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Revised draft analysis of standards and labels for low and near zero emission production and products

Cover note

A. Background

1. As per activity C.3.1 of its rolling workplan (2023-2027), the TEC works to promote low and near zero emission production and products, including in the steel, cement, chemical and petrochemical industries, through the support of innovation, enabling environment, sustainable purchasing commitments, and financing to inform the preparation and implementation of NDCs.

2. At TEC 31, the TEC considered the draft analysis of standards and labels for low and near zero emission production and products in hard-to-abate-industries and requested the open-ended activity group to prepare a revised draft analysis, reflecting comments provided by the TEC members at the meeting, for consideration at TEC 32.

B. Scope of the note

3. The annex to this note contains the revised draft analysis of standards and labels for low and near zero emission production and products in hard-to-abate-industries.

C. Possible actions by the Technology Executive Committee

4. The TEC will be invited to consider the revised draft analysis contained in the annex and provide guidance to the activity group with a view to finalizing it after TEC 32.

Annex

Revised Draft Analysis of Standards and Labels for Low and Near Zero Emission Production and Products

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Glossary of abbreviations

AI : Artificial Intelligence
ASEAN : Association of Southeast Asian Nations
ASTM : American Society for Testing and Materials
BAT : Best Available Technology
BF : Blast Furnace
BIM : Building Information Modelling (used in sustainable construction)
BOF : Basic Oxygen Furnace (steelmaking)
BRE : Building Research Establishment (United Kingdom of Great Britain and Northern Ireland)
BREEAM : Building Research Establishment Environmental Assessment Method
CAGR : Compound Annual Growth Rate
CAPEX : Capital Expenditure
CBAM : Carbon Border Adjustment Mechanism
CBI : Carbon Bonds Initiative
CCS : Carbon Capture and Storage
CCUS : Carbon Capture, Utilisation and Storage
CEMBUREAU : European Cement Association
CEN : European Committee for Standardization
CFP : Carbon Footprint
CI : Carbon Intensity
CORSIA : Carbon Offsetting and Reduction Scheme for International Aviation
CSC : Concrete Sustainability Council
CSI : Cement Sustainability Initiative
DESNZ : Department for Energy Security and Net Zero (United Kingdom of Great Britain and Northern Ireland)
DNSH : Do No Significant Harm (European Union taxonomy principle)
DOE : Department of Energy (United States of America)
DRI : Direct Reduced Iron
EAF : Electric Arc Furnace
EC : European Commission
EFC : Earth Friendly Concrete
EN : European Standard (Norme Européenne)
EPA : Environmental Protection Agency (United States of America)
EPD : Environmental Product Declaration
ESG : Environmental, Social, and Governance
ETS : Emissions Trading System
EUA : European Union Allowance (carbon permit)
FMC : First Movers Coalition
GASSA : Global Arrangement on Sustainable Steel and Aluminium
GBEI : Global Benchmark for Emissions Intensities
GCCA : Global Cement and Concrete Association
GHG : Greenhouse Gas(es)
GHO : Green Hydrogen Organisation
GPP : Green Public Procurement
GW : Gigawatt
GWP : Global Warming Potential
HYBRIT : Hydrogen Breakthrough Ironmaking Technology (Swedish steel process)

IBU : Institute Bauen und Umwelt (German environmental certificate)
ICCA: International Council of Chemical Associations
ICTU : Information for Clarity, Transparency, and Understanding
IDDI : Industrial Deep Decarbonisation Initiative
IEA : International Energy Agency
IPCC : Intergovernmental Panel on Climate Change
IRA : Inflation Reduction Act (United States of America)
ISCC : International Sustainability and Carbon Certification
ISO : International Organization for Standardization
ITA : Industrial Transition Accelerator
LCA : Life Cycle Assessment
LCFS : Low Carbon Fuel Standard
LCI : Life Cycle Inventory
LCR : Low-carbon Ratings
LEDS : Low-Emission Development Strategy
LEED : Leadership in Energy and Environmental Design
LEILAC : Low Emissions Intensity Lime and Cement (European Union project)
MJ : Megajoule
MRV : Monitoring, Reporting and Verification
NET: Negative Emissions Technology
NDC : Nationally Determined Contribution under the Paris Agreement
NRDC : Natural Resources Defense Council
NRMCA : National Ready Mixed Concrete Association (United States of America)
NSF : National Science Foundation (United States of America)
NZE : Net-Zero Emissions
OECD : Organisation for Economic Co-operation and Development
OPC : Ordinary Portland Cement
PAS : Publicly Available Specification (BSI standard)
PAT : Perform, Achieve and Trade (India’s energy efficiency scheme)
PCF : Product Carbon Footprint
PCR : Product Category Rules (LCA standards)
PLC : Portland Limestone Cement
PTC : Production Tax Credit (United States of America renewables incentive)
RDF : Refuse-Derived Fuel (waste as fuel)
RED : Renewable Energy Directive (European Union)
RFNBO : Renewable Fuels of Non-Biological Origin (European Union taxonomy)
RFS : Renewable Fuel Standard (United States of America)
RMI : Rocky Mountain Institute
RSB : Roundtable on Sustainable Biomaterials
RTFO : Renewable Transport Fuel Obligation (United Kingdom of Great Britain and Northern Ireland)
SBCH : Sector-Based Carbon Harga (price) – Indonesian carbon tax policy
SBTi : Science-Based Targets Initiative
SCM : Supplementary cementitious materials
SME : Small and Medium Enterprises
SUD : Sulphur-Dioxide (SO_2)
TEC : Technology Executive Committee
TPI : Transition Pathway Initiative

UNFCCC : United Nations Framework Convention on Climate Change
UNIDO : United Nations Industrial Development Organization
USD : United States of America Dollar
WBCSD : World Business Council for Sustainable Development
WEF : World Economic Forum
WRI : World Resources Institute

Executive Summary

The cement, steel, and (petro)chemicals sectors are widely labelled as “hard-to-abate” because of the significant economic and technical challenges to reducing their energy- and process-emissions. Each sector currently has a heavy reliance on fossil fuels, high energy requirements and the maturity of key decarbonization technologies is limited, whilst high upfront investment costs and long investment cycles introduce additional economic barriers to decarbonisation. Cement alone contributes 7-8% of global CO_2 emissions, steel approximately 7%, and (petro)chemicals around 4-6%. As such, supporting the transition of these sectors towards net zero emissions will be key to achieving global decarbonization targets. This report provides a synthesis of existing regulatory and voluntary carbon intensity standards, labeling schemes, and emissions thresholds that are shaping the transition to low- and near-zero emission production across these three sectors. It maps current initiatives, assesses gaps and implementation challenges, and identifies opportunities to accelerate progress toward industrial net-zero goals, whilst also presenting several national case studies of implementation to support countries in developing and implementing their own carbon intensity standards.

Key Findings

- **Rapidly Evolving Landscape:** Across all sectors, a growing array of regulatory policies (e.g., European Union Taxonomy, Buy Clean laws, CBAM) and voluntary initiatives (e.g., GCCA Low Carbon Ratings, ResponsibleSteel™, and ISO/EPD frameworks) is emerging to define, verify, and incentivize low-carbon production routes.
- **Carbon Intensity Thresholds Are Converging and Forward-looking:** Standards across cement, steel, and hydrogen-based chemicals increasingly are aligning around indicative benchmarks. In cement, “low-carbon” thresholds centre around ~750 kg CO_2/t (clinker basis), and some frameworks define “near-zero” targets as low as 125 kg CO_2/t. In steel, voluntary coalitions (e.g., First Movers Coalition and ResponsibleSteel™) signal indicative targets below 400 kgCO_2/t of crude steel. These reflect future-oriented benchmarks proposed by select voluntary initiatives, but their feasibility at scale remains to be validated through demonstration and commercial-scale implementation. Product-level variations also remain significant and not all categories of steel may be technically or economically able to meet such targets in the near term. In chemical sector, hydrogen standards are also converging around 1–4 kg CO_2/kg H_2, whilst a number of countries have adopted alternative-fuel standards linked to emissions savings compared to conventional fuels. These benchmarks signal the direction of travel and are best interpreted as forward-looking targets rather than current industry averages. Nonetheless, given the evolving nature of standard-setting and persistent fragmentation across sectors, these figures should be understood as illustrative rather than definitive, and not as universally accepted thresholds.

- **MRV Systems, EPDs and Product Labeling Are Foundational:** Measurement, Reporting and Verification (MRV) systems and Environmental Product Declarations (EPDs) based on life cycle assessments are the cornerstone of emerging transparency, certification, and procurement frameworks. When combined with credible product labelling schemes, these tools enhance traceability and market differentiation for low-carbon products. Their credibility is essential to enabling policy enforcement and cross-border trade.
- **Fragmentation and Gaps Persist:** Divergent methodologies, inconsistent thresholds, and a lack of harmonized system boundaries across schemes are barriers to interoperability. Uptake of low-carbon certified products remains uneven, hindered by high costs, limited infrastructure, and insufficient policy support especially in emerging markets, developing countries and for smaller producers. For the chemicals sector, the issue of high green premiums and limited demand for clean products continues to be a particular challenge. The lack of market depth hinders the investments needed for deployment of deep decarbonisation technologies.
- **Uneven Maturity Across Sub-Sectors:** While cement and hydrogen have increasingly well-defined standards and public visibility, many other chemicals (including both basic and speciality chemical product groups) and certain steel processes lack robust, sector-wide benchmarks or harmonized certification mechanisms.
- **Lack of adaptation metrics for climate-resilient industry:** Current standards and labels focus on mitigation (GHG) and largely omit comparable, MRV-ready indicators of physical-risk exposure and resilience performance; integrating sector-specific adaptation metrics into standards and procurement would steer capital to assets that remain operable under 2030–2050 climate conditions and reduce maladaptation.

Summary of Recommendations

To scale a credible, efficient, and equitable global market for low- and near-zero emission industrial products from these sectors, the following actions are recommended:

- **Co-develop international standards with staged targets (not one-size-fits-all)**: Use agreed international platforms (e.g., ISO and regional standardization bodies) to develop standards and guidelines through joint working groups that include national standards bodies from both developed and developing countries. Define multi-tier intensity bands, so countries can design and implement transition strategies progressively according to national circumstances, data readiness, and supply maturity. Provide clear equivalence and mutual-recognition pathways to minimize duplicate verification and reduce trade frictions.

- **Promote interoperability of national standards:** Map national definitions, thresholds, and system boundaries onto a shared multi-tier framework to enable mutual recognition and reduce trade frictions. Coordinate through agreed in platforms to develop unified approaches for cement, steel, and key chemical products, with meaningful and inclusive participation from organisations across developing and developed countries.

- **Integrate Standards into Climate Policy:** Embed sector-specific thresholds and certification criteria into national climate policies, taking into account each country's national circumstance, to signal long-term policy direction and ensure accountability.
- **Strengthen MRV Infrastructure and Digital Tools:** Invest in digital MRV systems, automated EPD platforms, and open-access data systems to reduce compliance costs and increase transparency. This is particularly important for supporting consistent application in developing countries.
- **Aggregate Demand Through Procurement:** explore the use of government procurement policies and preference programs such as Buy Clean, Green Public Procurement and similar policy initiatives to aggregate demand and create stable and predictable markets for verified low-carbon products, including through clear CO_2 thresholds in tendering and contracting. Recent implementation examples from IDDI member countries underscore feasibility at national scale: (1) Canada's Treasury Board Standard on Embodied Carbon mandates a 10% GWP reduction below baseline for concrete and 30% for buildings, alongside performance-based steel procurement requirements (effective 2022-2025); (2) the United Kingdom of Great Britain and Northern Ireland's Ministry of Justice has advanced "Low Carbon Prisons" under its Net Zero Strategy 2024; and (3) Germany has operationalized VDZ CCC and LESS standards, with a target of allocating 15% of GDP through public procurement. Emerging examples from India, Türkiye, and Brazil further illustrate momentum in developing countries, with green steel and cement thresholds being introduced in public tenders and regional declarations supporting sustainable procurement (UNIDO, 2024; MoEF India, 2023; Belem Declaration, 2025).
- **Mobilize Finance and De-risking Mechanisms:** Scale concessional finance, tax incentives, and instruments such as Carbon Contracts for Difference (CCfDs)-including Germany's EUR 4 billion (2024) and EUR 19 billion (2025) rounds-to support first-of-a-kind investments in decarbonization technologies, especially in the steel and chemicals sectors where CAPEX requirements are high, and in emerging economies where the cost of capital is high.
- **Develop inventory of targeted products and chemistries:** Identify an initial set of products and/or chemistries suitable for intensity benchmarking and standard setting with input from the chemicals industry, based on data availability, practical emission reduction potential, and global footprint.
- **Support Just and Inclusive Transition:** Provide tailored technical and financial support to small- and medium-sized enterprises (SMEs), emerging economies, and diverse subsectors. This includes capacity-building, regional EPD templates, and access to digital verification infrastructure to lower entry barriers and ensure equitable participation.

Implications for Policy and Practice

For Policymakers:

- Promote interoperability of credible standards by integrating them into national policy frameworks.
- Promote harmonization of industry-specific carbon accounting methodologies and thresholds across jurisdictions, to facilitate international trade and collaboration, recognising the needs of different industrial subsectors.
- Align the use of fiscal tools to performance-based product standards to drive innovation and emissions reductions.

For Industry:

- Adopt, align and/or support the development of emerging, industry-applicable voluntary standards to maintain access to global markets and anticipate future regulatory shifts.
- Engage in shaping MRV protocols and product category rules to ensure feasibility and credibility in emissions disclosures, considering competitive, legal, regulatory, and practical barriers, including lack of custody over data.
- Collaborate across value chains to accelerate decarbonization and demonstrate compliance with procurement-based requirements.

For International Actors:

- Promote mutual recognition of standards across global forums (e.g., G7 Climate Club, ISO, UNFCCC).
- Develop public goods such as open-source MRV protocols, EPD generators, and emissions factor databases to reduce duplication and ensure ease of access.
- Support capacity building and provide technical and financial assistance to EMDEs to ensure inclusive participation in standards development, implementation, and compliance.

Table 1 Implications for Policy and Practice

Policy Pathway	Key Mechanisms & Actions	Objective & Rationale	Implementation Notes & Examples
Demand-Side Policies	**Green Public Procurement (GPP):** Adopt policies that mandate the use of low-carbon products in public projects, complemented by labelling schemes and tax incentives (e.g., green tax deductions) to stimulate market demand.	Creates durable market signals and aggregates demand for compliant products.	A phased approach is recommended, starting with mandatory EPD disclosure and evolving to performance-based limits. Initiatives like the IDDI provide guidance for governments.
	Clean Product Standards: Implement regulatory limits on the carbon intensity of low carbon products sold in the market, with thresholds that tighten over time. Consider bio-based product mandates where applicable (e.g., bioplastics, bio-chemicals).	Establishes a level playing field for all producers and drives industry-wide innovation beyond public projects.	Harmonizing the methodology internationally can avoid trade frictions. Bio-based mandates can complement carbon-based thresholds where relevant.
Economic Instruments	**Carbon Pricing:** Establish or strengthen carbon pricing mechanisms (e.g., Emissions Trading Systems, carbon taxes) for the industrial and bio-based sectors. Voluntary Carbon Markets (VCMs) may also play a role in certain contexts, such as for bio-based chemicals	Internalizes the cost of emissions, making low-carbon production more cost-competitive.	The European Union's ETS demonstrates how phasing out free allowances based on CI benchmarks can incentivise investment into abatement.
	Carbon Border Adjustment Mechanisms (CBAMs): Implement or coordinate with border adjustment mechanisms to price the carbon content of imported good.	Prevents "carbon leakage" and protects domestic industries while encouraging global uptake of standards.	Requires international coordination on metrics for calculating embedded emissions. The Climate Club is a possible platform that could support this alignment.
Financial & Investment Support	**Financial De-risking:** Offer concessional loans, guarantees, and results-based finance tied to verifiable emissions reductions.	Lowers the cost of capital and addresses the high upfront cost of deep decarbonization technologies, unlocking private investment.	De-risking: Models should prioritize support for SMEs (which face a host of additional barriers) and regional MRV infrastructure. Knowledge-sharing tools, such as international financial toolkits, can support institutional readiness.

Policy Pathway	Key Mechanisms & Actions	Objective & Rationale	Implementation Notes & Examples
	Investment Alignment Tools: Leverage sustainable finance taxonomies and disclosure frameworks to direct capital toward eligible low-carbon industrial activities	Provides guidance and clarity to investors, helping align finance with decarbonization priorities	Taxonomies: Initiatives like the European Union taxonomy provide reference points to screen green investments and can inform industry-aligned financing strategies.
	Targeted Subsidies & Tax Incentives: Provide instruments like production tax credits for CO_2 reduction or Carbon Contracts for Difference (CCfDs).	Guarantees a return on investment for expensive, first-of-a-kind projects like CCUS, ensuring a viable business case.	Incentives: The Industrial Transition Accelerator (ITA) can help package financing models with technical assistance. Additional tailored support can assist stakeholders in evaluating and deploying the most impactful instruments across industrial sectors.
	Innovation & R&D Funding: Co-fund pilot plants and demonstration projects for breakthrough technologies.	Accelerates the technical readiness and market confidence in next-generation solutions.	R&D: Should be technology-neutral and aligned with forward-compatible performance benchmarks to avoid "technology lock-in"
International Standardization & Cooperation	**Mutual Recognition of Standards:** Adopt policies that mutually recognize credible standards and labels developed with internationally harmonized principles.	Reduces duplicative compliance burdens, lowers costs for producers, and facilitates access to global markets.	Recognition: The G7 Climate Club could be a key forum for exploring this approach to reduce trade friction.
	Harmonization via Standards Bodies: Utilize international bodies like ISO and CEN to develop unified standards with opportunities for stakeholder input, such as a Publicly Available Specification (PAS) for "near-zero cement".	Creates a global reference for certification and guides the development of consistent national standards and policies.	Harmonization: The process should be guided by principles from the UNFCCC and could result in an "International Code of Conduct" that members pledge to adopt into domestic policy.
Foundational Enablers (Capacity & Infrastructure)	**Digital MRV Infrastructure:** Encourage digital reporting for EPDs and subsequent investment in open-access data platforms and automated EPD generators.	Reduces compliance costs, enhances data transparency and traceability, and enables scalable and trusted carbon labelling.	Lessons from the United States of America EPA and Dutch DuboCalc system show that digitization reduces administrative burdens.
	Capacity Building & Technical Assistance: Provide tailored training and financial support for SMEs and developing countries.	Ensures a just and inclusive transition, lowers entry barriers for compliance, and builds the local expertise needed to implement and enforce standards.	Support can include regional verification hubs, standardized EPD templates, and open-source calculation tools to level the playing field.

Table 2 Matrix: Integration of Standards and Labels into National Climate Framework/Strategies Across Key Industrial Sectors

Integration Area	Cement Sector	Steel Sector	Chemicals Sector
1. Sectoral Inclusion in Climate Action Framework/Strategies	Include quantitative emissions targets (e.g., kg CO_2/ton cement) and material efficiency improvements (e.g., clinker ratio).	Clarify the action roadmap and phased goals for carbon neutrality.	Include share or carbon intensity thresholds for clean hydrogen, ammonia, methanol, or bio-based fuels.
2. Link to Climate Finance & Article 6	Align certified low-carbon cement products (e.g., LC3, geopolymer) with Article 6 crediting schemes.	Link certified near-zero steel to international carbon markets and green trade mechanisms (e.g., CBAM-compatible).	Enable crediting and investment through clean hydrogen and certified low-carbon fuels under international mechanisms.
3. Demand-Side Alignment (Procurement, Trade)	Reflect GPP and Buy Clean policies in climate plans with performance-based GWP thresholds.	Integrate First Movers Coalition goals and public steel procurement thresholds in LT-LEDS.	Harmonize national standards for hydrogen and fuels with European Union RED III, LCFS, RTFO, and import-export policy coherence.
4. Support for Verification Infrastructure	Scale digital EPD platforms and open-access MRV databases; provide SME capacity building.	Expand digital MRV, blockchain pilots, and third-party verification for emissions tracking and certification.	Invest in lifecycle MRV tools (e.g., PCF, openLCA), verification capacity for SMEs, and traceable digital certificates.
5. Coordination with Industry Targets	Align national targets with GCCA 2050 roadmap and SBTi commitments.	Harmonize with ResponsibleSteel™ standards, SBTi targets, and hydrogen demand forecasts.	Coordinate with CertifHy, Green Hydrogen Standard, and industry-science platforms like the SBTi for chemicals.

1. Introduction

1.1 Background: Industrial Emissions from Cement, Steel and (Petro)Chemicals Production and Global Climate Targets

Cement, steel, and (petro)chemicals are among the most carbon-intensive industries in the global economy. Together, they account for a substantial share of global greenhouse gas (GHG) emissions, making addressing emissions from the sector a central focus in achieving the Paris Agreement's goals. All three sectors are typically included within the category of "hard-to-abate", in recognition of their high energy consumption, reliance on fossil fuels and limited technological maturity of decarbonisation technologies. These hard-to-abate sectors are also foundational to economic development, providing essential materials for infrastructure, housing, agriculture, energy, and manufacturing. The IPCC's Sixth Assessment Report calls for global emissions to fall by at least 43% by 2030, and the industrial sector will need to deliver a substantial share of these reductions (Intergovernmental Panel On Climate Change, 2023). Delivering these emissions reductions, and building globally interoperable product emissions standards to support them, will require a scaleup in effort from both industry and policy stakeholders.

1.1.1 Cement

Cement, the key binding agent in concrete – the second-most consumed material globally after water – is essential to modern infrastructure and societal development. However, its production results in significant greenhouse gas emissions, released both from fossil fuels consumed to provide heat and electricity but also directly from the chemical process of cement production. In 2022, global cement output surpassed 3.8 billion tonnes, resulting in approximately 1.6 gigatonnes of CO_2 emissions, or around 8% of total global CO_2 emissions (Cheng et al., 2023a; IEA, 2023e, 2024a). Without strong mitigation measures, emissions from the cement sector are projected to increase substantially by mid-century, in response to growing demand. In contrast, the IEA's Net Zero Emissions by 2050 (NZE) scenario requires an average carbon intensity reduction of 4% per year through 2030 for the cement sector globally (IEA, 2023e).

To keep the 1.5 °C goal within reach and to address the climate crisis in this critical decade, the cement industry faces a profound challenge. Cement production emissions arise primarily from two sources: (1) *Process emissions (calcination):* Accounting for over 50–60% of the total, these are released when limestone ($CaCO_3$) is heated and chemically transforms into lime (CaO), a core component of clinker. (2) *Combustion emissions:* Representing 30–40% of the total, these come from burning fossil fuels to heat kilns to the required 1450°C (Andrew, 2019; Cheng et al., 2023b; Clean Air Task Force, 2025; Miller et al., 2021). This dual emissions profile designates cement as a "hard-to-abate" sector.

As with other hard-to-abate sectors, reducing emissions associated with the energy-intensive clinker manufacturing process requires changes and capital investment for new equipment, technology, and infrastructure, as well as modifications to fuel and energy supply chains. Reducing process emissions, however, a practical reality of the chemical conversion process from limestone to clinker, requires a separate set of feedstocks and/or carbon management strategies while maintaining the performance criteria needed for use in building, transportation, and other sectors.

1.1.2 Steel

Steel is a metal alloy used in every aspect of our lives. Its manufacture involves removing oxygen and other impurities from iron ore, and then combining the resulting iron with carbon, recycled steel and small amounts of other elements. It is ubiquitous in the global economy, with uses ranging cars to construction products, refrigerators to washing machines, and cargo ships and surgical scalpels (World Steel Association, 2025). Steel production accounts for 7% of global CO_2 emissions due to its reliance on coal-based primary production (IEA, 2020a). About 71% of steel is produced through the blast furnace–basic oxygen furnace (BF–BOF) route, which emits ~2.3 tonnes of CO_2 per tonne of steel (Mission Possible Partnership, n.d.; Zhao et al., 2024a). This pathway dominates in regions such as Japan, South Korea and developing countries, where over 90% of steel follows this route. In contrast, the electric arc furnace (EAF) method, which uses scrap steel and electricity, emits only ~1.4 tCO_2/t steel (Gervásio & Da Silva, 2023). EAF is currently used for ~29% of global steel production, with lower uptake in Asia.

A widespread debate predominates between the concepts of phasing-in and phasing-out in the steel industry. Countries like European Union, China, Japan and India are supporting the phase-in of green steel by proposing subsidies and public investments. On the other hand, countries from different regions adopt different strategies leading to subsidy disparities. On one hand, non-OECD countries propose high subsidies per unit of steel produced while OECD countries usually prioritise domestic growth. These divergent strategies leads to complicated alignment of priorities (OECD, 2023).

1.1.3 (Petro)Chemicals

Chemicals and petrochemicals are estimated to account for 6% of total global emissions (The Royal Society, 2024). Demand for products like plastics, ammonia, and methanol has risen rapidly over recent decades and is expected to continue to grow, with developed economies currently consuming up to 20 times more plastic and 10 times more fertilizer than developing ones (IEA, 2018b). Alongside common challenges facing other hard-to-abate sectors such as iron & steel and cement, the chemicals sector also faces unique challenges due to fossil fuels being used both as fuel and feedstock. As a result, carbon is embedded in the final products themselves, with many chemical products currently having no technologically mature alternative production pathways (and so necessitating the potential use of CCS or NETs to address residual emissions).

The chemicals sector is not a single sector per se, but an aggregation of many different subsectors manufacturing tens of thousands of chemistries which are them themselves used in hundreds of thousands of distinct products globally. The production processes in the chemical industry are based on a complex transformation value chain, with a range of feedstocks, intermediate products and energy requirements. Emissions measurement and standard setting are subsequently complicated by the diversity and variability of the energy inputs, feedstocks, products, and process technologies used, and the frequent presence of "coproduct" chemistries and products.

Chemical products and subsectors can be organized in a variety of different ways, to make analyzing the sector and its overall dynamics easier. Common distinctions include division into *organic chemicals* (which contain carbon atoms), with chemicals lacking carbon labelled *inorganic chemicals*. Organic chemicals derived from fossil fuel feedstocks are commonly labelled as *petrochemicals,* whilst similar or other chemicals derived from biomass feedstocks are referred to as *bio-based chemicals*, though it may be possible to manufacture the same chemical group from bio-based, fossil fuel or circular recovered secondary feedstocks. For petrochemicals, most processes start from the same building blocks, often referred to as basic chemicals (e.g., ethylene, propylene, mixed xylenes, benzene, ammonia, hydrogen, chlorine, and methanol). Using these basic chemicals, a diverse range of chemical derivatives and polymers (e.g., polypropylene, polyethylene, PET, PVC) can be produced. Throughout this work, the chemicals sector is taken to include all petrochemical processes (as opposed to distinctions made by other work in treating the petrochemicals subsector separately). This decision on scope was informed by the dominance of petrochemical feedstocks in most chemical processes; hereon both sectors are referred to as the (petro)chemicals sector.

A common approach by climate policymakers to address the complexity of the chemicals sector is to focus on a list of key industrial chemicals that together account for the majority of sectoral emissions, including but not limited to ethylene, propylene, methanol, ammonia, benzene, toluene and xylene. Within these chemicals, methanol and ammonia production account for the largest portion of emissions globally from primary chemicals (73%), with high value chemicals such as ethylene, propylene, benzene, toluene and mixed xylenes accounting for the remaining 27% (IEA, 2023f).

Even with such narrowing approaches, the complexity of individual chemical value chains can be daunting, as reflected in the European Union's decision to postpone a decision on adding chemicals and plastics to its Carbon Border Adjustment Mechanism, citing, among other considerations, the need for "more precise accounting methods to capture the complex production routes and emissions of the chemical industry" (European Union Commission, 2025d).

1.1.4 Rising Demand and Rising Emissions Projections

Another challenge in reducing emissions from these sectors is the parallel challenge of meeting rising demand, driven largely by industrialisation. Demand for cement, steel and petrochemicals is projected to rise significantly over the next 25 years, particularly in developing economies. Without rapid decarbonization, industrial emissions are projected to rise by 2050. Cement emissions alone could grow to 3.5–3.8 Gt CO_2 per year under a business-as-usual scenario. The steel and chemicals sectors show similar trajectories, with deep reductions required for progress to to keep the 1.5 °C goal within reach and to address the climate crisis in this critical decade.

Alignment with global climate targets

Efforts to limit the increase in the global average temperature to well below 2°C above preindustrial levels, an effort to limit temperature increase to 1.5°C above pre-industrial levels, as outlined in the Paris Agreement, require urgent and far-reaching reductions in greenhouse gas emissions. According to the IPCC's Sixth Assessment Report, global emissions must fall by at least **43% by 2030 and 60% by 2035** relative to 2019 levels to remain on track for the 1.5°C scenario (IPCC, 2023). The industrial sector which accounted for approximately 34% of total emissions in 2019, including indirect emissions from electricity and heat must deliver a substantial share of these reductions (IPCC, 2022).

Hard-to-abate sectors such as cement, steel, and (petro)chemicals are central to this transition, as they account for nearly 60% of industrial energy use and roughly 70% of direct industrial CO_2 emissions.(UNFCCC TEC & UNIDO, 2023) Yet progress in the decarbonization of these sectors remains slow, with progress in reducing the carbon intensity of production largely being outweighed by rising demand. For example, the global average CO_2 intensity for cement has remained relatively flat, ranging from 0.56 to 0.60 tonnes of CO_2 per tonne of cement between 2015 and 2022, with only marginal improvements due to regional shifts in production practices (IEA, 2023c). Total emissions, however, have risen by 10% over the same period, driven by rapidly rising demand in China, India and other industrializing countries (Global Carbon Budget, 2024). Similarly, total emissions from the iron and steel sector have also risen over the past decade due to rising steel demand, despite a fall in direct carbon intensity. Direct emissions from the (petro)chemicals sector globally have also remained relatively constant over recent years, despite limited increases in production, with a relatively stable CO_2 intensity at 1.3 tonnes of CO2 per tonne of primary chemical (IEA, 2023d). "Primary chemical" here refers to high-volume base chemicals that serve as feedstocks for a wide range of industrial and consumer products, including petrochemicals and fertilizers.

To align with the **IEA's Net Zero Emissions by 2050 (NZE) scenario,** hard-to-abate sectors such as cement, iron & steel and (petro)chemicals need to reduce their emissions intensity significantly. Under this scenario, the cement industry must reduce its carbon intensity by approximately 4% per year through 2030 (IEA, 2023c), whilst the iron & steel sector needs to reduce its carbon intensity from 1.41 to 1.07 tCO2 per tonne of steel. The required reductions for the (petro)chemicals sector are even larger, from current levels of approximately 1.3 tCO2 per tonne of primary chemicals to 0.92 tCO2 per tonne by 2030. Achieving these reductions will require a suite of coordination actions, including adoption of alternative fuels, energy efficiency improvements, rollout of electrification technologies, substitution of petrochemical feedstocks and deployment of carbon capture, utilization, and storage (CCUS) technologies, tailored to regional and local conditions, available resources, and relevant product chemistries. Emerging innovations for cement production - which faces unique challenges due to process-based emissions accounting for nearly two thirds of all emissions and so which will require innovations to address - such as limestone-calcined clay cement (LC3) and electrochemical cement production show potential but remain at pilot or demonstration phases (WEF, 2024). In short, hard-to-abate industries faces a dual challenge over the coming decades: meeting rising global demand for development, while simultaneously achieving deep reductions in CO_2 emissions. Accordingly, industrial decarbonization and associated mitigation actions are increasingly featured in Long-Term Low Emission Development Strategies (LT-LEDS) and Nationally Determined Contributions and their corresponding ICTU (NDCs) (UNFCCC TEC & UNIDO, 2023).

Policy responses and industry initiatives

Policy momentum for decarbonizing hard-to-abate industries is gaining traction globally. ***China***, the world's largest cement producer, has committed to peaking emissions from the building materials sector by 2030 as part of its 2060 carbon neutrality objective (Global Times, 2022). The ***European Union***'s Green Deal Industrial Plan includes financial mechanisms and regulatory frameworks to accelerate industrial decarbonization, including support for low-carbon production routes Similarly, the ***United States of America****'s* Inflation Reduction Act (2022) provided funding for CCUS and other clean industrial technologies essential to decarbonizing the hard-to-abate industries, though some incentives were limited or eliminated in 2025. Japan has established a financial programme to support capital investment in projects aimed at reducing emissions in hard-to-abate industries and enhancing industrial competitiveness.

Parallel to governmental efforts, industry associations have outlined detailed roadmaps for decarbonization. The ***Global Cement and Concrete Association (GCCA)***, which represents approximately 80% of the global cement industry outside China, has committed to achieving carbon-neutral concrete by 2050 and aims to reduce CO_2 emissions by 25% by 2030 (GCCA, 2021a, 2025a). The **World Steel** group, whose members represent around 85% of global steel, fully supports the aims of the Paris Agreement and is committed to continuing to reduce carbon emissions from iron and steel production. Similarly, the **International Council of Chemical Associations** has also outlined its commitment to the Paris Agreement and the ambition to achieve climate neutrality by midcentury (ICCA, 2021), along with an exploration of four pathways and key enablers discussing a broad range of energy, feedstock and manufacturing strategies policymakers and companies may consider for the industry to reach climate neutrality (ICCA, 2024). Europe, ***European Cement Association (CEMBUREAU)***'s 2024 Net Zero Roadmap sets ambitious interim targets: a 37% emissions reduction from cement production and a 50% reduction across the value chain by 2030, with a goal of carbon neutrality by 2050 (CEMBUREAU, 2024b).

The ***International Energy Agency (IEA)*** also provides important analytical frameworks, co-designed and informed by industry and government stakeholders. For example, its 2018 Technology Roadmap for cement projected a 24% reduction in global direct cement-related emissions by 2050 under a 2°C scenario (IEA, 2018a). More recently, the IEA's NZE analysis calls for a 4% annual reduction in cement emissions through 2030 (IEA, 2023c). The alignment of national governments, international organizations, and industry bodies on decarbonization pathways for hard-to-abate sectors shows a growing global consensus and establishes a clear, science-based pathway for policy and investment decisions.

1.2 Rationale, Objectives, and Scope of the Synthesis Report

Rationale for Focusing on Standards and Labels

Regulatory standards and product labels are pivotal instruments for guiding market transformation in the hard-to-abate sectors. They are essential for translating high-level climate ambitions into practical, verifiable, and product-level actions. ***Standards*** articulate clear, measurable, and verifiable definitions of what constitutes low-carbon or near-zero emission industrial productions. By establishing transparent benchmarks, typically expressed as carbon intensity thresholds (e.g., kg CO_2 per tonne of cement), they foster accountability and performance-based competition (Hasanbeigi & Sibal, 2023; IEA, 2018a, 2023c). ***Labeling and certification schemes*** convert these technical specifications into accessible market signals. They empower procurement agents, developers, and policymakers to differentiate products based on environmental performance, thereby creating market pull for cleaner production methods (Clean Air Task Force, 2025).

From a policy perspective, standardized definitions form the basis for effective green public procurement (GPP), sustainable infrastructure planning, and investment frameworks. A fragmented landscape of competing standards, conversely, generates market confusion, impedes trade, and deters long-term investment. International harmonization is therefore a strategic priority (European Commission, 2023b). Recognizing this strategic importance, the UNFCCC Technology Executive Committee (TEC) and the United Nations Industrial Development Organization (UNIDO) have prioritized the harmonization of low-emission product standards within hard-to-abate sectors. A joint mapping exercise in 2023 identified fragmentation in carbon intensity standards across jurisdictions, evidencing the need for international cooperation and knowledge exchange to promote best practices (UNFCCC TEC & UNIDO, 2023, 2024).

Robust and harmonized standards serve multiple functions. They provide trusted performance metrics to benchmark progress; support the monitoring, reporting, and verification (MRV) of emissions reductions; stimulate private-sector investment in mitigation technologies; and build public confidence in climate-related product claims. When standards are both performance-based and technology-neutral, they allow manufacturers flexibility in achieving compliance.

Sectoral implications

In the **cement sector**, standards and labels can encourage innovation by accommodating a variety of mitigation pathways, including greater use of supplementary cementitious materials (SCMs), fuel substitution, carbon capture and storage (CCS), and the development of emerging technologies such as limestone-calcined clay cement (LC3) (IEA, 2020c).

In the **steel sector**, standards and labels can play an equally vital role in addressing the carbon intensity of different production routes. The distinction between conventional blast furnace-based steelmaking and cleaner electric arc furnace or hydrogen-based processes must be verified through trusted benchmarks. While labels developed by ResponsibleSteel™ and the First Movers Coalition have provided early frameworks for industry alignment, it is increasingly recognized that broader institutional coordination – potentially through multi-country or intergovernmental platforms – may be needed to ensure mutual recognition and international legitimacy. These efforts support clarity for buyers and procurement agents, as well as low-carbon procurement commitments and global supply chain alignment (Climate Strategies, 2014; Wesseling et al., 2017). Indicative carbon intensity thresholds (e.g., <0.4 tCO_2/t steel) though currently aspirational and not yet achieved at scale, help define what constitutes "clean steel" and can be embedded in trade policies, GPP, and international climate strategies. However, care must be taken that such thresholds are grounded in demonstrable progress and do not pre-emptively shape trade measures before broader industry feasibility is established. Without such standards, greenwashing and inconsistent measurement could undermine climate progress (Gervásio & Da Silva, 2023).

In the **(petro)chemicals sector**, carbon intensity standards are essential due to the complexity of production processes and the use of fossil feedstocks for many carbon-based product chemistries and their presence in most product value chains. The complexity and diversity of product chemistries, production processes, feedstocks and other supply chain inputs have also made measurement and standard-setting particularly challenging. Since individual chemicals chemistries have different structural chemical, carbon lifecycle profiles, and carbon intensity ranges, product-level standards may require detailed analysis of hundreds or more distinct chemicals of interest for a comprehensive regulatory program. Setting standards based on product classes or categories can reduce the number of individual standards required, but the result may suffer from aggregation bias, in which the category average and/or standard bears little correlation to the range of intensities values for any given chemical within the category. Therefore, to date, most labelling and standards efforts have focused on a subset of specific, relatively well-characterized chemical processes and products – such as hydrogen, ammonia and alternative fuels – with expanding attention to polymer-based products such as ABS plastics derived from ethylene chains, which are now increasingly subject to carbon footprint disclosure requirements. In these cases, carbon labels have enabled transparent communication of emissions profiles to downstream users and regulators. For example, emerging clean hydrogen standards currently vary from 1.0 to 4.0 kg CO_2 per kg H_2, depending on the methodology and boundary assumptions (IEA, 2023b). These standards are necessary to meet border adjustment rules like the European Union CBAM, set eligibility standards for clean energy and manufacturing incentives, and to inform MRV practices across chemical products value chains.

However, fragmentation persists across sectors. For steel, there is still no globally agreed definition of “low-carbon” or “net-zero” steel (Hasanbeigi et al., 2024a), and (petro)chemicals certification schemes often differ in scope, emission factors, or verification protocols. This lack of harmonization imposes administrative burdens, increases costs, and creates uncertainty for investors and buyers alike. A fragmented landscape of competing standards and non-aligned labels also risks undermining the potential benefits that standards could bring. For example, inconsistent definitions of “low-carbon” industrial products, coupled with unclear certification protocols, can generate market confusion, impede trade, and deter long-term investment in clean production capacity. To be effective, standards and labels must act as a bridge between climate ambition and on-the-ground industrial action. They translate national and international climate targets into measurable requirements at the product level, embedding sustainability into everyday decisions made by engineers, procurement officers, and material suppliers across the construction sector.

Objectives

The report provides a comprehensive global review of existing regulatory and voluntary standards, certifications, and labeling initiatives for low- and near-zero emissions cement, steel and (petro)chemicals. It synthesizes carbon-intensity standards, labeling schemes, and emissions thresholds shaping the transition across the three sectors; maps current initiatives; assesses gaps and implementation challenges; and identifies opportunities to accelerate progress toward industrial net-zero goals. The report also presents national case studies to support countries in developing and implementing their own carbon-intensity standards.

For the cement sector, the report aims to:

- *Map the current landscape of standards and labels relevant to cement decarbonization.*
- *Analyse gaps, best practices, and lessons learned from their implementation.*
- *Discuss implementation challenges and explore potential solutions.*
- *Recommend pathways to better harmonize and scale these instruments internationally and integrate them into national climate policies.*

For the steel sector, the report aims to:

- *Map and categorize current voluntary and regulatory standards and labels used to define low- and near-zero emission steel*
- *Identify best practices in terms of adoption, harmonization, and implementation across jurisdictions*
- *Highlight the lack of uniform definitions for “clean” steel and the emerging role of MRV and certification systems*
- *Propose policy-relevant insights on how these standards are influencing public procurement, investment decisions, and innovation pathways*

For the (petro)chemicals sector, the report focuses on the carbon intensity standards and certifications that apply to a narrow set of product chemistries such as hydrogen, ammonia, and low-carbon transport fuels. The limited scope of chemistries discussed in the report reflects the current lack of standards applicable to the diverse range of chemical products and processes, due to the sector's heterogenous nature. The report highlights the challenges associated with characterizing the broader (petro)chemicals sector, offering lessons relevant to the larger universe of chemical products that can be taken from existing experience.

It aims to:

- *Survey both regulatory and voluntary standards for carbon intensity, including those linked to international climate mechanisms such as the European Union Carbon Border Adjustment Mechanism*
- *Highlight methodological diversity and the challenges in accounting for embedded emissions from fossil-based feedstocks*
- *Identify opportunities to use standards and labelling to incentivize innovation in cleaner chemical production technologies.*

Scope

The report provides a global scope with attention to diversity of contexts, covering international standard-setting efforts, national/regional regulatory approaches, and voluntary/private-sector initiatives. It focuses on three sectors–cement (and concrete), steel, and (petro)chemicals–and includes concrete where labelling schemes address downstream product performance. The time frame emphasizes current and near-term initiatives (predominantly since 2020) as the landscape is rapidly evolving in this decade of climate action. For the (petro)chemicals sector, there have been limited current and near-term initiatives that cover the diverse range of products and processes beyond selected basic chemicals (largely hydrogen, ammonia and alternative fuels).

A clear distinction is maintained between **regulatory** and **voluntary** instruments. **Regulatory standards** are promulgated by public authorities and possess legal or administrative force (e.g., regulations, building codes, conformity standards incorporated by reference into law, emissions-trading benchmarks, and procurement specifications mandating Environmental Product Declarations or performance limits). Compliance is therefore mandatory within the relevant jurisdiction. **Voluntary standards** are developed by non-governmental entities–such as associations, standards bodies acting in a non-regulatory capacity, certification programmes, or buyer coalitions–and are market-driven and non-binding unless subsequently incorporated into public policy.

The report employs a non-prescriptive, country-agnostic framing that recognises differing national circumstances and capabilities; embeds just-transition considerations through stepwise, context-specific pathways rather than fixed, time-specific mandates; uses accurate, numbered references to standards; and reports performance ranges/benchmarks with notes on representativeness and uncertainty. Discussion of trade-related instruments is neutral and descriptive, acknowledges multi-jurisdictional developments and distributional impacts, and avoids prescriptive technology timelines.

Overall, the scope supports the growing recognition that achieving net-zero industrial emissions require cross-sectoral coordination, harmonized verification frameworks, and coherent product-level standards that reflect the carbon performance of industrial materials used worldwide.

1.3 Approach (Methodology) and structure of the report

Methodology and scope

This report utilizes a structured review methodology, based on the **Rapid Evidence Assessment (REA)** approach, to synthesize existing evidence on standards and labels in the sectors. analysis draws upon **peer-reviewed literature** and **grey literature,** including technical reports, policy briefs, and guidelines from international organizations (e.g., United Nations Industrial Development Organization (UNIDO), International Energy Agency (IEA), national governments, standardization bodies (e.g., International Organization for Standardization (ISO), European Committee for Standardization (CEN). For cement, the report draws on industry initiatives (e.g., Global Cement and Concrete Association (GCCA), The European Cement Association (CEMBUREAU). For steel, the REA draws on sources including ResponsibleSteel™, the First Movers Coalition, and industry roadmaps, as well as recent academic studies on emissions accounting and standardization. For (petro)chemicals, the analysis includes technical documentation from the IEA, UNIDO, and emerging certification schemes such as ISCC+, RED II/III, and CORSIA. Key industry publications and peer-reviewed studies were reviewed to address the methodological gaps and challenges in applying carbon intensity standards to complex chemical supply chains.

The assessment for all sectors was guided by a central research question: “What are the existing voluntary and regulatory carbon intensity standards, labels, and their applications for low- and near-zero emissions products and processes?” To answer this, the report applied a five-step REA process, including:

1. Definition of sectoral scopes and sub-sectors for review
2. Literature search and identification of relevant standards, certifications, and labels
3. Screening of evidence for quality and relevance
4. Mapping of initiatives based on geographic region, type (regulatory/voluntary), carbon threshold, and uptake
5. Synthesis of findings with policy implications and recommendations

Report structure

Table 3 Seven structures of the report.

Section	Topic	Details
Section 0	Executive Summary	A synopsis of key findings, recommendations, and implications for policy and practice
Section 1	Introduction	Background on industrial emissions and climate targets, the importance of standards and labels, and the objectives, scope, and methodology
Section 2	Mapping of Standards, Labels and Thresholds	An overview of existing standards and labeling initiatives across cement, steel, and (petro)chemicals sectors. Subsections cover thresholds, MRV, and uptake
Section 3	Implementation Challenges	Discussion of challenges in adopting, aligning, and enforcing standards and labels in each sector
Section 4	Case Studies and Lessons Learned	Examples of how standards and labels are implemented across different countries and sectors. Highlights MRV tools, regulatory pilots, and industry coalitions
Section 5	Pathways to Harmonize Standards Nationally and Internationally	Strategies and recommendations for harmonization, enabling policy, and integration into climate strategies and procurement frameworks
Section 6	Conclusions and Recommendations	Final summary of findings and recommended actions to scale and align product-level carbon standards globally

2. Mapping of Standards, Labels and Thresholds for all Sectors

The global landscape of standards for the cement, steel and (petro)chemicals sectors is comprised of a multi-actor governance system, featuring both top-down regulatory frameworks and bottom-up voluntary initiatives.

2.1 Overview of Regulatory and Voluntary Standards

A diverse and rapidly proliferating set of standards, labels, and certification frameworks aims to support the decarbonization of cement, steel and (petro)chemicals production. These can be categorized as regulatory mandates, technical standards that define methodology, and voluntary schemes led by industry or buyer coalitions.

Cement Overview

The global cement sector has experienced a rapid proliferation of standards, labels, and certification frameworks aimed at supporting the decarbonization of cement production, which is largely more advanced than the steel or (petro)chemicals sectors. ***Regulatory standards*** often embedded within national energy and climate legislation typically establish carbon performance benchmarks (e.g., kilograms of CO_2 per tonne of cement) and eligibility criteria for participation in emissions trading systems, carbon markets, or government procurement schemes. Notable regulatory mechanisms include the European Union Carbon Border Adjustment Mechanism (CBAM), the European Union Taxonomy for Sustainable Finance-whose alignment with green public procurement in countries such as Germany (representing ~15% of GDP) underscores market-shaping potential-, and the United States of America's Buy Clean programs.

In parallel, a growing number of ***voluntary schemes*** have emerged, offering performance benchmarks, timelines for emissions reduction, and definitional frameworks for low-carbon and near-zero products. Key examples include the Global Cement and Concrete Association's (GCCA) Low Carbon Ratings (LCR), the Industrial Deep Decarbonization Initiative (IDDI), and the First Movers Coalition (FMC) pledges. (First Movers Coalition & WEF, 2021; GCCA, 2024; UNFCCC TEC & UNIDO, 2024). Some national voluntary standards have also been developed through alignment to global standards, for example the German VDZ carbon labelling scheme for cement (which is aligned with the GCCA Low Carbon Ratings), Programs such as Climate Earth's Digital Environmental Product Declaration (EPD) system and the ConcreteZero initiative have also contributed to the definition and promotion of low-carbon or near-zero concrete.

At the global level, ***international frameworks*** have sought to clarify what constitutes low and near-zero emission cement. The International Energy Agency (IEA) has developed widely-referenced performance thresholds ranging from 40 to 125 kg CO_2 per tonne of cement, depending on the clinker content which have influenced subsequent initiatives (IEA, 2024b). Standard harmonization has also been prioritized by the UNFCCC Technology Executive Committee (TEC) and the United Nations Industrial Development Organization (UNIDO), which have included this objective in their respective work programmes (UNFCCC TEC & UNIDO, 2023).

Technical standardization efforts have been further supported by the International Organization for Standardization (ISO), with relevant frameworks including ISO 19694-3:2023 for cement-sector greenhouse gas emissions, and ISO 14067 and EN 15804 for environmental product declarations (EPDs) (CEMBUREAU, 2020a) . While the European standard EN 197-1 remains foundational across the European Union, it is widely regarded as prescriptive and slow to incorporate emerging cement technologies. In contrast, the United States of America ASTM C1157 standard adopts a performance-based approach, offering greater flexibility and fostering innovation (Clean Air Task Force, 2025; GCCA, 2021a).

At the ***national level***, diverse developments on carbon intensity standards for cement are underway. The State of California has introduced Buy Clean rules governing low-carbon concrete procurement; and India continues to implement the Perform-Achieve-Trade (PAT) scheme targeting industrial energy efficiency (Hasanbeigi & Sibal, 2023; UNFCCC TEC & UNIDO, 2023). Complementing these regulatory instruments are voluntary mechanisms such as the GCCA's proposed banding system, the Concrete Sustainability Council's CO_2 Performance Module and the German VDZ voluntary carbon intensity labels for cement.

Steel Overview

In the steel sector, decarbonization is similarly guided by both regulatory mechanisms and voluntary certification frameworks. Regulatory instruments include the European Union Emissions Trading Scheme (EU ETS), which imposes a carbon price on emissions from industrial facilities (ICAP, 2024), and the Carbon Border Adjustment Mechanism (CBAM), which targets embedded emissions in steel imports (Zhao et al., 2024b) The United States of America's Inflation Reduction Act (IRA) supports low-emissions steel production through green hydrogen subsidies, while bilateral initiatives like the Global Arrangement on Sustainable Steel and Aluminium (GASSA) are being explored to align international trade with sustainability goals (Algers & Åhman, 2024). In 2025, the Ministry of Ecology and Environment of the People's Republic of China issued the "Work Plan for Covering the Steel, Cement and Aluminum Smelting Industries in the National Carbon Emission Trading Market". This marked that China officially included the steel industry in the management of the carbon emission trading market (Ministry of Ecology and Environment, 2025).

Voluntary programs are playing an increasingly important role. Notable initiatives include the ResponsibleSteel™ certification, a multi-stakeholder framework promoting ESG criteria and emissions standards (Vogl et al., 2018), and the Hydrogen Breakthrough Ironmaking Technology (HYBRIT) initiative in Sweden, which substitutes coal with green hydrogen as a feedstock (Vogl et al., 2018). The Low Emission Steel Standard (LESS) is another voluntary scheme that was introduced in the European Union and is backed by industry. LESS comprises of a structured labelling system that assess the carbon footprint and the scrap content in steel production, based on the ISO 14067, prioritising comparability and transparency in steel production in both the private and public sector (Fleschen, 2025). LESS covers more than 45% of the European Union crude steel production companies ranging from ArcelorMittal and the German Steel

Association and stretching across Belgium, Luxembourg, France and Spain (Fleschen, 2025). On December 23, 2025, the first one million-tonne-level near-zero-carbon steel production line of Baosteel's Zhanjiang Steel Plant was fully connected. The near-zero carbon production line mainly uses "hydrogen-based vertical furnace direct reduction iron + scrap steel" as its raw materials to produce low-carbon emission billets. It utilizes the existing steel rolling facilities to produce low-carbon and near-zero carbon steel products, forming a complete low-carbon metallurgical process flow of "hydrogen-based vertical furnace reduction - efficient electric furnace smelting - low-carbon rolling production". Compared with the traditional BF-BOF process technology of the same production scale, this project is expected to achieve a carbon reduction of 50% - 80% and can reduce carbon dioxide emissions by over 3.14 million tons per year at the maximum (Southern Daily, 2025).

Additionally, the World Steel Association's Action Program is encouraging companies to disclose lifecycle emissions metrics and standardize CO_2 intensity reporting. While adoption rates vary, these mechanisms contribute to the broader effort to develop low-carbon and near-zero steel definitions. For example, the United States of America Department of Energy's Buy Clean initiative includes procurement standards that prioritize verified low-carbon steel products (The White House, 2024). India is a distinct case amongst developing countries having introduced its own Green Steel Taxonomy (Choo et al., 2024) to assess emission intensity, paving the way for potential labelling of green steel. While no specific labelling has been announced, the system is based on star rating which could propose a model for other countries to follow.

(Petro)Chemicals Overview

For the (petro)chemicals sector, regulatory and voluntary carbon intensity standards are more fragmented due to the sector's complexity and diversity. However, progress has been made in establishing product-level carbon benchmarks for some narrow categories of chemistries, including clean hydrogen, ammonia, and alternative fuels (IEA, 2018). **Regulatory standards** have typically been focused on hydrogen production, establishing carbon intensity benchmarks below which production can be labelled "clean" or "low carbon". Notable countries with existing hydrogen standards include the United States of America, United Kingdom of Great Britain and Northern Ireland, India and Japan, whilst the European Union has developed its own Renewable Hydrogen Standard. For other basic chemicals, there has been limited to no regulatory standards implemented, with the exception of industrial producers under the remit of the European Union Emissions Trading Scheme, which sets best-in-class benchmarks for a number of chemicals production sites. Alternative fuels, including bio-based fuels, have also had long standing regulatory frameworks in a few markets including the United Kingdom of Great Britain and Northern Ireland, European Union, United States of America and Brazil.

Several **voluntary standards** have evolved, including the International Sustainability and Carbon Certification's (ISCC) Carbon footprint certification and the Carbon Trust foot printing scheme certify emissions data across supply chains. These are largely focused on providing standardised and certifiable methodologies for emissions assessments, with the Production Carbon Footprint guideline developed by Together for Sustainability highlighting an example of a standard that is applicable across the (petro)chemicals industry. Given that the (petro)chemicals sector is heavily reliant on fossil fuel inputs for carbon-based feedstocks, which complicates emissions accounting, it is important to have sector-specific guidance to support accurate assessments of carbon intensity. Therefore, emerging standards can also target upstream transparency and supply chain traceability.

Standards and labels are particularly relevant given the global trade flows of chemical products and are essential for compliance with mechanisms like the European Union Carbon Border Adjustment Mechanism (CBAM). For example, in the European Union CBAM, fertilisers and hydrogen are covered alongside imports of cement, aluminium, electricity, and iron & steel. In December 2025, the European Union Council postponed a decision on additional chemical products including plastics until 2027. The proposed United Kingdom of Great Britain and Northern Ireland CBAM would also initially be aligned with this scope. Aligning national standards with international methodologies is thus a priority for both trade access and climate credibility.

Standards to date have focused on a small subset of basic chemicals, with limited to no coverage for many organic basic chemicals. An exception to this is the voluntary Basic Chemicals standards developed by the Climate Bonds Initiative, which covers the range of basic organic and inorganic chemicals (Climate Bonds Initiative, 2023), representing a first step towards coverage of subsectors that to date have not been included as carbon intensity standards into national regulatory frameworks. Unlike many other standards inventoried in this work, the carbon intensity benchmarks vary with time, falling in line with sectoral decarbonisation requirements. However, its inclusion of restrictions on the use of fossil inputs – not just carbon intensity standards – may reduce its utility as a sector standard.

Table 4 Selected Regulatory and Voluntary Standards in hard-to-abate sectors

Functional Category	Name / Framework	Type	Governing Body / Initiative	Key Features / CO_2 Thresholds	Status
A. Core Policy & Financial Regulation	European Union Taxonomy (Cement)	Regulatory	European Union	Defines sustainable investment eligibility with thresholds: ≤0.498 t CO_2/t cement, and ≤0.766 t CO_2/t clinker	Mature (Implemented since 2021)
	European Union Carbon Border Adjustment Mechanism (CBAM)	Regulatory (Tariff)	European Union	Prices the embodied carbon of imported cement to prevent carbon leakage.	Implemented / In transition (Reporting-only for phase 2023-2025; Certificates from 2026)
	European Union ETS Benchmarks (Cement, Steel and Chemicals)	Regulatory	European Union	Benchmarks based on top 10% of efficient installations; used for free allowances in European Union ETS.	Mature (Phase 4 in operation (2021-2030)
	Brazil Low-Carbon Hydrogen Law (Law 14,948/2024)	Regulatory (Hydrogen Policy & Certification)	Brazil	Establishes lifecycle-based carbon-intensity assessment and certification architecture for hydrogen and derivatives; enables subsequent technical rules and registries.	Implemented 2024; secondary regulation under development
	China Green Building Material Product Certification and Labeling	Voluntary	China	For voluntary certified green building materials, carbon emission reports need to be provided, by there are no specific requirements for carbon footprint indicators.	Implemented since 2020
	France RE2020 Building Code	Regulatory (Building Code)	France	Sets mandatory embodied carbon limits for new buildings, creating demand for low-carbon materials.	Implemented in 2022-2023
	India Perform-Achieve-Trade (PAT) Scheme	Regulatory (Efficiency)	India	Covers cement and steel sectors; incentivizes energy efficiency and reduces CO_2 emissions.	Mature (Multiple PAT cycles completed)

Functional Category	Name / Framework	Type	Governing Body / Initiative	Key Features / CO_2 Thresholds	Status
	Indonesia Cement Intensity Benchmarks & Sector Roadmaps	Regulatory (Sectoral Benchmarks / Strategy)	Indonesia	Phased cement-intensity targets (2% voluntary 2011–2015; 3% mandatory 2016–2020) embedded in national strategies; forward pathways emphasize SCMs, alternative fuels, efficiency, and prospective CCS; groundwork for a national “green cement” standard.	Initial phase completed; next-stage standardization planned
	Nigeria Climate Change Act & Disclosure Alignment	Regulatory (Climate Governance & Disclosure)	Nigeria	Statutory framework (carbon budgets; net-zero by 2060) with phased adoption of sustainability disclosure baselines; enables product/facility GHG MRV supporting sector standards.	Implemented (Act 2021); disclosure roll-out ongoing
	Türkiye Climate Law & National ETS Framework	Regulatory (Carbon Market Framework)	Türkiye	Establishes legal basis for a national ETS and alignment of accounting with major trading partners.	Enacted 2025; ETS design/launch phase
	United States of America Inflation Reduction Act – Industrial Tax Credits	Regulatory / Financial Incentive	United States of America	Provides tax credits for low-carbon steel and hydrogen production (e.g., 45V hydrogen PTCs).	Mature (Enacted in 2022 but reduced in scope and duration in 2025)
B. Public Procurement Initiatives	United States of America EPA Low-Embodied-Carbon Labelling Program	Regulatory (Procurement-linked)	United States of America	Establishes a federal label for low-carbon materials to be preferred in government projects.	Defunded by United States of America Congress in July 2025
	California Buy Clean Law	Regulatory (State-level)	State of California	Requires EPDs and sets GWP limits for materials used in state-funded construction projects.	Mature (adopted since 2017; updated in 2021)
	Industrial Deep Decarbonization Initiative (IDDI) Pledge	Voluntary (Gov’t Pledge)	Coalition of governments coordinated by UNIDO	Aggregates public demand for low-emission cement and steel.	Emerging
	United States of America Buy Clean (Steel)	Regulatory (Procurement-linked)	United States of America	Prioritizes verified low-carbon steel in federal procurement.	Emerging (Guidelines in preparation)

Functional Category	Name / Framework	Type	Governing Body / Initiative	Key Features / CO_2 Thresholds	Status
C. Foundational Methodologies & Standards	EPD (Environmental Product Declarations)	Transparency / Reporting Tool	Various EPD Program Operators	Provides standardized, third-party verified disclosure of a product's GWP based on its life cycle.	Mature (Widely adopted in European Union, United States of America, Canada)
	ISO 19694-3:2023	Standard (Methodology)	International Organization for Standardization (ISO)	Provides a harmonized GHG accounting methodology specifically for the cement industry.	Mature (published 2023)
	ISO 14067, ISO 14025, EN 15804	Standards (Methodology)	ISO, European Committee for Standardization (CEN)	The core set of international standards that govern the creation of EPDs and product carbon footprints.	Mature
	EN 197-1	Standard (Prescriptive)	CEN	A "recipe-based" standard defining common cement types; mandatory for market access in the European Union.	Mature
	ASTM C1157	Standard (Performance-based)	ASTM International	A performance-based standard specifying strength and durability, which facilitates the use of innovative cements.	Mature (widely adopted)
	ASTM C595, C618, C1866	Standards (for SCMs)	ASTM International	A suite of standards that govern the use of supplementary cementitious materials (SCMs) in blends.	Mature
	ResponsibleSteel™ Standard	Voluntary (Certification)	ResponsibleSteel	ESG + CO_2 certification for steel; site and product level coverage.	
	ISO 14067 (Chemicals)	Standard (Methodology)	ISO	Used for carbon footprinting of hydrogen and fuels.	Mature
D. Industry-Led Roadmaps & Commitments	CEMBUREAU Roadmap	Voluntary / Industry Roadmap	The European Cement Association (CEMBUREAU)	Outlines the European cement industry's technology pathway and targets for achieving climate neutrality by 2050.	Non-binding but widely adopted

Functional Category	Name / Framework	Type	Governing Body / Initiative	Key Features / CO_2 Thresholds	Status
	ICCA Roadmaps	Voluntary / Industry Roadmap	International Council of Chemical Associations (ICCA)	Outlines and models different portfolio approaches (pathways) for chemical sector abatement and is the most comprehensive industry-driven effort to date	Non-binding but developed and driven by industry stakeholders
	WBCSD Cement Sustainability Initiative (CSI)	Voluntary / Industry Collaboration	World Business Council for Sustainable Development (WBCSD)	A foundational industry initiative (now merged into GCCA) that pioneered voluntary emissions reporting.	Mature (endorsed by >40 companies)
	GCCA Low Carbon Ratings (LCR) System	Voluntary (Industry Label)	Global Cement and Concrete Association (GCCA)	A global rating system (AA-G) to simplify and standardize the procurement of low-carbon cement and concrete.	Launched in 2024
	GCCA Environmental Product Declaration (EPD) Tool	Transparency / Industry Tool	GCCA	A free online tool for members to generate standardized, verified EPDs.	Widely used
	World Steel Association Action on Climate	Voluntary / Industry Roadmap	World Steel Association	Lifecycle CO_2 reporting guidance for different steelmaking routes.	Launched
	First Movers Coalition – Steel Commitment	Voluntary (Buyers' Club)	World Economic Forum	10% near-zero steel procurement commitment ($<0.4\ tCO_2$/t steel).	Launched
E. Private Sector & Buyer-Led Initiatives	IEA Near-Zero and Low-Emission Definitions	International Guideline	International Energy Agency (IEA)	Provides influential, globally recognized performance thresholds that underpin many other initiatives.	Widely referenced
	First Movers Coalition (FMC) Cement/Concrete Pledge	Voluntary (Buyer's Club)	World Economic Forum / Member Companies	Creates early markets for breakthrough technologies by committing members to procure a percentage of near-zero cement.	Mature (member-led)
	Concrete Sustainability Council (CSC) Certification	Voluntary (Industry Certification)	Concrete Sustainability Council (CSC)	A holistic certification for concrete plants, recognized by green building systems like LEED and BREEAM.	Adopted by major suppliers

Functional Category	Name / Framework	Type	Governing Body / Initiative	Key Features / CO_2 Thresholds	Status
	Green Building Certifications (LEED, BREEAM) & EC3	Certification / Tool	United States of America Green Building Council, BRE, etc.	Creates indirect demand by awarding points or credits for using materials with lower embodied carbon.	Widely used
	ISCC PLUS Certification (Chemicals)	Voluntary (Certification)	ISCC	Chain-of-custody carbon certification for fuels and chemical feedstocks.	Mature
	GH2 Green Hydrogen Standard	Voluntary (Product Standard)	Green Hydrogen Organization (GH2)	≤1 kg CO_2/kg H_2; ≥90% renewable electricity input.	Widely referenced
F. Proprietary & National Labels	Building Materials Carbon Label (China)	Voluntary / Pilot	China Building Materials Federation	Building Material Carbon Label.	Piloted (Regional adoption)
	Company-Specific Product Labels	Corporate Claim / Proprietary Label	Individual companies	Environmental branding by major producers to market their own lines of low-carbon products.	Implemented (Company-level adoption)

2.1.1 Regulatory standards

A. Instruments with cross-border reach

- **European Union Taxonomy for Sustainable Finance:** The European Union Taxonomy provides standardized criteria for classifying economic activities as environmentally sustainable, guiding investments towards climate-aligned sectors. For manufactured products such as iron & steel, cement and organic basic chemicals, the taxonomy sets specific carbon intensity thresholds to define eligibility for green finance and procurement. For example, cement production is considered taxonomy-aligned if it meets the following performance thresholds: ≤0.498 t CO_2e per tonne of cement and ≤0.766 t CO_2e per tonne of clinker, whilst for iron and steel produced using electric arc furnaces the benchmark is below 0.266 t CO_2e per tonne of steel. Organic basic chemicals and ammonia production also have their own specific limits. These limits apply to cradle-to-gate emissions, including direct and indirect sources. In addition to the emissions thresholds, taxonomy alignment requires compliance with minimum social safeguards and “Do No Significant Harm” (DNSH) criteria. Activities falling within these criteria may qualify for preferential treatment under green financing schemes, European Union procurement, and corporate disclosure frameworks (European Commission, 2023a; FORESIGHT Climate & Energy, 2022a).
- **European Union Emissions Trading System (EU ETS):** The European Union ETS is the European Union’s cap-and-trade scheme covering major industrial emitters, including cement, steel, and (petro)chemicals. Within the cement sector, installations are benchmarked against the top 10% of most efficient plants. For example, for cement the current benchmark for grey clinker is set at 0.766 tCO_2 per tonne of clinker (European Commission, 2025b; ICAP, 2024b). Free allowances are allocated up to this benchmark, while emissions above it must be covered through allowance purchases. Similar benchmarking applies in the steel and petrochemical sectors, with allowances linked to best-performing facilities (ICAP, 2024a). These values determine which installations receive cost-free allowances and which must purchase additional EUAs.
- **European Union Carbon Border Adjustment Mechanism (CBAM):** The European Union CBAM is a regulatory tariff mechanism introduced by the European Union to prevent carbon leakage by imposing carbon pricing on imported goods, including steel, cement and fertilizers. Operating within the European Union market, it targets imports by applying an embodied carbon pricing approach that aligns with the European Union ETS, with prices derived from the European Union ETS. Importers are required to report the embedded CO_2 emissions of their products and pay a corresponding fee if these emissions exceed European Union benchmarks. CBAM aims to level the playing field for European Union producers, incentivize global emissions reductions, and support the integrity of the European Union carbon market (European Commission, 2025a).

B. Foundational transparency and accounting standards (technical)

- **Environmental Product Declarations (EPDs):** EPDs are standardized, third party-verified documents that report the environmental impacts of industrial products (e.g., cement and concrete) using life cycle assessment (LCA). They quantify indicators such as Global Warming Potential (GWP) per tonne or cubic meter and follow international standards (ISO 14025, ISO 21930, EN 15804), ensuring consistency and comparability. EPDs are essential tools in decarbonization, serving as the data backbone for green public procurement, low-carbon labels, and industry benchmarks. Widely adopted in Europe, North America, and increasingly in Asia, they underpin policies like the European Union Taxonomy, Buy Clean programs, and the GCCA Low Carbon Ratings (GCCA, 2024; Hasanbeigi & Sibal, 2023). Of all three-sector studied, the cement sector has the greatest number of standards.

- **ISO 19694-3:2023:** This standard is an international standard developed by the International Organization for Standardization (ISO) for calculating greenhouse gas (GHG) emissions specifically for the cement industry. It provides a harmonized methodology to quantify both direct emissions (e.g., fuel combustion, limestone calcination) and indirect emissions (e.g., purchased electricity, imported clinker), aligning with ISO 14064-1. This standard supports transparent, consistent GHG accounting across cement plants and corporate groups, enabling compliance with regulatory schemes like the European Union ETS, and participation in voluntary decarbonization and labeling initiatives (ISO, 2023).
- **ISO 14067, ISO 14025, ISO 21930 / EN 15804:** A set of international standards governs the quantification and communication of carbon footprints and environmental product declarations (EPDs) for industrial products, ensuring consistency, comparability, and credibility. ISO 14067 provides life cycle assessment (LCA)-based methodology for calculating product carbon footprints; ISO 14025 outlines principles for developing Type III EPDs; ISO 21930 and EN 15804 offer sector-specific rules for construction products (cement). Developed by ISO and the European Committee for Standardization (CEN), these standards support transparent, harmonized reporting at global and regional levels. Collectively, they enable robust environmental data essential for green procurement, product differentiation, and advancing low-carbon markets in hard-to-abate sectors (UNFCCC TEC & UNIDO, 2023).
- **ResponsibleSteel™**: ResponsibleSteel™ advanced emissions accounting, environmental management, and lifecycle impact assessment for steel production. The standard aligns with GHG Protocol and ISO 14067 methodologies to ensure compatibility with broader reporting frameworks (Vogl et al., 2018).
- **World Steel Association disclosure:** The association promotes lifecycle assessment (LCA) and CO_2 intensity reporting across production routes particularly BF-BOF and EAF through its CO_2 data collection program. This enables steelmakers to benchmark performance and assess decarbonization progress (World Steel Association, 2025).
- **(Petro)chemicals standard: ISO 14067** is widely used to calculate the carbon footprint of products such as hydrogen, ammonia, and alternative fuels. It also provides a framework that can be applied to the production of organic chemicals. The standard forms the methodological basis for numerous voluntary certification schemes, such as CertifHy and the GH2 Green Hydrogen Standard, which use specific GWP thresholds (e.g., $\leq$1 kg CO_2/kg H_2) to qualify products as “low-carbon” or “green”.
- Additional technical standards in the (petro)chemical sector include **the International Sustainability and Carbon Certification (ISCC) framework**, which applies chain-of-custody and mass-balance tracking methodologies for bio-based and recycled feedstocks, and the GHG

Protocol Product Life Cycle Standard, used to support MRV (monitoring, reporting, and verification) systems for diverse chemical products.

C. Global product specifications enabling interoperability (technical)

- **EN 197-1**: EN 197-1 is a regulatory harmonized standard developed by the European Committee for Standardization (CEN) and applied across the European Union. It follows a prescriptive, recipe-based approach, defining 27 distinct types of common cements (CEM I to CEM V) with strict compositional limits on clinker and other constituents, as well as strength and durability criteria. This standard is mandatory for CE marking and market access within the European Union, making it a cornerstone of cement regulation. However, its rigid formulation constraints may hinder the adoption of innovative or low-clinker cement types, posing challenges for low-carbon alternatives (CEN, 2011).
- **ASTM C1157 (performance-based)**: ASTM C1157 (issued by ASTM International, is a performance-based standard used primarily in North America and internationally. Unlike prescriptive standards, it does not constrain chemical composition but instead specifies performance outcomes such as compressive strength, setting time, durability, sulfate resistance, and heat of hydration. This flexible approach facilitates the market entry of novel and blended cement types, encouraging innovation in low-carbon cement technologies as long as performance criteria are met (ASTM International, 2017).
- **ASTM C595, C618, and C1866:** This suite is a prescriptive and performance-based standards from ASTM International governing the use of supplementary cementitious materials (SCMs) in cement and concrete. ASTM C595 outlines specifications for blended hydraulic cements, allowing incorporation of materials such as fly ash, slag, and limestone. ASTM C618 covers the chemical and physical requirements for coal fly ash and natural pozzolans, while ASTM C1866 focuses on ground-glass pozzolans. These standards collectively support the formal integration of SCMs in construction materials, playing a crucial role in reducing the carbon footprint of cement production by enabling alternative binders and circular material use (ASTM International, 2024).

D. Instruments applied within one jurisdiction

- **Brazil: ABNT NBR 16697:2018 (Cimento Portland – Requisitos), EPD program, and Low-Carbon Hydrogen law.** Brazil's unified cement norm ABNT NBR 16697:2018 (Cimento Portland – Requisitos) consolidates national cement families and enables deep clinker substitution within mainstream grades–e.g., **CP II-E** (Portland composite with slag) and **CP III** (blast-furnace cement)–while preserving performance requirements; peer-reviewed overviews in these families, their SCM windows, and alignment with ASTM types (e.g., CP II-E ≈ ASTM Type IT; CP II-F ≈ ASTM Type IL) (Natalli et al., 2021). Brazil also has active **Type III EPD** infrastructure aligned to **ISO 14025**, with Brazil-scoped, third-party-verified EPDs (e.g., Saint-Gobain Brazil) illustrating operational cradle-to-gate disclosure for construction products (Saint-Gobain Brasil, 2024). In (petro)chemicals, **Law**

No. 14,948/2024 establishes Brazil's **Low-Carbon Hydrogen** legal framework–defining lifecycle-based categories, a national certification system, and incentives–creating a pathway to interface with international carbon-intensity schemes (Mayer Brown, 2024; Yanasse et al., 2024).

- **China: Green Building Material Product Certification and Labeling:** Operating within national industrial and construction sectors, the system integrates low-carbon performance criteria into national industrial standards and green product certification schemes. By the end of 2025,, China had issued 100 green building material standards (11 more items will be added in 2026), with certification rules defined for 72 categories, covering key products such as cement, ready-mix concrete, and insulation materials (National Accreditation and Certification Administration, 2020 & The State Administration for Market Regulation, 2024). These standards now increasingly require the disclosure of carbon emissions, even though quantitative thresholds for embodied CO_2 are not yet widely established. A key element of the system is the China Green Building Material Product Certification and Labeling, which evaluates products based on a 1- to 3-star rating system. This framework traditionally emphasized parameters like durability and recycled content, but currently it has not incorporated carbon footprint standards into the evaluation system.
- **France: RE2020 Building Code** is a regulatory (building code) led by French government (ZEROCO2, 2022). It adopts an embodied carbon limits for buildings approach. Key features include thresholds for total embodied emissions of construction materials in new buildings, tightening every three years until 2031. This standard/framework plays a role in the market by creating demand for low-carbon materials and making the real estate sector bear the cost premium.
- **India: Perform-Achieve-Trade (PAT) Scheme** is a regulatory (energy efficiency focus) led by Bureau of Energy Efficiency (BEE) (Bureau of Energy Efficiency, n.d.). It sets energy consumption norms and standards for intensive industry sectors, including iron & steel, cement and certain petrochemical processes. This standard/framework plays a role in the market by Incentivizing investment in energy-efficient technologies, although it is not a direct carbon intensity standard.
- **Indonesia**: **Portland Composite Cement (SNI 15-7064; 2004/2014/2016 updates) and sector roadmap.** National standard for Portland Composite Cement (PCC) specifying allowable additions (e.g., pozzolan, limestone, slag in ~6–35 % range across PCC grades) and performance requirements; widely used in domestic markets. Complementary ministerial roadmap set CO_2-intensity reduction targets of 2% (voluntary, 2011–2015) and 3% (mandatory, 2016–2020) for cement, anchoring measures like SCM uptake, alternative fuels and efficiency.
- **Mexico: NMX-C-414-ONNCCE-2017 (Cementos hidráulicos).** National specification governs composition, performance classes, and conformity assessment for hydraulic cement placed on the domestic market. It defines families (e.g. Ordinary Portland and Composite Portland) and commercial grades (e.g. CPC 30, CPC 40, CPC 30R for rapid strength), and sets mechanical, physical, and chemical acceptance tests. By recognizing composite formulations and their test regimes, the norm provides a regulatory basis for clinker substitution (e.g., limestone/pozzolan/slag within the families defined) while safeguarding strength and durability–supporting EPD generation and low-carbon product claims (International EPD System, 2023; Portland Cement Association, 2024).

- **Nigeria: NIS 444-1 (Common cements).** Nigeria's cement standard aligns with the EN 197-1 family structure, specifying CEM I–V types and standard strength classes 32.5 / 42.5 / 52.5 with normal/rapid early strength variants. It codifies composition ranges and 28-day compressive-strength requirements, strengthening QA/QC for domestic production and imports, and facilitating wider use of limestone and other SCMs in Portland-limestone and composite cements while maintaining structural reliability (Joel & Ikpughur, 2016).
- **South Africa: SANS 50197-1 (Common cements).** South Africa's adoption of EN 197-1 through SANS 50197-1 standardizes the CEM I–V families and permits blast-furnace slag cements (CEM III) with slag contents in the range of 36–65%. National practice and guidance indicate frequent use of high-SCM concretes–typically incorporating around 50% ground granulated blast-furnace slag (GGBS) or 30% fly ash–to moderate heat of hydration and reduce embodied GHG emissions (Department of Trade, Industry and Competition, 2021).
- **Türkiye: Climate Law & national ETS framework.** Türkiye's Climate Law entered into force in July 2025, establishing the legal basis for a national ETS aligned with the 2053 net-zero target and European Union-facing trade alignment. The environment ministry subsequently issued a draft ETS regulation (July 2025) proposing an intensity-based cap, benchmark-guided free allocation, and coverage of power and industrial installations ≥50,000 tCO_2e/year; public consultation closed in August 2025 and a pilot launch from 2026 has been signposted. Together, the law and draft rules formalize MRV, allowance issuance and trading, and governance–positioning carbon pricing as a core lever for industrial decarbonization (including cement and steel) (GIDE, 2025; ICAP, 2025).
- **United States of America: United States of America Environmental Protection Agency (EPA) Low-Embodied-Carbon Labeling Program.** A federal labeling initiative, originally mandated by **the Inflation Reduction Act of 2022 (IRA) and rescinded in 2025**, identified lower-embodied-GHG construction materials (e.g., cement and concrete) using EPDs and recognized GHG methodologies (United States of America EPA, 2025; White House, 2023). In 2025, the program was defunded due to Senate budget reconciliation; however, several states have proceeded independently. California's Buy Clean Law requires EPDs and tightening GWP limits for public projects by 2025, with similar standards in Colorado, New York, and other states. This scheme effectively set regional benchmarks for maximum CO_2 per unit of cement/concrete used in public procurement (California Department of General Services, 2025; United States of America EPA, 2025; White House, 2023). Additionally, the **United States of America IRA** provides production and investment tax credits for clean hydrogen and industrial decarbonization technologies applicable to both steel and (petro)chemicals. Under the IRA's 45V credit, hydrogen producers can claim up to USD 3/kg of hydrogen depending on lifecycle emissions, encouraging its adoption in low-emission steelmaking and chemical synthesis pathways (Algers & Åhman, 2024), though the cut-off for eligibility was moved to 2028 under the revised budget bill passed by the United States of America Senate in 2025.
- **Japan: Strategic Domestic Production Promotion Tax Incentive.** Japan has established a Strategic Domestic Production Promotion Tax Incentive that provides tax credits based on the volume of production and sales for specified strategic products. Covered products include electric vehicles and related products, green steel, green chemicals, sustainable aviation fuel (SAF), and

semiconductors (microcontrollers and analog semiconductors). Under the scheme, green steel refers to steel produced by shifting the production process from conventional blast furnace–basic oxygen furnace routes to electric arc furnace processes, resulting in lower CO_2 emissions during production. The applicable tax credit is JPY 20,000 per tonne. Green chemicals refer to basic chemical products manufactured by switching feedstocks from fossil-based naphtha to alternative feedstocks such as biomass or recycled waste plastics. The applicable tax credit for green chemicals is JPY 50,000 per tonne.

2.1.2 Voluntary standards and certification schemes

- **CEMBUREAU**, the European Cement Association, serves as the voice of the cement industry across the European Union and has developed a comprehensive 2050 Net Zero Roadmap, most recently updated in May 2024. The roadmap outlines a phased decarbonization strategy targeting a 37% reduction in CO_2 emissions from cement production and a 50% reduction across the full value chain by 2030, progressing to 78% by 2040, with the aim of achieving full carbon neutrality by 2050 and even enabling negative emissions downstream. Key levers include clinker substitution, deployment of alternative fuels, carbon capture and storage (CCS), and circular economy approaches. The strategy aligns with the European Union Green Deal, climate targets, and innovation frameworks, and also positions the roadmap as a regional blueprint for standard-setting, policy advocacy, and industry-wide decarbonization alignment (CEMBUREAU, 2024b).
- The **Cement Sustainability Initiative (CSI)**, launched in 1999 under the World Business Council for Sustainable Development (WBCSD), was a global, industry-led platform comprising 24 major cement producers operating in over 100 countries (WBCSD, 2002). It played a pioneering role in advancing voluntary sustainability practices in the sector, including the development of the Getting the Numbers Right (GNR) database and the Cement CO_2 and Energy Protocol, which became foundational tools for emissions accounting and transparency. CSI established performance benchmarks and promoted climate action within the cement industry until its transition in 2018, when its core functions and member companies were integrated into the Global Cement and Concrete Association (GCCA), which continues to build on CSI's legacy in driving industry-wide decarbonization and reporting frameworks.
- The **IEA Near-Zero and Low-Emission Definitions**, published in late 2022 by the International Energy Agency (IEA), provide globally harmonized voluntary guidance for defining climate performance thresholds in cement production. Operating globally, this framework uses a performance-based sliding scale approach, with benchmarks ranging from 125 kg CO_2e/tonne for 100% clinker (near-zero) to 750 kg CO_2e/tonne (low-emission, Band E), and down to 40 kg CO_2e/tonne for 0% clinker. These thresholds support methodological consistency and are designed to inform policymaking, public procurement, and decarbonization program design. The IEA definitions have influenced the development of subsequent international standards and industrial transition initiatives (IEA, 2024b).

- The **Global Cement and Concrete Association (GCCA),** representing approximately 40% of global cement production (and 80% outside China), has emerged as a key actor in shaping decarbonization benchmarks for the industry. The GCCA Low Carbon Ratings (LCR) System, launched around COP29 in late 2024 by the Global Cement and Concrete Association (GCCA), is a voluntary industry-led performance labeling framework designed to support standardized low-carbon procurement (GCCA, 2024). Operating globally with provisions for national adaptation, the system uses a rating scale from AA to G, categorizing cement and concrete products based on their global warming potential (GWP) as reported in Environmental Product Declarations (EPDs), and benchmarked against IEA's low- and near-zero emission thresholds. This system simplifies complex carbon data into a user-friendly format aimed at guiding procurement and corporate disclosure practices.

- Complementing this, the **GCCA EPD Tool** is a free, web-based platform enabling cement and concrete producers to generate third party-verifiable EPDs aligned with ISO 14025 and EN 15804. It covers a wide range of products including clinker, cement, concrete, aggregates, and precast elements and supports consistent, harmonized lifecycle reporting across global markets. The tool underpins the LCR system and is a core enabler of GCCA's broader Net Zero Roadmap by promoting transparency, comparability, and compliance with green public procurement policies (GCCA, 2023).

- **Industrial Deep Decarbonization Initiative (IDDI) Green Public Procurement Pledge**: Led by a coalition of governments under the Clean Energy Ministerial and UNIDO, the IDDI Green Public Procurement (GPP) Pledge is a voluntary international government commitment aimed at accelerating demand for low-carbon construction materials. Participating countries pledge to specify low-emission or near-zero cement and steel in public projects by no later than 2030, using the IEA's sliding-scale thresholds as reference. The pledge supports standardized carbon accounting and procurement language, enabling cross-country interoperability and creating strong public-sector demand signals for decarbonized materials (Clean Energy Ministerial, 2021).

- The **First Movers Coalition (FMC) Cement/Concrete Pledge** is a global voluntary procurement initiative led by the World Economic Forum and the United States of America government, aimed at accelerating early markets for near-zero emission construction materials. Member companies commit to procuring at least 10% of their cement and concrete purchases from near-zero emission sources by 2030, with defined thresholds of ≤184 kg CO_2/t for cement and 70–144 kg CO_2e/m^3 for concrete, depending on strength class. By aggregating forward demand, FMC incentivizes innovation and production scale-up of clean technologies in hard-to-abate sectors (First Movers Coalition & WEF, 2021).

- The First Movers Coalition also includes a **Steel Commitment**, where members pledge to procure at least 10% of their steel from near-zero emission sources (<0.4 tCO_2/t steel) by 2030. This voluntary demand-side signal is designed to accelerate the market for innovative steelmaking technologies including hydrogen-based direct reduced iron (DRI) and EAF.

- **ResponsibleSteel™** is the leading global multi-stakeholder standard and certification initiative for the steel industry. It includes 13 principles, covering GHG emissions, responsible sourcing, and water stewardship. Its GHG requirements are aligned with the GHG Protocol and ISO 14067, and it offers a credible verification platform for low-carbon steel, enabling recognition by green building certification programs and climate finance channels (Vogl et al., 2018).
- The **World Steel Association** supports voluntary emissions reporting through its CO_2 data collection program. It facilitates plant-level disclosure of emissions intensity and encourages best practice sharing between BF-BOF and EAF producers. Participating members use this data to benchmark decarbonization pathways across geographies and production routes (World Steel Association, 2025).
- In the (petro)chemicals sector, the **GH2 Green Hydrogen Standard** (developed by the Green Hydrogen Organization) sets a voluntary carbon intensity threshold of ≤1 kg CO_2/kg H_2 and mandates >90% renewable electricity usage. It provides a lifecycle-based, globally credible standard used to verify hydrogen-based chemistries and derivatives (GHO, 2022).
- The **CertifHy scheme** in the European Union (Clean Hydrogen Partnership, 2019) and ISCC PLUS (ISCC, n.d.-c) globally are voluntary certification programs for low-carbon and renewable hydrogen, synthetic fuels, and chemicals, though currently have limited application to organic chemicals. They rely on ISO-compliant LCA methodologies and allow product differentiation in carbon intensity along supply chains through mass-balance and chain-of-custody mechanisms.
- The **Roundtable on Sustainable Biomaterials** (RSB) offers additional voluntary standards for sustainable fuels (Global Fuels, European Union RED and CORSIA Certification) and advanced chemical products (Global Advanced Products Certification), with lifecycle emission ductions of >70% (fuels) and >10% (non-energy products). The former are increasingly applied to aviation fuels and the latter to bio-based plastics in the (petro)chemicals sector (RSB, n.d.)
- The **Climate Bonds Initiative** has developed sector-specific benchmarks and criteria that are required to achieve its voluntary standard. For the (petro)chemicals sector, it offers certification to eligible assets, projects and companies producing a select number of organic and inorganic basic chemicals, including ammonia, chlorine, nitric acid, aromatics and high value chemicals. For each basic chemical, there are carbon and energy intensity thresholds that need to be met, with a sliding scale depending on the year. For example, for high value chemicals production (ethylene, propylene and butadiene) to be certified, it must have a carbon intensity below 0.51 tCO_2e/t in 2022, below 0.28 tCO_2e/t in 2030, 0.15 tCO_2e/t in 2040 and 0.09 tCO_2e/t in 2050 (Climate Bonds Initiative, 2023).
- **Concrete Sustainability Council (CSC) Certification (with CO_2 Module):** The CSC Certification, a global voluntary label led by the Concrete Sustainability Council, combines holistic sustainability auditing with a dedicated CO_2 performance module. Plants can earn a rating from 1 to 4 stars based on verified reductions in embodied carbon compared to a regional benchmark. The broader certification has Bronze, Silver, Gold, and Platinum levels. It is recognized by LEED, BREEAM, and other green building programs, positioning it as a key enabler of sustainable construction (The Concrete Sustainability Council (CSC), 2023).

- **Green Building Certifications & Material Libraries (LEED, BREEAM, EC3):** Programs like LEED (United States of America Green Building Council) and BREEAM (Building Research Establishment) provide indirect market influence by awarding credits for projects using EPD-backed, low-carbon materials. The EC3 Tool (by Building Transparency) complements these efforts by compiling a searchable database of EPDs, allowing users to filter materials by carbon intensity. Together, these systems incentivize the use of low-emission cement and concrete in construction through market rewards rather than mandates.
- **Building Materials Carbon Label** is a carbon performance evaluation system led by the China Building Materials Federation (CBMF), designed to support China's dual carbon goals. This system adopts a product-level carbon intensity benchmark and based on the CO_2 emission intensity of different strength grades of ready-mix concrete, assesses their low-carbon grades (ranging from 1 to 3), as shown in the figure below. It serves as both a compliance and procurement tool, promoting greener construction materials in public and private projects across China.

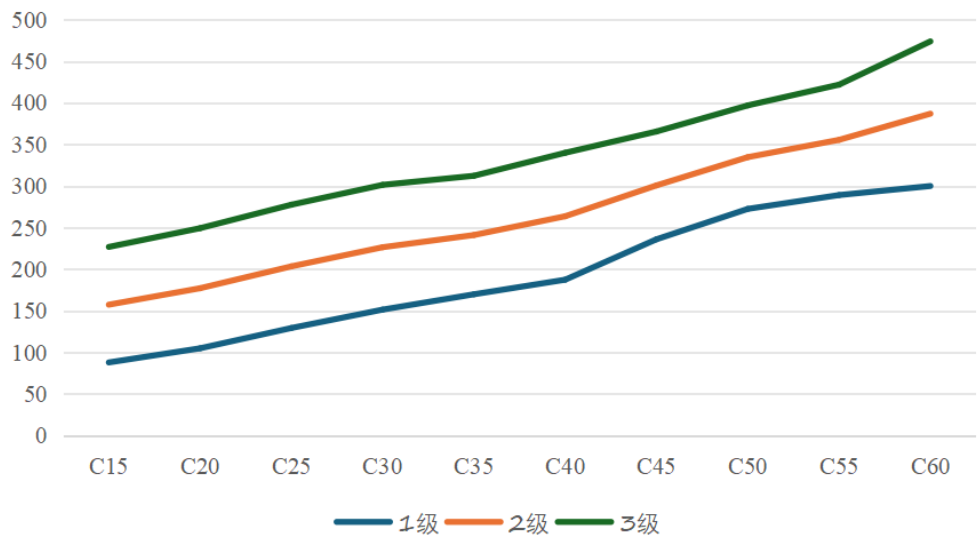

Figure 1: Low-carbon concrete classification range (unit: $kgCO_2/m^3$)

- **Company-Specific Product Labels (e.g., Holcim ECOPlanet, Unicem Eco Label, Cemex Vertua):** Major cement producers have developed proprietary environmental labels to showcase low-carbon products. These labels are supported by EPDs or internal LCAs, but verification methods and thresholds vary.
    - Holcim ECOPlanet: Holcim (formerly LafargeHolcim) launched the ECOPlanet brand as part of its global low-carbon product line. These cements contain reduced clinker, higher proportions of recycled materials, and in some markets integrate alternative binders. Products marketed under the ECOPlanet label typically offer a ≥30% reduction in CO_2 footprint compared to conventional cement (Holcim, 2021). The brand is available in multiple developing regions, including Latin America and Asia, positioning

Holcim as a driver of voluntary low-carbon standards (Kumari & Joshi, 2025; Viardot, 2024).

- Unicem Eco Label (Nigeria): In 2023, Lafarge Africa, Holcim's Nigerian subsidiary, introduced the Unicem Eco Label cement, validated by the Standards Organization of Nigeria. This product delivers approximately 30% lower carbon intensity relative to standard Nigerian cements and is marketed as a pioneering low-carbon brand in West Africa (Lafarge, 2023).
- Cemex Vertua: Cemex has developed Vertua, a global brand for low-carbon cement and concrete products, which is being introduced in Latin America, Africa, and Asia. Depending on the product, Vertua claims CO_2 reductions ranging from 25% to net-zero (via carbon offsets and advanced technologies) compared with conventional products (Cemex, 2023).

The mapping highlights a diverse ecosystem of both top-down regulatory frameworks such as emissions thresholds, taxonomy criteria, and harmonized standards and bottom-up voluntary initiatives, including certifications, buyer commitments, and corporate product labels. The mapping also evidences cement as the sector with the most standards and labels.

2.2 Transparency and carbon intensity thresholds

Transparency underpins credible decarbonization standards in hard-to-abate sectors. Across cement, steel, and (petro)chemicals, Environmental Product Declarations (EPDs) provide the core disclosure infrastructure, quantifying Global Warming Potential (GWP) per functional unit, following international standards like ISO 14025 and EN 15804 to ensure data comparability. A growing number of frameworks have adopted quantitative thresholds to define **"low-emission"** and **"near-zero"** performance.

Cement Sector

Table 5 Carbon Intensity Thresholds – Cement Sector

	Framework / Initiative	Category / Band	Threshold (GWP)	Clinker Basis	Targeted Use
1	IEA / GCCA Low Carbon Ratings	Near-Zero (Band AA)	≈ 125 kg CO_2e/t	100% clinker, sliding scale	Target for ultra-low-carbon product labels.
2	*GCCA* Low Carbon Ratings (LCR)	Low Emission (Band E upper limit)	≤ 750 kg CO_2e/t	100% clinker, sliding scale	Benchmark for low-carbon labelling
3	First Movers Coalition (FMC)	Near-Zero	≤ 184 kg CO_2e/t	Assumed average	Procurement threshold requiring transformative technologies.

4	European Union Taxonomy	Taxonomy-Aligned Cement	≤ 498 kg CO_2e/t cement	≤ 766 kg CO_2e/t clinker	Binding regulatory threshold for sustainable finance classification.
5	European Union ETS	Cap-and-trade benchmark	≤ 693 kg CO_2e/t clinker (benchmark) (Regulation (EU) 2021/447, 2021)		Basis for allocation of free allowances and carbon pricing signal for emitters.
6	European Union CBAM	Import Emissions Declaration	≤ 870 kg CO_2/t clinker (ETS-aligned) (European Union CBAM, 2023)	Reported or default clinker basis	Applies European Union carbon price to imported cement based on declared cradle-to-gate emissions.

Cement's EPDs are third-party verified, ISO-compliant documents prepared specifically under ISO 14025 and ISO 21930 (ISO, 2017), and for cement used in construction products, are typically aligned with the European standard EN 15804 (CEMBUREAU, 2020b), which provides a harmonized approach to data comparability and verification across geographies and producers. This harmonization enables cross-producer and cross-border comparability. EPD infrastructure is now widely established and increasingly used in procurement and rating schemes (e.g., GCCA Low Carbon Ratings, FMC commitments, national Green Public Procurement) (First Movers Coalition & WEF, 2021, 2025; GCCA, 2024).

Steel Sector

Table 6 Carbon Intensity Thresholds – Steel Sector

	Framework / Initiative	Sector	Threshold	Scope / Boundary	Use / Notes
1	ResponsibleSteel™ Certification	Steel	~1.1–1.8 t CO_2/t crude steel	Site-level, BF-BOF or EAF	Based on ISO 14067 and GHG Protocol
2	First Movers Coalition (Steel)	Steel	≤ 0.4 t CO_2/t steel	Lifecycle (cradle-to-gate)	Near-zero threshold for procurement pledges
3	European Union ETS Free Allocation Benchmark	Steel	~1.328 t CO_2/t hot-rolled steel	Average of 10% best performers	Used for allocating free emissions allowances

In the **steel** industry, transparency is increasingly achieved through site-level emissions reporting aligned with the GHG Protocol and ISO 14067 standards. The World Steel Association facilitates benchmarking through its CO_2 data collection program, which allows plants to report emissions intensity by production route (e.g., BF-BOF or EAF) (World Steel Association, 2025). Tools like the ResponsibleSteel™ certification further promote harmonization by embedding lifecycle carbon assessments into their multi-criteria sustainability verification process (Vogl et al., 2018).

(Petro)Chemicals Sector

Table 7: Carbon Intensity Thresholds – (Petro)Chemicals Sectors

	Framework / Initiative	Subsector	Threshold	Scope / Boundary	Use / Notes
1	Climate Bonds Basic Chemicals Standard	All	Sliding scale with time, depends on chemical	LCA (cradle-to-gate)	Used to specify whether an investment / asset can be considered sustainable
2	SGS Assured Standard	All	No set threshold	LCA (cradle-to-gate)	Provides a methodology for third-party certification of the carbon intensity of chemical materials
3	European Union Sustainable Finance Taxonomy	Selected basic chemicals	Set thresholds for each chemical group e.g., ethylene oxide: $0.314tCO_2/t$	LCA (cradle-to-gate)	Used to specify whether investments in the European Union are considered sustainable or not, based on carbon intensity benchmarks. Comparable taxonomies have been developed in ASEAN region also include thresholds for high-value chemicals like ethylene.
4	European Union ETS Free Allocation Benchmark	Selected basic chemicals	Varies depending on chemical	Average of 10% best performers	Used for allocating free emissions allowances; boundaries set for individual product types
5	GH2 Green Hydrogen Standard	Hydrogen & derivatives	≤ 1.0 kg CO_2/kg H_2	LCA (cradle-to-gate)	Requires >90% renewable electricity
6	CertifHy Low Carbon Hydrogen	Hydrogen & derivatives	≤ 4.4 kg CO_2/kg H_2	Cradle-to-gate	European Union-recognized voluntary certification
7	ISCC PLUS (Chemicals)	Hydrogen & derivatives	RED II/III thresholds	Mass balance, chain of custody	Widely used for sustainable fuels, with limited application to non-energy products

In the **(petro)chemicals** sector, transparency mechanisms are emerging through lifecycle-based certifications. The GH2 Green Hydrogen Standard, for example, requires third party-verified assessments of cradle-to-gate emissions for hydrogen production, mandating ≤1 kg CO_2/kg H_2 for "green" classification. Similarly, the CertifHy scheme in Europe and ISCC PLUS globally apply standardized accounting methodologies to ensure comparability across supply chains. These schemes have become crucial in contexts such as carbon border adjustment, climate finance, and trade compliance. Standards like ISO 14067 and EN 15804, already prominent in cement, are equally relevant for product-level carbon footprinting in both steel and (petro)chemicals, enabling MRV (monitoring, reporting, and verification) for traded materials under initiatives like CBAM or Buy Clean. The harmonization of these methodologies is particularly important for enabling cross-sector comparability in carbon intensity disclosures.

EPD infrastructure and current use

The infrastructure for creating and verifying EPDs in these sectors is already well-established. Thousands of product-specific and average EPDs have been published globally, with notable uptake in regions promoting embodied carbon transparency such as through Buy Clean initiatives in the United States of America, which generated over 14,000 new concrete EPDs in a single year (OneClickLCA, 2024). These declarations are now inputs into leading market-based and regulatory instruments (particularly for cement), including the Global Cement and Concrete Association's (GCCA) Low Carbon Ratings (LCR), the First Movers Coalition (FMC) procurement commitments, and national green public procurement programmes (First Movers Coalition, 2024; First Movers Coalition & WEF, 2021; GCCA, 2024).

Methodological consistency and boundary alignment

While EPDs establish a robust platform for emissions disclosure, challenges remain regarding methodological consistency. For example for cement, the International Energy Agency (IEA) defines near-zero emissions using cradle-to-gate boundaries (Modules A1–A3) (IEA, 2022), but diverges from EN 15804 by treating some supplementary cementitious materials (SCMs) such as fly ash and slag as zero-emission inputs (CEMBUREAU, 2020b). These methodological deviations may constrain the comparability of carbon intensity data unless the analytical boundaries are clearly stated and harmonized (GCCA, 2025b; IEA, 2022). Similarly, in steel, differences in system boundaries between ISO-based reporting and national regulations (e.g., ETS, CBAM) can affect how emissions from scrap recycling or DRI inputs are treated, leading to discrepancies in reported carbon intensity. This highlights the need for clear boundary definitions across all sectors.

Carbon intensity thresholds for "low-emission" and "near-zero" products

A growing number of global frameworks have adopted quantitative GWP thresholds to define what constitutes "low-emission" or "near-zero" industrial products. These thresholds support product differentiation, performance-based procurement, and alignment with net-zero pathways.

- Near-zero cement: The IEA defines a sliding-scale threshold based on clinker content, with 125 kg CO_2e/t for cement made with 100% clinker and proportionally lower values for blended products (e.g., ~100 kg CO_2e/t at 70% clinker content). This benchmark represents an 80–90% reduction compared to global production averages and is reflected in the GCCA LCR as Band AA (GCCA, 2025b; IEA, 2022).
- Low-emission cement: GCCA and IEA define the upper boundary of the "low-emission" range (Band E) at ≤750 kg CO_2e/t for 100% clinker, reflecting incremental improvement over best available conventional technology (~850 kg CO_2e/t). For blended cement with 70% clinker, the equivalent threshold is approximately 550 kg CO_2e/t (GCCA, 2025b).
- European Union Taxonomy thresholds for industrial products: The European Union Taxonomy for Sustainable Activities defines strict regulatory thresholds for assets and investments to be considered sustainable, typically based on the benchmark performance of the top 10% most efficient European Union installations. This threshold is a binding criterion for sustainable

finance classification and corporate disclosure under the European Union Sustainable Finance Framework (European Commission, 2023a; FORESIGHT Climate & Energy, 2022a).

- First Movers Coalition (FMC) threshold: The FMC, a global industry-led initiative, sets a near-zero threshold of ≤184 kg CO_2e/t of cement. This is intended to incentivize adoption of transformative technologies, including high SCM substitution, carbon capture, and novel binders. Members commit to purchasing only cement and concrete that meets or outperforms this threshold by 2030 (First Movers Coalition, 2024; First Movers Coalition & WEF, 2021).
- Near-zero steel: The First Movers Coalition (Steel Track) defines a near-zero threshold of ≤0.4 t CO_2 per tonne of crude steel. This level is intended to incentivize breakthrough technologies such as hydrogen-based Direct Reduced Iron (H_2-DRI) and EAF pathways powered by renewable electricity (World Economic Forum, 2023).
- Low-emission steel: ResponsibleSteel™ and similar frameworks recognize emissions intensities ranging from ~1.1–1.8 t CO_2/t steel for BF-BOF and 0.6–1.0 t CO_2/t steel for EAF-based production. These reflect reductions achievable through best available technologies and use of scrap, renewable energy, or natural gas in DRI (Vogl et al., 2018; World Steel Association, 2025)
- Low-emissions hydrogen and other derivatives: Multiple international and national standards define low-emission hydrogen as having ≤4.4 kg CO_2/kg H_2 (e.g., CertifHy), while near-zero or “green” hydrogen must meet thresholds of ≤1.0 kg CO_2/kg H_2 or lower, combined with ≥90% renewable electricity use.
- Alternative transport fuels: The European Union Renewable Energy Directive III (RED III) defines low-carbon fuels as those achieving >80% emissions reductions versus fossil fuel comparators, while United States of America Renewable Fuel Standards and California’s Low-Carbon Fuel Standard use specific gCO_2e/MJ thresholds to define compliance categories(California Air Resources Board, 2018; US DOE, n.d.)
- Non-energy chemical products: There has been more limited application of standards to non-energy products from the (petro)chemicals sector, with the main standard being the RSB Advanced Products Certification which requires at least 10% emissions reductions relative to the lifecycle emissions of a comparable fossil product (RSB, n.d.-c)

These cross-sector thresholds not only support procurement, certification, and trade alignment but also provide a benchmark for climate finance eligibility, emissions disclosure, and performance-based incentives across global supply chains. Unifying methodologies and carbon metrics across sectors will be crucial to enabling fair market access and fostering a coordinated industrial transition.

2.3 Level of Uptake of Carbon Intensity Standards and Labels

Despite the proliferation of carbon intensity standards in recent years, actual use across the cement, steel and (petro)chemicals sectors globally still remains in an early stages, with a noticeable gap between ambition and current industry compliance (FORESIGHT Climate & Energy, 2022a; GCCA, 2025b; IEA, 2022).

- In cement, there is no precise global statistic on the share of products certified under emerging near-zero or low-emission thresholds, and many lower-clinker blended cements that meet performance criteria in practice are not formally labelled. The Net-Zero Industry Tracker estimates near-zero-emission cement was less than 1% of the market in 2022, underscoring nascent uptake and noticeable adoption barriers.
- In the steel sector, near-zero or clean steel output accounts for less than 1% of global production, despite pilot projects such as HYBRIT and SALCOS (IEA, 2020b). MRV systems are being piloted but lack full operational coverage. Harmonized emissions thresholds, such as those under the ResponsibleSteel™ scheme or Buy Clean programs in the United States of America, have been introduced, but uptake remains low (Vogl et al., 2018; World Bank, 2022).
- In the (petro)chemicals sector, less than 1% of hydrogen is currently produced through low-emissions pathways that meet regulatory or voluntary thresholds, reflecting high costs and limited offtake (IEA, 2023a). Carbon intensity benchmarks exist for hydrogen and fuels but remain unaligned across countries, and their cross-border application is impeded by a lack of industrial applications along with high production costs. Standards for non-energy products are extremely limited.
- Regional Disparities: Adoption of verified low-carbon industrial products is led by Europe and North America, supported by policy mandates and a larger range of certifications. Emerging market and developing economies are at an earlier stage, though notable exceptions exist.

Transparency and EPD Uptake

In **cement** sector, compliance with existing certification schemes has been limited to date. As of 2023 only 11% of European Union cement plants operated below the European Union Taxonomy emissions threshold of 0.498 tCO_2e/t of cement, while nearly 75% risked non-compliance under strict enforcement (FORESIGHT Climate & Energy, 2022a). Although alignment reporting is mandatory under European Union sustainable finance regulation, initial disclosures revealed limited conformity underscoring the implementation lag and the need for deeper transformation (European Commission, 2019) Environmental Product Declarations (EPDs) have also been increasingly adopted for cement, particularly in Europe and North America. In the United States of America, the National Ready Mixed Concrete Association has published thousands of mix-level EPDs, while virtually all major producers in Europe disclose EPDs at plant or product level (OneClickLCA, 2024). However, these declarations are not yet systematically used for procurement or regulatory compliance. The transparency enabled by EPDs remains underutilized without consistent reference to carbon intensity thresholds or performance labels.

In **steel** sector, ResponsibleSteel™ certification includes requirements for GHG emissions disclosure and is supported by third-party MRV systems, but uptake remains low globally (Vogl et al., 2018). Similarly, the World Steel Association's Action Plan requires intensity reporting (tonne CO_2 per tonne steel), but participation varies by region and company capacity.

In the **(petro)chemicals** sector, the application of the Product Carbon Footprint voluntary standard from the "Together for Sustainabiity" initiative is largely led by large multinational firms, who have the resources to conduct detailed life-cycle analysis and supplier coordination, whilst smaller companies and regional players have been slower to adopt due to lack of capacity. ISO 14067 is an international standard that provides comprehensive guidelines for quantifying and communicating the carbon footprint of products throughout their entire life cycle, including raw material extraction, production, use, and disposal phases, whilst the TfS PCF standard is a sector-specific guideline developed for the chemical industry to complement and aligns with ISO 14067 and other standards such as the GHG Protocol. However, compared to cement, for example, there has been much more limited uptake of EPDs and other applications of LCAs such as ISO 14067 and the TfS PCF standard, largely due to some of the sector challenges facing decarbonisation efforts.

Standards and emission thresholds

Despite technological readiness, adoption of emissions thresholds remains limited, in part due to limited alignment in the standards and definitions across different public and private organizations.

In the cement sector, for instance, several potential standards exist:

- The IEA and GCCA define near-zero cement as ≤125 kg CO_2e/t for 100% clinker (GCCA, 2025b; IEA, 2022).
- The European Union Taxonomy defines low-emission cement at ≤498 kg CO_2e/t cement (European Commission, 2019; FORESIGHT Climate & Energy, 2022a).
- The First Movers Coalition (FMC) sets a more ambitious near-zero threshold of ≤184 kg CO_2e/t, designed to stimulate investment in breakthrough technologies (Boston Consulting Group, 2023; First Movers Coalition & WEF, 2021).
- The ResponsibleSteel™ standard uses a tiered approach aligned with GHG Protocol accounting. FMC steel members commit to purchasing steel with <0.4 tCO_2 per tonne of product by 2030 (World Economic Forum, 2023)

Globally, less than 5% of cement products are certified under such thresholds. Many available products like Portland-limestone cement (PLC) or fly ash-blended cements may meet low-emission performance ranges (e.g., GCCA Band E ≤750 kg CO_2e/t) but are not formally labelled as such (GCCA, 2025b). More than 30 cement and concrete companies are aligned with the GCCA "Net Zero by 2050" roadmap, including intermediate targets for 2030 (GCCA, 2025b). Technological readiness is advancing through: widespread adoption of **Portland Limestone Cement (PLC)** which offers approximate 10% CO_2 reduction, high blending rates in India (70% of production) using **fly ash and slag** (GCCA, 2022;

Nayak et al., 2022), innovation in **LC3** (Limestone calcined clay cement), and early-stage **carbon capture** initiatives. However, these measures are often driven by economic and political considerations, not binding emissions performance standards highlighting the need for formal thresholds to guide product differentiation.

Aligning jurisdictions is essential to drive effective decarbonisation, manage overcapacity and minimise conflicts among trade partners. In the steel sector, current standards are highly fragmented across supporting jurisdictions. One example of an international standard in the steel sector is the ResponsibleSteel™ standard. It uses a tiered approach aligned with GHG Protocol accounting. FMC steel members commit to purchasing steel with <0.4 tCO_2 per tonne of product by 2030 (World Economic Forum, 2023).

In the (petro)chemicals sector, due to the diversity of processes, feedstocks and products, there has been no alignment of emissions thresholds across jurisdictions for the majority of the key basic chemicals, with regulatory frameworks still in early stages of evolution outside of the European Union ETS. The exception to this is carbon intensity standards for hydrogen production (and related derivatives), with many major markets have developed regulatory definitions that range from 0.6 to 7.0 kg CO_2e/kg H_2 across countries. Despite the evolution of standards in selected markets, low-carbon hydrogen still accounts for less than 2% of production, with uptake hindered by the high cost of low-carbon production routes relative to those relying on fossil fuel feedstocks. Voluntary certifications like the Green Hydrogen Standard (≤1.0 kg CO_2/kg H_2) also have limited uptake due to similar economic barriers.

Certification programs and market signals

The volume of certified industrial products remains modest. In the cement and concrete sector, the Concrete Sustainability Council (CSC) has certified several hundred concrete plants globally, with a smaller subset completing its CO_2 performance module (The Concrete Sustainability Council (CSC), 2023). Germany's VDZ label is in pilot phase, and the United States of America EPA low-carbon cement label remains under development. As of late 2023, the FMC identified only five to six suppliers globally offering cement or concrete meeting its near-zero threshold (First Movers Coalition, 2024). In steel, certification schemes like ResponsibleSteel™ have gained recognition, but coverage is partial and largely skewed toward European producers. For the (petro)chemicals sector, schemes such as the Clean Hydrogen Certification Scheme in Brazil and CertifHy in the European Union offer labels for hydrogen, but the lack of harmonized definitions or interoperable standards constrains mutual recognition and market adoption.

Despite these limitations, demand signals are strengthening:

- The Industrial Deep Decarbonization Initiative (IDDI) includes at least 10 governments planning to green public procurement of cement by 2030 (UNFCCC TEC & UNIDO, 2023).
- National and subnational "Buy Clean" policies have been enacted in the United States of America, Ireland, Türkiye, California, New York, and Colorado (OneClickLCA, 2024).

- Private-sector coalitions like ConcreteZero and the FMC are shifting buyer preferences toward verified low-carbon products (Concrete Group, 2025; First Movers Coalition, 2024; UNFCCC Global Climate Action NAZCA, 2025).

In steel, HYBRIT, H2GreenSteel, Baosteel's Zhanjiang Steel Plant and SALCOS demonstrate viable pathways to near-zero products, but high cost and low demand for certified products hinder broader diffusion. In (petro)chemicals, while hydrogen certification has advanced, most producers cannot yet meet even the relaxed thresholds due to fossil-based inputs and high CAPEX for alternatives. Europe and North America currently lead in verified low-carbon cement adoption, supported by policy mandates and green building certifications. In contrast, emerging economies are at an earlier stage. Notable exceptions for cement, for example, include Ultratech in India, which markets low-carbon cements with recycled content, and Middle Eastern suppliers supporting mega-projects like NEOM in Saudi Arabia, where low-CO_2 concrete is specified for sustainability goals (NEOM, 2024; UltraTech, 2023). However, most small and mid-sized producers in developing countries lack incentives or capacity to pursue certification without clear policy or procurement drivers. The certified low-carbon cement market was valued at USD 2 billion in 2023, and the certified concrete market at USD 15 billion, with projected compound annual growth rates (CAGR) of 11–14% and 13–14% respectively (UNFCCC TEC & UNIDO, 2023). However, these figures are minor compared to the global blended cement market, which exceeded USD 370 billion in 2024 dominated by Asia-Pacific (Fortune Business Insights, 2025).

2.4 Analysis of findings

The mapping of standards, labels, and market mechanisms for decarbonizing all sectors reveals a maturing but still fragmented ecosystem. Several key findings emerge:

1. Fragmentation and emerging convergence

The global landscape of low-carbon cement standards remains fragmented, with varying thresholds, system boundaries, and methodologies. A single producer may need to comply with different definitions of “low-carbon” across jurisdictions–ranging from the European Union Taxonomy to the United States of America Environmental Protection Agency (EPA) labeling scheme, or private buyer requirements such as those from the First Movers Coalition (European Commission, 2023a; First Movers Coalition & WEF, 2021). This lack of alignment complicates compliance and creates market entry barriers, particularly for exporters. However, convergence is emerging through initiatives led by the International Energy Agency (IEA), the Global Cement and Concrete Association (GCCA), and the G7 Climate Club, which have proposed globally harmonized thresholds for near-zero (e.g., 125 kg CO_2e/t cement at 100% clinker) and low-emission cement (GCCA, 2024; IEA, 2022, 2024b) A similar pattern of fragmentation exists in the steel sector, where initiatives such as ResponsibleSteel™, the Climate Bonds Initiative, and the First Movers Coalition each propose differing thresholds, boundaries, and verification mechanisms (Mission Possible Partnership, n.d.; Vogl et al., 2018). In (petro)chemicals , thresholds for low-carbon hydrogen vary widely, from 0.6 to 7.0 kg CO_2/kg H_2, depending on the country and program, whilst for non-energy chemicals there is limited coverage due to the heterogenous nature of the sector, with the only widely applicable standards produced by the Climate Bonds Initiative (basic chemicals standard) and RSB (Advanced Products Certification). The lack of harmonized accounting rules across these sectors also poses challenges for multinational producers.

2. Harmonization with regional flexibility

While global alignment is desirable, there is increasing recognition of the need for regionally adaptable frameworks. For instance, GCCA's Low Carbon Ratings allow individual countries to adjust the clinker ratio baseline while maintaining the ambition of the IEA-aligned performance bands (GCCA, 2025b). This principle of "common but adaptable" standards championed by the G7 Climate Club aims to balance global comparability with national context, especially for emerging economies. While global alignment is the goal, regional tailoring is increasingly recognized. For example, GCCA allows countries to contextualize clinker benchmarks while maintaining the global ambition of 40 – 125kg CO_2e/t (GCCA, 2025b). The Climate Club is advancing this principle of "common but adaptable" standards, balancing coherence with practicality for emerging economies (IEA, 2022). Steel and chemical sectors face similar regional dynamics. For example, the dominant production process of the steel industry in Japan, South Korea and developing countries is the blast furnace-basic oxygen furnace (BF-BOF) route. By contrast, the European Union emphasizes electric arc furnace (EAF) and direct-reduced iron (DRI) pathways (Zhao et al., 2024a). In (petro)chemicals, Brazil's hydrogen standard is up to 7.0 kg CO_2/kg H_2, more closely aligned to current production realities, whereas Australia's standard is the most stringent at 0.6 kg CO_2/kg H_2 threshold. In ethylene production, there are significant differences in the carbon emission intensity of ethylene produced via coal-based, naphtha-based, and natural gas-based technological routes. The range of standards and the technology routes of the basic chemical illustrate the need for flexibility while maintaining alignment with long-term climate objectives.

3. EPDs: important yet inconsistent tools

Environmental Product Declarations (EPDs) remain the foundational mechanism for transparency in cement decarbonization. However, methodological inconsistencies, such as variations in Product Category Rules (PCRs), life cycle boundaries, and SCM allocation, limit cross-border comparability (GCCA, 2024, 2025b; ISO, 2017).

In the cement sector although widely accepted EPDs often lack harmonized treatment of supplementary cementitious materials or allocation rules, which can lead to misaligned comparisons (IEA, 2022). Although some standards now recommend complementary guidance, there is still no globally harmonized PCR for cement and concrete carbon footprints, underscoring the need for standardization. In the steel sector, ResponsibleSteel™ requires GHG disclosure but does not standardize lifecycle modules (e.g., A1–A3 vs. A1–A5), reducing comparability. In (petro)chemicals, Life Cycle Inventory (LCI) data for complex products like ammonia and methanol are rarely standardized, with no universally accepted PCRs complicating integration into public procurement frameworks. These gaps make it difficult to benchmark performance and aggregate emissions across supply chains.

4. Performance banding over binary labels

Multi-tiered performance ratings - such as those used in the GCCA Low Carbon Ratings (Bands AA–E) or proposed by Agora Industry – provide bands corresponding to equally spaced carbon intensity benchmark and are showing early signs of increased effectiveness than single value based standards (GCCA, 2024). These systems encourage continuous improvement and mitigate threshold-induced stagnation. Lessons from other sectors, like energy efficiency in appliances, suggest these bands must periodically tighten to remain credible and aligned with decarbonization trajectories. Steel sector initiatives like the Climate Bonds Initiative and FMC steel thresholds apply a similar banding logic, with performance tiers aligned with net-zero pathways (e.g., <0.4 tCO_2/t crude steel) (Mission Possible Partnership, n.d.). For hydrogen production in the chemicals sector, GH2 and the World Business Council for Sustainable Development define low-, medium-, and ultra-low-carbon hydrogen, creating early signals for investors and buyers. These tiered systems are gaining traction across sectors as more flexible and inclusive alternatives to binary certifications.

5. Voluntary momentum needs policy reinforcement

While voluntary initiatives have catalyzed early action, lasting market transformation requires policy backing. Experiences from California's Buy Clean legislation and the European Union's alignment with the Taxonomy Regulation demonstrate how regulation can shift market norms and accelerate EPD adoption (European Commission, 2019; OneClickLCA, 2024). Voluntary action alone is unlikely to deliver the scale and speed required for decarbonization. Steel producers in Europe are benefiting from CBAM, while United States of America companies face Buy Clean requirements that increasingly mandate verified GHG disclosures. Whilst the United States of America Administration in 2025 curtailed the Buy Clean program, many states such as California, Washington and Oregon lead individual efforts. Their individual commitment will not impede low carbon construction efforts (Metzger, 2025). However, in many countries, voluntary certification remains disconnected from industrial policy. Scaling voluntary initiatives into national regulation is essential to bridge this gap.

6. Risk of exclusion and disparity

Adoption of decarbonization standards is currently concentrated among large producers in high-income markets. SMEs particularly in low- and middle-income countries face barriers to participation, including the cost of verification and lack of technical capacity (UNFCCC TEC & UNIDO, 2023). Without supportive policies, this could result in de facto exclusion from global markets. Tiered compliance models and capacity-building support from development finance institutions will be essential to enable inclusive participation. This challenge is acute in steel and chemicals, where emerging market producers face rising costs from CBAM or low-carbon product procurement but have limited access to affordable decarbonization technologies. Regional disparities are evident: over 80% of certified green hydrogen projects are in OECD countries, while ResponsibleSteel™ certifications are clustered in Western Europe. Equitable access to finance, verification tools, and technical assistance can close this implementation gap.

7. Technology-forcing role of standards

Ambitious benchmarks, such as IEA's near-zero threshold, serve as market signals that steer investment and innovation in breakthrough technologies including carbon capture, fuel switching, and alternative binders (First Movers Coalition & WEF, 2025; IEA, 2024b). However, these must remain grounded in technical feasibility to maintain credibility and industry buy-in. Most current thresholds assume breakthrough technologies are not yet at scale, warranting a phased approach to standard implementation. In the steel sector, standards are pushing adoption of green hydrogen-based DRI and CCUS-equipped BF/BOF pathways, despite limited commercial-scale deployment. In chemicals, thresholds have accelerated electrolysis pilot plants for hydrogen, though broader product categories such as polymers remain unstandardized.

Overall, the analysis reveals that while technical definitions and measurement frameworks are increasingly aligned, market uptake and implementation lag behind. Key gaps include inconsistent EPD methodologies, low certification coverage, lack of harmonized product definitions, and insufficient support for small producers. Bridging these gaps will require international coordination, integration of standards into public procurement frameworks, and a more equitable enabling environment. These findings inform the next section, which addresses the implementation challenges and potential solutions for scaling up adoption.

3. Implementation Challenges in the All Sectors

The widespread adoption of low-carbon standards is constrained by a combination of institutional, financial, technical, and policy-related barriers.

Table 8 Key Implementation Challenges

Key Challenges	Descriptions
Limited Market Adoption of Standards and Labels	Risk aversion amongst engineers, contractors and procurement agencies operating in the construction sector - with associated perceptions of new low-carbon materials as having unproven performance risks often leads to a prioritization of traditional materials and specifications over innovative low-carbon alternatives. Many small and medium-sized enterprises (SMEs) also lack the technical and financial capacity to pursue emissions monitoring and certification without clear policy signals or market incentives, with the potentially high costs associated certification and limited ability to shape the evolution of standards also introduce barriers. In the steel sector, the complexity of certifying carbon intensity across BF-BOF and DRI-EAF routes has limited uptake of standards such as ResponsibleSteel™. In (petro)chemicals, only a small share of hydrogen projects meets emerging global low-carbon thresholds due to data limitations and methodological inconsistencies.

Key Challenges	Descriptions
Lack of Harmonization of Standards and Labels	Divergent definitions, system boundaries, and performance thresholds across various global and regional initiatives result in market fragmentation and administrative complexity. Methodological inconsistencies in Product Category Rules (PCRs) further limit the comparability of data across borders. In the steel sector, different standards define “green” steel based on either absolute emissions, process routes, or carbon intensity per tonne. Similarly, for (petro)chemicals, the treatment of scope 3 emissions and feedstock origin varies across certification systems, challenging comparability and aggregation.
Lack of Policies to Support Adoption	The impact of voluntary initiatives remains constrained without sufficient policy reinforcement. In many jurisdictions, public procurement guidelines do not yet mandate the use of certified low-carbon cement, and building codes often remain prescriptive rather than performance-based, restricting market entry for innovative products. This gap is equally evident in steel, where demand-side policies such as Buy Clean and green public procurement have been adopted in only a few countries.
Financial, Institutional, and Technical Barriers	Decarbonizing the cement sector is capital-intensive, with technologies like Carbon Capture and Storage (CCS) potentially increasing production costs by 50–70%. Access to finance remains a bottleneck, and many countries lack the institutional capacity for robust Measurement, Reporting, and Verification (MRV). The steel industry faces similarly steep costs, particularly for green hydrogen-based direct reduction or CCUS retrofits on existing blast furnaces (Rissman et al., 2020). In (petro)chemicals, electrifying production or switching to biogenic feedstocks involves substantial capital and operational expenses, often without access to concessional finance. Moreover, gaps in MRV infrastructure persist across all sectors, especially in developing countries, where local capacity for third-party verification is often limited or non-existent.
Data and Methodological Barriers	Low-carbon standard setting for the broader chemical sector is complicated by the complexity and diversity of chemistries, fuel, feedstocks, process technologies, and end-use applications across thousands of products. Even selecting a limited subset of chemistries poses challenges, as reflected in the European Union decision to defer a decision on adding chemicals and plastics to the European Union CBAM until 2027

3.1 Limited market adoption of standards and labels

Despite the availability of robust standards and labeling schemes, market adoption has been notably slow. This is in part attributable to the inherently conservative nature of the construction sector, where long-standing specifications and performance requirements dominate decision-making processes. Engineers, contractors, and procurement agencies often prioritize structural reliability and proven materials, resulting in hesitancy toward the adoption of new or modified cement formulations, even when such alternatives meet equivalent performance criteria (GCCA, 2024; IEA, 2022). Moreover, the fragmented structure of the cement industry, particularly in emerging markets, presents additional constraints. Many small and medium-sized enterprises (SMEs) lack the technical and financial resources required to engage in emissions monitoring, generate Environmental Product Declarations (EPDs), or pursue third-party certification (UNFCCC TEC & UNIDO, 2023). In the absence of clear policy signals or strong market incentives, these firms have limited motivation to shift away from conventional production methods. The steel sector faces similar hurdles. Certification schemes such as ResponsibleSteel™ and the Global Benchmark for Emissions Intensities (GBEI) have not seen widespread uptake due to limited awareness, a lack of harmonized thresholds, and technical reporting burdens. Market adoption is especially constrained in developing countries, where producers often lack MRV infrastructure and financing for greener technologies such as Direct Reduced Iron (DRI).

In the (petro)chemicals sector, uptake of carbon intensity standards remains uneven. While hydrogen has seen progress in standard-setting, fewer than 10% of clean hydrogen projects are currently certified under low-carbon thresholds. Adoption is constrained by methodological variation, limited downstream demand for certified products, and lack of alignment with national procurement or climate strategies.

3.2 Lack of harmonization of standards and labels

A major impediment to international progress is the absence of harmonized carbon accounting standards and performance thresholds. Currently, global initiatives diverge in their definitions, system boundaries, and metrics. For example, the European Union Taxonomy sets a threshold of 498 kg CO_2e/t cement (cradle-to-gate), while the First Movers Coalition defines near-zero cement at ≤184 kg CO_2e/t, and the GCCA offers a sliding scale down to 125 kg CO_2e/t at 100% clinker (First Movers Coalition & WEF, 2025; GCCA, 2024; IEA, 2024b). These variations reflect regional policy contexts but result in market fragmentation, administrative complexity, and uncertainty for producers seeking multi-market access. Methodological inconsistencies, particularly within Product Category Rules (PCRs), further limit comparability across borders. Differences in the treatment of supplementary cementitious materials (SCMs), allocation methods, and the inclusion or exclusion of quarrying activities can affect reported emissions figures. In the absence of mutual recognition frameworks or globally accepted protocols, producers are required to navigate overlapping or conflicting requirements, increasing compliance costs and delaying innovation (GCCA, 2024; ISO, 2017). In the steel sector, harmonization is complicated by variations in accounting for scrap content, upstream mining emissions, and grid electricity mixes. For example, the emissions intensity of Electric Arc Furnace (EAF) production can vary dramatically depending on electricity source, yet not all standards reflect this variability consistently (Rissman et al., 2020). Chemicals standards diverge based on product type hydrogen, ammonia, plastics and geographic jurisdiction, with limited coverage of many traditional organic chemicals as discussed earlier in this report. Differing lifecycle boundaries (e.g., well-to-gate vs. cradle-to-grave), assumptions for feedstock emissions, and treatment of process energy further limit comparability between schemes. Efforts by ISO and national authorities have not yet converged into a unified global baseline for (petro)chemicals certification.

3.3 Lack of policies to support adoption of standards and labels

Although voluntary initiatives have played a catalytic role in advancing decarbonization, their impact remains constrained without policy reinforcement. Empirical evidence from both developed and developing economies shows the importance of public policy in catalyzing change. For instance, California's implementation of Buy Clean legislation accelerated the generation of EPDs and encouraged emissions reductions across supply chains (OneClickLCA, 2024). Similarly, the Industrial

Deep Decarbonization Initiative (IDDI), led by UNIDO and supported by multiple governments, aims to make low-carbon procurement mandatory by 2030 (UNFCCC TEC & UNIDO, 2023). However, policy adoption remains uneven. In most jurisdictions, procurement guidelines do not mandate the use of certified low-carbon cement, and national building codes often remain prescriptive specifying material types rather than performance outcomes. This misalignment between industrial policy, procurement rules, and climate objectives continues to restrict market entry for innovative and high-performance low-carbon products (IEA, 2022; UNFCCC TEC & UNIDO, 2023). Furthermore, the absence of a carbon pricing mechanism in many regions limits the economic incentive to transition away from high-emission cement production (First Movers Coalition, 2024). In the steel sector, despite the emergence of initiatives like IDDI and the G7 Climate Club, few countries have embedded steel emissions thresholds into their national procurement strategies (Steel Sector Report). Public procurement in steel-heavy sectors such as infrastructure or automotive rarely includes performance-based carbon limits. For (petro)chemicals, public procurement and trade policy have not yet integrated low-carbon product standards for most commodity chemicals.

3.4 Financial, institutional, and technical barriers

Decarbonising hard-to-abate sectors is challenging, due in part to the capital-intensive nature of required measures. Key decarbonisation technologies such as carbon capture and storage can increase production costs by an estimated 50–70%, (IEA, 2022), introducing competitiveness challenges for all producers given potential reluctance of customers to pay for a green premium this large for commodities which are globally traded. The existence and lack of harmonization of carbon intensity standards across different jurisdictions can have implications for competitiveness, which some countries have chosen to address through the implementation of carbon border adjustment mechanisms. Whilst some clean technologies including those based on electrification technologies, such as electric arc furnaces for steelmaking – are more mature and so offer lower green premiums, they also require substantial upfront investment. Access to finance remains a key bottleneck, especially in developing economies, like the deployment of other clean energy measures. Despite the expansion of climate finance over recent decades, very few instruments are tailored to support industrial decarbonization or sector-specific transitions within cement, with less than 1% of overseas climate development aid from OECD countries directed towards industrial decarbonization (OECD & Climate Club, 2024). Risk perceptions related to technological maturity and the absence of guaranteed market demand also act as a substantial barrier to private and institutional investors (Boston Consulting Group, 2023). Institutional capacity also presents a potential challenge to the deployment and effective use of carbon intensity labels and standards. Many countries lack the necessary infrastructure for Measurement, Reporting, and Verification (MRV), including accredited verification bodies and trained professionals. Without this capacity, it is difficult to ensure credible implementation of standards or enforcement of labels, even if they were present or implemented. These challenges are further compounded by the absence of stable, long-term policy vision-such as sectoral targets, decarbonization roadmaps, and comprehensive regulatory frameworks-which can undermine investor confidence and slow industrial transitions ((GCCA, 2024; ISO, 2017). These constraints are particularly pronounced for smaller producers and institutions in developing countries. As a reference point, Germany has introduced supportive measures such as free access to the GCCA EPD Tool for standardized reporting, financial support for verification costs targeting smaller producers, and the development of regional certification hubs-offering examples of targeted solutions that could be adapted in other contexts.

From a technical standpoint, material supply chain limitations present further challenges. In the cement sector, traditional SCMs such as fly ash and blast furnace slag are in decline due to the phase-out of coal and primary steel production. While alternatives like calcined clay and recycled materials offer promise, their commercialization is hindered by quality variability, limited market familiarity, and slow regulatory adaptation (IEA, 2024b). In addition, some low-carbon formulations alter cement setting times, workability, or early strength, requiring new construction practices and retraining of labor forces (UNFCCC TEC & UNIDO, 2023). Steel production faces similar investment hurdles, with green hydrogen-based DRI facilities require over USD 1 billion in upfront investment per plant, whilst retrofit costs for CCUS exceed \$100–150 per tonne of CO_2 abated. These costs remain prohibitive in the absence of strong policy signals or risk-sharing mechanisms. The (petro)chemicals sector similarly suffers from a lack of tailored climate finance and policy incentives towards low-carbon solutions. Many clean chemical pathways, such as electrification of ethylene production or green ammonia, remain commercially unviable without public subsidy or carbon pricing, as also underscored in the OECD Climate Club Financial Toolkit, which assesses financing gaps and enablers across sectors including petrochemicals, plastics, cement, and steel (OECD, 2024). Furthermore, technical MRV protocols for multi-product and by-product chemical plants are more complex than in cement, requiring tailored software, sector-specific emission factors, and chemical-specific allocation rules.

4. Case Studies in all the Sectors and Lessons Learned

4.1 Country-level implementation of standards and labels

The decarbonisation of the cement, steel and (petro)chemicals sectors is being supported by the increasing number of regulatory standards, voluntary certifications, and harmonized carbon intensity thresholds. Evidence from across all three sectors highlights the importance of integrating standards into public procurement policies, strengthening MRV systems to create enabling environments for markets for low carbon industrial products. Notably, aside from China, India and Brazil, there has been limited implementation of carbon intensity standards for industrial sectors in other developing countries and has largely been concentrated on the cement and steel sectors. The examples presented here discuss national experiences with the development and integration of carbon intensity standards into decarbonisation strategies, with the full list of existing standards and labels developed detailed in the Annex of this report.

Table 9 Summary of National Approaches and Key Lessons

Country/Region	Primary Approach	Key Lesson Learned
Brazil	Low-carbon Hydrogen and Biofuels Standards: Brazil has developed national carbon intensity thresholds and certification schemes for hydrogen and renewable fuels, aligned with decarbonization goals across sectors including chemicals.	Government-industry collaboration through initiatives like the Solatio H2 Piauí and Acelen Renewables projects demonstrates how regulatory clarity and investment support can facilitate standards adoption and international alignment.
China	Incremental Progress through Pilots and Green Ratings: China, the world's largest cement producer, accounts for 57% of global cement consumption in 2020 ((Wang et al., 2023). The country is guiding the market to adopt low-carbon products through environmental labeling products and green product certifications. In 2024, the Ministry of Ecology and Environment of the People's Republic of China released the "Implementation Plan for Establishing a Carbon Footprint Management System", setting a plan to formulate about 100 product carbon footprint calculation standards by 2027 and about 200 by 2030, covering major industrial sectors and products.	China's incremental, pilot-first approach enables rapid policy testing and scaling of measures that align climate goals with energy-efficiency and air pollution control priorities. This linkage supports pragmatic roll-out standards, labels, and facility performance schemes while production and market conditions evolve. A comprehensive design and planning were carried out for the product carbon footprint management system, the construction of key product carbon footprint accounting standards (covering industries such as steel and chemicals), the establishment of a product carbon footprint factor database, the establishment of a product carbon marking certification system, the establishment of a product carbon footprint classification management system, and the carbon footprint information disclosure system.
European Union	Regulatory Alignment and Public Procurement: The European Union integrates carbon intensity thresholds into regulatory frameworks like the European Union Taxonomy and supports them with public procurement tools and financial mechanisms like the European Union Innovation Fund.	The experience highlights the importance of coupling emissions thresholds with procurement mandates, financial support, and a harmonized regulatory architecture to create a cohesive and powerful policy signal.
India	Regulatory Efficiency and Support for Innovation: India has combined regulatory efficiency schemes, such as the Perform-Achieve-Trade (PAT) mechanism, with proactive support for innovative technologies like Limestone Calcined Clay Cement (LC3). LCS is also being piloted in a number of other countries, including Ghana, Malawi and Togo.	India's experience illustrates the power of integrating innovation, pilot-scale demonstration, and rapid regulatory approval to scale novel low-carbon solutions in emerging economies.
Indonesia	Cement Intensity Benchmarks and Roadmaps: Indonesia has embedded sectoral roadmaps for cement, steel, and chemicals within its NDC and LTS–LCCR. For cement, intensity reduction targets (2% voluntary, 3% mandatory) led to a 5% emissions reduction by 2020, with future pathways focused on	Indonesia demonstrates how embedding sector-specific benchmarks and emissions modelling into national strategies can deliver measurable reductions. However, achieving deep decarbonization will require integrating carbon pricing, green product standards, and

	SCM substitution, fuel switching, energy efficiency, and CCS	CCS within a coherent industrial policy framework.
Nigeria	Industrial Investment Planning and Climate Legislation: Nigeria's Green Investment Plan estimates 9.2 billion USD in financing needs by 2030 to decarbonize cement, steel, and chemicals. This is supported by the Energy Transition Plan (ETP) toward net-zero by 2060 and the Climate Change Act (2021), which the country pledged a 47% emission reduction by 2030. Policy milestones are being developed for CCUS in cement and petrochemicals.	Nigeria illustrates the importance of coupling financial roadmaps with legally binding climate legislation. The case highlights that international finance, institutional capacity, and technology transfer are critical for scaling capital-intensive solutions such as CCUS and renewable integration in cement production.
Türkiye	Green Public Procurement to Accelerate Decarbonisation: Türkiye has mandated the use of low-carbon cement in public infrastructure projects, and is increasingly aligning its industrial emissions standards with the European Union ETS to ensure competitive access under the European Union CBAM	Türkiye's experience demonstrates the power of harnessing green public procurement to drive progress towards carbon intensity goals and the importance of aligning standards to international or regional benchmarks.
United Kingdom of Great Britain and Northern Ireland	Targeted Consultation and Stakeholder Engagement: The United Kingdom of Great Britain and Northern Ireland developed its Low Carbon Hydrogen Standard through an open consultation process, engaging over 125 stakeholders.	Transparent consultation and flexible threshold setting, combined with progressive tightening over time, help build industry consensus and prepare markets for compliance.
Germany	Flagship Low-Carbon Projects and Public-Private Partnerships: Germany has launched large-scale industrial decarbonization projects in cement and steel through coordinated public-private investment and regulatory support. Key initiatives include ThyssenKrupp's tkH2Steel project, targeting near-zero steel with projected abatement of 3.5 Mt CO2/year by 2029, and Heidelberg Materials' carbon capture portfolio, with over 170,,, tonnes CO2/year across the Lengfurt CCU facility and LEILAC-2 demonstration plant in Ennigerloh. These projects are backed by strategic public finance and aligned with national and European Union-level climate and innovation frameworks	Germany's experience illustrates how integrating industrial strategy, public funding, and technology deployment can accelerate near-zero industrial production. Public-private collaboration has proven critical to de-risking early-stage technologies and achieving emissions reductions at commercial scale.

United States of America	Federal Signals and State-Level Innovation: In recent years, United States of America started to shift from voluntary measures to regulatory instruments, particularly at the state level, with states like California leading on "Buy Clean" legislation. At the federal level, the 2022 Inflation Reduction Act provided funding to accelerate state and federal action on low-carbon labeling and procurement, though these programs are currently under review	The United States of America case demonstrates the effectiveness of a phased approach that begins with mandatory disclosure (EPDs) as a precursor to establishing enforceable performance limits, thereby building market readiness.
Japan	Green Public Procurement to Accelerate Decarbonisation: Japan has strengthened its green public procurement framework through the revision of the Basic Policy under the Act on Promoting Green Procurement (Cabinet decision of January 2025). Under the revised policy, products that use steel as a raw material are newly subject to procurement criteria, and those made with steel accompanied by verified emissions reduction achievements (“quantified reduction results”) are positioned as having higher environmental performance and are actively prioritized in public procurement.	

European Union: Regulatory Alignment and Public Procurement Leverage

The European Union stands at the forefront of integrating carbon intensity thresholds into both regulatory frameworks and public procurement practices. The European Union Taxonomy for Sustainable Activities, in force since 2021, defines a carbon performance threshold of 0.498 tCO_2 per tonne of cement as the criterion for taxonomy-aligned products.(European Commission, 2023a) Although uptake remains nascent, the requirement has improved emissions disclosure and catalyzed strategic shifts among European cement manufacturers (FORESIGHT Climate & Energy, 2022b).

Several member states have further operationalized these standards through Green Public Procurement (GPP) tools. The Netherlands and Sweden utilize life-cycle carbon budget systems–such as DuboCalc and the Environmental Cost Indicator (ECI)–that embed carbon intensity into infrastructure project evaluations (Diemel & Fennis, 2018). Ireland's 2024 mandate requiring blended cements for public projects demonstrates how procurement policy can create direct market pull for lower-carbon materials (IEA, 2023c). In parallel, the European Union Innovation Fund has supported early investments in breakthrough technologies (e.g., CCS projects in Norway and France), exemplifying how financial support can accelerate compliance with future standards. Similar regulatory alignment and procurement leverage have been instrumental in the steel sector, where tools like the European Union ETS, CBAM, and ResponsibleSteel™ certification promote market clarity and investment certainty for low-carbon steel. In the (petro)chemicals sector, the European Union Renewable Hydrogen Standard and ETS benchmarks similarly define performance thresholds, providing financial incentives while enabling MRV systems that drive transparency and trust. In both sectors, European Union-level harmonization reduces fragmentation across member states, aligning industry investments with long-term decarbonization trajectories.

Lesson: European Union experience highlights the importance of coupling emissions thresholds with procurement mandates and financial support, alongside a harmonized regulatory architecture that reduces market fragmentation across member states.

United States of America: Federal Signals and State-Level Innovation

The United States of America has increasingly moved from voluntary measures to regulatory instruments in driving cement decarbonization. The Buy Clean California Act, enacted in 2017 and updated in 2021, mandates the submission of Environmental Product Declarations (EPDs) and sets global warming potential (GWP) limits for concrete based on compressive strength classes. (California Department of General Services, 2025) The federal Inflation Reduction Act (IRA) of 2022 provided funding for the United States of America Environmental Protection Agency (EPA) to develop a national Low-Carbon Labeling Program, currently under consultation (White House, 2023). At the subnational level, New York State has implemented the Buy Clean Concrete program, which applies phased GWP limits based on local EPD benchmarks. Colorado and other states are following similar pathways. These efforts reflect a strategic progression–from mandating disclosure to establishing performance thresholds. Importantly, industry groups such as the Portland Cement Association (PCA, now called the American Cement Association) have been actively engaged in shaping definitions and implementation timelines. This federal-state coordination model also features prominently in the steel sector, where the First Movers Coalition and federal tax incentives (e.g., hydrogen tax credits under the IRA) have catalyzed low-carbon procurement, while subnational initiatives like California’s Buy Clean legislation support market scaling. In the (petro)chemicals sector, tiered support in the United States of America Clean Hydrogen Standard promotes a similar phased compliance approach rewarding lower carbon intensity outputs through scalable incentives. These examples emphasize the catalytic effect of integrating disclosure, performance standards, and fiscal policy into a cohesive regulatory signal.

Lesson: The United States of America case shows the catalytic role of mandatory disclosure as a precursor to enforceable limits. It also shows the value of coordination across federal and state levels to allow both harmonized national standards and regionally tailored procurement mechanisms.

China: Incremental Progress through Pilots and Green Ratings

China–which in 2021 produced approximately 2.4 billion tonnes of cement, about 55% of global output (shares vary year-to-year)–is advancing cement decarbonization primarily through performance-based industrial policies and pilot initiatives (Hasanbeigi et al., 2024b). The Ministry of Industry and Information Technology (MIIT) has issued guidelines for evaluating “green” cement manufacturing, with rating systems based on energy use and emissions intensity. However, there is not yet a national carbon threshold for cement. The Chinese government has issued a recommended standard, "Technical Requirements for Environmental Labelled Products - Cement (HJ 2519-2012)", which stipulates "comparable specific CO_2 emission", which is the comparable value obtained after correcting the unit CO_2 emission of cement clinker or cement products within the statistical period based on the altitude of the cement production line and the strength grade of the cement. The unit comparable CO_2 emission of cement clinker shall not exceed 880 kg/t. The unit comparable CO_2 emission limit for cement products should comply with the requirements in Table 10 depending on the type and strength grade of the cement. Additionally, China has integrated cement into the second phase of its national Emissions Trading Scheme (ETS), with a national carbon registry in development (World Bank Group, 2024). A similar pilot-driven approach characterizes China's steel transition, where industrial capacity controls and regional MRV pilots are allowing for phased deployment of standards prior to national enforcement. Likewise, the (petro)chemicals sector highlights how voluntary low-carbon product ratings and regional pilot schemes are being used to test and refine thresholds for hydrogen and synthetic fuels before national rollout. In all cases, alignment with broader policy goals such as energy efficiency and air pollution control strengthens institutional buy-in.

Lesson: China's incremental, pilot-first approach allows for rapid policy testing at scale. Voluntary standards linked to government-recognized "green product" labels are gaining traction, supported by strong MRV infrastructure and alignment with broader goals such as air pollution control and energy efficiency.

Table 10 The comparable CO2 emission limits for units using different types and strength grades of cement

Type	Strength	Unit comparable CO2 emission limit value (kg /t)
Portland cement	42.5(R)	<785
	52.5(R)	<795
	62.5(R)	<840
Ordinary Portland cement	42.5(R)	<665
	52.5(R)	<755
Portland blast furnace slag cement	32.5(R)	<240
	42.5(R)	<410
	52.5(R)	<665
Volcanic ash silicate cement Fly ash silicate cement	32.5(R)	<485
	42.5(R)	<580
	52.5(R)	<665
Complex Portland cement	32.5(R)	<460
	42.5(R)	<580
	52.5(R)	<665

India: Regulatory Efficiency and Support for Innovation

India has combined regulatory efficiency schemes with voluntary certification to advance cement decarbonization. The Perform-Achieve-Trade (PAT) scheme, an energy efficiency trading mechanism, has led to reductions in cement sector energy intensity and indirect CO_2 emissions (India Bureau of Energy Efficiency, 2022). On the voluntary front, the GreenPro ecolabel, administered by the

Confederation of Indian Industry (CII), promotes low-clinker and high-performance cement products for use in green buildings. Notably, India has pioneered standards for Limestone Calcined Clay Cement (LC3), a novel low-carbon binder developed through international research cooperation. Following successful pilot demonstrations, the Bureau of Indian Standards (BIS) approved commercial use of LC3 in 2022 (Rocky Mountain Institute (RMI), 2023). India's dual strategy mirrors its broader industrial decarbonization policies in steel, where schemes like the National Green Hydrogen Mission and potential CCS deployment in the BF-BOF steel pathway are supported by regulatory targets and voluntary initiatives. In the (petro)chemicals sector, India's clean hydrogen standard (2 kg CO_2/kg H_2) and its inclusion under the national mission reflect a proactive stance in defining performance-based standards for hard-to-abate industries. This integrated approach combining regulatory efficiency, innovation support, and targeted standard-setting builds capacity while maintaining market flexibility.

Lesson: India's experience illustrates the power of integrating innovation, regulatory approval, and pilot-scale demonstration. Programs such as PAT and GreenPro also show how voluntary and compliance mechanisms can work in tandem to shift the domestic market toward more sustainable cement options.

Türkiye: Carbon Pricing Architecture and Green Public Procurement to Accelerate Decarbonisation

In July 2025, Türkiye enacted its first Climate Law, establishing the legal basis for a national emissions trading system (ETS) aligned with the 2053 net-zero target and creating core governance (including a Carbon Market Board). On 22 July 2025, the climate authority published a draft ETS regulation for consultation outlining an intensity-based cap, benchmark-guided free allocation, and coverage of power and industrial installations emitting ≥50,000 tCO_2e/year, with a pilot launch signposted for 2026. Together, the law and draft regulation formalize MRV, allowance issuance and trading, and market oversight–positioning carbon pricing as a central decarbonization instrument for trade-exposed sectors such as cement and steel (Turkish Law Blog, 2025). Complementing carbon pricing, Türkiye adopted a Communiqué on the Promotion of the Use of Green Cement in Public Procurement (Official Gazette, 16 March 2024), which limits the clinker/cement ratio in public works to 0.80 for 2025–2029 and 0.75 from 2030 onward. The policy explicitly favors EN 197-1 low-clinker families (e.g., CEM II–V) in tenders, creating a demand pull for lower-embodied-carbon cements and supporting CBAM-aligned competitiveness. Sector estimates suggest the measure could avoid ~11 Mt CO_2 over ten years, contingent on enforcement and SCM availability. On the supply side, electric-arc furnace (EAF) routes already dominate Türkiye's steelmaking (≈70–75% of capacity), yielding lower average embodied emissions than blast-furnace routes and strengthening the sector's position under European Union CBAM-linked procurement and trade (Vorontsov, 2025). Türkiye is also a major cement producer–the largest in Europe and among the top five globally–underscoring the importance of aligning national instruments with European Union-facing market rules (e.g., CBAM) and international product standards (World Cement, 2024).

Lesson: Türkiye's experience illustrates how ETS design aligned with trading-partner rules and green public procurement with explicit clinker-ratio caps can work in tandem: the former sets a price signal and MRV backbone; the latter aggregates early demand for compliant low-carbon materials, accelerating investment in SCM supply, alternative fuels, and process upgrades (ICAP, 2025).

Embedding Sectoral Targets in National Climate Strategies: Case Studies from Indonesia and Nigeria

Indonesia: Cement Sector Benchmarks and Pathways

Indonesia has prioritized the cement, iron and steel, and (petro)chemicals sectors in its Nationally Determined Contribution (NDC) and its Long-Term Low-Carbon and Climate Resilient Strategy (LTS–LCCR) (Republic of Indonesia, 2021, 2022). In the cement sector, regulatory emission-intensity targets were first introduced through sectoral roadmaps, with a 2% voluntary reduction target for 2011–2015 and a 3% mandatory reduction for 2016–2020 compared with baseline intensity. These measures enabled the industry to achieve an overall 5% reduction in CO_2 emissions by 2020. Future decarbonization is expected from reducing clinker content through supplementary cementitious materials (SCMs), increasing the share of alternative fuels such as biomass and refuse-derived fuel (RDF), and improving kiln energy efficiency (Junianto et al., 2023). A system dynamics model projects that integrated mitigation, particularly a roadmap proposed by the Indonesian Cement Association, could achieve a 27% emissions reduction by 2050. This will require a comprehensive policy package, including carbon pricing, a national green cement standard, revisions to product benchmarks, renewable energy deployment, and progressive CCS integration (Junianto et al., 2023).

Lesson: Indonesia shows how sectoral benchmarks and emissions modelling can be embedded in national strategies. Long-term success depends on combining pricing instruments, standards, renewables, and CCS within a coherent industrial policy framework.

Nigeria: Industrial Sector Integration & Investment Planning

Nigeria has identified its industrial and heavy sectors, particularly cement, steel, and (petro)chemicals, as critical to its emissions trajectory. The government's Green Investment Plan, aligned with national climate commitments, estimates that 9.2 billion USD will be required by 2030 to decarbonize these industries through energy transitions, deployment of low-carbon technologies, and cleaner production systems (Njume, 2025; The Federal Government of Nigeria, 2021). This investment roadmap underpins the Energy Transition Plan (ETP), launched at COP26, which outlines Nigeria's pathway to net-zero emissions by 2060. The ETP prioritizes power and industrial decarbonization, with cement and steel specifically targeted for energy-efficiency improvements and renewable integration (Nigeria's Energy Transition Plan, 2024). The Climate Change Act (2021) establishes climate governance through the National Council on Climate Change (NCCC), mandates carbon budgets and requires a Net-Zero Plan. Nigeria's Updated NDC commits to a 20% unconditional and 47% conditional reduction by 2030. The long-term low-emission strategy further identifies CCS as critical, with a goal to capture 58% of cement sector emissions by 2060, supported by clinker substitution and alternative fuels (National Climate Change Council, 2024; Okafor et al., 2025).

Lesson: Nigeria demonstrates how financing, governance, and strategy can be aligned for industrial decarbonization. Achieving cement sector targets will depend on mobilizing international finance, strengthening capacity, scaling CCS and alternative fuel deployment.

Lessons learned across country case studies

Analysis of national implementation experiences yields several overarching lessons that can inform the global scaling of low-carbon cement standards and labeling systems:

1. **Policy signals drive market response.** Clear and consistent policy signals, whether through regulation, procurement mandates, or public investment, are enablers of change. Experiences from the European Union, California, and China demonstrate that even ambitious standards can gain industry traction when supported by coherent policy frameworks. In the steel sector, strong policy tools such as the European Union ETS, Carbon Border Adjustment Mechanism (CBAM), and the Inflation Reduction Act (IRA) in the United States of America have created vital demand-pull dynamics, encouraging investment in low-carbon technologies such as green hydrogen and CCS (Gervásio & Da Silva, 2023). Similarly, the Renewable Energy Directive III and national hydrogen strategies have provided the (petro)chemicals sector with targeted incentives and carbon intensity thresholds that catalyze compliance and innovation.
2. **Sequencing matters: measure, disclose, then regulate.** A phased approach beginning with emissions measurement, followed by mandatory disclosure, and culminating in performance requirements, has proven effective in building institutional capacity and stakeholder buy-in. This stepwise progression allows for learning and adjustment while avoiding early resistance. This progression is reflected in United States of America policies like the Buy Clean initiative, where Environmental Product Declarations (EPDs) act as a precursor to enforceable limits. Similarly, the Product Carbon Footprint standard developed by the chemical industry follows a cradle-to-gate methodology aligned with ISO 14067, enabling structured emissions disclosure prior to standard enforcement.
3. **Context-specific strategies with global alignment.** While the underlying goal of cement decarbonization is global, implementation must reflect national circumstances. India has leveraged abundant clay resources to scale Limestone Calcined Clay Cement (LC3), the European Union has capitalized on its regulatory infrastructure, and China has applied a pilot-led approach through central planning. These diverse approaches can converge over time through alignment with international benchmarks such as those from the IEA or GCCA. Similarly, in the steel sector, China has introduced a mandatory emissions threshold for 2030 while piloting MRV systems and capacity restrictions in selected provinces (Zhao et al., 2024a). In contrast, India's National Green Hydrogen Mission focuses on integrating CCS and electrification options within national contexts where energy supply chains are less decarbonized (Algers & Åhman, 2024). The (petro)chemicals sector reflects this as well, with carbon intensity thresholds for hydrogen ranging from 0.6 kg CO_2/kg H_2 in Australia to 7.0 kg in

Brazil, demonstrating the necessity of nationally tailored thresholds (Australian Government, 2025; Lira, 2024).

4. **Collaboration between government and industry is essential.** Collaborative governance models produce more effective outcomes than adversarial dynamics. In the United States of America, coordination between the Portland Cement Association and state governments has informed pragmatic threshold-setting. Similarly, India's LC3 success was enabled by partnerships among industry, standards bodies, and international research institutions. This pattern is echoed in the ResponsibleSteel™ certification scheme, which was built through multi-stakeholder engagement and includes both ESG criteria and emissions thresholds aligned with global climate goals (World Economic Forum, 2023). In the chemical sector, the United Kingdom of Great Britain and Northern Ireland's Low Carbon Hydrogen Standard was developed through public consultation involving over 125 stakeholders from academia, local government, and industry (DESNZ, 2022).

5. **Start now, refine overtime.** Waiting for universally accepted or technically "perfect" standards may delay progress. Case studies show that incremental action, such as introducing basic disclosure requirements or voluntary thresholds, can catalyze momentum and be progressively tightened as data, capacity, and market maturity improve. This approach underpins the Climate Bonds Standard and Certification Scheme, which progressively tightens hydrogen emissions thresholds from 3.0 kg CO_2/kg H_2 in 2022 to 0.0 by 2050 (Climate Bonds Initiative, 2020). Similarly, in the steel sector, early pilot projects like HYBRIT and H2Green Steel in Sweden have helped de-risk future investment and regulatory adoption, even while carbon pricing frameworks and verification tools continue to evolve (Johnsson et al., 2024).

4.2 Industry-led initiatives

Proactive initiatives from within energy-intensive industries such as cement, iron & steel and (petro)chemicals have been important to advancing decarbonization efforts.

Sectoral Leadership and Tools Development

The **Global Cement and Concrete Association (GCCA)** has emerged as a central coordinating body for industry decarbonization. Its *Concrete Future 2050 Net Zero Roadmap* commits the sector to full decarbonization, with an interim goal of reducing CO_2 emissions by 25% by 2030 (GCCA, 2021a). To operationalize this ambition, the GCCA has launched two tools: the *Low Carbon Ratings (LCR) system*, which benchmarks cement products against IEA-aligned carbon thresholds, and a digital *Environmental Product Declaration (EPD) Tool*, designed to standardize emissions reporting across member companies. These tools support lifecycle-based transparency and enable alignment with emerging procurement and policy frameworks (GCCA, 2023, 2025b; IEA, 2024b). The steel industry has followed a similar trajectory with the ResponsibleSteel™ certification an industry-led initiative defining ESG criteria and emissions thresholds to promote transparency, traceability, and performance across the value chain (Vogl et al., 2018). The First Movers Coalition, including major auto manufacturers like Ford and Volvo, has committed to purchasing steel with less than 0.4 tCO_2/t by 2030, creating measurable market pressure to innovate (World Economic Forum, 2023). Meanwhile, the (petro)chemicals sector has developed the Product Carbon Footprint Guideline for the Chemical Industry, which applies lifecycle assessment methods (aligned with ISO 14067) to provide harmonized reporting tools across diverse product categories (Together for Sustainability, 2024).

In parallel, **CEMBUREAU** the European Cement Association has complemented GCCA's global work by engaging in policy advocacy at the European Union level. While endorsing the European Union Taxonomy and broader Green Deal objectives, CEMBUREAU has worked to ensure technical feasibility, successfully advocating for the inclusion of refuse-derived fuels (RDFs) under the Do No Significant Harm (DNSH) criteria and the differentiated treatment of white cement based on inherent process emissions. (CEMBUREAU, 2020b, 2024b) This case evidences the value of industry input in refining regulatory implementation. At a regional level, industry associations such as **FICEM** (Latin America) and the **Cement Association of Canada** have taken similar leadership roles. The latter released a *Roadmap to Net-Zero Concrete* and is collaborating with the government on policies like clean procurement and updated building codes (Cement Association of Canada, 2023). Regional associations have also been instrumental. For example, **FICEM** in Latin America and the **Cement Association of Canada** have each released roadmaps and engaged in co-design of national procurement frameworks, emissions benchmarks, and sustainable building codes (Cement Association of Canada, 2023). In the global (petro)chemical sector, the **International Council of Chemical Associations**, whose members account for more than 90 percent of global chemical sales, commissioned a report, Pathways for the global chemical industry to climate neutrality, outlining a portfolio of pathways and scenarios to support climate neutrality strategies (ICCA, 2024).

Science-Based Targets and Corporate Leadership

The **Science-Based Targets initiative (SBTi)** has become a key mechanism for translating voluntary climate commitments into measurable emissions pathways. More than 50 cement and concrete producers globally have committed to emissions reductions aligned with scenarios that meet the Paris Agreement temperature goal of holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change; (Science Based Targets, 2025). Notably, *Dalmia Cement* in India has pledged to become carbon negative by 2040, leveraging strategies such as high clinker substitution, renewable electricity, and increased use of alternative fuels.

Likewise, major actors in the steel sector such as H2Green Steel, SSAB, and Salzgitter are demonstrating leadership by launching pilot-scale or commercial green steel production with hydrogen-DRI, backed by corporate net-zero targets (Johnsson et al., 2024). The (petro)chemicals sector is similarly seeing early movers particularly in hydrogen production align with the Green Hydrogen Standard (1 kg CO_2/kg H_2) or national thresholds (e.g., United Kingdom of Great Britain and Northern Ireland: 2.4 kg; India: 2.0 kg), using lifecycle assessment methods to verify emissions performance. Whilst it has been adopted by some members of the chemical sector, challenges associated with implementation have been raised as concerns by the sector in past inputs to the chemical sector guidance, particularly associated with its requirements to phase out fossil fuels and feedstocks by a certain timeframe. Given how integral carbon is to organic chemicals and the

challenges in transitioning to 100% biobased carbon feedstocks, these requirements create a major barrier for adoption.
These corporate commitments help set precedents for ambitious action and serve as peer benchmarks within the sector, challenging the perception that deep decarbonization is not commercially viable.

Innovation through Collaborative Consortia
Several multi-stakeholder research and development partnerships have emerged to de-risk emerging technologies. The **LC3 Consortium**, **Project LEILAC**, and **CLEANKER** exemplify public-private collaboration to advance solutions such as limestone calcined clay cements and direct calcination for carbon capture. For instance, **Heidelberg Materials** piloted the LEILAC system at its plant in Lixhe, Belgium, demonstrating that carbon capture can be integrated into existing infrastructure with minimal disruption (European Commission, 2021a).
This mirrors similar initiatives in the steel sector, where pilot projects like HYBRIT in Sweden and SALCOS in Germany have proven the viability of hydrogen-DRI and electrified steelmaking, supported by European Union Innovation Fund and national investment banks (Gervásio & Da Silva, 2023). In the (petro)chemicals sector, innovation hubs such as the Solatio H2 Piauí and Acelen Renewables Agripark in Brazil are demonstrating clean hydrogen and biofuels production aligned with regulatory standards. These innovation hubs are largely supported by the European Commission, with co-funding from private industry, and provide a replicable model for other regions seeking to scale up technology readiness.

In China, an energy and chemical industry carbon footprint alliance was initiated by eight major energy and chemical enterprises such as China National Petroleum Corporation, China Petrochemical Corporation, China National Offshore Oil, CHN Energy, Sinochem Group Company Limited and others. Through the sharing and cooperation of technologies and experiences among members, this alliance aims to promote precise carbon footprint accounting and application in China's energy and chemical industry chain, as well as to advance international cooperation and mutual recognition. It is planned that by 2027, a product carbon footprint management system will be initially established, and about 20 key product carbon footprint accounting rules and standards will be formed, helping to achieve carbon emission reduction in the industry.

In the United States of America, the **Clean Concrete Pledge Initiative**, a collaboration between RMI, NRDC, and the NRMCA, encourages commitments across procurement, pilot projects, and supplier investment, promoting supply chain transformation through voluntary action (Rocky Mountain Institute, n.d.). Similarly, the ConcreteZero initiative, led by the Climate Group, aggregates demand by bringing together real estate firms and infrastructure developers committed to using 30% low-emission concrete by 2030 (Concrete Group, 2025; UNFCCC Global Climate Action NAZCA, 2025). This buyer-led coalition creates pressure on suppliers to innovate and label their products accordingly. The Product Carbon Footprint standard (PCF) was developed by the industry group Together for Sustainability (Together for Sustainability, 2024), in response to growing regulatory demands and stakeholder expectations**.** Guidance and standards for assessing the carbon intensity and footprint of products already exist, including through the Greenhouse Gas Protocol and ISO frameworks such as

ISO 14067, but there has been limited treatment through these general guidelines of the complexities and multi-output nature of the (petro)chemicals sector. The PCF standard was defined through engagement with chemical firms, suppliers and industry stakeholders to develop a suitable methodology for the (petro)chemicals sector that aligns with international frameworks such as ISO14067 and the Greenhouse Gas Protocol.

The First Movers Coalition has played a similar role in both the steel and (petro)chemicals sectors, using collective purchasing power to de-risk market entry for low-carbon materials (Climate Bonds Initiative, 2020) (World Economic Forum, 2023). Aggregated demand commitments send strong market signals, encouraging suppliers to meet new standards and accelerating commercialization of emerging technologies.

Finally, the **Industrial Transition Accelerator (ITA)** has recently emerged to support high-ambition pilot projects. While still new, ITA is expected to help catalyze cement decarbonization in developing regions by connecting capital, policy, and technical know-how, helping overcome the "first-of-a-kind" financing and demonstration barriers (Industrial Transition Accelerator, 2024).

Lessons from Industry Initiatives

The following cross-cutting lessons emerge from these industry-led efforts:

- Pre-competitive collaboration is essential for building shared technical foundations and harmonized tools (e.g., EPD and MRV systems).
- Corporate leadership through net-zero commitments and investment in pilots accelerates credibility and readiness for regulation.
- Strategic advocacy ensures that emerging regulations remain technically feasible and economically viable.
- Aggregated demand signals from public and private buyers can accelerate innovation and bring low-carbon products to scale.

These dynamics are evident across steel and (petro)chemicals sectors, where voluntary initiatives like SBTi, ResponsibleSteel™, and the Green Hydrogen Standard have rapidly evolved from pilot to policy-relevant standards. However, voluntary efforts alone are insufficient to drive sectoral transformation. Their effectiveness ultimately depends on alignment with public policy, harmonized standards, and supportive regulatory frameworks.

4.3 Role of technology tools and digital MRV in implementing standards and labels

Robust Measurement, Reporting, and Verification (MRV) are essential for the effective implementation of low-carbon standards, and digital tools have emerged as enablers.

Digital monitoring and automation at plant level

Modern industrial facilities are increasingly adopting Industry 4.0 technologies, integrating sensors, automated control systems, and cloud-based platforms to monitor carbon-related metrics in real time.

These systems track variables such as fuel mix, kiln temperature, CO_2 concentrations, and electricity consumption, feeding directly into GHG accounting frameworks like ISO 19694 and the GHG Protocol. In China, for example, major cement producers use centralized digital dashboards to aggregate emissions data from multiple plants, supporting compliance with emerging national emissions trading requirements (UNFCCC TEC & UNIDO, 2023). Such automation reduces reporting burdens, improves accuracy, and facilitates continuous compliance with evolving carbon thresholds whilst holding the potential to identify cost savings from inefficiencies and energy losses. In the steel sector, similar advancements are occurring, with digital MRV tools enabling automation of emissions tracking through smart sensors, AI-based analytics, and satellite imaging to support facility-level oversight (World Bank, 2022). Automation is necessary for legacy blast furnace facilities, where energy flows and emissions need continuous optimization (Gervásio & Da Silva, 2023). In the (petro)chemicals sector, digital MRV is helping address the complexity of multi-output processes by enabling high-resolution lifecycle assessments and real-time GHG data collection across large industrial facilities (Together for Sustainability, 2024). Complementing these efforts, public tools like EC3 (Embodied Carbon in Construction Calculator) allow procurement teams to filter cement and concrete products by verified GWP, making carbon performance a visible and actionable metric in project-level decision-making. The widespread availability of such tools enhances transparency, competitiveness, and alignment with policy instruments like Buy Clean and green public procurement (GPP).

Environmental product declarations (EPDs) and lifecycle software

Digital tools have streamlined the generation of Environmental Product Declarations. Software platforms like OneClick LCA, SimaPro, and the open-source openLCA allow manufacturers to conduct life cycle assessments (LCA) using preloaded databases tailored to the cement and concrete sectors (OneClickLCA, 2024). The GCCA's EPD Tool exemplifies this trend, offering standardized modules, default datasets, and automated reporting aligned with EN 15804 and ISO 14025 requirements (GCCA, 2023). In the United States of America, the National Ready Mixed Concrete Association (NRMCA) provides a digital platform that links mix designs to EPD generation, supporting wider adoption of low-carbon concrete in procurement. Complementing these efforts, public tools like EC3 (Embodied Carbon in Construction Calculator) allow procurement teams to filter cement and concrete products by verified GWP, making carbon performance a visible and actionable metric in project-level decision-making. The widespread availability of such tools enhances transparency, competitiveness, and alignment with policy instruments like Buy Clean and green public procurement (GPP). Steel manufacturers have begun adopting similar tools to support transparent product disclosures. For instance, the Buy Clean Initiative in the United States of America includes benchmarks for steel and mandates EPDs as prerequisites for procurement eligibility, although was recently defunded by the new Administration. Voluntary certifications such as ResponsibleSteel™ also incorporate lifecycle assessment data as part of their third-party verification requirements. The (petro)chemicals sector uses the Product Carbon Footprint Guideline and ISO 14067 standards to facilitate EPD generation for products like hydrogen, ammonia, and methanol, supported by platforms such as the Greenhouse Gas Protocol Product Standard.

Digitalization and data integrity in MRV

Distributed ledger technologies (e.g., blockchains) are being explored to enhance traceability and prevent data manipulation in emissions reporting. The WBCSD-led Project Carbon Transparency has piloted blockchain applications that assign digital tokens to construction materials including cement with verified CO_2 footprints across the supply chain (WBCSD, 2002). By integrating EPD data with QR codes or unique identifiers, cement shipments can be tracked from factory to construction site, enabling tamper-proof verification and future integration with digital product passports. Similar use cases have emerged in the steel sector, where blockchain tools are being explored to trace low-carbon steel across the supply chain and enhance MRV compliance under mechanisms like the CBAM and Article 6 of the Paris Agreement (World Bank, 2022). In the (petro)chemicals sector, several voluntary standards (e.g., CertifHy for hydrogen) use unique digital identifiers to ensure traceability across borders, promoting mutual recognition of certification (European Partnership, 2019).

Geospatial and AI-Powered Verification

To support external verification and enforcement, satellite imagery and artificial intelligence (AI) are being trialed to detect clinker production volumes, emissions hotspots, and facility-level anomalies. While not a substitute for direct measurement, geospatial analysis offers an additional layer of oversight particularly valuable in jurisdictions with limited MRV capacity. These tools can cross-reference reported output against observed activity, flagging discrepancies for further review by regulators. In steelmaking, AI and satellite data have been used to monitor fugitive emissions and verify production throughput in regions with limited on-site reporting infrastructure (World Bank, 2022). The chemical sector's use of geospatial overlays remains limited but has potential for monitoring distributed hydrogen or biofuel production sites, particularly in areas lacking strong national MRV systems.

Digital MRV in Policy Platforms

International initiatives such as the Industrial Deep Decarbonization Initiative (IDDI) are embedding digital MRV into their toolkits. The forthcoming IDDI Green Public Procurement (GPP) Toolkit will include web-based calculators, default emission factors, and reference benchmarks that national governments can customize for local conditions.(UNFCCC TEC & UNIDO, 2023) Similarly, the UNFCCC's Climate Action Data Trust is creating a global metadata registry for carbon tracking, potentially expandable to include product-level certificates for low-carbon cement. Steel sector policies such as the European Union CBAM and United States of America Buy Clean require robust MRV tools to validate embedded emissions in imported and domestically produced steel (Zhao et al., 2024). Similarly, in the chemical sector, carbon intensity thresholds for hydrogen production such as those under the United States of America 45V tax credit are tied to precise, digitally verified emissions data to determine incentive eligibility (US DOE, 2023).

Integration with Building Information Modeling (BIM)

As Building Information Modeling becomes standard practice in the construction sector, cement and concrete products with digitally accessible EPDs can automatically contribute to building-level embodied carbon calculations. Some producers now embed QR codes linking to digital EPDs, enabling seamless integration into BIM software and facilitating compliance with whole-building carbon caps, such as France’s RE2020. Similar BIM-integrated pathways are emerging in the steel industry, where structural steel elements with verified carbon footprints are being incorporated into lifecycle carbon calculations at the design stage (Gervásio & Da Silva, 2023). Though less mature in the (petro)chemicals sector, efforts are underway to embed verified carbon data into digital product passports for construction-related chemicals and adhesives, particularly in European Union markets.

4.4 High-impact initiatives and project examples

Demonstration projects validate emerging technologies and building market confidence.

Baosteel's **Zhanjiang Steel Plant (China): Near-Zero-Carbon Steel Production Line**

On December 23, 2025, the first one million-tonne-level near-zero-carbon steel production line of Baosteel's Zhanjiang Steel Plant was fully connected. The near-zero carbon production line mainly uses "hydrogen-based vertical furnace direct reduction iron + scrap steel" as its raw materials to produce low-carbon emission billets. It utilizes the existing steel rolling facilities to produce low-carbon and near-zero carbon steel products, forming a complete low-carbon metallurgical process flow of "hydrogen-based vertical furnace reduction - efficient electric furnace smelting - low-carbon rolling production". Compared with the traditional BF-BOF process technology of the same production scale, this project is expected to achieve a carbon reduction of 50% - 80% and can reduce carbon dioxide emissions by over 3.14 million tons per year at the maximum.

Solid waste-based low-carbon SCMs: Many enterprises in China have already established mature production lines

Solid waste-based low-carbon SCMs are water-hardening cementitious materials made by grinding and processing steel slag, granulated blast furnace slag, and industrial by-product gypsum as the main raw materials, and one or several types of industrial solid wastes such as fly ash, red mud, metal tailings, silicon-manganese alloy slag, copper slag, and alkali slag as auxiliary raw materials. According to calculations, the CO_2 emissions for producing one ton of solid waste-based low-carbon SCMs are approximately 75 kg. Compared to ordinary portland cement, the CO2 emissions are reduced by approximately 87%. Currently, the solid waste-based low-carbon SCMs industry in China has reached an annual production capacity of over 15 million tons. A lot of production lines have been established in Shanxi, Hebei, Jiangsu, and Shandong. The products are applied in ready-mixed concrete, mortar, and mining filling fields.

Norcem (Norway): Full-Scale Carbon Capture Integration

At its Brevik plant, Norcem is installing a commercial-scale carbon capture and storage (CCS) system projected to capture approximately 400,000 tonnes of CO_2 annually, equating to nearly 50% of the plant’s process emissions. This flagship project, supported by Norway’s Longship CCS program and the European Union, demonstrates the technical viability of CCS in the cement sector. The captured CO_2 will be transported and stored through the Northern Lights infrastructure, enabling near-zero emissions cement production. Norcem’s product though compositionally similar to conventional CEM I/CEM II could qualify under international near-zero labels once operational, with estimated emissions potentially as low as 100–200 kg CO_2/t cement. The project exemplifies the importance of strong public co-financing and cross-industry collaboration for scaling hard-to-abate technologies (IEA, 2023d; UNFCCC TEC & UNIDO, 2023). CCS has also emerged as a cornerstone technology in the steel sector, with similar-scale pilots funded through the European Union Innovation Fund. Projects in France and Germany have demonstrated integration of CCS with blast furnace retrofits, and in Brazil, low-carbon hydrogen production is being piloted alongside CO_2 sequestration as part of the Acelen Renewables Agripark (Gervásio & Da Silva, 2023) (Lira, n.d.)

Limestone Calcined Clay Cement (LC3): Pilots in Cuba and India

LC3–a clinker-reducing blend of 50% clinker, 30% calcined clay, 15% limestone, and 5% gypsum offers up to 40% CO_2 emissions reduction. Supported by the Swiss government, the LC3 Consortium piloted LC3 production in Cuba and India, validating technical performance in housing and infrastructure projects. Following pilot success, national standards in Cuba and India were updated to include LC3, and companies like Ultratech and JK Lakshmi Cement are now scaling production. The LC3 example shows how coordinated R&D, public-private partnerships, and regulatory inclusion can rapidly accelerate adoption of novel cements in emerging economies (UNFCCC TEC & UNIDO, 2023).

Solidia Cement and CO_2 Curing (United States of America)

Solidia Technologies has developed a novel binder with lower limestone content and kiln temperatures, combined with CO_2-curing for precast concrete. This integrated approach achieves CO_2 reductions of up to 70%. Commercial pilots in the United States of America precast industry, backed by United States of America DOE support, demonstrate the feasibility of combining binder innovation with carbon utilization. Solidia's model is especially promising for cement–concrete product ecosystems where early-age strength and modular curing conditions are advantageous.

High-Profile Construction Applications

Flagship infrastructure and commercial projects are increasingly adopting low-carbon concrete mixes. The United Kingdom of Great Britain and Northern Ireland's HS2 high-speed rail project, for instance, uses alkali-activated concrete in tunnel segments, achieving 50% CO_2 reductions. Similarly, Microsoft and Google campuses have integrated low-carbon concrete into their builds, contributing to green building certifications and demonstrating large-scale viability. These examples help mainstream low-emission materials by proving performance under demanding conditions.

HYBRIT (Sweden): Fossil-Free Steel via Green Hydrogen

The HYBRIT (Hydrogen Breakthrough Ironmaking Technology) project is a world-first initiative replacing coking coal with renewable hydrogen in the direct reduction of iron ore. A pilot plant has already produced steel with a carbon intensity close to zero, used by Volvo to manufacture a prototype vehicle. The project is supported by SSAB, LKAB, and Vattenfall, with backing from the Swedish Energy Agency.
Emission reduction: Up to 90–95% compared to BF-BOF route.
Significance: First commercial-scale deployment is planned for 2026. (Johnsson et al., 2024)

H2Green Steel (Sweden): Commercial-Scale Hydrogen-DRI

H2Green Steel is building a greenfield facility in northern Sweden to produce 5 million tonnes of near-zero emissions steel annually by 2030. The plant integrates on-site renewable electricity with hydrogen-based DRI and EAF processes.

Emission reduction: 95% compared to conventional steel.
Backers: Supported by large-scale public and private capital, including the European Union Innovation Fund (Johnsson et al., 2024).

SALCOS (Germany): Industrial Retrofit to Green Hydrogen

The SALCOS (Salzgitter Low CO_2 Steelmaking) initiative retrofits existing blast furnace operations by switching to hydrogen-based DRI and EAF. A phased transition is already underway, backed by German federal support and private investment.
Emission reduction: From 2.3 to ~0.4 tCO_2/t steel.
Innovation: Integrates existing infrastructure with hydrogen retrofitting.(Gervásio & Da Silva, 2023)

First Movers Coalition: Demand Aggregation by Leading Buyers

Ford, Volvo, and other members of the First Movers Coalition have committed to procuring steel with <0.4 tCO_2/t by 2030. This demand aggregation sends a strong signal to producers, catalysing innovation and investment across supply chains.
Significance: Creates early markets to de-risk investment in green steel.
(World Economic Forum, 2023)

Solatio H2 Piauí (Brazil): 3 GW Green Hydrogen and Ammonia

This ITA-supported project combines 3 GW of renewable energy capacity with large-scale electrolysis to produce green hydrogen and ammonia for industrial and export use.
Impact: Will qualify under Brazil's 7.0 kg CO_2/kg H_2 threshold and future export standards (e.g., European Union's 3.4 kg CO_2/kg H_2) (UNFCCC TEC & UNIDO, 2023) (Lira, n.d.)

Acelen Renewables Agripark (Brazil): Advanced Biofuels from Macauba Oil

This integrated biorefinery uses native macauba oil to produce low-carbon fuels and bio-based chemicals. The project aligns with Brazil's RenovaBio scheme and includes full lifecycle carbon intensity accounting.
Emission reduction: Up to 80% vs fossil fuels. (Ministry of Mines and Energy, 2021)

Green Hydrogen Standards: Global Benchmarking of Clean Hydrogen

Countries have established thresholds ranging from 0.6 kg CO_2/kg H_2 (Australia) to 4.0 kg (United States of America) and 7.0 kg (Brazil).
Key reference: The Global Green Hydrogen Standard sets a voluntary benchmark at 1.0 kg CO_2/kg H_2 with 100% renewable power. *(GH2, 2022; US DOE, 2023; Australian Government, 2025)*

CertifHy and PCF Standards

The **CertifHy** scheme in Europe and the **Product Carbon Footprint (PCF)** Guideline from the Together for Sustainability coalition enable voluntary certification for low-carbon chemical products. **Use case:** CertifHy labels "green" and "low-carbon" hydrogen with traceability, while PCF enables cradle-to-gate lifecycle reporting for downstream products (European Partnership, 2019). (Together for Sustainability, 2024)

Low-Carbon Fuel Standards: California, European Union, Brazil

- **California's LCFS** mandates a 20% carbon intensity reduction by 2030, creating a tradable credit system.
- **European Union RED III** requires >80% emissions savings for new installations producing RFNBOs.
- **Brazil's RenovaBio** links biofuel certification to a national decarbonization credit market.

ITA-Aligned and Future Projects

The **Industrial Transition Accelerator (ITA)**, launched at COP28, aims to de-risk and accelerate investment in first-of-a-kind decarbonization projects in heavy industry. While specific cement projects are still under development, ITA is expected to play a catalytic role facilitating low-carbon certification schemes, MRV infrastructure, and demonstration projects in emerging markets. Potential projects could include biomass-based fuel switching in Latin America or digital MRV integration in African cement plants, supported by concessional finance and capacity building (UNFCCC TEC & UNIDO, 2023). In the steel sector, ITA-supported projects are expected to focus on hydrogen retrofitting and green steel trade routes, particularly in India, Brazil, and Africa (Zhao et al., 2024). The (petro)chemicals sector may benefit from ITA-aligned work on lifecycle MRV for hydrogen, helping countries qualify for trade under global emissions thresholds like those set in the European Union Taxonomy or United States of America 45V credit (European Partnership, 2019).

5. Guidance to Harmonize Standards and Labels

Achieving global net-zero emissions will require a harmonized approach to standards and policy. This section outlines pathways to better align these efforts, following an initial discussion of key material carbon accounting rules and guidelines that have emerged from the range of standards inventories in this work.

Key Carbon Accounting Rules for Energy Intensive Industries

Boundary and scope: Use a consistent cradle-to-gate (A1-A3) boundary in alignment with ISO and EN standards to ensure comparability, with third-party verified EPDs to improve confidence in carbon intensity reporting

Inputs: Disclose all key inputs and corresponding emissions factors, prioritising use of vender-specific data over standard emissions factors. Disclose the electricity emissions factors in gCo2/kWh and the corresponding year to increase transparency.

Transparency and thresholds: Apply clear carbon intensity thresholds and encourage full disclosure of data to enable fair comparisons and improve confidence.

Steel guidance: Clearly state the production route, the scrap share, hydrogen source and the percentage of renewable electricity to distinguish low-carbon steel pathways. Apply transparent scrap accounting methods to reflect carbon impacts.

Cement guidance: Report the clinker ratio, types and shares of supplementary cementitious materials (SCMs) and apply a harmonized SCM allocation approach which aligns with relevant standards (e.g., EN15804) to avoid inconsistent accounting. Ensure that all assessments for cement plants algin with ISO 19694-3

Petrochemicals guidance: Ensure feedstocks meet corresponding thresholds and treat contract manufactured products like trading goods or any other purchased raw materials. Follow corresponding guidance for accounting for biogenic emissions and removals.

CCUS and NETs: Report both the amount of CO2 captured, minimum capture rates and the net amount stored, utilized or removed, with information on storage permanence and crediting approaches to ensure integrity of emissions claims.

Sector Applicability: Account for the complexity and diversity inherent in manufacturing subsectors, products, and supply chains when seeking to “standardize” methods and metrics or comparing different products or chemistries.

5.1 Enabling policies, financing models and incentive structures

A robust enabling environment is essential to transition the hard-to-abate sectors from voluntary action to systemic change. Here, this section provides a summary of the enabling policies and pathways for decarbonization of each subsector, highlighting the key mechanisms, objectives and considerations for implementation.

Cement Sector - Guidance to Harmonize Standards and Labels

Table 11 Summary of Enabling Policies and Pathways for Cement Decarbonization

Policy Pathway	Key Mechanisms & Actions	Objective & Rationale	Implementation Notes & Examples
Demand-Side Policies	**Green Public Procurement (GPP):** Adopt policies that mandate the use of low-carbon cement in public projects.	Creates durable market signals and aggregates demand for compliant products.	A phased approach is recommended, starting with mandatory EPD disclosure and evolving to performance-based limits. Initiatives like the IDDI provide guidance for governments.
	Clean Product Standards: Implement regulatory limits on the carbon intensity of cement sold in the market, with thresholds that tighten over time.	Establishes a level playing field for all producers and drives industry-wide innovation beyond public projects.	Harmonizing the methodology internationally can improve trade frictions.
Economic Instruments	**Carbon Pricing:** Establish or strengthen carbon pricing mechanisms (e.g., Emissions Trading Systems, carbon taxes) for the industrial sector.	Internalizes the cost of emissions, making low-carbon production more cost-competitive.	The European Union's ETS demonstrates how phasing out free allowances can force investment in abatement.
	Carbon Border Adjustment Mechanisms (CBAMs): Implement or coordinate with border adjustment mechanisms to price the carbon content of imported cement.	Prevents "carbon leakage" and protects domestic industries while encouraging global uptake of standards.	Requires international coordination on metrics for calculating embedded emissions. The Climate Club could be a platform for this alignment.
Financial & Investment Support	**Financial De-risking:** Offer concessional loans, guarantees, and results-based finance tied to verifiable emissions reductions.	Lowers the cost of capital and addresses the high upfront cost of deep decarbonization technologies, unlocking private investment.	De-risking: Models should prioritize support for SME upgrades and regional MRV infrastructure.

	Targeted Subsidies & Tax Incentives: Provide instruments like production tax credits for CO_2 reduction or Carbon Contracts for Difference (CCfDs).	Guarantees a return on investment for expensive, first-of-a-kind projects like CCUS, ensuring a viable business case.	Incentives: The Industrial Transition Accelerator (ITA) can help package financing models with technical assistance.
	Innovation & R&D Funding: Co-fund pilot plants and demonstration projects for breakthrough technologies.	Accelerates the research and development as well as engineering verification of raw material substitution, clinker substitution and new types of cementitious materials.	R&D: Should be technology-neutral and aligned with forward-compatible performance benchmarks to avoid "technology lock-in"
International Standardization & Cooperation	**Mutual Recognition of Standards:** Adopt policies that mutually recognize credible standards and labels developed with internationally harmonized principles.	Reduces duplicative compliance burdens, lowers costs for producers, and facilitates access to global markets.	Recognition: The G7 Climate Club is a key forum for exploring this approach to reduce trade friction.
	Harmonization via Standards Bodies: Utilize international bodies like ISO and CEN to develop unified standards, such as a Publicly Available Specification (PAS) for "near-zero cement".	Creates a global reference for certification and guides the development of consistent national standards and policies.	Harmonization: The process should be guided by principles from the UNFCCC and could result in an "International Code of Conduct" that members pledge to adopt into domestic policy.
Foundational Enablers (Capacity & Infrastructure)	**Digital MRV Infrastructure:** Mandate digital reporting for EPDs and invest in open-access data platforms and automated EPD generators.	Reduces compliance costs, enhances data transparency and traceability, and enables scalable and trusted carbon labelling.	Lessons from the United States of America EPA and Dutch DuboCalc system show that digitization reduces administrative burdens.
	Capacity Building & Technical Assistance: Provide tailored training and financial support for SMEs and developing countries.	Ensures a just and inclusive transition, lowers entry barriers for compliance, and builds the local expertise needed to implement and enforce standards.	Support can include regional verification hubs, standardized EPD templates, and open-source calculation tools to level the playing field.
Integration into National Climate Strategy	**Alignment Cement Targets with National Climate Strategy:** Include specific, quantitative targets for cement sector decarbonization	Elevates cement decarbonization to a national priority and ensures actions are tracked as part of a country's official climate commitments.	Including sectoral targets can help mobilize international climate finance and technical support.
	Map Pathways in Alignment with LT-LEDS: Use Long-Term Low-Emission Development Strategies to outline a phased transition to 2050, including milestones for standards adoption.	Provides a clear, long-term signal to industry and investors, guiding industrial policy, infrastructure planning, and investment decisions.	Strategies should be aligned with global benchmarks (e.g., IEA/GCCA values) to promote international coherence.

Key Messages for Cement Harmonisation:

1. Public procurement as a market lever: Align public procurement with harmonized carbon intensity thresholds (UNFCCC TEC & UNIDO, 2023). Where applicable, procurement specifications should recognise verifiable CCS/CCUS and CDR contributions under robust MRV and permanence rules to avoid double counting.

2. Financial de-risking and green label incentives: Use concessional loans, guarantees, tax incentives and results-based payments to scale certified low-carbon cement (UNFCCC TEC & UNIDO, 2024). Financing windows should explicitly accommodate CCS/CCUS (capture–transport–storage) and eligible CDR pathways with clear eligibility, additionality, durability and liability criteria. Taxonomies can also serve as key frameworks to guide financial flows, and tools like the OECD & Climate Club's Financial Toolkit provide a comprehensive overview of de-risking and financial instruments to support such efforts (OECD, 2024).

3. Technology-Neutral subsidies and innovation grants: Investment in breakthrough technologies such as CCUS, and digital MRV systems through innovation funds and public-private consortia. Funding and standards should reference forward-compatible definitions of "low-carbon" or "near-zero" cement, and allow CDR-enabling routes where they meet agreed accounting and permanence thresholds, thereby avoiding a "technology lock-in" (GCCA, 2021b).

4. Recognition and mutual acceptance of standards: Advance mutual recognition of cement standards and labels developed using internationally harmonised principles (e.g., ISO, EN 15804 alignment) and ensure convergence on CCS/CDR accounting (system boundaries, permanence, chain-of-custody). This reduces duplicative audits and facilitates cross-border market access.

5. Digital infrastructure and transparency tools: Consider applying machine-readable EPDs and digitized disclosures to enable automated MRV and benchmark tracking across markets (e.g., EC3, One Click LCA). For products claiming CCS/CCUS or CDR benefits, digital systems should capture capture-rate data, transport/storage verification, mineralisation process data, uncertainty, additionality and durability to maintain integrity and interoperability. Digitization can reduce administrative burdens and enhances compliance integrity (CEMBUREAU, 2024a).

Steel Sector – Guidance to Harmonize Standards and Labels

Table 12 Summary of Enabling Policies and Pathways for Steel Decarbonization

Policy Pathway	Key Mechanisms & Actions	Objective & Rationale	Implementation Notes & Examples
Demand-Side Policies	Green procurement, minimum recycled content, Buy Clean mandates	Create guaranteed demand for green steel	United States of America Buy Clean; FMC procurement targets (The White House, 2024; ResponsibleSteel, 2023)

Economic Instruments	Carbon pricing, CBAM, steel-specific tax credits	Make green steel competitive with BF-BOF processes	CBAM pressures on Chinese exports (Zhao et al., 2024)
Financial & Investment Support	Public-private partnerships, hydrogen subsidies, CfDs	De-risk hydrogen DRI, retrofits, CCS	European Union Innovation Fund; German SALCOS program (Johnsson et al., 2024)
International Standardization	Harmonized carbon intensity thresholds, MRV alignment	Facilitate cross-border trade, avoid leakage	EN-based benchmarks, ISO 19694, G7 coordination (Vogl et al., 2018; Wesseling et al., 2017)
Foundational Enablers	Digital MRV (smart sensors, AI), certification systems	Ensure data integrity and comparability	Blockchain, EPD platforms, pilot digital MRVs (WORLD BANK, 2022; Gervásio & da Silva, 2023)
Alignment Targets and Action with National Climate Strategy	Include steel-specific targets, technology roadmaps	Align national priorities with global steel decarbonization goals	PAT mechanism in India; LT-LEDS with hydrogen transition paths (Algers & Åhman, 2024)

Key Messages for Steel Harmonization:

1. Green Procurement as a Driver: Harmonized performance-based thresholds should be tied to public infrastructure tenders (e.g., 0.4 tCO_2/t steel), as pioneered by First Movers Coalition commitments (ResponsibleSteel, 2023).
2. Hydrogen Subsidy Alignment: Consistent support for green hydrogen is required; the United States of America 45V tax credit (USD 3/kg for <2.0 kg CO_2/kg H_2) must align with European Union and Japanese subsidy frameworks (US DOE, 2023; European Commission, 2023).
3. MRV System Convergence: Digital MRV systems must allow automated benchmarking and verification to support cross-border compliance and CBAM calculations (WORLD BANK, 2022).
4. International Standards Convergence: Harmonize definitions of "near-zero steel" (e.g., <0.4 tCO_2/t steel) using ISO and IEA values to guide global recognition.
5. Capacity Building for Emerging Markets: Targeted support for MRV implementation and verification infrastructure is needed in countries like India, Brazil, and South Africa.

(Petro)Chemicals Sector – Guidance to Harmonize Standards and Labels

Table 13 Summary of Enabling Policies and Pathways for the (Petro)Chemicals Sector

Policy Pathway	Key Mechanisms & Actions	Objective & Rationale	Implementation Notes & Examples
Demand-Side Policies	Low-carbon product labels, fuel blend mandates	Drive demand for verified clean hydrogen, ammonia, methanol	United Kingdom of Great Britain and Northern Ireland RTFO, California LCFS (Department for Transport, 2013; California Air Resources Board, 2018)
Economic Instruments	Tax credits, feed-in tariffs for RFNBOs	Reduce cost gap between conventional and low-emission products	United States of America 45V (Clean Hydrogen Standard); Canada and India follow suit (US DOE, 2023; MNRE, 2023)

Financial & Investment Support	Hydrogen hubs, concessional project finance, carbon credit access	De-risk large-scale projects like green hydrogen and advanced biofuels	ITA-aligned Brazilian projects (Lira, 2024; UNFCCC, 2023), Climate Bonds Certification program for basic chemicals
International Standardization	Harmonized CI thresholds for hydrogen and fuels	Enable trade and recognition across jurisdictions	GH2 Standard, CertifHy, ISO 14067 alignment (GH2, 2022; Clean Hydrogen Partnership, 2019)
Foundational Enablers	Digital lifecycle tools, voluntary MRV platforms	Strengthen credibility, build trust across complex value chains	PCF Standard, GHG Protocol Product Standard (Together for Sustainability, 2024; WRI, 2010)
Alignment Targets and Action with National Climate Strategy	Include emissions targets for hydrogen, ammonia, methanol	Guide policy development and attract blended finance	

Key Messages for (Petro)Chemicals Harmonization:

1. Harmonize Hydrogen Standards: Align national benchmarks (e.g., European Union: 3.4 kg CO_2/kg H_2, United States of America: 4.0 kg, India: 2.0 kg) with trade-driven thresholds and lifecycle boundaries (GH2, 2022; MNRE, 2023).
2. Fuel Standards and Market Access: Integrate RED III, LCFS, and RTFO policies into unified emissions intensity scoring systems to facilitate international fuel trade (European Commission, 2023).
3. Digital MRV and PCF Expansion: Promote PCF tools like openLCA and ISO-aligned templates for all key product groups not just hydrogen to build out harmonized certification schemes (Together for Sustainability, 2024).
4. Link to Global Registries: Connect national tracking systems to UNFCCC's Climate Action Data Trust for cross-verification and data interoperability (UNFCCC, 2023).
5. Technical Assistance for SMEs: Funding and training are needed to onboard small producers into MRV platforms and help them access finance for clean technology upgrades.
6. Engage petrochemicals industry on rational and pragmatic approaches to design/implement product-level carbon intensity standards and prioritization of product chemistries
7. Adopt well-designed science-based carbon emissions accounting frameworks at the product level that reflects the complexities and variability of energy, feedstock, and manufacturing technology inputs and co-processes
8. Complex products, processes, and value chains: Account for the complexity and diversity inherent in manufacturing subsectors, products, and supply chains, and recognize unique role of carbon-based feedstocks
9. Design for success: Utilize science-based PCA methods and data verification processes that are unbiased, cost-effective, reliable, practicable, and scalable to diverse regulated entities and value chains
10. Promote like-to-like comparisons: Product carbon accounting metrics should not be used to compare chemistries, materials, or products with inherently different characteristics, even if contained in a specific category (e.g., Trade Codes)

6. Recommendations and Conclusion

6.1 Summary of key findings

1. Convergence Around Carbon Intensity Thresholds

There is growing alignment across sectors on two-tier frameworks for defining "low-carbon" and "near-zero" products:

- Cement initiatives are converging on benchmarks such as ≤0.5 tCO_2/t for low-carbon cement and ≤0.2 tCO_2/t for near-zero products.
- Steel initiatives like ResponsibleSteel™ and First Movers Coalition target ≤0.4 tCO_2/t for near-zero steel, with low-carbon steel defined
- Hydrogen benchmarks in the (petro)chemicals sector range from 1.0 kg CO_2/kg H_2 (ultra-low carbon) to 3–4 kg CO_2/kg H_2 (low-carbon), shaping both regulatory and voluntary standards (GH2, 2022; US DOE, 2023).
- It is too early to tell what benchmarks may emerge for other specific chemistries, but the diversity and variability of individual chemicals may reduce the utility of category-wide benchmarks as used in other industries.

2. Transparency Tools Are Underutilized and Disconnected from Policy

Environmental Product Declarations (EPDs), Product Carbon Footprints (PCFs), and lifecycle based MRV systems are expanding, but their uptake remains uneven and often decoupled from regulatory or procurement enforcement:

- In cement, EPDs are common but rarely mandated in public procurement outside of select jurisdictions (e.g., Netherlands, California).
- Steel producers are adopting EPDs and third-party certification (e.g., ResponsibleSteel™), but harmonization is lacking across national schemes.
- In the (petro)chemicals sector, lifecycle tools like ISO 14067 and the GHG Protocol Product Standard exist but are not yet tied to performance thresholds or trade compliance.

3. Persistent Barriers Undermine Standard Uptake and Scale

All three sectors face similar systemic barriers:

- **Policy Gaps:** Lack sector-specific emissions targets or technology pathways, limiting clarity for investment and implementation.
- **Fragmented Standards:** A lack of globally harmonized definitions and methodologies impedes mutual recognition, trade, and certification.

- **High Costs and Infrastructure Gaps:** First-of-a-kind technologies like hydrogen-DRI steel, CCUS for cement, or green hydrogen plants face long payback periods and infrastructure bottlenecks.
- **Limited Access to Finance and Capacity:** SMEs, especially in emerging markets, struggle to meet compliance standards or access MRV tools, raising concerns around equity and inclusion.

4. Phased, Policy-Linked Approaches Are Effective

Case studies across all three sectors demonstrate that **sequenced regulatory strategies** starting with transparency and progressing to performance mandates are essential for sectoral transformation:

- California's Buy Clean for cement and steel, and India's PAT scheme for cement and steel, began with disclosure requirements before tightening thresholds.
- In (petro)chemicals, hydrogen standards have evolved from voluntary frameworks (e.g., CertifHy) to binding tax credit thresholds (e.g., 45V in the United States of America).
- Public procurement has proven to be a powerful demand lever in all sectors, especially when aligned with EPD-based eligibility rules and embedded GWP caps.

Such stepwise policy architecture allows time for stakeholder learning and infrastructure development while sending consistent market signals.

5. Digital Infrastructure and MRV Systems Are Foundational

Robust, interoperable digital MRV platforms are necessary for enforcement, comparability, and unlocking finance:

- In cement and steel, platforms like EC3 and One Click LCA support product-level benchmarking for procurement decisions.
- In (petro)chemicals, blockchain-based tracking, CertifHy digital certificates, and lifecycle inventory tools (e.g., openLCA) are enabling real-time verification of clean hydrogen and biofuels.
- Governments must scale digital systems for EPD generation, embed unique product identifiers, and ensure integration with procurement and climate tracking systems (e.g., UNFCCC Climate Action Data Trust).

6. International Recognition and Mutual Standards Acceptance Are Crucial

To avoid trade frictions, audit fatigue, and market fragmentation:

- Standards and labels must be mutually recognized across jurisdictions e.g., if a product meets EN 15804 or ISO thresholds in one region, it should be accepted in others.

- Forums like the G7 Climate Club, ISO, and UNFCCC can enable shared methodologies, international codes of conduct, and pilot cross-border certification schemes.
- Sectoral standardization through bodies like GCCA (cement), ResponsibleSteel™, and CertifHy (chemicals) provides a platform for aligning industry and policy.

7. Access to reliable data and representative carbon intensity methodologies is essential

Without reliable, comparable data and agreement on fit-for-purpose and administratively workable product carbon accounting methodology design, it will be difficult to expand the range of chemicals covered by reliable, comparable standards. Relevant considerations include:

- Attribution of emissions in complex processes with multiple production routes, co-processes, and co-products
- Tracking and comparing variable value chains
- Barriers to data access and transparency, including lack of custody over data, data collection and disclosure policies, and practical constraints
- Verifying and recognizing reductions or removals across all low-carbon pathways, allowing for diverse fuel, feedstock, and process technologies
- The inherent differences in carbon content and emissions characteristics based on composition and structure

6.2. Policy and industry recommendations

A set of coordinated actions is required from all key stakeholders to accelerate the transition to low- and near-zero emission cement and steel production. While sector-specific technologies and timelines differ, policy frameworks, finance mechanisms, and digital infrastructure needs are largely shared and mutually reinforcing.

Table 14 Key Recommendations for Accelerating Low-Carbon Standards – Cement, Steel, and (Petro)Chemicals

Stakeholder Groups	Short-Term Recommendations (1–3 Years)	Medium-Term Recommendations (3–5+ Years)
1. National Policymakers & Regulators	Cement: Launch GPP pilot programs requiring EPDs. Steel: Expand Buy Clean mandates with emissions benchmarks (The White House, 2024). (Petro)chemicals: Define low-carbon thresholds for hydrogen and fuels once the application scenarios for zero- and low-carbon hydrogen industries become clear (MNRE, 2023; US DOE, 2023).	Cement: Mandate performance-based codes; introduce CBAM-linked policies. Steel: Phase out free allowances; align targets and action with national climate strategy (Zhao et al., 2024). (Petro)chemicals: Align hydrogen/ammonia targets with national climate strategies (European Commission, 2023).
	Cement: Establish task forces for standards development. Steel: Align sector roadmaps with industrial strategies. (Petro)chemicals: Establish national definitions and certification schemes for hydrogen and RFNBOs.	Cement: Implement carbon pricing mechanisms. Steel: Link emissions targets to procurement and trade.

		(Petro)chemicals: Create integrated sectoral pathways in climate policy frameworks, including methanol and ammonia.
2. Industry Associations & Producers	Cement: Harmonize PCRs for EPDs; adopt digital LCA tools. Steel: Align ResponsibleSteel™ and EPD systems with ISO standards. (Petro)chemicals: Adopt and promote voluntary CI standards (e.g., CertifHy, PCF); engage in mutual recognition efforts (Together for Sustainability, 2024).	Cement: Scale up SCM deployment. Steel: Co-invest in H_2-DRI, CCUS, and clean electricity. (Petro)chemicals: Co-develop carbon intensity tracking tools and system boundaries for complex feedstock chains. Strengthen the construction of product carbon footprint standards and carbon footprint factor libraries, and promote the mutual recognition of international standards and rules
	Cement: Lead demonstration projects (e.g., Industrial solid waste utilization). Steel: Launch green steel pilots. (Petro)chemicals: Pilot clean hydrogen and synthetic fuel production tied to CI thresholds (Lira, 2024).	Cement: Commit to large-scale tech investment. Steel: Retrofit or decommission high-emitting assets. (Petro)chemicals: Transition to fossil-free feedstocks; support standard-setting for multi-output processes.
3. Finance & Investment Community	Cement: Include GWP/EPDs in green bond frameworks. Steel: Align green finance with near-zero thresholds. (Petro)chemicals: Use CI benchmarks in hydrogen and fuel finance instruments (GH2, 2022).	Cement: Launch blended finance tools for novel tech. Steel: Create dedicated transition finance vehicles. (Petro)chemicals: Establish green finance eligibility frameworks for hydrogen, ammonia, methanol (US DOE, 2023).
	Cement & Steel: Support early-stage MRV and LCA innovators. (Petro)chemicals: Fund pilot certification systems and product labelling schemes for key chemical streams.	Cement & Steel: Develop sector-specific transition funds. (Petro)chemicals: Support development of regional hydrogen hubs and sustainable chemical clusters.
	Cement & Steel: Engage companies on disclosure and standard alignment. (Petro)chemicals: Encourage companies to adopt PCF reporting and ISO 14067.	Cement & Steel: Integrate climate risk in portfolio strategies. (Petro)chemicals: Include transition risk in credit ratings for chemical firms reliant on fossil feedstocks.
4. International Organizations (UNFCCC, UNIDO, ITA, G7)	Cement: Facilitate mutual recognition of standards (e.g., EN 15804). Steel: Advance convergence of global steel CI thresholds. (Petro)chemicals: Support international convergence on hydrogen CI thresholds and certification standards (Clean Hydrogen Partnership, 2019).	Cement: Build a global, open EPD registry. Steel: Promote global recognition of near-zero steel. (Petro)chemicals: Develop global CI standards for fuels and hydrogen, aligned with ISO and regional schemes.
	Cement & Steel: Develop GPP toolkits for developing economies. (Petro)chemicals: Create policy templates for integrating hydrogen CI into transport and energy planning.	Cement & Steel: Standardize financing and de-risking models. (Petro)chemicals: Expand harmonized MRV systems and mutual certification for traded products (UNFCCC, 2023).
	Cement: Map SCM availability. Steel: Map H_2 infrastructure gaps. (Petro)chemicals: Map global clean hydrogen capacity and identify regional opportunities for production and trade.	Cement: Promote South-South tech cooperation. Steel: Launch regional innovation hubs. (Petro)chemicals: Facilitate global learning platforms for clean production pathways.

6.3. Opportunities for Future Alignment and Action

Achieving decarbonization at scale hinges on strategic alignment across geographies, institutions, and value chains.

1. Advance global harmonization of standards and labels

There is an urgent need to converge on core definitions, thresholds, and methodologies for what constitutes "low-carbon" and "near-zero" industrial materials. Foundational alignment on accounting principles, lifecycle boundaries, and emissions limits will reduce market fragmentation and increase comparability.

- **Cement:** Work toward a harmonized Product Category Rule (PCR) for cement and concrete, with ongoing coordination by the GCCA, UNIDO, and ISO (IEA, 2022; GCCA, 2021).
- **Steel:** Align global emissions thresholds (e.g., ≤0.4 tCO_2/t steel) through ISO and ResponsibleSteel™ frameworks, supported by CBAM-compatible lifecycle standards (Vogl et al., 2018; Zhao et al., 2024).
- **(Petro)Chemicals:** Standardize carbon intensity benchmarks for hydrogen and fuels across RED III, LCFS, and national clean hydrogen standards (GH2, 2022; US DOE, 2023; European Commission, 2023), whilst recognising the challenges with chemical product benchmarking across the industry's heterogeneity of product chemistries, supply chains, LCA profiles and emissions intensity ranges from one organic chemical to another.

A global platform–under UNFCCC, ISO, or Climate Club–could coordinate a cross-sectoral task force to align standards and facilitate mutual recognition.

2. Expand and link green public procurement (GPP) programs

Governments can drive demand for verified low-carbon products by linking procurement to harmonized standards and emissions thresholds:

- **Cement:** Apply GWP benchmarks for concrete in tenders, starting with EPD-based scoring (UNIDO, 2023).
- **Steel:** Build on Buy Clean models with specific limits for embodied emissions in construction steel, tied to performance bands or strength classes (The White House, 2024).
- **(Petro)Chemicals:** Introduce green procurement standards for clean hydrogen, sustainable fuels, and bio-based chemicals in public infrastructure, transport, and defence programs (Department for Transport, 2013; US DOE, 2023).

Regional alignment (e.g., Africa, ASEAN, Latin America) can amplify impact through mutual recognition of certification systems.

3. Develop and Fund Regional MRV and Verification Capacity

To implement standards and labels at scale, reliable measurement, reporting, and verification (MRV) systems are essential. Investment is needed in local verifiers, EPD program operators, and digital infrastructure. Donors, multilateral banks, and technical agencies can help establish regional verification hubs and provide open-source tools (UNFCCC, 2023; Climate Club, 2023). Over time, harmonized digital MRV will also support carbon border adjustment mechanisms and green trade policies. Robust MRV is the backbone of standard implementation and certification.

- **Cement:** Scale EPD program operators and digital MRV platforms (e.g., EC3, One Click LCA) across developing markets (CEMBUREAU, 2022).
- **Steel:** Expand digital infrastructure for emissions tracking, satellite-based verification, and blockchain-based traceability across steel supply chains (WORLD BANK, 2022).
- **(Petro)Chemicals:** Localize PCF and ISO 14067 tools for multi-output chemical products; build capacity for certifying hydrogen and biofuels (Together for Sustainability, 2024).

Multilateral finance institutions can fund open-source software, training, and regional MRV hubs to support fair participation in climate-linked trade.

4. Catalyze innovation through coordinated pilots and financing

New Supplementary Cementitious Materials (new SCMs), and carbon-cured concretes will require coordinated deployment to scale. Stakeholders can collaborate to de-risk adoption by aligning demonstration projects with emerging standards, embedding performance-based specifications into tenders, and supporting the development of local supply chains. Institutions like the ITA and Mission Possible Partnership can serve as accelerators, linking technical readiness with finance and policy support (ITA, 2025; GCCA, 2021).

5. Encourage mutual recognition and modular labeling

To facilitate market uptake, stakeholders should work toward mutual recognition of certifications (e.g., VDZ, CSC, EPA) and support modular label systems that allow for incremental progress (e.g., A–C ratings or star-based scores). These systems can reward early movers without creating binary access barriers and help raise ambition over time through ratcheting thresholds (CEMBUREAU, 2022; UNIDO, 2023).

6. Align industry roadmaps and national policies

Many leading firms have adopted ambitious net-zero targets under initiatives such as SBTi, GCCA, and ConcreteZero. Governments can partner with these companies to develop national transition pathways, combining bottom-up corporate action with top-down policy signals. Such partnerships can provide realistic timelines, mobilize investment, and align definitions, benchmarks, and reporting platforms (GCCA, 2021; Climate Group, 2023).

7. Addressing the adaptation metrics gap for climate-resilient industry

While the standards and labels landscape are rapidly maturing for mitigation (carbon intensity, product thresholds, MRV for GHGs), there is a clear gap on adaptation and climate-resilience metrics for cement, steel and (petro)chemicals. Without common, verifiable indicators for physical-risk exposure and resilience performance, buyers and policymakers cannot distinguish products and projects that are robust to increasing heat, drought, flooding, storms, and grid instability. This creates three risks: (i) misallocation of capital to assets vulnerable to near-term climate hazards, (ii) maladaptation (e.g., measures that cut emissions but raise exposure to climate risk), and (iii) slower market adoption in regions where climate risks and insurance costs are already material.

Sector-appropriate, MRV-ready adaptation indicators that can sit beside carbon metrics in standards, labels, procurement and finance. Thus, the following could be considered in the future:

1. Embed adaptation metrics in Green Public Procurement and trade tools (e.g., alongside GWP limits, require minimum resilience bands or hazard-adjusted performance for projects in high-risk zones).
2. Develop sectoral Product Category Rules (PCR) addenda for adaptation, defining system boundaries, data sources, and calculation rules so adaptation indicators are comparable and auditable across jurisdictions–mirroring the discipline of EPDs for GHGs.
3. Build enabling data infrastructure: open hazard layers, standardized site-level reporting templates, and low-cost verification pathways to avoid excluding SMEs and producers in data-scarce regions.

Adding adaptation metrics can close a material blind spot in today's mitigation-only standards. It aligns investment with assets that will still perform under 2030–2050 climate conditions, reduces insurability and downtime risks, and makes low/near-zero products bankable and reliable in the places they are most needed.

Achieving future alignment in the cement sector is not a default outcome; it must be intentionally designed through structured collaboration, the establishment of consistent metrics, and the development of shared platforms. A window of opportunity is now open. Decarbonization standards are maturing, public and private sector buyers are mobilizing to create demand, and the necessary breakthrough technologies are increasingly available. The imperative, therefore, is to integrate these elements into cohesive and interoperable global architecture.

The ultimate goal would be to ensure that a ton of "low-carbon cement" signifies the same high standard of climate performance and contributes to the same global decarbonization objective, anywhere in the world.

6.4 Conclusion

The three sectors considered in this report have laid the groundwork for a transition to low- and near-zero emission production, but this progress will stall without cohesive policy support, digital infrastructure, and international coordination. The challenge is now one of governance and finance as much as it is technical.

Across all three sectors, early progress has been made in defining emissions thresholds, developing transparency tools, and piloting new technologies. However, the full transition to low- and near-zero emissions production remains hindered by persistent policy, financial, and implementation barriers and coordinated action is now needed across governance, finance, infrastructure, and international cooperation especially to benefit emerging economies.

Annexes

Annex A: Annotated Reference List and Source Materials

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Annex B: Detailed Table of Standards and Thresholds by Sector

Table 10: Cement Standards and labels Classified by Functions

Functional Category	No.	Name / Framework	Type	Governing Body / Initiative	Geographic Scope	Primary Approach	Key Features / CO_2 Thresholds	Verification / Basis	Market Role / Uptake
A. Core Policy & Financial Regulation	1	European Union Taxonomy (Cement)	Regulatory	European Union	European Union	Finance classification / Threshold-based	Clinker < 0.766 tCO_2/t; Cement < 0.498 tCO_2/t	Monitoring through company disclosures; European Union MRV for ETS	Deems cement manufacturing sustainable for investment if thresholds are met.
	2	European Union Carbon Border Adjustment Mechanism (CBAM)	Regulatory (Tariff mechanism)	European Union	European Union (imports)	Embodied carbon pricing	Uses European Union's internal benchmark (~0.733 tCO_2/t clinker initially from European Union ETS)	Measures embodied CO_2 of cement imports	Incentivizes foreign producers to lower emissions to maintain market access.
	3	China Green Building Material Standards	Voluntary (National, integrated into industrial standards)	Chinese government	China	Certification / Disclosure / Future thresholds	Requires disclosure of carbon emissions	Certification rules, likely EPDs	Incorporate the requirements for carbon emission reports into the group standards and the green building materials certification system.
	4	India Perform-Achieve-Trade (PAT) Scheme	Regulatory (Energy efficiency focus)	Bureau of Energy Efficiency (BEE)	India	Market-based mechanism for energy efficiency	Focuses on energy intensity, leading to lower energy use per ton cement	Monitoring specific energy consumption	Incentivizes investment in energy-efficient technologies.
	5	France RE2020 Building Code	Regulatory (Building code)	French government	France	Embodied carbon limits for buildings	Sets thresholds for total embodied emissions of construction materials in new buildings, tightening every three years until 2031	Indirectly pressures cement emissions	Creates demand for low-carbon materials by making real estate sector bear cost premium.
B. Public Procurement Initiatives	6	United States of America EPA Low-Embodied-Carbon Labeling Program	Regulatory (in development, voluntary but tied to procurement)	United States of America Environmental Protection Agency (EPA)	United States (federal procurement)	Labeling / Performance-based	Identifies and labels products with lower-than-average embodied GHG emissions;	EPD required; EPA to manage compliance audits	United States of America government plans to prefer labelled low-carbon products in projects.

Functional Category	No.	Name / Framework	Type	Governing Body / Initiative	Geographic Scope	Primary Approach	Key Features / CO_2 Thresholds	Verification / Basis	Market Role / Uptake
							thresholds not yet set		
	7	California Buy Clean Law	Regulatory (State-level)	State of California	California	Procurement standards / GWP limits	Requires EPDs and meeting tightening GWP limits by 2025 for public projects	EPDs	Sets regional benchmarks for maximum CO_2 per unit of concrete/cement in government-funded construction.
	8	Industrial Deep Decarbonisation Initiative (IDDI) Green Public Procurement Pledge	Government Procurement (Voluntary Pledge)	Coalition of governments (under Clean Energy Ministerial and UNIDO)	International (member countries)	Coordinated public procurement	Governments pledge to specify low-emission materials by 2030; adopts IEA's sliding-scale definition	EPDs to document bids; common guidelines	Drives demand for low-carbon cement and steel in public projects.
C. Foundational Methodologies & Standards	9	EPD (Environmental Product Declarations)	Transparency / Reporting Tool	Various EPD Program Operators (e.g. NSF, UL, IBU)	Global	Standardized lifecycle GHG disclosure	Reports GWP (kg CO_2e per functional unit) for A1–A3 stages	ISO 14025, ISO 21930, EN 15804; third-party verified	Widely used for public procurement and voluntary labels.
	10	ISO 19694-3:2023	Standard (Methodology)	International Organization for Standardization (ISO)	Global	Harmonized GHG accounting methodology	Specifies methodology for calculating GHG emissions from cement industry (direct and indirect sources)	Provides consistent rules for quantification	Underpins credible labels and reporting.
	11	ISO 14067, ISO 14025, ISO 21930 / EN 15804	Standards (Methodology for EPDs)	ISO, European Committee for Standardization (CEN)	Global (ISO), Europe (EN)	Life-cycle assessment, EPDs	ISO 14067 for CFP; ISO 14025 for EPDs; ISO 21930 for sustainability of construction works; EN 15804 for EPDs of construction products	Standardized environmental reporting, third-party verification	Provide common methodology for transparent, comparable environmental data.
	12	EN 197-1	Regulatory (Harmonized standard)	European Committee for Standardization (CEN)	European Union	Prescriptive / Recipe-based	Defines 27 distinct types of common cements based on strict compositional limits	Compositional limits	Mandatory for CE marking and market access in the European Union; can be a barrier to innovation.
	13	ASTM C1157	Standard (Performance-based)	ASTM International	North America / Global	Performance-based	Specifies performance characteristics (strength,	Performance testing	Provides pathway for innovative cements to

Functional Category	No.	Name / Framework	Type	Governing Body / Initiative	Geographic Scope	Primary Approach	Key Features / CO_2 Thresholds	Verification / Basis	Market Role / Uptake
							setting time, durability) without dictating composition		enter the market.
	14	ASTM C595, C618, C1866	Standards (Prescriptive/Performance for SCMs)	ASTM International	North America / Global	Specifications for blended cements and SCMs	C595 for blended hydraulic cements; C618 for coal fly ash and natural pozzolans; C1866 for ground-glass pozzolans	Chemical and physical property limits, performance tests	Supports the use of SCMs, enabling emissions reduction.
D. Industry-Led Roadmaps & Commitments	15	CEMBUREAU Roadmap	Voluntary / Industry Roadmap	CEMBUREAU (The European Cement Association)	European Union	Roadmap / Technology pathway	2030 target: -37% CO_2 (cement); -50% (value chain); 2050: climate neutrality	Member disclosures; aligned with European Union Green Deal	Guides sector innovation and European Union policy alignment.
	16	ICCA Pathways to Chemical Sector Climate Neutrality	Voluntary / Industry roadmap	ICCA (International Council of Chemicals Associations)	Global	Technology pathways	Modelling study covering eighteen large-volume chemicals and exploring multiple climate-neutral pathways	Industry-led effort	Outlines multiple portfolio approaches for abatement based on local/national/regional conditions
	17	WBCSD Cement Sustainability Initiative (CSI)	Voluntary / Industry Collaboration	World Business Council for Sustainable Development (WBCSD)	Global	Voluntary reporting, performance indicators	GNR database; benchmarks CO_2 intensity, energy use, clinker ratio	Self-reported and peer-reviewed data from companies	Widespread industry adoption; merged into GCCA in 2018.
	18	IEA Near-Zero and Low-Emission Definitions	International Guideline (Voluntary)	International Energy Agency (IEA)	Global	Performance thresholds / Sliding scale	Near-zero: 125 kg CO_2/t (100% clinker); Low-emission (Band E): 750 kg CO_2/t (100% clinker)	Aligned with LCA/EPD conformity	Heavily influences subsequent programs and definitions.
	19	GCCA Low Carbon Ratings (LCR) System	Industry Standard (Voluntary Label)	Global Cement and Concrete Association (GCCA)	Global (with national adaptation)	Performance-based rating (AA to G scale)	Categorizes concrete/cement based on GWP from EPD, benchmarked against IEA definitions	Third-party verified EPDs	Aims to simplify and standardize low-carbon procurement globally.
	20	GCCA EPD Tool	Transparency / Industry Tool	Global Cement and Concrete Association (GCCA)	Global (members in >80 countries)	Online tool for lifecycle emissions reporting	Generates EN 15804-compliant EPDs for cement and concrete	Based on ISO 14025, EN 15804; independently verified	Used by GCCA members; supports alignment with LCR bands.

Functional Category	No.	Name / Framework	Type	Governing Body / Initiative	Geographic Scope	Primary Approach	Key Features / CO_2 Thresholds	Verification / Basis	Market Role / Uptake
E. Private Sector & Buyer-Led Initiatives	21	IEA Near-Zero and Low-Emission Definitions	International Guideline (Voluntary)	International Energy Agency (IEA)	Global	Performance thresholds / Sliding scale	Near-zero: 125 kg CO_2/t (100% clinker); Low-emission (Band E): 750 kg CO_2/t (100% clinker)	Aligned with LCA/EPD conformity	Heavily influences subsequent programs and definitions.
	22	First Movers Coalition (FMC) Cement/Concrete Pledge	Buyer's Club (Voluntary Commitment)	World Economic Forum and United States of America government (companies as members)	Global (member companies)	Demand signal / Procurement commitment	Members pledge 10% near-zero cement/concrete procurement by 2030; Near-zero cement: 184 kg CO_2/t	Supplier must provide EPD or third-party proof	Creates early markets for clean technologies, pushes suppliers to meet thresholds.
	23	Concrete Sustainability Council (CSC) Certification (with CO_2 Module)	Industry Certification (Voluntary Label)	Concrete Sustainability Council (CSC)	Global	Holistic certification + CO_2 performance rating	Bronze, Silver, Gold, Platinum levels; CO_2 Module provides a 1–4-star label based on percentage reduction vs. regional average	EPD or calculated footprint; audit by CSC-accredited body	Recognized by green building rating systems (LEED, BREEAM).
F. Proprietary & National Labels	24	Building Materials Carbon Label (China)	Voluntary / Pilot (Industry-led)	China Building Materials Federation	China (domestic market)	Performance-based / Star-rating system	1–3 stars based on lifecycle carbon emissions; aligned with national green standards	EPD-style footprint assessment; criteria include GWP and energy use	Piloted in 2023; limited uptake; aligns with China's 2030/2060 climate goals
	25	Company-Specific Product Labels (e.g., Holcim ECOPlanet, Cemex Vertua)	Corporate Claim / Proprietary Label	Individual companies	Varies by company	Environmental branding	Varies (e.g., ≥30% CO_2 reduction vs. OPC for ECOPlanet)	Internal LCA; some externally verified EPDs	Response to market demand, highlights need for standardized definitions.

Table 11: Cement Standards and label Classified by Types (Regulatory and Voluntary)

No.	Name / Framework	Type	Governing Body / Initiative	Geographic Scope	Primary Approach	Key Features / CO_2 Thresholds	Verification / Basis	Market Role / Uptake
Regulatory Standards								
1	European Union Taxonomy (Cement)	Regulatory	European Union	European Union	Finance classification / Threshold-based	Clinker < 0.766 tCO_2/t; Cement < 0.498 tCO_2/t	Monitoring through company disclosures; European Union MRV for ETS	Deems cement manufacturing sustainable for investment if thresholds are met.

No.	Name / Framework	Type	Governing Body / Initiative	Geographic Scope	Primary Approach	Key Features / CO_2 Thresholds	Verification / Basis	Market Role / Uptake
2	European Union Carbon Border Adjustment Mechanism (CBAM)	Regulatory (Tariff mechanism)	European Union	European Union (imports)	Embodied carbon pricing	Uses European Union's internal benchmark (~0.766 tCO_2/t clinker initially from European Union ETS)	Measures embodied CO_2 of cement imports	Incentivizes foreign producers to lower emissions to maintain market access.
3	United States of America EPA Low-Embodied-Carbon Labeling Program	Regulatory (in development, voluntary but tied to procurement)	United States of America Environmental Protection Agency (EPA)	United States of America (federal procurement)	Labeling / Performance-based	Identifies and labels products with lower-than-average embodied GHG emissions; thresholds not yet set	EPD required; EPA to manage compliance audits	United States of America government plans to prefer labelled low-carbon products in projects.
4	California Buy Clean Law	Regulatory (State-level)	State of California	California	Procurement standards / GWP limits	Requires EPDs and meeting tightening GWP limits by 2025 for public projects	EPDs	Sets regional benchmarks for maximum CO_2 per unit of concrete/cement in government-funded construction.
5	China Green Building Material Standards	Voluntary (National, integrated into industrial standards)	Chinese government	China	Certification / Disclosure / Future thresholds	Requires disclosure of carbon emissions; 1- to 3-star rating system; developing unified PCF labelling system	Certification rules, likely EPDs	Incorporate the requirements for carbon emission reports into the group standards and the green building materials certification system.
6	India Perform-Achieve-Trade (PAT) Scheme	Regulatory (Energy efficiency focus)	Bureau of Energy Efficiency (BEE)	India	Market-based mechanism for energy efficiency	Focuses on energy intensity, leading to lower energy use per ton cement	Monitoring specific energy consumption	Incentivizes investment in energy-efficient technologies.
7	France RE2020 Building Code	Regulatory (Building code)	French government	France	Embodied carbon limits for buildings	Sets thresholds for total embodied emissions of construction materials in new buildings, tightening every three years until 2031	Indirectly pressures cement emissions	Creates demand for low-carbon materials by making real estate sector bear cost premium.
8	EPD (Environmental Product Declarations)	Transparency / Reporting Tool	Various EPD Program Operators (e.g., NSF, UL, IBU)	Global	Standardized lifecycle GHG disclosure	Reports GWP (kg CO_2e per functional unit) for A1–A3 stages	ISO 14025, ISO 21930, EN 15804; third-party verified	Widely used for public procurement and voluntary labels.
9	ISO 19694-3:2023	Standard (Methodology)	International Organization for Standardization (ISO)	Global	Harmonized GHG accounting methodology	Specifies methodology for calculating GHG emissions from cement industry (direct and indirect sources)	Provides consistent rules for quantification	Underpins credible labels and reporting.

No.	Name / Framework	Type	Governing Body / Initiative	Geographic Scope	Primary Approach	Key Features / CO_2 Thresholds	Verification / Basis	Market Role / Uptake
10	ISO 14067, ISO 14025, ISO 21930 / EN 15804	Standards (Methodology for EPDs)	ISO, European Committee for Standardization (CEN)	Global (ISO), Europe (EN)	Life-cycle assessment, EPDs	ISO 14067 for CFP; ISO 14025 for EPDs; ISO 21930 for sustainability of construction works; EN 15804 for EPDs of construction products	Standardized environmental reporting, third-party verification	Provide common methodology for transparent, comparable environmental data.
11	EN 197-1	Regulatory (Harmonized standard)	European Committee for Standardization (CEN)	European Union	Prescriptive / Recipe-based	Defines 27 distinct types of common cements based on strict compositional limits	Compositional limits	Mandatory for CE marking and market access in the European Union; can be a barrier to innovation.
12	ASTM C1157	Standard (Performance-based)	ASTM International	North America / Global	Performance-based	Specifies performance characteristics (strength, setting time, durability) without dictating composition	Performance testing	Provides pathway for innovative cements to enter the market.
13	ASTM C595, C618, C1866	Standards (Prescriptive/Performance for SCMs)	ASTM International	North America / Global	Specifications for blended cements and SCMs	C595 for blended hydraulic cements; C618 for coal fly ash and natural pozzolans; C1866 for ground-glass pozzolans	Chemical and physical property limits, performance tests	Supports the use of SCMs, enabling emissions reduction.
				Voluntary Standards				
14	CEMBUREAU Roadmap	Voluntary / Industry Roadmap	CEMBUREAU (The European Cement Association)	European Union	Roadmap / Technology pathway	2030 target: -37% CO_2 (cement); -50% (value chain); 2050: climate neutrality	Member disclosures; aligned with European Union Green Deal	Guides sector innovation and European Union policy alignment.
15	WBCSD Cement Sustainability Initiative (CSI)	Voluntary / Industry Collaboration	World Business Council for Sustainable Development (WBCSD)	Global	Voluntary reporting, performance indicators	GNR database; benchmarks CO_2 intensity, energy use, clinker ratio	Self-reported and peer-reviewed data from companies	Widespread industry adoption; merged into GCCA in 2018.
16	IEA Near-Zero and Low-Emission Definitions	International Guideline (Voluntary)	International Energy Agency (IEA)	Global	Performance thresholds / Sliding scale	Near-zero: 125 kg CO_2/t (100% clinker); Low-emission (Band E): 750 kg CO_2/t (100% clinker)	Aligned with LCA/EPD conformity	Heavily influences subsequent programs and definitions.
17	GCCA Low Carbon Ratings (LCR) System	Industry Standard (Voluntary Label)	Global Cement and Concrete Association (GCCA)	Global (with national adaptation)	Performance-based rating (AA to G scale)	Categorizes concrete/cement based on GWP from EPD, benchmarked against IEA definitions	Third-party verified EPDs	Aims to simplify and standardize low-carbon procurement globally.

No.	Name / Framework	Type	Governing Body / Initiative	Geographic Scope	Primary Approach	Key Features / CO_2 Thresholds	Verification / Basis	Market Role / Uptake
18	GCCA EPD Tool	Transparency / Industry Tool	Global Cement and Concrete Association (GCCA)	Global (members in >80 countries)	Online tool for lifecycle emissions reporting	Generates EN 15804-compliant EPDs for cement and concrete	Based on ISO 14025, EN 15804; independently verified	Used by GCCA members; supports alignment with LCR bands.
19	Industrial Deep Decarbonisation Initiative (IDDI) Green Public Procurement Pledge	Government Procurement (Voluntary Pledge)	Coalition of governments (under Clean Energy Ministerial and UNIDO)	International (member countries)	Coordinated public procurement	Governments pledge to specify low-emission materials by 2030; adopts IEA's sliding-scale definition	EPDs to document bids; common guidelines	Drives demand for low-carbon cement and steel in public projects.
20	First Movers Coalition (FMC) Cement/Concrete Pledge	Buyer's Club (Voluntary Commitment)	World Economic Forum and United States of America government (companies as members)	Global (member companies)	Demand signal / Procurement commitment	Members pledge 10% near-zero cement/concrete procurement by 2030; Near-zero cement: 184 kg CO_2/t	Supplier must provide EPD or third-party proof	Creates early markets for clean technologies, pushes suppliers to meet thresholds.
21	Concrete Sustainability Council (CSC) Certification (with CO_2 Module)	Industry Certification (Voluntary Label)	Concrete Sustainability Council (CSC)	Global	Holistic certification + CO_2 performance rating	Bronze, Silver, Gold, Platinum levels; CO_2 Module provides 1–4-star label based on percentage reduction vs. regional average	EPD or calculated footprint; audit by CSC-accredited body	Recognized by green building rating systems (LEED, BREEAM).
22	Green Building Certifications (LEED, BREEAM) & Material Libraries (EC3)	Certification / Tool (Indirect influence)	United States of America Green Building Council, BRE, Building Transparency	Global	Rewards use of low-carbon materials / EPD data compilation	LEED awards points for concrete with EPDs and embodied carbon reduction; EC3 compiles EPD data, allows filtering by carbon intensity	EPDs	Creates indirect pull for labelled low-carbon cement/concrete.
23	Building Materials Carbon Label (China)	Voluntary / Pilot (Industry-led)	China Building Materials Federation	China (domestic market)	Performance-based / Star-rating system	1–3 stars based on lifecycle carbon emissions; aligned with national green standards	EPD-style footprint assessment; criteria include GWP and energy use	Piloted in 2023; limited uptake; aligns with China's 2030/2060 climate goals.
24	Company-Specific Product Labels (e.g., Holcim ECOPlanet, Cemex Vertua)	Corporate Claim / Proprietary Label	Individual companies	Varies by company	Environmental branding	Varies (e.g., ≥30% CO_2 reduction vs. OPC for ECOPlanet)	Internal LCA; some externally verified EPDs	Response to market demand, highlights need for standardized definitions.

Table 12: Chemicals and Petrochemicals sector standards and labels

Standard	Sector	Subsector or product (if applicable)	Type	Region	Carbon Intensity Limit / GHG reductions

European Union Renewable Hydrogen Standard (European Commission, 2025c)	Chemicals	Hydrogen	Regulatory	European Union	3.4 kg CO_2/ kg H_2
United States of America Clean Hydrogen Standard (US DOE, 2023)	Chemicals	Hydrogen	Regulatory	United States of America	4.0 kg CO_2/ kg H_2
United Kingdom of Great Britain and Northern Ireland Low Carbon Hydrogen Standard (DESNZ, 2022)	Chemicals	Hydrogen	Regulatory	United Kingdom of Great Britain and Northern Ireland	2.4 kg CO_2/ kg H_2
Japan Low-Carbon Hydrogen Standards (GR Japan, 2024)	Chemicals	Hydrogen	Regulatory	Japan	3.4 kg CO_2/ kg H_2
India Green Hydrogen Standard (Ministry of New and Renewable Energy, 2023)	Chemicals	Hydrogen	Regulatory	India	2.0 kg CO_2/ kg H_2
Renewable Transport Fuel Obligation (Department for Transport, 2013)	Chemicals	Hydrogen (transport)	Regulatory	United Kingdom of Great Britain and Northern Ireland	4.0 kg CO_2/ kg H_2
Brazilian Hydrogen Certification Scheme (SBCH2) (Lira, n.d.)	Chemicals	Hydrogen	Regulatory	Brazil	7.0 kg CO_2/ kg H_2
Australian Production Tax Incentive (Australian Government, 2025)	Chemicals	Hydrogen	Regulatory	Australia	0.6 kg CO_2/ kg H_2
European Union Taxonomy (European Commission, 2021c)	All	Hydrogen	Regulatory	European Union	3.0 kg CO_2/ kg H_2
European Union Taxonomy (European Commission, 2021c)	All	Hydrogen-based synthetic fuels	Regulatory	European Union	3.4 kg CO_2/ kg H_2
European Union Taxonomy (European Commission, 2021c)	All	Organic Chemicals	Regulatory	European Union	HVC: 0.693 tCO_2e/t Aromatics: 0.0072 tCO_2e/t Vinyl chloride: 0.171 tCO_2e/t Styrene: 0.419 tCO_2e/t Ethylene oxide: 0.314 tCO_2e/t Adipic acid: 0.32 tCO_2e/t
Low-carbon Fuel Standard (LCFS) (California Air Resources Board, 2018)	Chemicals	Hydrogen (transport)	Regulatory	California (United States of America)	1.3 – 19.8 kg CO_2/ kg H_2 Depending on production pathway
Clean Hydrogen Investment Tax Credit (Government of Canada, 2023)	Chemicals	Hydrogen	Regulatory	Canada	Under 4.0 kg CO_2/ kg H_2
Clean and Renewable Hydrogen Standard: China Hydrogen Alliance (China Hydrogen Alliance, 2020)	Chemicals	Hydrogen	Voluntary (group/association standard)	China	4.9 kg CO_2/ kg H_2

Climate Bonds Standard & Certification Scheme (Climate Bonds Initiative, 2023)	Chemicals	Nitric Acid	Voluntary	Global	2022: 0.038 t CO_2e/t 2030: 0.021 t CO_2e/t 2040: 0.011 t CO_2e/t 2050: 0.007 t CO_2e/t
Climate Bonds Standard & Certification Scheme (Climate Bonds Initiative, 2023)	Chemicals	Carbon black	Voluntary	Global	2022: 1.141 t CO_2e/t 2030: 0.63 t CO_2e/t 2040: 0.34 t CO_2e/t 2050: 0.2 t CO_2e/t
Climate Bonds Standard & Certification Scheme (Climate Bonds Initiative, 2023)	Chemicals	High value chemicals (ethylene, propylene, butadiene)	Voluntary	Global	2022: 0.51 t CO_2e/t 2030: 0.28 t CO_2e/t 2040: 0.15 t CO_2e/t 2050: 0.09 t CO_2e/t
Climate Bonds Standard & Certification Scheme (Climate Bonds Initiative, 2023)	Chemicals	Aromatics BTX (benzene, xylene and toluene)	Voluntary	Global	2022: 0.0072 t CO_2e/t 2030: 0.004 t CO_2e/t 2040: 0.0021 t CO_2e/t 2050: 0.0012 t CO_2e/t
Climate Bonds Standard & Certification Scheme (Climate Bonds Initiative, 2023)	Chemicals	Disodium carbonate Soda ash	Voluntary	Global	2022: 0.789 t CO_2e/t 2030: 0.44 t CO_2e/t 2040: 0.23 t CO_2e/t 2050: 0.14 t CO_2e/t Requires renewable power either on site or purchased
Climate Bonds Standard & Certification Scheme (Climate Bonds Initiative, 2020)	Chemicals	Hydrogen Ammonia Methanol	Voluntary	Global	2022: 3.0 kg CO_2/ kg H_2 2030: 1.5 kg CO_2/ kg 2040: 0.6 kg CO_2/ kg 2050: 0 kg CO_2/ kg
World Business Council of Sustainable Development (WBSCD, 2021)	Chemicals	Hydrogen	Voluntary	Global	Reduced carbon: 6.0 Low carbon: 3.0 Ultra-low carbon: 1.0
GH2 Global Green Hydrogen Standard (GHO, 2022)	Chemicals	Hydrogen	Voluntary	Global	1.0 kg CO_2/ kg H_2 100% or near 100% renewable powered electrolysis
TUV SUD CMS 70 Renewable Hydrogen Standard (TUV SUD, 2021)	Chemicals	Hydrogen	Voluntary	Germany	70% or more below reference value (94 g CO2e/MJ)
CertifHy (Clean Hydrogen Partnership, 2019)	Chemicals	Hydrogen	Voluntary	Europe	4.4 CO_2/ kg H_2
ISO 14067:2018 (International Standards Organisation, 2018)	All		Voluntary	Global	Methodological
GHG Protocol Product Life Cycle Standard (WRI & WBCSD, 2010)	All		Voluntary	Global	Methodological
Production Carbon Footprint Guideline for the Chemical Industry (Together for Sustainability, 2024)	Chemicals	All	Voluntary	Global	Methodological

Science Based Targets Initiative: Chemicals Sector Guidance (Science Based Targets Initiative, n.d.)	Chemicals	All	Voluntary	Global	Methodological
Renewable Energy Directive II (Joint Research Centre, 2018)	Chemicals	Transport fuels	Regulatory	European Union	>65% reductions for biofuels, >70% for RFNBO
Renewable Energy Directive III (European Commission, 2023c)	Chemicals	Transport fuels	Regulatory	European Union	>80% reductions Replaces RED II
Low-carbon Fuel Standard (LCFS) (California Air Resources Board, 2018)	Chemicals	Transport fuels	Regulatory	California (United States of America)	>20% reduction by 2030
Renewable Transport Fuel Obligation (Department for Transport, 2013)	Chemicals	Transport fuels	Regulatory	United Kingdom of Great Britain and Northern Ireland	Sets out an annual obligation to suppliers for the supply of sustainable renewable fuel
Renewable Fuel Standard (US DOE, n.d.)	Chemicals	Transport fuels	Regulatory	United States of America	>20% for conventional biofuels >50% for advanced biofuels >60% for cellulosic biofuels
RenovaBio Standard (Ministry of Mines and Energy, 2021)	Chemicals	Transport fuels	Regulatory	Brazil	>11.4% reduction by 2030
2BSvs Bio-balance (2BS Voluntary Scheme, 2024)	Chemicals	Transport fuels	Voluntary	Global	RED II thresholds
International Sustainability and Carbon Certification European Union (ISCC, n.d.-d)	Chemicals	Transport fuels	Regulatory	Global	RED III thresholds
International Sustainability and Carbon Certification CORSIA (ISCC, n.d.-b)	Chemicals	Sustainable aviation fuels	Voluntary	Global	CORSIA for sustainable aviation fuels
International Sustainability and Carbon Certification Plus (ISCC, n.d.-c)	Chemicals	Sustainable aviation fuels	Voluntary	Global	Voluntary application
Roundtable on Sustainable Biomaterials European Union RED Fuel Certification (RSB, n.d.-b)	Chemicals	Transport fuels	Regulatory	Global	>50-65% lifecycle for biofuels and bioliquids, depending on installation start date
Roundtable on Sustainable Biomaterials Global Advanced Products (RSB, n.d.-c)	Chemicals	Advanced products	Voluntary	Global	>10% lower lifecycle emissions, on a cradle-to-grave basis
Roundtable on Sustainable Biomaterials Global Fuels (RSB, n.d.-d)	Chemicals	Transport fuels	Voluntary	Global	>70% lower lifecycle emissions

Roundtable on Sustainable Biomaterials CORSIA (RSB, n.d.-a)	Chemicals	Aviation Fuels	Voluntary	Global	>10% lower lifecycle emissions, in additional to compliance with biofuels / RFNBO reductions
European Union ETS Phase 4 free-allocation benchmarks (Ecofys et al., 2016)	Chemicals		Regulatory	European Union	Based on the average emissions of the top 10% most efficient installations
Carbon Trust Verified CO2e footprint (Carbon Trust, n.d.)	All		Voluntary	Global	Verifies that a brand is working to measure and reduce carbon intensity, with reductions YoY
International Sustainability and Carbon Certification (ISCC, n.d.-a)	Chemicals		Voluntary	Global	Certification of product carbon footprints
Transition Pathway Initiative: Oil and Gas (TPI, n.d.-b)	Petrochemicals	Oil & Gas	Voluntary	Global	Carbon intensity requirements vary in line with Paris Agreement benchmarks (Benchmarks scaled to 1.5°C, <2°C, and NDC scenarios)
Transition Pathway Initiative: Oil and Gas (TPI, n.d.-a)	Chemicals		Voluntary	Global	Carbon intensity requirements vary in line with Paris Agreement benchmarks (Benchmarks scaled to 1.5°C, <2°C, and NDC scenarios)
European Union ETS Phase 4 Benchmark Values (European Commission, 2021b)	All	Refinery products Nitric acid Ammonia Steam cracking Aromatics Ethylenoxid PVC	Regulatory	European Union	Free allocations based on emissions intensity performance of the 10% best installations covered by the European Union ETS
SGS Carbon Assured Standard (SCS Global Services, n.d.)	Chemicals	All	Voluntary	Global	Provides a methodology for third-party certification of the greenhouse gas intensity and reduction in carbon dioxide equivalents of a chemical material.

Table 13: Steel Sector standards and labels

Standard	Sector	Subsector or product (if applicable)	Type	Region	Carbon Intensity Limit / GHG reductions
European Union ETS	Steel	All	Regulatory	European Union	Benchmark-based; varies by installation
European Union Sustainable Finance Taxonomy	All	Steel	Regulatory	European Union	Sets carbon intensity benchmarks for each step of the iron & steel production process
Carbon Border Adjustment Mechanism (CBAM)	Steel	All	Regulatory	European Union	Emissions must align with European Union ETS; border tariff applies
Inflation Reduction Act (IRA)	Steel	All	Regulatory	United States of America	Support for green hydrogen-based steel production

Global Arrangement on Sustainable Steel and Aluminium (GASSA)	Steel	All	Regulatory/Policy	European Union–United States of America	Promotes low-emission steel; bilateral agreement
India National Green Hydrogen Mission	Steel	BF-BOF with CCS	Regulatory	India	Aims to reduce 150 Mt of CO_2; standard TBD
ResponsibleSteel™	Steel	All	Voluntary	Global	ESG certification; includes GHG thresholds and traceability
HYBRIT Project	Steel	DRI with green hydrogen	Voluntary	Sweden	Pilot target: <0.4 tCO_2 per tonne of steel
First Movers Coalition (FMC)	Steel	All	Voluntary	Global	Companies commit to <0.4 tCO_2 per tonne of steel by 2030
World Steel Association LCA Protocol	Steel	All	Voluntary	Global	Tonnes CO_2 per tonne steel; LCA-based reporting encouraged

Annex C: Methodology Notes

The work presented here follows the Rapid Evidence Assessment approach to gather evidence on standards for low- and near-zero emission production and products across the three hard-to-abate sectors examined in this report. Rapid Evidence Assessments are a structured review and synthesis of comprehensive research evidence, aiming to inform decisions or identify knowledge gaps. REAs are widely applied to the policy contexts, including for energy and climate policy.

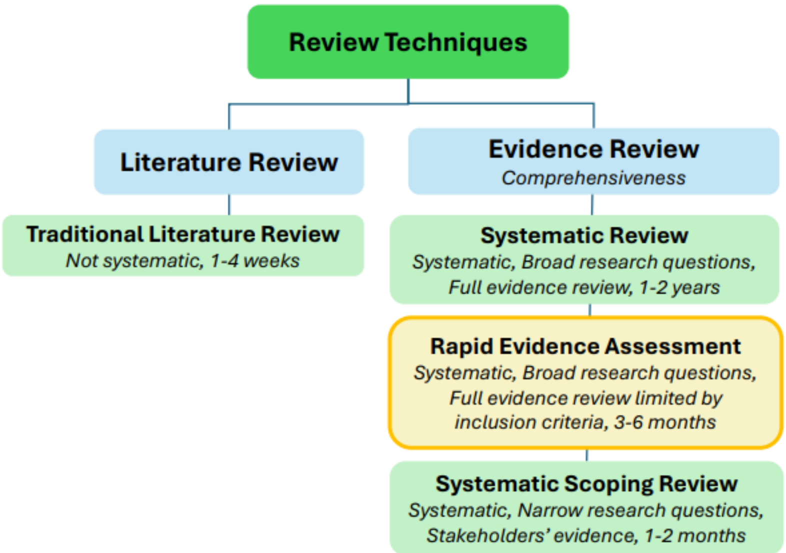

Figure 1: Visualization of the range of evidence reviews frameworks (Adapted from Thomas et al., 2013)

Stage 1: Develop of Searching Strategy	Status
Setting research questions	☑
Scoping study	☑
Setting inclusion and exclusion criteria	☑

Stage 2: Searching	Status
Searching for evidence	☑
1) Peer-reviews articles	☑
2) Grey literature	☑

Stage 3: Screening	Status
Screening evidence	☑

Stage 4: Quality assessment	Status
Quality assessment	☐
Creating systematic map database	☐

Stage 5: Data extraction	Status
Data extraction and systhesis	☐

Stage 6: Report and dissemination	Status
Interpretating findings	☐
Report and dissemination	☐

Figure 2: Visualisation of Search Strategy

Analysis of standards for low and near-zero emission production and products in hard-to-abate industries

As of 23 July 2025

REA question

What are the existing voluntary and regulatory carbon intensity standards, labels, and their application for low- and near-zero emission production and products in steel, cement, chemical and petrochemical industries?

Scope of the REA	
Timeframe:	2015 – 2025
Geography:	Global (with examples from G20, EU, US, etc.)
Scoping Sectors:	Steel, Cement, Chemicals, Petrochemicals
Scoping areas:	Standards, labels, certifications, and procurement schemes related to carbon intensity, in both voluntary and regulatory frameworks
Search platforms:	Peer-reviewed articles (Web of Science, Scopus)
	**Peer-reviewed articles may not be the most effective sources for identifying existing standards, but they are more suitable for analyzing policy barriers and impacts. (Further details are provided in the Keywords section.)*
	Grey literature (e.g. reports, standards and regulations, published by International organizations, governments, and private sector)

Preliminary search results	
Grey literature:	3 structured mapping documents found (Approximate 279 policies were identified.)
	20 standards identified
Academic papers:	37 articles identified

Figure 3 Methodology application (initial search)

	Search keywords					WoS	Relevant (-,+,++,+++)	Scopus	Relevant (-,+,++,+++)	Recommendations to use the keywords
1	Carbon intensity standard					3304	+	3956	+	No
2	Carbon intensity standard	AND	Hard-to-abate sectors			2	+	3	+	No
3	Carbon intensity standard	AND	Steel			156	-	193	+	No
4	Carbon intensity standard	AND	Cement			29	-	37	+	No
5	Carbon intensity standard	AND	Chemical and Petrochemical			5	-	5	-	No
6	Carbon intensity	AND	Standards and Labels			85	-	42	-	No
7	Carbon intensity	AND	Standards and Labels	AND	Steel	0	-	1	-	No
8	Carbon intensity	AND	Standards and Labels	AND	Cement	1	-	1	-	No
9	Carbon intensity	AND	Standards and Labels	AND	Chemical and Petrochemical	0	-	0	-	No
10	Carbon emission standard	AND	Steel industry			174	+	261	-	No
11	Carbon emission standard	AND	Cement industry			212	+	340	-	No
12	Carbon emission standard	AND	Chemical and Petrochemical industry			13	-	29	-	No
13	Voluntary carbon standard					283	+	448	+	Maybe
14	Voluntary carbon standard	AND	Steel			4	+	6	+	Maybe
15	Voluntary carbon standard	AND	Cement			1	+	5	+	Maybe
16	Voluntary carbon standard	AND	Chemical and Petrochemical			1	-	0	-	No
17	Regulatory carbon standard	AND	Steel			29	-	67	-	No
18	Regulatory carbon standard	AND	Cement			18	+	42	+	Maybe
19	Regulatory carbon standard	AND	Chemical and Petrochemical			3	-	5	-	No
20	Industrial decarbonization	AND	Standards and Labels	AND	Steel	1	+	0	-	No
21	Industrial decarbonization	AND	Standards and Labels	AND	Cement	1	+	0	-	No
22	Industrial decarbonization	AND	Standards and Labels	AND	Chemical and Petrochemical	0	-	0	-	No
23	Decarbonization standard	AND	Steel			39	+	47	+	Maybe
24	Decarbonization standard	AND	Cement			35	+	32	+	Maybe
25	Decarbonization standard	AND	Chemical and Petrochemical			2	-	2	-	No
26	Carbon intensity	AND	Regulatory			572	++	847	++	Yes (Need to scope down)
27	Carbon intensity	AND	Regulatory	AND	Steel	18	-	18	-	No
28	Carbon intensity	AND	Regulatory	AND	Cement	5	+	6	+	Maybe

Figure 4 Search keywords applied