0.08** tCO_2/t steel	**4-6**

B MOE and electrowinning can outperform existing decarbonisation routes where clean electricity costs are low

MOE and electrowinning could outcompete other low carbon variations if electricity costs are at or below $65/MWh, almost half the cost of CCUS route[13]

Sensitivity analysis of the levelised cost of heat $/t steel **at different electricity prices**[11] $/MWh

DRI (clean hydrogen)- EAF | MOE - EAF | Electrowinning-EAF



Different steel decarbonisation routes have different requirements[12,13]

BF-BOF carbon capture with CCUS	DRI-EAF with green hydrogen	Molten oxide electrolysis & electrowinning
Requires CO_2 networks and storage sites, to make CCUS viable.	Requires low-cost green hydrogen, driven by declining costs of electrolysers and low-cost clean electricity supply.	Requires low-cost clean electricity, often with near-constant supply.

C Some projects have entered pilot stage, with commercialisation unlikely before end of 2030

Pilot projects are emerging across both routes, but they are small in scale (~0.3–80 kt/year)

	Company	Demonstration	Annual capacity	Launch/ target year
Molten Oxide Electrolysis	BOSTON METAL	Raised ~$420m, MOE Critical Metals plant in Brazil nearing commercial production, demonstrated at ~1,600°C with clean power.[14]	N/A	2026
Electrowinning	ArcelorMittal John Cockerill	Volteron project, demonstrating direct electrolysis to produce blast-furnace-grade products at ~110°C, compatible with intermittent power.[15]	40-80 kt/year	2027
Electrowinning	electra	Raised ~$186m to scale clean iron electrowinning, producing ~99% pure iron, compatible with intermittent renewable power.[17]	0.5 kt/year	2026
Electrowinning	ELEMENT ZERO	Raised ~$10m seed, demonstrating a membrane-free electrochemical process at ~250–300°C, compatible with intermittent power.[18]	0.3 kt/year	2025

These pilots are at ~5–8% of typical commercial scale (~1 Mt/year)[20]

MOE and Electrowinning: Electrifying steel production

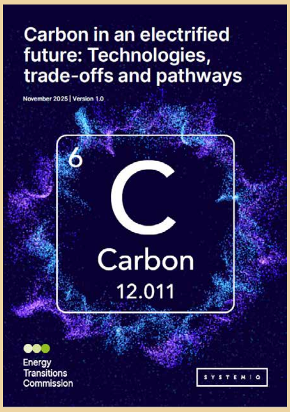
MOE and Electrowinning can:

Offer a pathway to decouple steel decarbonisation from the global scale-up and cost reductions of both CCUS and electrolysers. They can therefore help de-risk the transition, particularly in regions where CO_2 storage is unavailable.

Reduce overall fossil fuel use in steelmaking

Three priorities to scale MOE and Electrowinning

Key priorities	Key players	Key actions
Targeted innovation to improve performance	• Technology developers • Steel producers • Investors	Continue innovation to prove stable operation and equipment durability (including high-temperature materials/anodes for MOE). Standardise designs and build supply chains and delivery capability to help replicate projects at scale and move from technology readiness 4–5 toward commercial deployment by the early 2030s.
Robust carbon pricing & demand side market creation	• Governments • Regulators • Steel producers	Robust carbon pricing (≥ $100/tonne) and carbon boarder adjustment mechanisms can help close the cost gap and create predictable demand for clean steel. Public procurement, long-term offtake and contracts-for-difference which include MOE and electrowinning technologies can de-risk early projects and reduce OPEX risk.
Clean power supply and grid infrastructure	• Grid operators • Governments • Power producers	Secure low-cost clean electricity at industrial scale, with grid connections and capacity for high-load processes. This includes streamlined permitting for new renewable generation, investment in transmission and distribution, and market frameworks that enable long-term power purchase agreements to provide price stability for capital-intensive projects.



Further reading: Also in this Innovation Brief Series

Electrification will drive the global transition to net zero, powering cleaner industries, homes and transport. But even in a world where electricity dominates, carbon molecules will play a remaining role in producing essential fuels and materials.

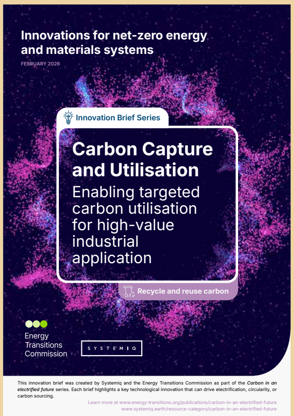
This innovation brief is part of the ***Carbon in an electrified future*** series. Each brief highlights a key technological innovation that can drive electrification, circularity, or sustainable carbon sourcing across three steps towards net-zero emissions energy and materials systems.

Explore more in the other briefings:

Reduce carbon use → **Recycle and reuse carbon** → **Source sustainably and manage end-of-life**

Sodium-ion batteries
Diversifying beyond lithium-ion with a scalable alternative

Molten Oxide Electrolysis and Electrowinning
Electrifying ore-based steel production



Carbon Capture and Utilisation
Enabling targeted carbon utilisation for high-value industrial application

Alternative Proteins
Unlocking land for nature and biomass

Sources and notes

1. IEA (2025) World Energy Outlook
2. Systemiq analysis for the ETC & QCF based on ARENA (2024), Fortescue – low temperature direct electrochemical reduction for zero emissions iron; Agora Industry (2024), Low-carbon technologies for the global steel transformation; Carbon Commentary (2023), Decarbonising steel: hydrogen or metal oxide electrolysis; Fast company (2024), This Boston startup wants to make the steel industry go green; MIT (2024), Making steel with electricity; IEA (2024), ETP Clean Energy Technology Guide; TNO (2020), Low temperature electrowinning for steelmaking.
3. OECD (2025) OECD Steel Outlook 2025
4. WEF (2024) WEF Net Zero Industry Tracker 2024 Steel
5. Worldsteel Association (2025) 2025 World Steel in Figures
6. Worldsteel Association (2025) 2025 World Steel in Figures
7. Systemiq analysis based on Mission Possible Partnership (2022), Making net-zero steel possible.
8. IEA (2026), ETP Clean Energy Technology Guide
9. ETC and Systemiq (2025). Technology readiness level (TRL) is a standard scale used to assess the maturity of a technology, from 1 (basic principles observed and documented) to 9 (technology proven in operation and in industrial production)
10. IEA (2025) World Energy Outlook
11. Boston Metal (2026) Boston Metal – Fact Sheet
12. ETC and Systemiq (2025) Carbon in an electrified future: Technologies, trade-offs and pathways
13. Assumed over 10 years, average over different electrification technologies and average BF-BOF CAPEX assumed; for energy consumption 11.7 GJ/t steel for coking coal and 6.8 GJ/steel for lower-grade steel assumed; for CCU/S cost emissivity for best available technology assumed 1.8 tCO2/t steel and a capture price of $100/t CO2. 5. $3/kg H2. The $65/MWh represents the electricity cost to the factory gate. Capex for MOE is $795 per t/steel, with energy demand of 4 MWh/t steel. CAPEX for electrowinning is $825 per t/steel, with energy demand of 4.2 MWh/t steel
14. Boston Metal (2026) Boston Metal – Fact Sheet
15. European Commission (2025) Low temperature electrolysis of iron ore in an aqueous alkaline solution - Volteron™
16. Latitude Media (2025) Meta is buying green ironmaker Electra's first EACs
17. Electra (2026) Our Technology
18. Business Wire (2024) Element Zero Raises US$10M Seed Funding Led by Playground Global to Scale up Green Materials Platform, Decarbonize Iron and Other Critical Metals Production
19. ETC and Systemiq (2025) Carbon in an electrified future: Technologies, trade-offs and pathways