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Ultra-Low Emission Strategies in Steel, Coking, and Cement Industries: Pathways to Decarbonization and Sustainability

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ABSTRACT

Steel, coking and cement industries make up nearly 30% of global industrial CO_2 emissions and are key to becoming net-zero. Although earlier research usually looked at each industry in isolation, this paper provides an overview of ULE strategies that examines both technology and policy together across the various industries. Recent improvements in hydrogen-based steelmaking, molten oxide electrolysis, coke dry quenching, catalytic reforming coke oven gas, alternative binders for cement and carbon capture are synthesized and evaluated for capacity, costs and environmental impact.

The review uniquely compares what causes emissions in different sectors, how far away each technology is from being fully developed, how far digitization has advanced and what roadblocks stand in the way. The paper introduces new results on CO_2 control, energy used in processes and marginal abatement costs to evaluate the practical feasibility of new technologies.

AI controls, modular CCUS, hydrogen infrastructure and the industrial symbiosis framework are explored in terms of how they push the sector into transformation. Ultimately, the review suggests areas of research and policy such as combining electrification and CCUS into systems, creating free-to-use lifecycle tools and reforming institutions to support ULE use in SMEs and developing areas. This review sets out roadmaps using several approaches that show how ULE strategies could be applied across hard-to-abate sectors with both technical and institutional support.

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1. Introduction

To hit net-zero targets, it is crucial to decarbonize the steel, coking and cement industries which account for around a third of the global industrial CO_2 emissions. Strategies to cut emissions quickly are increasingly centred on industries that rely heavily on coal and old equipment. Not only do they improve worldwide construction, manufacturing and energy, but they also contribute technological development and create useful policies.

Last year, manufacturers released nearly 1.9 billion tonnes of crude steel; about 92 percent of this amount was produced using technology that creates around 1.83 tonnes of carbon dioxide for every one tonne of steel [1, 2]. About 8% of all global CO_2 comes from the cement sector and a big reason is the heating of limestone used in making cement [3, 4]. Though it causes less carbon dioxide pollution, the coking industry emits lots of VOCs, PAHs and $PM_{2.5}$, so it remains a significant source of local air pollution and health problems [5, 6].

In order to cut back on emissions in these sectors, a variety of ULE technologies are being designed now. To minimize pollution, metal companies use methods such as hydrogen-based DRI in steel making, molten oxide electrolysis, arc furnaces, carbon capture and alternative cements such as geopolymers and LC^3 [7, 8]. Even so, introducing these technologies is not equal everywhere. The high expense of setting them up, old system infrastructures and differences in regulations especially in developing countries create these problems.

Just as these actions are driving up the demand for low-emission materials and encouraging industry to adopt new technologies. Policies that show more action include the Fit for 55 package, CBAM and China's new ULE rules [9, 10].

We see separate case studies on technologies and sectors, but few studies that mix strategies between different sectors and follow newly developed regulations. This work bridges that gap by combining the various decarbonization methods from the steel, cement and coking industries into one summary. Analysis covers the emissions produced, how technology is growing, if the innovation can be upscaled and which policies and instruments are needed. HYBRIT in Sweden, Baowu Steel in China and LEILAC in Europe are examined to show how these innovations are being implemented. Using both methods, this review outlines methods to advance ultra-low emission technology implementations in hard-to-decarbonize parts of the economy. Three significant cases, HYBRIT (Sweden), Baowu Steel (China) and LEILAC (Europe), are discussed to highlight how these innovations are being put into action. By using both technical and institutional perspectives, this review lays out how to speed up the use of ultra-low emission technologies in difficult sectors.

2. Emission Sources and Challenges

Ultra-low emissions in heavy industry can be accomplished only when emission pathways, types of pollutants and limits of current technologies are fully understood for each specific sector. The steel, coke and cement industries release greenhouse gases, fine particles, nitrogen oxides, sulphur dioxide and volatile organic compounds and are a major reason for both global CO_2 emissions and local air pollution Fig. (**1**). In this section, we provide a sector-level analysis of top sources of emissions and the main problems that are slowing efforts to reduce them.

2.1. Steel Industry: Carbon Intensity and Multi-Pollutant Challenges

About 6–8% of all carbon emissions globally are due to the steel industry and BF–BOF is involved in producing over 70% of the world's steel [11]. This technique uses lots of coke which emits, on average, 1.83 tonnes of CO_2 every time a tonne of crude steel is made [12]. Both combustion inputs and production methods cause these emissions.

Besides CO_2, the process also leads to major amounts of NO_x, SO_2 and particulate matter (PM). About ninety percent of NO_x is demanded during the high-temperature operations of blast furnaces and reheat furnaces. Economic activities such as making coke and iron ore, cause SO_2 emissions and PM is a result of handling and working with raw materials [13, 14]. Because of these pollutants, the air can become unsafe and contribute to more public health risks [15].

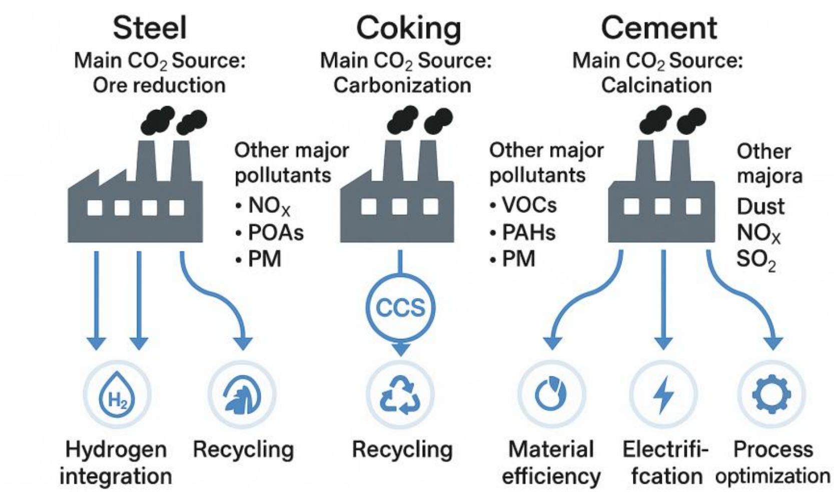

Figure 1: Sector-specific CO_2 sources, major pollutants, and key mitigation strategies across steel, coking, and cement industries.

The main obstacles to decarbonization are: (i) existing infrastructure can rarely be changed or adapted, (ii) the technologies being developed are incompatible with current furnaces and (iii) using new processes requires significant investment [16, 17]. In specific areas, the adoption of new technology is restricted due to green hydrogen supply and problems on the grid [18].

2.2. Coking Industry: Emissions of VOCs and Aromatic Compounds

Emissions of both VOCs and aromatic compounds are common in the coking industry. Making metallurgical coke uses the coking industry which releases a mix of dangerous emissions. Among the main types of VOCs are benzene, toluene, xylene and polycyclic aromatic hydrocarbons (PAHs), several of which are cancerous [19]. Emissions mainly occur in the coal carbonizing, gas collecting and by-product recovery processes, mainly at plants that are not regularly maintained or out of date.

$PM_{2.5}$ and PM_{10} are released during the steps of charging coal, quenching it and screening the coke for coal processing. By-product gas combustion and tar distillation generate NO_x and SO_2 which pollute the air and cause smog [20, 21].

The coking sector finds it challenging to decarbonize, with inefficient energy, ageing construction and limited tools to analyze their performance. While CDQ greatly enhances thermal recovery and reduces worker exposure to heat and particulates, many fail to adopt it due to issues related to investment and retrofit [22]. The need to meet ultra-low emission standards means developing economies must carry out comprehensive environmental retrofits [23].

2.3. The Cement Industry Releases Carbon Dioxide and Dust from Clinker

The cement industry is responsible for about 8% of the world's man-made CO_2 emissions. Sixty percent of all our emissions from cement come from the burning of limestone for clinker and another 40 percent is generated by fuel combustion in kilns running above 1,400°C [24, 25].

Cement plants produce dust, NO_x gas and SO_2 in addition to CO_2. Kiln exhaust, material grinding and handling give rise to dust emissions which can damage local people's lungs. NO_x emissions occur from both sources, as does energy from combustion, but SO_2 is related only to the sulphur found in the fuel and materials [26, 27].

A major problem with cement decarbonization is how to lower the amount of clinker without sacrificing important building features. The use of fly ash, slag and calcined clay which are SCMs, can help reduce total emissions, though there are difficulties in availability and with their performance [28, 29]. Calcination-related CO_2 can be captured and sequestered over the long term through CCS, but extremely low carbon prices and lack of policy measures make it difficult [30, 31].

2.4. Comparative Summary

Table **1** gives a short summary of the key differences in emission types, pollutants and the major problems in reducing emissions.

Table 1: Sectoral comparison of emission characteristics and decarbonization barriers.

Attribute	Steel	Coking	Cement
Main CO_2 Source	Ore reduction with coke	Carbonization + fuel combustion	Calcination of limestone
Other Major Pollutants	NO_x, SO_2, PM	VOCs, PAHs, $PM_{2.5}$	Dust, NO_x, SO_2
Process Emission Share (%)	~30–40%	~10–20%	~60%
Major Decarbonization Barriers	Legacy furnaces, hydrogen infra	Retrofit cost, VOC control tech	SCM availability, CCS cost
Readiness of Key Tech (TRL)	H_2-DRI (7–8), EAF (9)	CDQ (9), VOC capture (6–7)	LC^3 (6–8), CCS (6–7)

2.5. Transition to Strategy Pathways

With the emission features and boundary conditions outlined for each sector, the section that follows describes the main paths and technologies being applied to make steel, coking and cement industries much less emissions intensive.

3. Ultra-Low Emission Programmes and Methods

Highly polluting industries are being pushed to reduce their emissions by climate change getting worse and newly enforced environmental laws. Among the largest energy consumers, steel, coking and cement industries emit a great deal of carbon dioxide (CO_2), nitrogen oxides (NO_x), Sulphur dioxide (SO_2), particulate matter (PM) and volatile organic compounds (VOCs). It is progress in technology that enables us to achieve very low emissions in these areas. In this chapter, we review top technologies currently being developed or used, focusing on how much they can reduce greenhouse gas emissions, how easily they can be scaled up and their TRLs.

3.1. Steel Production: Sub-Sectors and Technologies

The process of decarbonizing steel is reaching a key moment, as the industry moves to hydrogen-based direct reduction, molten oxide electrolysis and electric arc furnaces. Though good results have been achieved in pilot studies, the large-scale use of CCS faces challenges from a lack of suitable infrastructure, more energy is needed and there is not enough green hydrogen to supply [32]. To achieve a full transformation, we need to add a lot more renewable energy to the grid and modernize it.

3.1.1. Hydrogen-Based Direct Reduction (H_2-DRI)

Using renewable hydrogen, H_2-DRI reduces iron ore without carbon-based reductants and only releases water vapour. When powered by renewable hydrogen, the H_2-DRI process can reduce emissions by about 90% [33]. The pilot project HYBRIT in Sweden has shown it is possible to replace traditional technology with green alternatives. But major obstacles include high expenses for generating hydrogen, a lack of infrastructure for storage and transport and much more renewable energy needed to make national steel [34].

3.1.2. Molten Oxide Electrolysis (MOE)

Metallurgical ore enrichment (MOE) takes place in a carbon-free method using electricity, resulting in only oxygen. This technology creates very clean steel and does not produce CO_2 directly from its process. At present, the technology stands at TRL 5-6 [35]. The process is not widely used due to its high-power needs, electrode wear and the need for further commercial use.

3.1.3. Scrap-Based Electric Arc Furnaces (EAFs)

EAFs use electricity to melt scrap and reduce their emissions by about 75% compared to the blast furnace–basic oxygen furnace route especially when powered by renewables, according to the IEA (2023a). Because coke combustion is excluded, the use of iron-graphite eliminates NO_x and SO_2. Yet, problems with purity, supplies and making top-quality flat products reduce the use of scrap in the automotive and construction sectors [36].

3.1.4. Carbon Capture, Utilization and Storage (CCUS)

In the steel industry, carbon capture, utilization and storage are being used to help prevent all the emissions that switching fuels and using electricity cannot address. Under initiatives such as ULCOS, amine scrubbing and oxy-fuel combustion have been tried out. Despite being able to capture over 50–60% of emitted CO_2, building and running a CCS system is expensive and made difficult by a lack of transport and storage for CO_2 (IEA, 2023b).

3.2. Coking Industry: Emission Control and Recovery

Producing metallurgical coke from coal is important for steel manufacturing, but not easy to reduce emissions from. Improving energy systems is difficult because the infrastructure is old, different companies own energy sources, and the systems harm the environment. Steps for innovation centre on dry quenching, catalytic use of coke oven gas (COG) and improvement in processing volatile organic compounds (VOCs) [37].

3.2.1. Coke Dry Quenching

The process recovers heat from hot coke to make energy and cut PM emissions by more than 90% [38]. In addition, it eliminates water vapor emissions associated with wet quenching processes. While CDQ is extremely popular in places such as Japan and China, introduction to less developed economies are slowed by the high costs of installing the necessary equipment and the required space.

3.2.2. Catalytic Cracking of Coke Oven Gas

By reforming heavy hydrocarbons in COG, the process creates a gas fuel that reduces VOC and PAH emissions and increases the plant's efficiency. Using nickel and zeolites is the most common application for catalysts. For deployment to work well, it is important to manage the reaction environment carefully and regularly restore the catalyst [39].

3.2.3. VOC Treatment and Recovery

For the purpose of controlling VOC emissions such as benzene and toluene, advanced systems such as regenerative thermal oxidizers, adsorption-condensation units and biofilters, are introduced. They cut emissions and at the same time, make it possible to recover the by-products from the mining process. Even so, sudden temperature changes in flue gas and varying VOCs in the process present problems for operations [40].

3.3. Cement Industry: Emission Reduction Tools

It is now materials and process improvements, rather than traditional focus on energy efficiency, that drive efforts to reduce cement CO_2 emissions. They comprise alternative binder materials, wider use of waste-derived energy and incorporating CCUS enabled by oxy-fuel combustion [41].

3.3.1. Alternative Binders (Geopolymers, LC^3)

Cements made this way require less of the carbon-heavy clinker used in the manufacturing process. According to Scrivener *et al*. (2021), using fly ash or slag in geopolymer cement leads to cutting emissions by 80%. You get to save up to 40% in energy and the equipment still works well [42]. It is not yet possible to create identical asphalt-based products globally and accurate long-term data and some materials are still lacking in some regions [43].

3.3.2. Fuels Derived from Waste (e.g., Biomass, RDF)

Replacing fossil fuel with biomass, refuse, sludge and plastic in melt-bath tanks can reduce thermal emissions by as much as 30% [44]. Due to new fuel types and variations in their heat content, manufacturers are required to install better systems to handle burning and treat exhaust gases.

3.3.3. Oxy-Fuel Combustion and CCUS

Air is replaced with extra oxygen in oxy-fuel combustion, boosting the amount of CO_2 in the off-gas, so it can be captured more effectively by amine scrubbing and membrane separation methods. Although experiments in the lab have very high capture rates, a large amount of energy and affordable oxygen are needed to make the process practical. In 2021, Gardarsdottir and colleagues describe the system as being in the range of 6 to 7 on the TRL scale [45].

Table 2: Sector-specific ULE technologies with TRL, barriers, and integration characteristics.

Sector	ULE Technology	Decarbonization Mechanism	TRL	Key Barrier	Integration Notes
Steel	H_2-DRI	Fuel switching (green hydrogen)	7–8	Hydrogen cost & infra	Deep retrofit required
	MOE	Electrification, inert anode	5–6	High power need	Still at pilot scale
Coking	CDQ	Thermal recovery	9	Capex, land use	Common in China/Japan
	COG Reforming	VOC/hydrocarbon removal	6–7	Catalyst maintenance	Decentralized plants struggle
Cement	LC^3	Clinker substitution	6–8	SCM availability	Regional supply varies
	Oxyfuel+ CCUS	CO_2 separation and capture	6–7	O_2 cost, energy demand	Retrofit potential

4. Policy and Regulatory Frameworks

The steel, coking and cement industries can't currently lower their carbon emissions without assistance. For these industries to achieve ultra-low emissions (ULE), both technology and supporting policies, regulations and market tools are required. They support efforts to reduce risks for investors and move development forward faster. This chapter explains the different global, national and economic policies that encourage the industrial world to reduce carbon emissions.

4.1. Global Emission Reduction Targets

The Paris Agreement adopted the main objective of ensuring the Earth's temperature does not exceed well below 2 ^{o}C ideally 1.5 ^{o}C above levels it had before the industrial era. Six to nine tenths of industrial GHG emissions need to be absent by 2050, relative to 2010 levels [46].

Future economic cooperation is now centred on making financial organisations support industrial decarbonization. UNIDO's Industrial Deep Decarbonization Initiative along with the UN's Race to Zero campaign are bringing together players in the steel and cement sectors to move toward net-zero operations. Countries are prompted to implement environmentally friendly policies for buying goods and to come up with standardised ways of measuring carbon outputs in all material supply chains [47].

More and more, development banks are helping emission-intensive industries in fast-developing nations, as well as funding pilot projects in green hydrogen, low-carbon cement and carbon capture.

4.2. National and Regional Regulatory Approaches

4.2.1. European Union: EU ETS, CBAM, and Fit for 55

For more than 15 years, since 2005, the EU Emissions Trading System (EU ETS) has overseen the world's greatest carbon market, regulating nearly 11,000 facilities in the steel, cement and chemical industries. Because emissions are being capped lower, more permits are needed and prices exceeded €90 per tonne of CO_2 last year [48].

With its new rules, "Fit for 55" urges a 55% drop in emissions by 2030 from 1990 levels. A main feature of the policies is the Carbon Border Adjustment Mechanism which prices imported materials like steel and cement to address carbon leakage and help keep firms on equal terms [49].

4.2.2. China: Ultra-Low Emission Standards and National Carbon Market

China's new ULE rules for steel and coking industries include fixed emissions limits for particulates and SO_2 and NO_x. Measures needed are dry quenching, low-NO_x burners and recovering sinter gas so that by 2025, 80% of steelmakers follow the rules [50].

In 2021, China made its national ETS for the power sector, with the intention to enroll steel, cement and petrochemicals in the future. Nevertheless, the progress is often affected due to complications in its monitoring, reporting and verification systems (MRV systems) [51].

4.2.3. United States: Inflation Reduction Act and Regulation for Clean Air

In 2022, the Inflation Reduction Act provided about $370 billion for programs that support reducing emissions and promoting clean energy. Major reasons that encourage innovation are:

- Up to $85 per tonne of CO_2 that is captured, used or stored is eligible under Section 45Q.
- Section 45V: Allowance of tax credits for making clean hydrogen.
- Supporting industrial centres and demonstration projects through additional means.

The EPA, aided by the Clean Air Act, Kennedy directs evolving emission standards for PM, SO_2 and NO_x. California makes its policy tougher than the federal one by using its Cap-and-Trade programme and requiring green purchasing [52].

4.3. Economic Instruments: Carbon Pricing and Market Incentives

Using markets, society is able to price carbon emissions and attract funding for technologies that help reduce greenhouse gases. Now, there are more than 70 systems using carbon pricing around the world.

Sweden and Switzerland set carbon taxes that are valued at more than $100 for every tonne of CO_2. EU, China, California, South Korea and various other places now have active Emissions Trading Systems. In some places, countries use output-based systems for pricing medications, including Canada's OBPS.

The removal of these caps also makes it possible for firms to reduce their compliance costs by purchasing from those who emit less. In industries like cement, where it's hard to lower emissions, additional support measures may include subsidies or carbon contracts-for-difference (CfDs).

Additional types of economic instruments are:

- This includes tax credits of 45Q in the United States for CCUS.
- Rate-based payments for green energy and support for industry in using electricity.
- Rules for green purchasing.
- Horizontal Programme grants offered by EU Horizon and Innovation Fund for industrial pilot projects [53].

To keep the integrity of these instruments, it's important to have the same way of measuring and to put strong protection against carbon leakage in place.

4.4. Linking Policy to Practice and Strategic Trends

Because of these regulations and economies, ULE innovations can now be used in practice. Thanks to financial support, Sweden's HYBRIT was able to replace coal in steel production with green hydrogen. Baowu Steel's CCUS project in China has been launched to meet both the new ULE rules and the support received from the government.

These measures form the basis for introducing emerging ULE solutions into a variety of industries and locations which helps guide the future trends mentioned in the next chapter.

5. Case Studies on Successful ULE Implementations

The cases show strategies for ultra-low emission transitions in various sectors. The examples come from the steel, cement and coking sectors, where emission levels, technology and supporting rules make each strategy unique.

5.1. HYBRIT (Sweden): Hydrogen-Based Steelmaking

HYBRIT (Sweden) is aimed at developing hydrogen-supported steelmaking technology.

The HYBRIT project, launched by SSAB, LKAB and Vattenfall, is the first in the world to use new technology to remove fossil fuels from primary steel-making. Since 2020, a trial facility in Luleå, Sweden has worked with green hydrogen made from water using electricity to lower iron ore in a shaft furnace. Using this solid-state process, hydrogen fuel turns steel making into a process that does not create CO_2 emissions in production [54].

The pilot has achieved 90% less CO_2 emissions compared to using the conventional blast furnace basic oxygen furnace procedure. Hydrogen use for sponge iron production is around 50-60 kg per tonne; to produce that amount, the process requires almost 3.5-4.0 MWh of renewable power [55]. Last year, Volvo Group confirmed that HYBRIT's fossil-free steel could be used in automobiles. Construction is underway on a commercial plant that will produce 2.7 million tonnes a year and it is expected to slash 10% of Sweden's total GHG emissions and 7% of Finland's.

Today, HYBRIT operates at level 7-8 (TRL) and its scale-up is supported by Sweden's Energy Agency and the EU Innovation Fund which contributed to early legal authorization for its implementation (European Commission, 2022) [56]. According to experts, it costs from €70–100 per tonne to remove CO_2, as much as 50 percent of which is spent on methods to create hydrogen [57].

5.2. Baowu Steel (China): Carbon Capture at Industrial Scale

Baowu Steel (China) is now capturing carbon emissions at a mass industrial level.

As the largest steelmaker in the world, the Baowu Steel Group is initiating major CCUS projects to support China's plan to reduce its carbon footprint in industry. A carbon capture facility has been installed in Shanghai by Baosteel since 2022 and the facility can remove up to 120,000 tonnes of CO_2 from blast furnace and converter emissions using amine absorption and real-time computer monitoring [58].

The CO_2 we capture is used to enhance oil extraction and increase gas output. A second facility designed for 1 Mt/year capture is being built at this time. The industrial sector is meeting China's ULE standards for the steel sector and receives some of its funding from the National Green Technology Innovation Centre and local government grants [47, 59].

The CCUS programme at Baowu has reached TRL 7, as it has finished pilot and demonstration phases and entered early operation on a commercial scale. The estimated cost to reduce CO_2 is from €45–65/tonne and this depends on how clean the gas flow is and if energy can be recovered (the Global CCS Institute, 2023) [60].

5.3. LEILAC (Europe): Process CO_2 Capture in Cement

The LEILAC project is designed to reduce the main process emissions from the cement industry, most of which come from the calcination of limestone. Indirect heating is used in a vertical reactor by LEILAC which enables CO_2 separation during calcination without changing either the fuel or the rotary kiln structure. The LEILAC-1 project at Heidelberg Materials' Lixhe plant (launched in 2019) has achieved a capture efficiency of 95% for calcination gases, working with an annual throughput of 25,000 tonnes [61].

The CO_2 purity is 95% which helps to cut back on excessive downstream compression. IMF Smart Power now has the LEILAC-2 project in Germany under construction, expecting to reach 100,000 tonnes/year with full CCUS infrastructure integration. The technology functions at TRL 7-8 and its estimated financial costs for capturing are from €40-60/tonne, much less than amine scrubbing, according to the European Commission (2021) [62].

Lucideon Environmental Innovations Low-carbon and Abbreviated Capacity (LEILAC) project started development due to support from the EU Horizon 2020 programme and the Innovation Fund [63].

5.4. Comparative Perspective

All these case studies point out the various technological means available to greatly reduce emissions in sectors that are tough to control. How emission typology, energy input, infrastructure levels and national policies work together to impact how decarbonization strategies are chosen is reflected in each project.

- HYBRIT represents changing the fuel type and developing the whole process, all supported by good policy matching within Sweden and the EU.
- Baowu uses post-combustion capture across a large network, supported by new regulations and boosted by green research money in China.
- The LEILAC method is an example of innovative, easy-to-add technology for cement, assisted by select EU research funds.

They show why it's important for technology to be linked with planned public policies, growth of national systems and the use of financial incentives to speed up world industrial changes.

6. Future Perspectives and Challenges

By conducting high-profile trials, ULE technology has been shown to be technically possible. But achieving their maximum contribution in steel, cement and coking industry sectors is difficult due to a range of economic, infrastructure and institutional challenges. This chapter describes the main tools for making progress and the main hurdles to overcome in decarbonizing manufacturing, as well as a pathway for the future.

6.1. Unlocking Scale: CAPEX Barriers and Investment Gaps

The most serious obstacle to using ULE is how much it costs to introduce. Although the above projects are advanced, building on them at larger scales can cost up to 30-40% more early on than building regular assets [64]. In practice, green hydrogen-based steel is currently over €1,000/t, far more expensive than steel made with the traditional BF–BOF method due to the expensive equipment, hydrogen and infrastructure needed [65].

When deep geological storage and long pipes are required, CCUS cement projects are likely to cost as much as \$80-120 per tonne of carbon dioxide, as seen in [66].

Debt challenges fall more heavily on emerging economies because their costs are higher and the chance to deal in concessional capital is restricted. For many businesses in industry, access to low-carbon transition will continue to be blocked without the help of tailored financial products like blended finance, CfDs and credit guarantees [67].

6.2. Powering ULE: Clean Energy Infrastructure Needs

Existing nuclear energy technologies require a lot of energy. The process of making green steel at one tonne consumes about four times more clean electricity than the traditional steel production [5]. Scaling this approach across the global steel industry would require using 3,000 TWh annually by 2050 which equals about 12% of what the world produces from electricity [68].

The use of cement electrification, hydrogen hubs and molten oxide electrolysis will cause electricity needs to increase further. Yet, there is often a deficit in clean energy where it is most needed by industry. The reasons for these problems are undeveloped transmission systems, shaky grid stability and missing storage.

Various infrastructure features allow audio communications to happen smoothly:

- Energy targets for renewables related to the country's industrial zones.
- Long-duration storage solutions are those made from hydrogen or vanadium flow batteries.
- Making upgrades to the grid and sending electricity across country borders.

The IEA thinks it will take $7.5 trillion in industrial energy infrastructure investments by 2050 to achieve a net-zero goal [69].

6.3. Digitizing Decarbonization: The Role of AI and MRV

ULE strategy now depends largely on AI, digital twins and platforms based on the Internet of Things (IoT). These systems:

- Cheque flue gas emissions as they happen.
- Estimate failure rates to boost system maintenance and improve the period the system is online.
- Improve both the amount of fuel entered and the kiln's parameters.

From what we know, using AI-based controls at Tata Steel, Cemex and ArcelorMittal manages to reduce energy use by 5-15% and meets the demands for both NO_x and SO_2 [70].

AI makes it possible to more readily monitor carbon pricing, as data about it gets logged automatically. It councils that using AI technology helps scale standard ETS programmes in new markets [71].

Nevertheless, digital adoption is not even across the economy. It is common for SMEs to have trouble using technology and the common difficulties cover workforce training, cybersecurity and expensive tools for quick start-up.

6.4. Financing the Transition: Incentives, SMEs, and Global Policy

Efforts to make heavy industry carbon neutral depend on good coordination among regulatory and financial measures. Important ways to guide policies and finances are by using:

- Through ETS, over 70 regions are achieving cuts in carbon and improving how industries operate. Prices for EU ETS were in the range of €90-100 per tonne of carbon dioxide during 2023 [72].
- U.S. incentives called 45Q and 45V can make using CCUS and green hydrogen up to 50% more affordable [73].

- The law requires all public buildings to feature steel and cement products duly registered under the IDDI and national GPP policies [74].
- Blended Finance: South Africa, India and parts of Southeast Asia are being helped by new industrial decarbonization funds from development banks [75].

Yet, companies in developing countries and SMEs are still served less by these various tools. Policy makers must include:

- The availability of SME grants and funding to build businesses' capacity.
- Creation of carbon-based trade measures.
- Making it easier to get approval for retrofits in industry.

Sharing standards and hastening the use of technologies worldwide can be accomplished by using frameworks such as the Breakthrough Agenda and Mission Innovation [76].

Table 3: Key barriers and enablers for scaling ULE technologies.

Challenge	Example Sector	Enabler/Policy Solution	Source/Status
High capital cost of hydrogen steel	Steel	CfDs, 45V tax credits	EU Innovation Fund, US IRA
Electricity intensity & grid limits	Steel/Cement	Grid modernization, energy storage, renewable targets	IEA (2023), WEF (2022)
Weak MRV systems	All sectors	AI-based MRV, digital twins, compliance analytics	IEA Digitalization Roadmap (2022)
SME exclusion from finance	All sectors	SME grants, blended finance, technical assistance	GIZ (2023), UNIDO (2021)
Emerging market finance gap	Cement/Coking	Climate finance, concessional loans, pooled investment vehicles	CPI (2022), MDB initiatives

7. Conclusions and Outlook

Decarbonizing the steel, coking, and cement sectors is central to meeting global climate goals, as these industries collectively account for nearly one-third of industrial CO_2 emissions. This review has provided a cross-sectoral synthesis of ultra-low emission (ULE) strategies, analyzing both technology and policy mechanisms that are reshaping these carbon-intensive sectors. From green hydrogen-based DRI and molten oxide electrolysis in steel, to alternative cement binders and integrated CCUS systems, progress is accelerating but unevenly distributed across regions and industries.

A key insight from the case studies HYBRIT in Sweden, Baowu Steel in China, and LEILAC in Europe is that technological maturity alone is not enough. The scalability of ULE systems depends equally on digital infrastructure, clean energy access, financial innovation, and regulatory alignment. Each case demonstrated how public-private coordination, innovation funding, and sector-specific policy design are essential for turning pilots into commercially viable systems. For instance, TRL 7-8 technologies are already in use, but their widespread deployment hinges on robust carbon pricing, grid modernization, and institutional capacity.

Across sectors, common bottlenecks persist high upfront costs, underdeveloped green power infrastructure, regulatory complexity, and limited SME access to finance. At the same time, promising enablers are emerging. AI-driven MRV tools, digital twins, and modular CCUS platforms are redefining monitoring and operational efficiency. Climate finance instruments such as blended finance, Contracts for Difference (CfDs), and green public procurement—are proving essential for early-stage industrial decarbonization in both developed and emerging markets.

Looking forward, several gaps demand targeted research and policy attention. These include:

- Advancing hybrid systems that combine electrification with CCUS for greater process flexibility.
- Creating open-access lifecycle analysis (LCA) tools that support green procurement across value chains.
- Scaling AI and digitalization in emission monitoring, especially for SMEs.
- Designing cross-border frameworks to accelerate ULE adoption in the Global South.

The road to net-zero in heavy industry is neither linear nor uniform. It requires systemic coordination across innovation, finance, and governance. As this review shows, transformative change is not only possible it is already underway. What is now needed is to expand the scope and scale of these efforts through integrated, forward-looking strategies that unite technology deployment with enabling policy ecosystems.

List of Abbreviations

AI	=	Artificial Intelligence
BF–BOF	=	Blast Furnace–Basic Oxygen Furnace
CBAM	=	Carbon Border Adjustment Mechanism
CCS	=	Carbon Capture and Storage
CCfD	=	Carbon Contract for Difference
CCUS	=	Carbon Capture, Utilization, and Storage
CDQ	=	Coke Dry Quenching
CfD	=	Contract for Difference
COG	=	Coke Oven Gas
CPI	=	Climate Policy Initiative
DRI	=	Direct Reduced Iron
EAF	=	Electric Arc Furnace
EC	=	European Commission
EPA	=	Environmental Protection Agency
ETS	=	Emissions Trading System
EU	=	European Union
GHG	=	Greenhouse Gas
GIZ	=	Deutsche Gesellschaft für Internationale Zusammenarbeit
GPP	=	Green Public Procurement
HYBRIT	=	Hydrogen Breakthrough Ironmaking Technology
IEA	=	International Energy Agency
IDDI	=	Industrial Deep Decarbonization Initiative
IIoT	=	Industrial Internet of Things
IRA	=	Inflation Reduction Act
LCA	=	Life Cycle Assessment
LC^3	=	Limestone Calcined Clay Cement
LEILAC	=	Low Emissions Intensity Lime and Cement
LKAB	=	Luossavaara-Kiirunavaara Aktiebolag
MDB	=	Multilateral Development Bank

MEE	=	Ministry of Ecology and Environment
ML	=	Machine Learning
MOE	=	Molten Oxide Electrolysis
MRV	=	Monitoring, Reporting, and Verification
NO_x	=	Nitrogen Oxides
PAHs	=	Polycyclic Aromatic Hydrocarbons
PM	=	Particulate Matter
POAs	=	Primary Organic Aerosols
RDF	=	Refuse-Derived Fuel
SCM	=	Supplementary Cementitious Material
SMEs	=	Small and Medium-sized Enterprises
SO_2	=	Sulfur Dioxide
SSAB	=	Swedish Steel AB
TRL	=	Technology Readiness Level
ULCOS	=	Ultra-Low CO_2 Steelmaking
ULE	=	Ultra-Low Emissions
UNFCCC	=	United Nations Framework Convention on Climate Change
UNIDO	=	United Nations Industrial Development Organization
VOCs	=	Volatile Organic Compounds
WEF	=	World Economic Forum

Conflict of Interest

The authors declare that they have no conflicts of interest relevant to this manuscript.

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