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Scaling the Industrial Transition: Hard-to-Abate Sectors and Net-Zero Progress in 2025

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Foreword



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The industrial transition has entered its decisive period.

Across hard-to-abate sectors, the technologies required to cut emissions are proven. About half of industrial emissions can already be abated with mature solutions; the rest will depend on deeper innovation, stronger policy and enabling infrastructure. The task ahead is rapidly scaling solutions globally and profitably, ensuring the path to net zero strengthens industrial competitiveness and economic growth.

Scaling the Industrial Transition: Hard-to-Abate Sectors and Net-Zero Progress in 2025, developed by the World Economic Forum in collaboration with Accenture, captures this pivotal moment. Building on the Net-Zero Industry Tracker framework, it assesses progress across eight sectors that together account for nearly 40% of global greenhouse gas emissions.

This year's analysis marks a moment of adjustment and acceleration: progress is real but uneven. The next phase will hinge less on breakthroughs and more on deploying proven solutions that deliver security, competitiveness and sustainability. Clean technologies are advancing, but deployment is constrained by high costs, policy fragmentation and infrastructure gaps.

The focus is shifting from "Can we?" to "Can we deploy at cost and at scale?" under tightening economic, policy and energy constraints. Climate policy is moving from voluntary ambition to enforced accountability, but unevenly across regions, complicating trade and investment. Artificial intelligence (AI) and digitalization are projected to drive nearly 10% of global electricity growth by 2030, forcing industries to secure low-carbon power. Meanwhile, supply chain concentration in critical minerals has become a key area topic of discussion.

Four trends characterize this next phase:

- 1 **Economic viability:** Technologies are available, but scale depends on cost competitiveness, financing models and risk sharing. A 5% rise in interest rates can raise wind and solar costs by about 30%.
- 2 **Integration:** Synchronized investment in grids, carbon dioxide and hydrogen infrastructure, ports and industrial clusters is essential. Grid spending, about \$400 billion annually today, may rise to \$483 billion by 2030, yet BloombergNEF (BNEF) estimates \$811 billion per year will be required for net zero.
- 3 **Accountability:** Verified carbon intensity is becoming central to licensing, financing and trade. The EU's Carbon Border Adjustment (CBAM) and expanding Emissions Trading System (ETS) frameworks will cover over 45% of regional industrial emissions by 2030.
- 4 **Innovation:** Progress depends on lowering the cost of capital, building shared infrastructure and aligning global standards. Fewer than 10% of hydrogen projects and under half of carbon capture, utilization and storage (CCUS) projects have reached final investment decision (FID). The main barrier is not technology, but a lack of clear policy and reliable demand.

The transition is entering a more complex phase marked by regional divergence and system interdependence. Success will depend on how effectively markets, governments and industries align across demand, policy, infrastructure and capital to make proven technologies investable at scale. This paper calls for collective action to scale what works today, de-risk the next wave of innovation and deliver competitive, clean industrial systems.

Executive summary

2025 marks a defining moment for industry – where competitiveness and productivity, not technology alone, define sustainable transformation.

This past year was a defining moment for the industrial transition – defined by the realities of scaling amid tightening economics and rising energy demand. Across hard-to-abate sectors – aviation, shipping, trucking, steel, cement, aluminium, primary chemicals, and oil and gas – technologies to cut emissions exist, but scaling now depends on bankability, profitability, infrastructure and execution rather than invention.

This year's edition finds that confidence in technology remains high, but progress is constrained by enabling systems. Roughly half of industrial emissions can be abated with mature solutions; the other half depends on deeper innovation, stronger policy support, plus enabling infrastructure. Hydrogen and carbon capture, utilization and storage (CCUS) remain in early stages, progressing through pilots, but fewer than 1 in 10 projects reach the final investment decision. The primary constraint has shifted from technical feasibility to economic and operational viability. Energy costs, policy fragmentation and infrastructure gaps now determine what can scale.

Reaching net-zero across these sectors will require around \$30 trillion in additional investment, 57% from the broader ecosystem – grids, ports, carbon dioxide (CO₂) and hydrogen infrastructure – and 43% from industry itself. While Europe tightens compliance, the US – traditionally incentive-led – faces growing uncertainty following the rollback of several clean-energy measures, including renewable and electric vehicle tax credits. This fragmentation is redefining industrial competitiveness – markets now operate under different environmental standards, and costs and incentives rarely align. The result is a multi-speed transition. Clean energy investment will reach \$2.2 trillion in 2025 – twice that of fossil investment – but 90% of this capital since 2021 has gone to advanced economies and China as well as proven technologies, leaving emerging markets and early-stage solutions underfunded.

Several structural lessons emerge.

Policy fragmentation is reshaping markets:

Regions are moving towards compliance and accountability, but through divergent mixes of incentives, carbon pricing and disclosure frameworks.

Economic viability defines scale: Rising financing costs, combined with weak demand for low-carbon solutions, constrain investment. Competitiveness depends on reducing emissions while maintaining cost advantage through bankable projects, predictable offtakes and credible policy frameworks.

Integration for scale will determine success:

The next phase depends on aligning technology, infrastructure, policy and capital so proven solutions can scale profitably and predictably – connecting power grids, CO₂ transport and storage networks, hydrogen corridors and integrated industrial clusters. Looking ahead, several priority actions stand out.

- **Create demand certainty** through standardized green-material contracts, public procurement and buyers' alliances.
- **Build shared infrastructure** – integrated power, hydrogen and CO₂ transport and storage networks – that reduces costs and drives cross-sector scaling.
- **Lower the cost of capital** via blended finance, carbon contracts for difference and risk-sharing tools, particularly in emerging markets.
- **Scale market-ready solutions while nurturing innovation** – fast-track electrification, efficiency and storage; support hydrogen and CCUS where viable and enhance energy security and growth.
- **Balance top-down frameworks with bottom-up innovation** by aligning stable policy direction with flexible, locally driven business solutions.

The message from 2025 is clear: industrial transformation is advancing, but progress remains incomplete. The next frontier requires governments and industries to work in tandem so that low-carbon technologies become investable, scalable, inclusive and globally competitive.

1

Trends and progress in industrial transformation

Fragmented policies and trade are reshaping industrial transition – progress is real, but scaling now depends on economics and execution.

Key takeaways



Real momentum, but progress under pressure

Clean technology deployment is progressing – for instance, global electricity use in industry grew by almost 4% in 2024¹ – yet overall delivery is constrained by input prices, infrastructure gaps and uneven demand growth.



Policy fragmentation is redefining competitiveness

Divergent regional frameworks and carbon standards are driving asymmetries in trade and investment, creating uneven playing fields across markets.



Technology is advancing, but viability sets the pace

Roughly 50% of industrial emissions can already be abated with mature technologies, yet scaling now depends on bankability, demand certainty and financial feasibility.



Integration is the next frontier

Scaling requires moving beyond one-off low-carbon projects towards integrated portfolios, supported by aligned innovation, infrastructure and finance.

1.1 The year in review

In a world of rising demand, shifting trade patterns and digital and technological disruption, the central question is how industry can remain competitive while accelerating the energy transition. Can industrial systems sustain growth and efficiency while cutting emissions, adapting to new energy dynamics, and maintaining security

and cohesion in an increasingly fragmented global landscape?

Table 1 summarizes how key dynamics have evolved since 2024 – highlighting where progress has stalled, momentum has shifted and new constraints have emerged.

TABLE 1 2025 in review – what has changed?

Topic	2024 snapshot	2025 update	Strategic relevance
Net zero	Strong policy momentum and expanding corporate net-zero pledges; some efficiency and emissions improvements, though progress remains insufficient	Progress is uneven; corporate ambition continues to rise, yet regional policy momentum is diverging (EU, Middle East, India positive; US rollback); companies shifting towards commercially driven decarbonization strategies	↔
Economic/capital	High interest rates made capital availability a binding constraint	Rates eased slightly, but bottlenecks shifted to project economics/bankability with exchange-rate volatility raising costs in emerging markets	↔
Tariffs and trade policy	Limited policy attention; marginal to analyse	Now central, with new tariffs and policy uncertainty affecting supply chains, raising costs and refocusing on self-reliance	↑
Green technology	Strong policy support for emerging solutions such as hydrogen, biofuels and CCUS; early pilots showing promise	Deployment remains uneven: mature technologies (renewables, electrification and storage) are scaling rapidly, while hydrogen progress remains subdued amid cost pressures and demand uncertainty	↑
AI–energy nexus	Nascent technology with speculative benefits	Now fully operational, driving a surge in electricity demand and a race for green electrons and grid access, while also opening new opportunities to optimise energy assets and systems	↑

Note: Arrow indicates the overall trend in momentum since 2024.
Source: World Economic Forum.

Together, these shifts mark 2025 as a year of transition under tension. The foundations for reducing emissions in heavy industry exist, but are increasingly shaped by regional asymmetry and technological disruption.

New growth engines are reshaping energy demand. The surge of electrification (+4.3% in 2024),² automation and artificial intelligence (AI) has created new industrial loads and altered the geography of energy use. In 2024, global energy demand rose 2.2%, well above the decade’s average, with AI and data centres alone projected to drive nearly 10% of global power demand growth by 2030.³ These concentrated and inflexible loads are redefining how grids are planned, financed and operated – testing resilience, reliability and cost efficiency in real time.

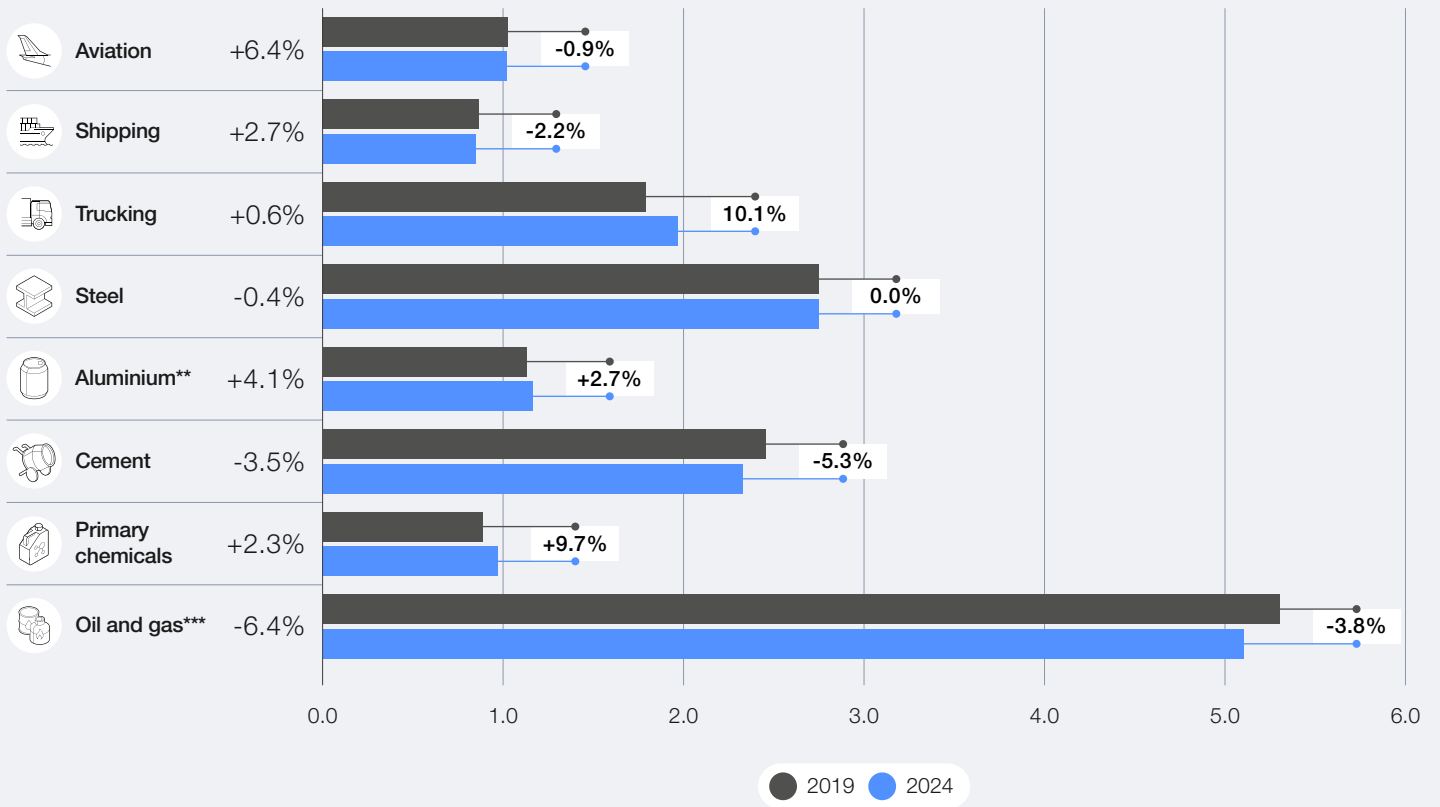
Industry alone accounted for nearly 40% of global electricity demand growth in 2024. Industrial electricity use rose nearly 4% – a marked acceleration from 2023, driven by expansion in electro-intensive manufacturing and broader industrial recovery.⁴ This surge in industrial

electrification signals progress but also intensifies pressure on grids, supply chains and power costs.

Meanwhile, carbon dioxide (CO₂) emissions rose 0.9% to 38.2 gigatonnes (Gt) of CO₂ in 2024 – a record high (Figure 1). Emissions trends vary sharply by sector, with recent declines in cement and steel, while aviation, aluminium and primary chemicals show notable increases. Under current policies, emissions are projected to remain near 38 Gt through 2035, showing no sustained decline. Stated policy pledges could modestly cut emissions – about 1% per year to 2050 – but only the Net Zero by 2050 Scenario, as outlined by the International Energy Agency (IEA), delivers a structural transformation, requiring a nearly 7% annual drop in global emissions this decade (Figure 2).⁵ This divergence underscores that reducing emissions in hard-to-abate sectors remains the defining challenge of the decade. Heavy industries, such as steel, cement, aluminium, oil and gas, and trucking, remain central to industrial value chains and account for a dominant share of global emissions (nearly 40%), exposing the delicate balance between energy security, affordability, and climate ambition.

FIGURE 1 | CO₂ emissions in hard-to-abate sectors in Gt CO₂ equivalent (CO₂e), 2019 vs. 2024

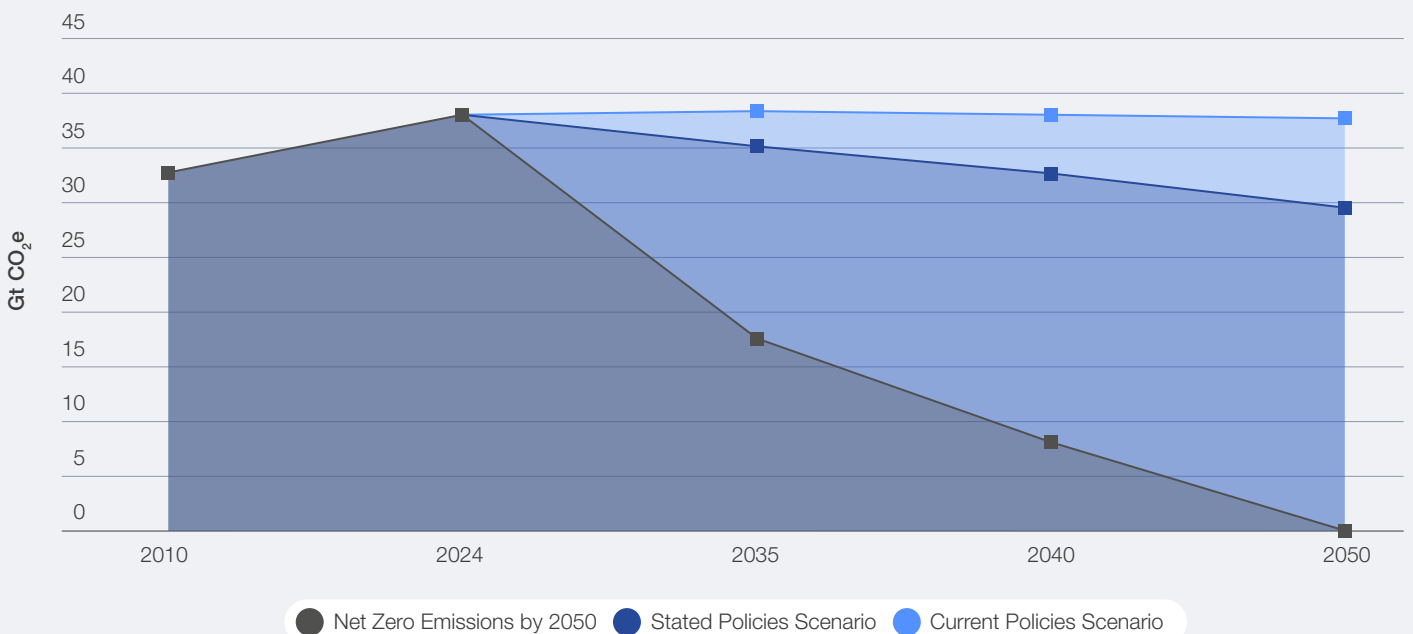
YoY change*



*Year-on-year (YoY) change represents 2024 vs. 2023 (except for oil and gas which is 2022 vs 2021); **Aluminium and primary chemicals 2024 data based on Accenture analysis; ***Oil and gas data for 2018–2022 since data onwards 2023 not available; oil and gas refers to Scope 1 and 2 emissions.

Source: World Economic Forum.

FIGURE 2 | World CO₂ emissions projection in Gt CO₂e, 2024–2050



Source: International Energy Agency (IEA); World Economic Forum.

“ In 2024, global CO₂ emissions rose 0.9% to about 38 Gt – the highest on record – as energy demand climbed roughly 2%, including a 4% increase in electricity use.

Technology progress is real, but scaling remains constrained by system readiness.

Energy sources are diversifying, but investment and policy clarity continue to lag. Renewables and nuclear are competing to anchor supply for both industrial and digital demand, yet cost structures, permitting timelines and infrastructure bottlenecks remain constraints. Sustainable aviation fuel (SAF) is advancing from pilots to early scale: global output is expected to roughly double to about 2 million tonnes (MT) in 2025 (approximately 0.7% of jet fuel)⁶ – a step up that is still far short of needs. Asia is adding capacity faster than local demand, likely exporting surplus and easing prices at the margin. The EU’s ReFuelEU mandates (2% SAF in 2025, ramping steeply thereafter to 70% by 2050)⁷ are set to strengthen demand signals and accelerate uptake.

Yet the transition is advancing under financial and structural strain. Energy prices have eased from their crisis peaks, but volatility persists, eroding competitiveness for energy-intensive users such as chemicals, aluminium and digital infrastructure, and exposing how fragile industrial competitiveness remains in competitive cost environment. Investment patterns are shifting too: clean energy investment remains resilient, expected to reach \$2.2 trillion in 2025, roughly twice the capital directed to fossil fuels.⁸ Yet annual

growth has slowed to 11% in 2024, down from the 24–29% expansion of previous years.⁹ Volatile interest rates, fiscal tightening and risk aversion – particularly in emerging economies – have made clean capital more expensive, with exchange-rate volatility further raising financing costs and deterring foreign investment.

Overlaying all of this is a new geography of energy and trade. Tariffs, regional carbon prices and export controls are redrawing trade and technology routes, reshaping cost structures and supply chains, and creating a more regionalized energy landscape. Demand for key minerals surged in 2024 – lithium up nearly 30%, nickel, cobalt, graphite and rare earths rising 6–8% year-on-year (YoY),¹⁰ and battery demand up 25%, driven by electrification.¹¹ Yet supply remains highly concentrated: China controls around 70% of global earth production and processes almost 90% of the world’s rare earth elements,¹² intensifying competition for access and creating pressure on other regions to secure alternative suppliers and diversify sourcing. As global supply chains reorganize around resilience rather than efficiency, affordability and security are increasingly seen as prerequisites for sustainability, not trade-offs. The transition will advance only as fast as access to these essential materials allow, because critical minerals underpin many low-carbon technologies.

BOX 1

Scaling the Industrial Transition: Hard-to-Abate Sectors and Net-Zero Progress in 2025

Scaling the Industrial Transition: Hard-to-Abate Sectors and Net-Zero Progress in 2025 marks a new phase in the evolution of the Net-Zero Industry Tracker (NZIT) focusing on a qualitative assessment of progress, readiness and system alignment across the world’s most emission-intensive sectors. It focuses on two core questions:

- 1 **How fast are sectors progressing today?**
- 2 **What conditions must be strengthened to accelerate their transformation?**

This year’s edition takes a different form.

Rather than serving as a data tracker, which will be made available online, the 2025 white paper synthesizes the main system-level barriers and enablers shaping industrial transition. It builds on the NZIT’s analytical framework but focuses on interpretation, readiness and scaling dynamics. The **quantitative dashboards and sector data** will be released separately, providing **data-driven snapshots and indicators** that complement this narrative assessment.

Launched by the World Economic Forum in 2022, the NZIT provides a fact-based framework to assess the decarbonization progress of hard-to-abate industries against net-zero targets for 2030 and 2050. Covering eight emission-intensive sectors – aviation,

shipping, trucking, steel, cement, aluminium, primary chemicals, and oil and gas – the NZIT benchmarks actual system performance and readiness to transform.

System performance is assessed through indicators such as industry output, operational process intensity, energy mix, and value chain emissions and offsets, providing a clear view of actual sectoral progress. Readiness is assessed across five enablers: technology, demand, policy, infrastructure and capital. These dimensions highlight where structural conditions are in place – and where gaps remain – to accelerate industrial transformation.

Each edition alternates between a comprehensive quantitative assessment (2024 edition) and a focused update (this edition), ensuring continuity of insights while balancing depth with efficiency. The NZIT integrates global net-zero pathways from key international and sectoral bodies and industry roadmaps, comparing business-as-usual trajectories with net-zero-aligned pathways to reveal the scale of action required.









By combining annual pulse checks with periodic deep dives, the NZIT helps decision-makers prioritize interventions, track sectoral progress, and accelerate the transition of the hard-to-abate sectors.

1.2 State of play of the industrial transition

In 2025, there has been progress in industrial transition, though it remains uneven (Table 2) – electrification is expanding, renewable generation is accelerating and energy storage is scaling rapidly. In 2024, renewables accounted for 92% of new electricity capacity,¹³ while sales of electric trucks surpassed 90,000, growing 80% YoY.¹⁴

At the same time, scale-up is constrained more by economics and system readiness than by technology: fewer than 1 in 10 clean hydrogen projects have reached final investment decision (FID),¹⁵ reflecting financing, permitting and infrastructure gaps that limit deployment and profitability.

TABLE 2 **Sectoral snapshot: demand growth, low-carbon supply and emissions trends**

Sector	Activity	YoY change in activity (2024 vs 2023)	Emissions (Gt CO ₂) and YoY change (2024 vs 2023)
 Aviation	8.8 trillion RPK* (actual passenger traffic carried)	+10.4%	1.108 (+6.4%)
 Shipping	121.7 trillion tkm* (annual distance covered)	+5.5%	0.847 (+2.7%)
 Trucking	35.1 trillion tkm* (annual distance covered)	+1.3%	1.968 (+0.6%)
 Steel	1,883 MT (annual production)	-1.1%	2.750 (-0.4%)
 Aluminium	113 MT (annual production)	+4.6%	1.162** (+4.1%)
 Cement	3,950 MT (annual production)	-3.9%	2.324 (-3.5%)
 Primary chemicals	754 MT (annual production)	+3%	0.971** (+2.3%)
 Oil and gas	Oil: 103 mbpd*	Oil: +4%	5.100*** (-6.4%)
	Gas: 411 bcfd* (annual production)	Gas: +1.5%	

*RPK = revenue passenger-km; tkm = tonne-km; mbpd = million barrels per day; bcfd = billion cubic feet per day. **Data sourced from World Economic Forum. ***Latest data available from 2022.

Sources: Airports Council International World & International Civil Aviation Organization (ICAO). (2025). *Joint ACI World-ICAO passenger traffic report, trends and outlook*; International Energy Agency (IEA). (2025). *World Energy Outlook 2025*; World Steel Association. (2025). *World Steel in Figures 2025*; International Aluminium Institute. (n.d.). *Primary aluminium production*; International Energy Agency (IEA). (2025). *Oil 2025: Analysis and forecasts to 2030*; International Energy Agency (IEA). (2025). *Gas 2025: Analysis and forecasts to 2030*.









Hard-to-abate sectors are entering a new phase. Efficiency remains a critical lever – particularly in aviation, shipping and trucking – where design and operational optimization deliver near-term emission cuts. In aviation, for instance, aircraft fuel efficiency improved by around 2.5% per year over the past decade, limiting a 35% rise in air travel demand to only a 20% increase in energy use. In shipping, activity rose nearly 30% between 2015 and 2024, yet oil demand increased by less than 5% to around

5 million barrels per day (mbpd), thanks to strong efficiency gains and gradual fuel diversification.¹⁶ Meanwhile, industries such as steel, aluminium and cement are transitioning from traditional, high-emission processes towards fuel switching to natural gas, hydrogen, electrification, recycling and carbon capture. Trucking exemplifies this dual transition, with battery-electric vehicles scaling for short-haul and hydrogen fuel cells emerging for heavy freight.

While aviation and shipping are advancing system-wide agendas through global frameworks such as the International Civil Aviation Organization's (ICAO) and International Maritime Organization's (IMO) Net-Zero Framework, the recent IMO decision to delay adoption by a year to October 2026 highlights uneven global regulation. Petrochemicals and oil and gas are also reframing their growth models,

shifting from fuel-based to materials-based value creation – using hydrocarbons as feedstocks for chemicals, materials (including advanced materials) and low-carbon fuels. In doing so, they are positioning themselves as enablers of the broader transition, anchoring integrated industrial clusters and carbon management systems (Table 3).

TABLE 3 Carbon reduction progress in 2025 across hard-to-abate sectors

Sector	Current progress	Core transition lever	Main barrier to scale
 Aviation	Gradual SAF uptake and aircraft efficiency gains as mandates in Europe come into effect and new aircraft is delivered	SAF and operational efficiency	High SAF fuel cost and commercial viability
 Shipping	Pilots in ammonia (NH ₃) and early commercial scale in methanol as regional regulation like EU Emissions Trading System (ETS) come into effect while dual-fuel new builds enter the fleets	Efficiency upgrades and low-carbon fuels (NH ₃ , H ₂)	IMO's delay on global regulation, supply chain alignment, fuel-infrastructure gaps
 Trucking	Electrification in short-haul, H ₂ pilots for heavy freight	Dual-tech approach (battery/H ₂) and integrated ecosystem (grid, charging)	Refuelling and charging infrastructure gaps, fleet turnover cost and limited fleet readiness
 Steel	Early adoption of H ₂ , electrification, recycling, CCUS pilots	Redesign of core production processes	High capital intensity, reliable clean energy supply, cost verification and premium
 Aluminium	Gradual use of low-carbon electricity and recycling, with early pilots in inert-anode and energy-efficient smelting technologies	Electrification and recycling, supported by breakthrough smelting technologies (inert anodes) and low-carbon power sourcing	Electricity costs, limited access to reliable low-carbon power, mobilizing recycling logistics and slow commercial readiness of next-generation smelting technologies
 Cement	Early-stage pilots in low-clinker materials and CCUS integration	CCUS integration and redesign of core production processes	Lack of clear demand signal from buyers, absence of regulation and public procurement favouring low-emission cement, limited financing for decarbonized production
 Primary chemicals	Moving from fuel-based to materials-based growth, early CCUS and CO ₂ -based feedstocks	CCUS integration and circular economy models	Weak demand and uncertain pricing for low-carbon products
 Oil and gas	Expanding CCUS and H ₂ hubs, methane-abatement efforts	Clustered CCUS and storage networks, methane reduction technologies	Asset decarbonization economics, volatile carbon prices and slow policy alignment

Source: World Economic Forum.



1.3 Industrial transition dynamics in 2025

“ Global climate policy is moving from ambition to accountability, with carbon performance now defining cost, access and competitiveness.

A change in the policy landscape

Global climate policy is shifting from voluntary ambition to enforceable accountability. Across regions, disclosure mandates, performance standards and carbon pricing mechanisms now make verified emissions data a condition for market access – not just a signal of corporate reputation.

As incentives and compliance frameworks converge, verified carbon intensity is becoming a key determinant of cost, financing and competitiveness. This shift is giving rise to hybrid policy models that tie emissions verification directly to economic outcomes – embedding carbon performance into the rules of trade and investment.

The result is a fragmented global policy landscape: compliance rules are designed and enforced locally, but their economic reach extends across borders. Multinational firms face a complex landscape of overlapping and sometimes conflicting systems, requiring them to balance diverse reporting regimes and price signals. Yet, as most incentives remain domestically focused, many exporters bear compliance costs without enjoying corresponding financial advantages.

The policy landscape is evolving unevenly across regions:

- **Europe** is deepening compliance frameworks through the expansion of the Emissions Trading System (ETS2), the implementation of the Carbon Border Adjustment Mechanism (CBAM) and sector-specific measures such as FuelEU and ReFuelEU. While CBAM directly links verified carbon performance to market access, FuelEU and ReFuelEU focus on driving decarbonization in transport through renewable fuel mandates and efficiency standards. Together, these measures embed carbon pricing and emissions accountability directly into trade, transport and industrial value chains.
- **US** policy remains largely incentive-led at the federal level, anchored in the Inflation Reduction Act (IRA), but recent changes and early terminations of key tax credits – including for renewables, electric vehicles and charging infrastructure – have introduced significant uncertainty. State-level initiatives (e.g. California’s Cap-and-Trade Program and Clean Fuel Standard) continue to advance more compliance-oriented mechanisms.¹⁷
- **The Middle East and Latin America** are establishing the foundations of compliance through measurement, reporting and verification (MRV) frameworks, green taxonomy standards and early regional coordination on carbon-

pricing readiness and cross-border trade alignment. While most regimes remain in the preparatory or “pre-compliance” phase, these frameworks position both regions for future participation in carbon markets and cross-border trade alignment.

- **Asia** is scaling emissions trading systems and disclosure rules, with China’s ETS expanding into new sectors, Japan and South Korea integrating corporate carbon reporting, and India piloting carbon-credit and MRV systems.

The policy model is shifting from ambition to accountability – but in a regionally fragmented way. Incentives such as tax credits and innovation funds now coexist with mandatory standards, disclosure obligations and pricing mechanisms. This dual structure enhances transparency but raises compliance complexity and geographical asymmetry – shaping investment risk and competitiveness.

For investors and exporters – especially those in emerging and trade-exposed economies – inconsistent policies across jurisdictions amplify uncertainty and raise the cost of capital. In this compliance-driven landscape, carbon performance defines both market access and competitive advantage. Yet, without greater policy alignment, uneven rules risk turning the global transition into a patchwork of regional markets rather than a cohesive global system.

Economic viability has become the key barrier to scale

Economic viability has always mattered, but its importance has sharpened as rising interest rates, cost inflation and fragmented policy signals reshape the conditions for investment. What was once a low-cost capital environment that masked structural weaknesses has given way to one where financing, execution and policy coherence now jointly determine what can scale. For instance, a recent analysis by the IEA shows that a 5% increase in interest rates only modestly raises the levelized cost of electricity (LCOE) for natural gas but raises the LCOE for wind and solar by around 30%.¹⁸

The IEA also finds that both hydrogen and CCUS projects are showing signs of delay, with around 20% of planned CCUS capacity and a growing share of low-emissions hydrogen projects being deferred beyond their original timelines due to cost inflation, permitting hurdles and supply-chain constraints.¹⁹ These setbacks underscore a broader reality: while technical progress continues, execution and financing remain the defining bottlenecks. Across low-carbon sectors, many

“ Technology is not the main barrier – alignment is. Scaling now depends on synchronizing policy, capital, demand and infrastructure to deliver proven solutions at scale.

projects still struggle to reach investment stage. Technology is largely proven, but bankability is constrained by rising input costs, higher financing rates and uncertain demand signals. Within companies, low-carbon projects compete directly with higher-margin, established products; when decarbonized options raise costs or compress returns, capital often flows towards legacy operations. Early projects have underperformed not because of technical limitations, but due to policy gaps, incomplete planning and fragile offtake or permitting frameworks.²⁰

Energy-intensive industries now face a structural cost squeeze. Power and feedstock prices remain volatile, while grid bottlenecks and permitting delays drive up development timelines and capital costs. Investors, confronted with unclear demand and fragmented policy environments, demand higher risk premiums – pushing the cost of capital beyond what most low-carbon projects can sustain. The economics of industrial transition is now inseparable from industrial performance: the goal is not only to cut emissions but to deploy technologies that lower costs, stabilize energy access and drive innovation-led growth.

At the same time, market structures still fail to accurately reflect the true cost of carbon, leaving low-carbon solutions at a disadvantage compared to incumbent systems. Weak demand signals and limited willingness to pay a green premium further constrain investment confidence. The combination of price volatility, uncertain offtake and uneven cost internalization is reshaping capital allocation – favouring regions with cheaper, more predictable energy and stronger policy frameworks. Ultimately, project competitiveness, both in markets and within corporate portfolios, now depends as much on demand certainty and policy coherence as on cost efficiency.

Integration for scale will determine success

The transition is not constrained by invention alone – technological progress continues, but the primary bottleneck has shifted to integration and execution. The next phase depends on aligning innovation, infrastructure, demand and capital so that proven and emerging technologies can scale profitably and predictably.

Even as low-carbon solutions advance – from hydrogen-based steelmaking to next-generation

biofuels and carbon capture – market demand remains shallow and uneven. Producers face a widening gap between the cost of cleaner production and what buyers can absorb, a gap that policy incentives and voluntary offtakes only partly bridge. Corporate net-zero commitments continue to expand globally, often featuring interim 2030 targets that establish clear trajectories for emissions reduction. According to Accenture's *Destination Net Zero 2025* report, 41% of the world's 2,000 largest companies (G2000) now have comprehensive net-zero targets covering their entire value chain (Scope 1, 2 and 3), while 73% have set targets covering at least their own operations (Scope 1 and 2). However, despite this growing ambition, pledges have yet to translate into sufficient near-term, large-volume procurement of low-carbon materials, leaving many industrial producers without reliable demand signals.²¹

At the same time, capital remains abundant but increasingly concentrated. Clean energy investment reached \$2.2 trillion in 2025 – nearly twice that of fossil investment²² – yet the vast majority of this capital has been flowing to advanced economies and China,²³ leaving emerging markets underfunded. Investment increasingly flows to projects that can demonstrate deliverability, transparency and credible offtakes – where grids, infrastructure and regulation are aligned. Elsewhere, projects stall because financing, permitting and demand cycles fail to move in sync.

Innovation remains vital – but its focus must evolve. The challenge is no longer just to invent cleaner technologies, but to innovate in how systems connect and operate: integrating renewables into grids, building CO₂ transport networks, enabling hydrogen logistics, securing feedstock supply, and coordinating permitting and financing frameworks. Equally important is innovation in immaterial infrastructure – such as credible emissions measurement and verification systems, and trusted book-and-claim frameworks that allow buyers to support low-carbon production even when they are geographically or sectorally distant. These forms of system-level innovation, both physical and immaterial, will determine whether proven technologies can achieve commercial scale and attract the demand-side premiums needed to sustain them.

Ultimately, progress will depend on synchronization – matching technology advancement with the policy, capital and infrastructure systems that can deliver it at scale.

2

Enabling systems for industrial transformation

The foundations of industrial transition exist; what's missing is synchronized execution across five enablers: technology, demand, policy, infrastructure and capital.

Key takeaways



From readiness to deliverability

The transition is now defined by the effective alignment of five key system enablers – technology, demand, policy, infrastructure and capital – to turn proven solutions into investable, scalable.



Technology is advancing but unevenly deployed

Renewables are scaling, electrification is expanding and early commercial projects in hydrogen and CCUS are taking shape. Yet deployment remains uneven. Most core technologies are technically viable but not yet commercially deployable at scale, constrained by cost, permitting and demonstration risk.



Demand is forming but still too thin

Green procurement, buyers' alliances and border measures are emerging, yet volumes and green premiums and regional policy and regulatory consistency (varying mandates and targets) remain insufficient to drive industrial-scale investment.



Policy is diverging into regional compliance models

Verified carbon data, product standards and pricing mechanisms are becoming conditions for market access, but frameworks are evolving unevenly across regions. This creates a multi-speed policy environment that influences competitiveness and investment risk.



Infrastructure is the bottleneck

Grid, CO₂, hydrogen and port systems are growing too slowly to match generation and industrial demand, trapping ready projects between pilot and commercial scale.



Capital is selective, not scarce

Investment remains resilient but highly concentrated, increasingly directed towards projects that are bankable and can demonstrate deliverability – with credible offtake agreements, verified carbon data and reliable access to clean power.

2.1 Technology landscape is advancing but uneven

“ Many low-carbon technologies are proven, but scaling is held back by high costs, permitting delays and infrastructure gaps.








The aviation and shipping sectors are advancing through the use of sustainable fuels, efficiency gains and emerging hydrogen- and ammonia-based propulsion. The steel, aluminium and cement sectors are moving towards hydrogen, electrification, recycling and carbon capture. Trucking is pursuing battery-electric and hydrogen fuel-cell technologies. Meanwhile, oil and gas and petrochemicals are focusing on methane abatement, CCUS integration and low-carbon feedstocks to support industrial clusters and cleaner material value chains.

While most core technologies are technically viable, few are commercially deployable at scale. Hydrogen, CCUS, advanced biofuels and small modular reactors (SMRs) remain constrained not by

science but by cost, permitting and demonstration risk, limiting bankability and slowing replication. Solar photovoltaic (PV) systems continue to dominate, attracting roughly \$450 billion in 2025,²⁴ while nuclear investment has increased by 50% in five years.²⁵ Yet critical imbalances persist – grid investment (approximately \$400 billion annually)²⁶ lags generation growth, leaving system bottlenecks that hinder industrial electrification.

Across sectors, the transition has entered a new phase – complementing incremental efficiency gains with a redesign of fuel and material systems (Table 4). While readiness has advanced, deployment remains uneven, revealing where supportive policy and capital frameworks are still lacking.

TABLE 4 Status of key low-carbon technologies

Technology	Current momentum	Main enablers	Key barriers
 Renewable electricity	Mature and expanding, solar alone expected to attract \$450 billion in 2025 investment ²⁷	Falling capital expenditure (CapEx), corporate power purchase agreements (PPAs), strong policy support	Grid congestion, storage integration and permitting delays
 Energy storage	Fastest-growing segment: projected 35% growth in 2025 (94GW*/247GWh**)	Policy incentives, falling LFP*** battery costs, system balancing needs	High upfront costs, supply-chain volatility, weak revenue models
 Biofuels/SAF	Production scaling under mandates, SAF expected 2 MT in 2025 ²⁸	Mandates (ReFuelEU), corporate offtakes, green bonds, book-and-claim systems	Feedstock limits, 2–5-fold cost premium, slow tech commercialization ²⁹
 Hydrogen	Deployment uneven, IEA cut 2030 low-emission outlook approximately 25% amid project delays ³⁰	Subsidies like the IRA, EU Hydrogen Bank, industrial clusters, offtake contracts	High production cost, permitting and transport infrastructure gaps
 Nuclear	Political momentum and 50% investment rise in three years since 2020 (\$60 billion) ³¹	Energy-security focus, advanced designs, public-private R&D	Long timelines, financing risk, regulatory and supply bottlenecks
 CCUS	Around 60% of planned capacity now advanced or under construction ³²	Policy support (US Department of Energy, EU Innovation Fund), cluster development, offtake models	Permitting delays, storage access, fragmented business models
 Efficiency and digital solutions	5–10% potential cut in global greenhouse gas (GHG) emissions by 2030 through AI-enabled solutions	AI optimization, automation, data transparency	Limited interoperability, uneven adoption in emerging markets

*gigawatt; **gigawatt-hour; ***lithium ferrophosphate

Note: A detailed table with sector-specific examples for relevant technologies is shown in the Appendix.

Source: World Economic Forum.



“ Industrial transition is advancing – from efficiency and new materials to CCUS and hydrogen – but uneven progress reveals deep regional and system gaps.

The following trends highlight where technological progress is accelerating – and where system, cost and policy barriers continue to hold it back.

- **Efficiency gains remain essential but transitional.** While operational and digital improvements deliver near-term emissions reductions and competitiveness gains – with energy efficiency alone reducing cumulative emissions by only 16% through 2050 – industrial electrification and hydrogen mandates achieve a 42% reduction. This demonstrates that deeper transformation of processes and fuel systems is essential.³³
- **Bio-based fuels are crucial in the near to medium-term.** Policy support continues to drive expansion, but with about 95% of biodiesel still derived from edible oils, feedstock and food security constraints, as well as technical barriers, limit its long-term scalability.³⁴ In aviation, despite strong policy backing such as ReFuelEU, SAF supplied less than 1% of total jet fuel demand in 2025, highlighting the difficulty of scaling new biofuel pathways even in well-supported sectors.³⁵
- **Material innovation accelerates transformation.** Breakthroughs in steel, cement and aluminium point to a shift from efficiency-driven progress to the redesign of industrial chemistry – the core of true decarbonization. In cement, using low-clinker limestone calcined clay cement (LC³) blends can cut emissions by up to 40%, while CCUS offers an additional 36% reduction, making these the sector’s most powerful decarbonization levers.³⁶
- **Electrification defines the next frontier of scale.** Expanding clean power access and electrified technologies is reshaping industrial energy demand, but slow permitting and grid

constraints remain major barriers. Although building transmission lines takes only 1–2 years, projects often require a decade to complete due to planning and approval delays.³⁷

- **Supply chains emerge as differentiators.** Competitive advantage increasingly depends on secure access to critical minerals, components and skilled labour; regions that can align energy, materials and logistics will scale faster and at lower cost. Persistent bottlenecks in nickel, silicon and rare-earth elements could leave the US short by over 730 gigawatts (GW) – about one-third of its 2050 clean-energy capacity goal.³⁸
- **Hydrogen progress remains uneven.** There have been advances in Europe, Japan and the Gulf, but fewer than 10% of announced projects have reached final investment decision due to high costs, slow permitting, uncertain pricing and weak offtake demand.³⁹
- **CCUS is entering its proof phase.** Deployment is expanding rapidly, with the number of operational CCUS facilities rising 54% YoY and total facilities up by 17%.⁴⁰ Despite this, system integration remains the key bottleneck to large-scale implementation – particularly in ensuring adequate storage capacity, transport infrastructure and streamlined permitting to connect capture sites with long-term storage solutions.⁴¹

The challenge now is synchronizing the enabling systems that make technologies scalable: power generation, hydrogen supply, CO₂ transport and storage, ports, and grid infrastructure have become the true bottlenecks of industrial decarbonization. Technology readiness increasingly outpaces system readiness, making coordination, permitting and infrastructure investment the defining factors of the next phase of the transition.

2.2 Low-carbon demand is growing too slowly

Global low-carbon demand is rebounding across sectors, but not yet in a way that drives clean supply. Two distinct dynamics are at play:

- **Energy demand activity** is strong – industrial production, freight and mobility continue to expand.
- **Low-carbon demand**, however, remains thin and fragmented, making it difficult to substantiate systemic, large-scale investment in new supply.

Industrial and transport activity continues to expand – air travel rose 10.4% YoY (2024 versus 2023),⁴² maritime demand increased 5.5% in 2024,⁴³

and trucking activity grew 1.3% YoY (2024 versus 2023)⁴⁴ – reflecting a strong rebound in trade and mobility. Yet this growth is not translating into cleaner operations: SAF met only 0.3% of global jet fuel demand,⁴⁵ and low-carbon bunkering remains negligible. Steel and cement output contracted slightly in 2024 (-1.1% YoY for steel⁴⁶ and -3.9% YoY for cement),⁴⁷ but largely for cyclical reasons rather than structural decarbonization, indicating limited progress in reducing fossil dependence. However, the carbon intensity of cement production continues to fall YoY (-2.2% decline in CO₂/tonne of cement from 2020–2022⁴⁸), according to the Global Cement and Concrete Association’s (GCCA) *Net Zero Progress Report*, suggesting incremental efficiency and process gains even amid flat or declining output.

🔗 **Emissions and demand are climbing, but clean supply investments are held back by weak offtake incentives, uneven policy support and high costs.**

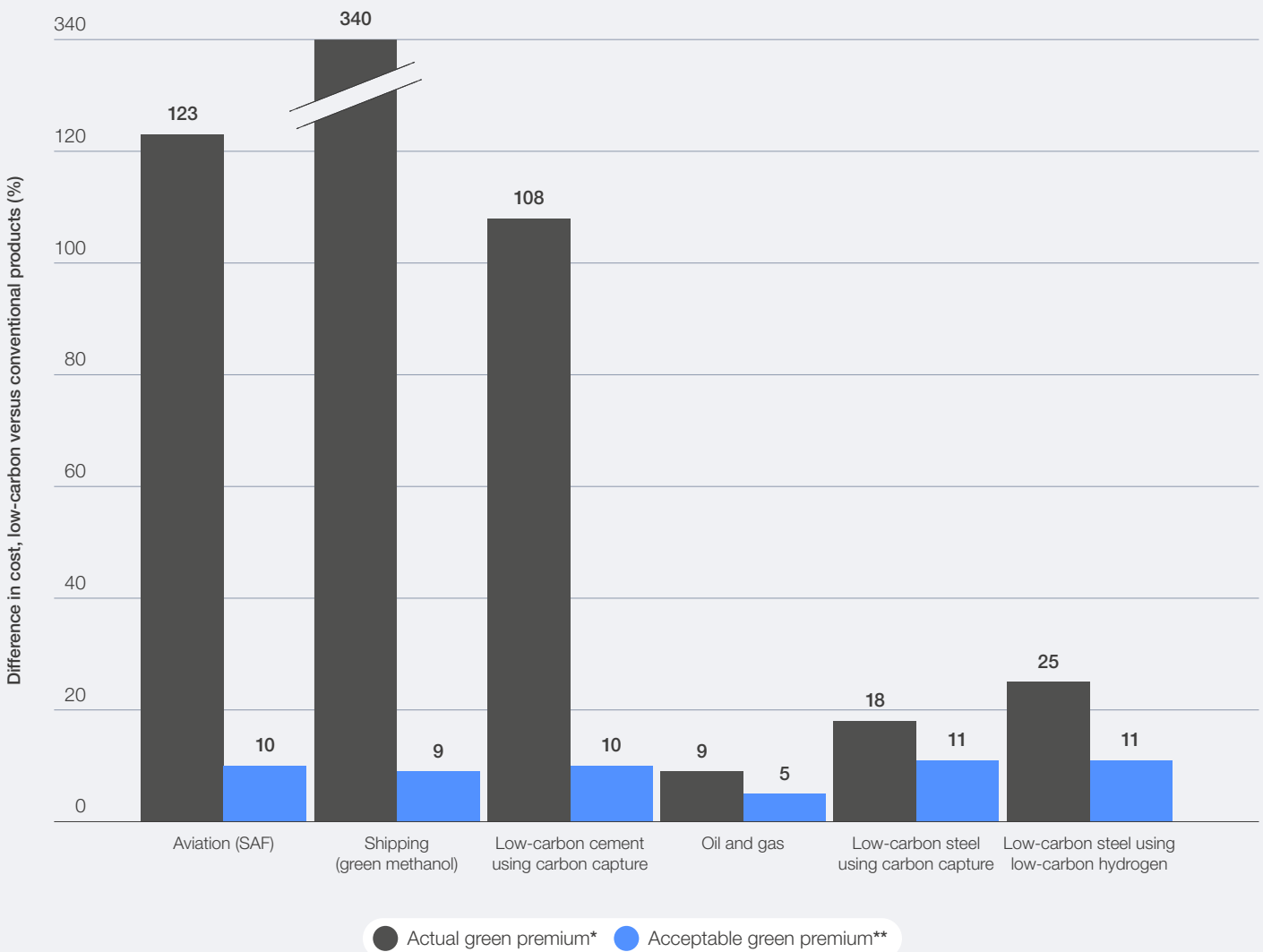
Corporate commitments to purchase green materials and fuels are rising, but voluntary uptake remains too limited to move markets alone. Price gaps, unclear certification, limited standardization and weak consumer willingness to pay continue to constrain procurement at scale. Across hard-to-abate sectors, demand for verified low-carbon products remains too fragmented to justify major investment in new supply.

The outcome is a widening demand–supply credibility gap: activity and emissions are climbing faster than clean-supply capacity. Global CO₂ emissions reached an all-time high in 2024,⁴⁹ and fossil-based output still dominates. Industry and transport already account for around 40% of global GHG emissions, and demand for these sectors is projected to rise by over 60% by 2050 – underscoring that without mandated and standards-based demand signals, clean supply cannot scale.⁵⁰

This demand–supply credibility gap persists because early frameworks and voluntary demand remain transitional. While regulatory frameworks are shaping price signals by embedding carbon costs and product standards, uptake still depends on voluntary and aggregated offtakes. Mechanisms such as the EU CBAM, ReFuelEU Aviation and FuelEU Maritime are creating early “compliance-driven demand”, while buyers’ alliances like the First Movers Coalition (FMC), SteelZero, ConcreteZero and Sustainable Steel Buyers Platforms generate “voluntary market pull”. These efforts de-risk early projects by providing credible buyers and demand visibility. Still, volumes, contract tenors and green premiums remain too limited to make projects bankable (Figure 3). Converting intent into investment will require scalable demand mechanisms – such as public procurement, border adjustments that reward low-carbon content and standardized green-material contracts – to turn early pledges into long-term, investable markets.

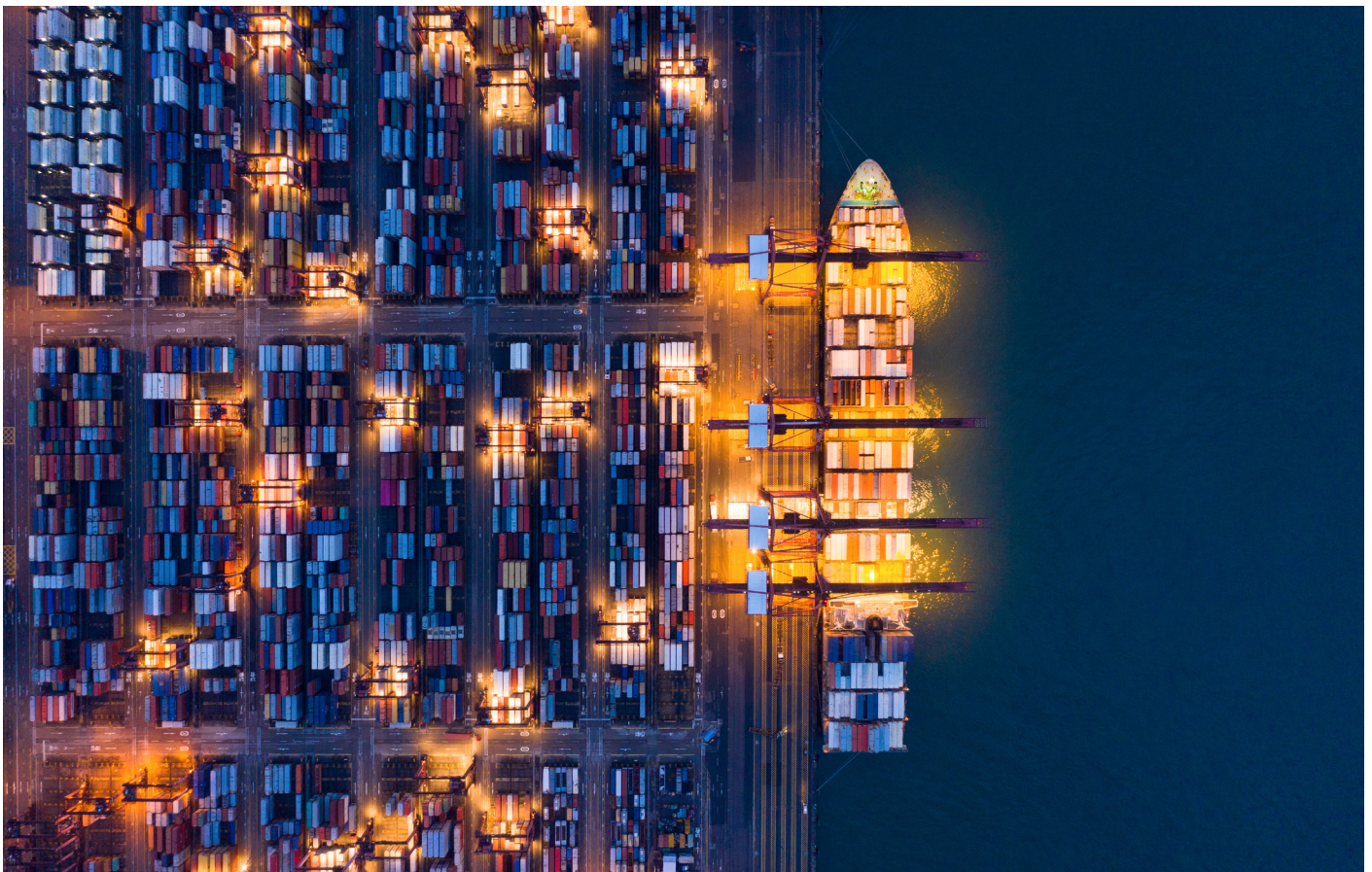
FIGURE 3 **Green premium gap across hard-to-abate sectors**

Actual vs. acceptable green premiums



*Difference in cost between low-carbon product versus conventional alternative; **Green premium that organizations are willing to pay

Source: Capgemini Research Institute.



2.3 Policy is fragmenting

“ Climate policy is shifting from ambition to accountability, entering a phase where incentives and compliance rules shape readiness together.

Verified carbon performance now defines cost, access and competitiveness, but the policy landscape is becoming regionally fragmented rather than uniformly convergent. Incentive-led systems are converging with mandatory compliance frameworks that link product carbon intensity directly to market access and trade. The EU is leading this shift. ETS prices are tightening (projected around €149/tonne of CO₂ by 2030)⁵¹ while free allocations will end for CBAM sectors from 2026, and the mechanism will move from reporting to full financial obligation. Moreover, ETS2 extends pricing to fuels by 2027, and ReFuelEU Aviation and FuelEU Maritime regulations will require verified emissions data and minimum use of sustainable fuels as conditions for market access.

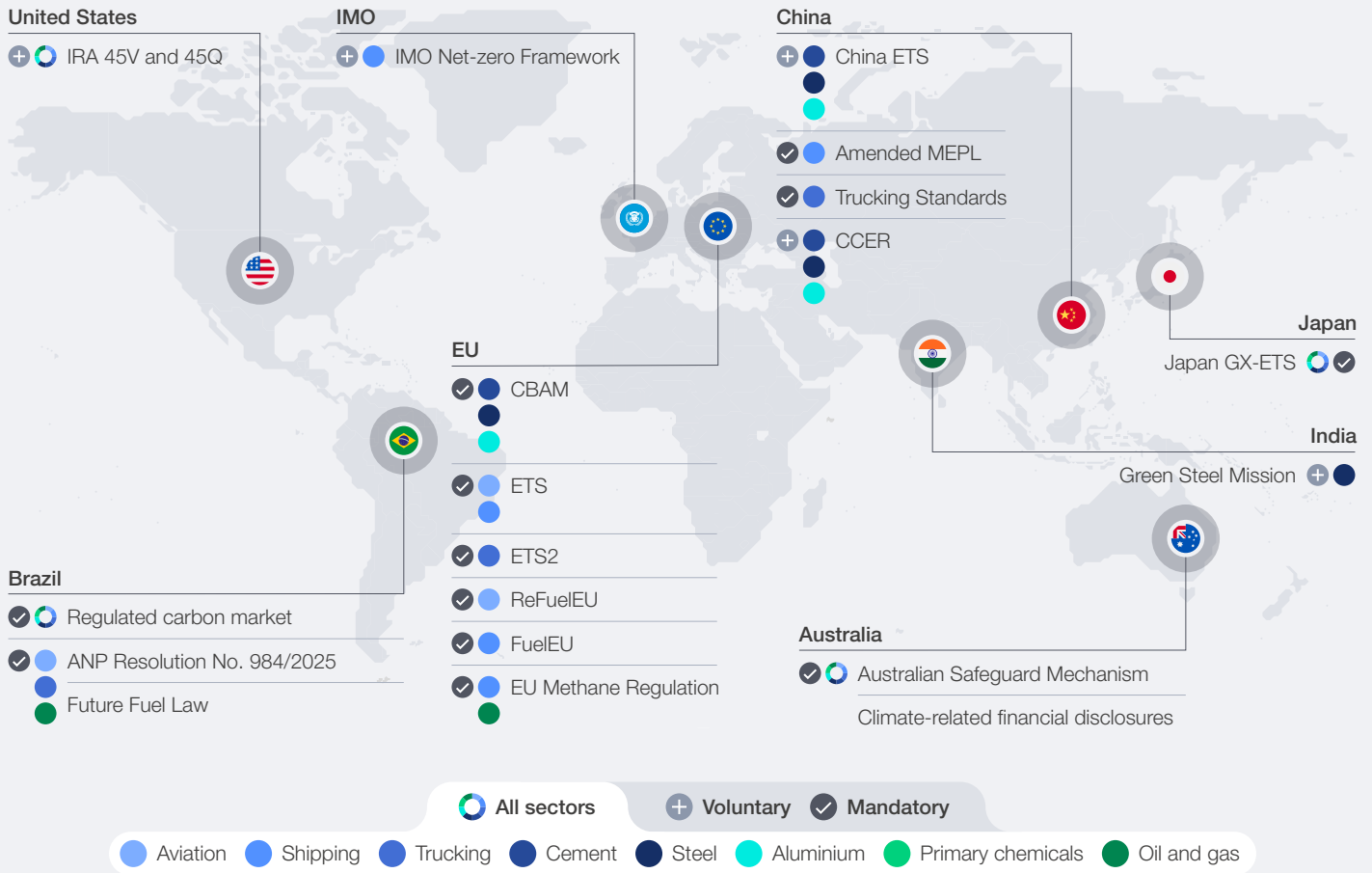
Compliance frameworks are proliferating globally, with major economies expanding carbon markets, disclosure rules and MRV systems (Figure 4). Elsewhere, policy divergence is widening. The US, historically focused on incentive-led policies under the IRA, has seen a rollback of several federal clean-energy provisions in 2025, with select tax credits – such as hydrogen (45V) and sustainable fuels (45Z) – consolidated under the new One Big Beautiful Bill Act (OBBBA). While federal support has narrowed, state-level initiatives such as California’s Cap-and-Trade Program, Clean Fuel Standard and regional

hydrogen hubs continue to drive compliance-oriented progress and investment. Asian economies are advancing carbon markets and MRV systems at varied speeds, and emerging regions are building foundational disclosure and taxonomy frameworks.

This patchwork creates a multi-speed policy environment in which cross-border trade, financing and carbon accounting remain uneven. Incentives remain vital – from the US IRA (despite rollbacks) and EU Innovation Fund to Germany’s Carbon Contracts for Difference (CfDs) and Japan’s Green Innovation Fund – but execution still lags ambition. CfDs, procurement rules and disclosure mandates, although large in scale globally, remain fragmented, varying in scope, stringency and timelines. Reversals such as the US Securities and Exchange Commission’s (SEC) 2025 rollback of climate disclosure rules⁵² underscore regulatory volatility.

The result is not a single shift from incentives to accountability, but a fragmented transition towards regional policy ecosystems, where competitiveness increasingly depends on verified carbon data and the ability to navigate overlapping standards. In this compliance era, auditable carbon data is the new passport for capital and trade: those who can prove low-carbon performance can secure investment and access, whereas those who cannot face rising costs and shrinking competitiveness.

FIGURE 4 | Global carbon reduction policy landscape



<p>EU</p> <p>CBAM: expanding coverage and refining emission methodologies to curb carbon leakage.</p> <p>ETS and ETS2: extending carbon markets to maritime, buildings, road transport and small industries, with tighter monitoring and methane reduction mandates.</p> <p>ReFuelEU: mandates rising use of SAF: 2% by 2025 and 70% by 2050.</p> <p>FuelEU: caps GHG intensity for large ships, targeting 80% reduction by 2050.</p> <p>EU Methane Regulation: enforces strict MRV, leak detection and bans routine flaring/venting in oil, gas and coal sectors.</p>	<p>China</p> <p>China ETS: Expanded to cement, steel and aluminium sectors covering an extra 3 billion tonnes of CO₂e.</p> <p>Revision of Marine Environment Protection Law (MEPL), Stage 4 fuel efficiency standards for heavy-duty vehicles, and launch of China Certified Emission Reduction (CCER) programme – China's national voluntary carbon market linked to the ETS.</p>	<p>Brazil</p> <p>Brazil finalized a regulated carbon market law in 2024, moving towards implementation.</p> <p>National Agency of Petroleum, Natural Gas and Biofuels (ANP) resolution (update to RenovaBio): Expands biofuel credits, incentivizing faster low-carbon fuel adoption.</p> <p>Future Fuel Law: Mandates escalating ethanol, biodiesel and SAF blend targets.</p>	<p>Australia</p> <p>Safeguard Mechanism: mandates large emitters (>100,000 tCO₂e/year) to cut emissions 4.9% annually.</p> <p>Climate related disclosures: mandatory ISSB-aligned climate reporting for large entities from January 2025.</p>
<p>IMO</p> <p>Combines mandatory marine fuel standard and GHG emissions pricing – originally planned to be enforced from 2027, now postponed until 2028.</p>	<p>Japan</p> <p>Currently a voluntary ETS aiming for 46% GHG reduction by 2030. It will transition to mandatory ETS by 2026.</p>	<p>India</p> <p>India aims to decarbonize the steel sector via production-linked incentives (PLI), green hydrogen pilots and standardized green steel taxonomy.</p>	<p>United States</p> <p>Provides tax credits for clean hydrogen production (45V: up to \$3/kg), carbon capture and storage (45Q: \$85/ton) and clean fuels.*</p>

*One Big Beautiful Bill, passed July 2025, accelerated phaseout – moving construction deadline from 2033 to 2025 for full credit eligibility.

Sources: US Department of Energy; US Energy Information Administration; Presidency of the Republic of Brazil; Mayer Brown; World Biogas Association; International Maritime Organization (IMO); European Commission; International Energy Agency (IEA); International Carbon Action Partnership; International Council on Clean Transportation; China Briefing; Ministry of Steel India; Australian Government, The Treasury; Asia Society.

2.4 Infrastructure is expanding but strained

“Clean energy generation is accelerating, but infrastructure is lagging – grid limits, CO₂ transport gaps and rising AI demand now test system readiness.

While clean-energy generation is accelerating, delivery systems are falling behind. Grid congestion,⁵³ constraints with CO₂ transport, hydrogen logistics and inadequate port capacity are now the main bottlenecks to scaling industrial transition. Rapid electrification – driven by transport, heavy industry and the expansion of AI – is colliding with a surge in power demand from data centres. The emerging “AI–energy paradox” exacerbates system strain,⁵⁴ forcing industrial players to compete directly with digital infrastructure for limited, low-carbon grid capacity. Yet, the same technologies contributing to higher demand can also hold part of the solution: AI applications across hard-to-abate sectors can improve efficiency, optimize operations and reduce emissions (Table 5).

Still, these efficiency gains cannot compensate for the scale of physical infrastructure required. Grid

expansion, CO₂ transport networks, hydrogen corridors and port upgrades are advancing too slowly to meet rising demand. Energy storage is the bright spot: BloombergNEF projects 35% growth from 2025 to 94 GW/247 GWh (gigawatt-hour), with large projects advancing across the US, China, Saudi Arabia, South Africa, Australia, Chile, the United Kingdom and the Netherlands (Figure 5).⁵⁵ Shared CO₂ and hydrogen infrastructure – such as pipelines, storage hubs and ammonia-ready ports – is emerging as the most practical and cost-effective model, allowing multiple industries to share networks and reduce investment risk. Yet progress remains fragmented. Without faster investment in grids, CO₂ hubs, hydrogen corridors and ports, ready-to-build projects will stay stuck between pilot and scale, making infrastructure alignment the real test of transition readiness.

TABLE 5 AI industrial applications in hard-to-abate sectors









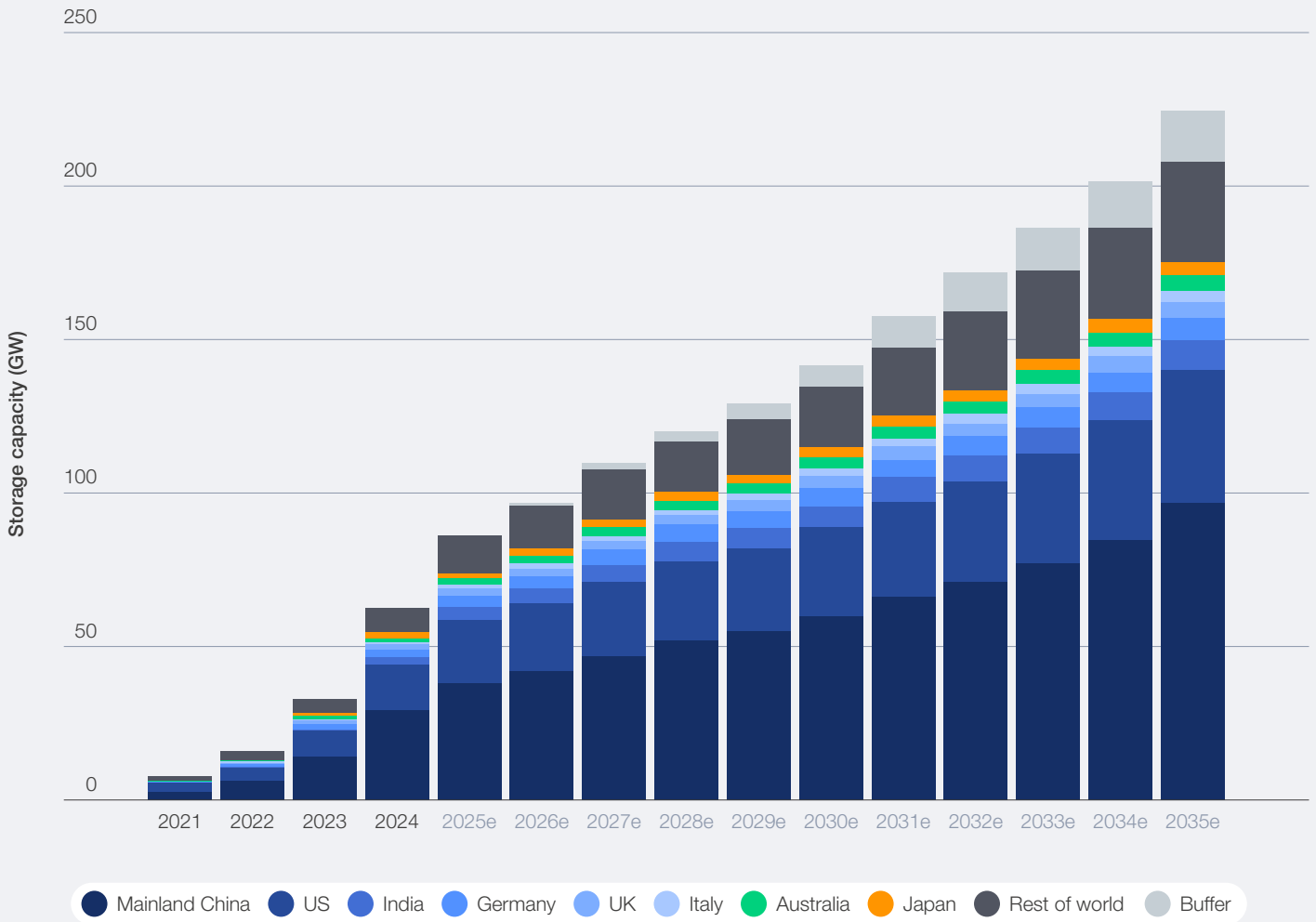
Sector	AI use cases	Decarbonization impact	Benefit
 Aviation	<ul style="list-style-type: none"> – Flight path optimization⁵⁶ – Demand analytics⁵⁷ – Predictive maintenance⁵⁸ 	Lower emissions per passenger-km, ⁵⁹ increased fleet efficiency, operational stability, ⁶⁰ potential reduction in non-CO ₂ impacts	3–8% fuel savings ⁶¹
 Shipping	<ul style="list-style-type: none"> – Route optimization⁶² – Digital twins of vessels⁶³ – Anomaly detection⁶⁴ 	Minimized fuel consumption, ⁶⁵ less downtime, lower CO ₂ emissions ⁶⁶	10% fuel savings per voyage 20% GHG emission reduction ⁶⁷
 Trucking	<ul style="list-style-type: none"> – Logistics and route optimization – Load management – Predictive vehicle maintenance⁶⁸ 	Reduces idle time, improves load factor, cuts per tonne of CO ₂ emissions	10–15% fuel savings, emission reduction ⁶⁹
 Steel	<ul style="list-style-type: none"> – Real-time furnace optimization⁷⁰ – Asset health prediction⁷¹ – Process control⁷² 	Reduces energy consumption, targets hotspots, improves operational efficiency ⁷³	5–10% emission reduction ⁷⁴
 Aluminium	<ul style="list-style-type: none"> – Load balancing – Predictive process control – Energy management⁷⁵ 	Reduced electricity consumption, higher smelting efficiency, fewer failures ⁷⁶	10% energy savings in smelters
 Cement	<ul style="list-style-type: none"> – Kiln process optimization⁷⁷ – Smart energy management⁷⁸ 	Lower energy use, clinker reduction, emission intensity drops ⁷⁹	10–15% energy reduction in kilns ⁸⁰
 Primary chemicals	<ul style="list-style-type: none"> – Process AI for safety⁸¹ – Catalyst design⁸² – Waste minimization⁸³ 	Decreases waste, flaring, energy use, boosts plant throughput	5% reduction in CO ₂ emissions, ⁸⁴ predictive maintenance improvements
 Oil and gas	<ul style="list-style-type: none"> – Energy optimization – Methane leak detection⁸⁵ – Predictive maintenance – Demand forecasting⁸⁶ 	Cuts methane leaks by up to 95%, ⁸⁷ improves energy efficiency, reduces Scope 1 and 2 emissions ⁸⁸	-40% methane reduction by 2030 ⁸⁹

FIGURE 5 | Global cumulative energy storage installations in gigawatts (GW), 2021–2035



Note: e = estimate

Source: BloombergNEF. (2025, 18 June). *Global Energy Storage Growth Upheld by New Markets*. <https://about.bnef.com/insights/clean-energy/global-energy-storage-growth-upheld-by-new-markets/>.

2.5 Capital flows are resilient but unevenly distributed

Investment momentum endures, but financing remains selective – favouring mature technologies and advanced economies over new projects and markets.

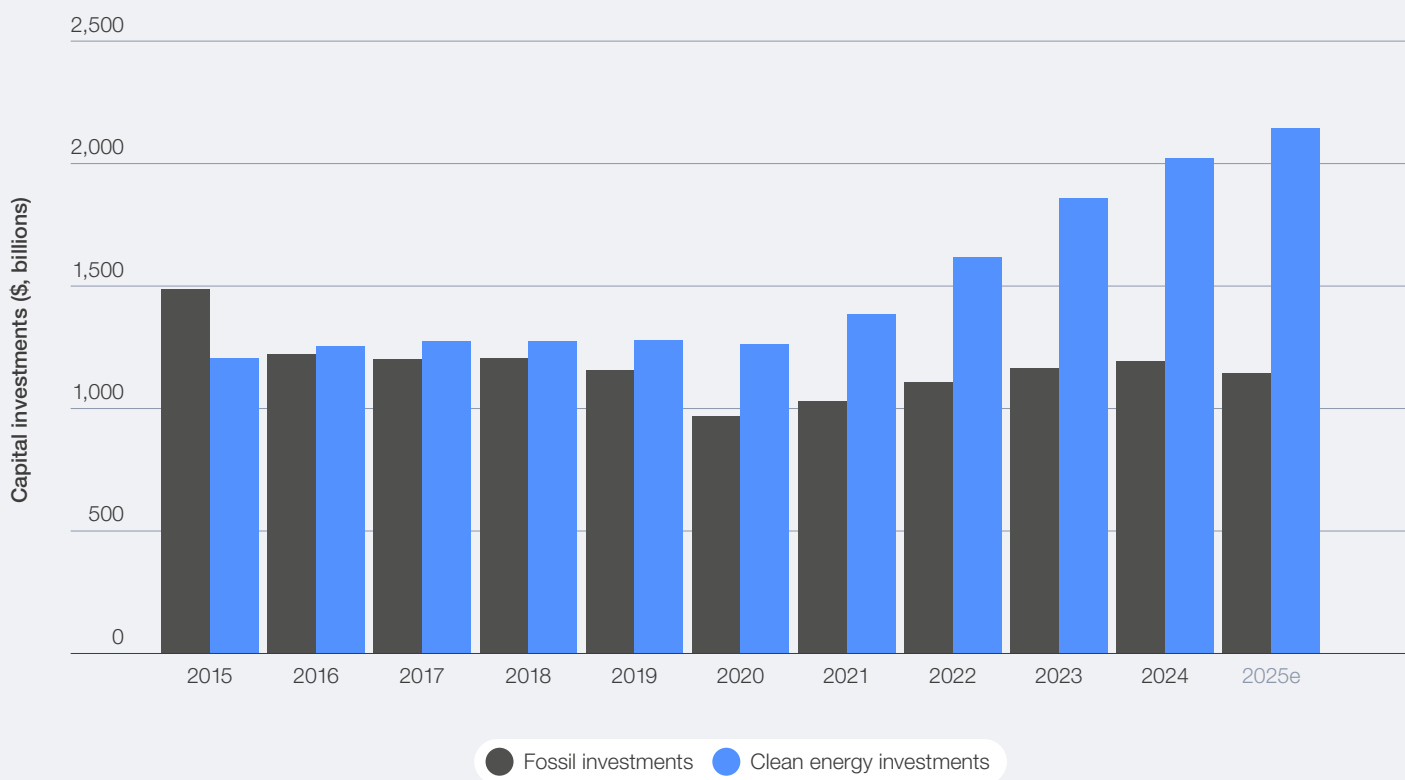
Investment in clean energy has increased, yet the growth has slowed to around 11% YoY in 2024, less than half the 24–29% YoY of previous years (Figure 6).⁹⁰ Higher interest rates, policy uncertainty and supply chain pressures have cooled investor appetite, making capital more selective, concentrated and costly. In hard-to-abate sectors, financing now flows only to projects that can prove deliverability – secure clean power access, credible offtakes and verifiable carbon data. Developments lacking these elements face higher premiums, delayed FIDs or cancellation. Investors are casting a wider technological net – from renewables and electrification to hydrogen, CCUS and sustainable fuels – but capital flow still favours technologies and initiatives that can deliver guaranteed returns, irrespective of diversification. A project

that cannot operate at market cost – even if innovative – will not scale. In aviation, over \$2 billion in green bonds have funded hydrogen and SAF infrastructure,⁹¹ while the EU Innovation Fund is backing SAF purchases through €100 million in ETS allowances.⁹²

In cement, sustainable finance volumes grew 17% in the first half of 2024,⁹³ led by Heidelberg and UltraTech's \$1.7 billion in CCUS and low-clinker investments.⁹⁴ Hydrogen-based pilots in steel and chemicals advances are observed mainly in Europe, Japan and the Gulf, where carbon pricing and offtake guarantees de-risk returns. Emerging tools such as transition bonds are also helping high-emission industries finance credible decarbonization without eroding competitiveness.



FIGURE 6 | Capital investments in energy (\$, billions), 2015–2025



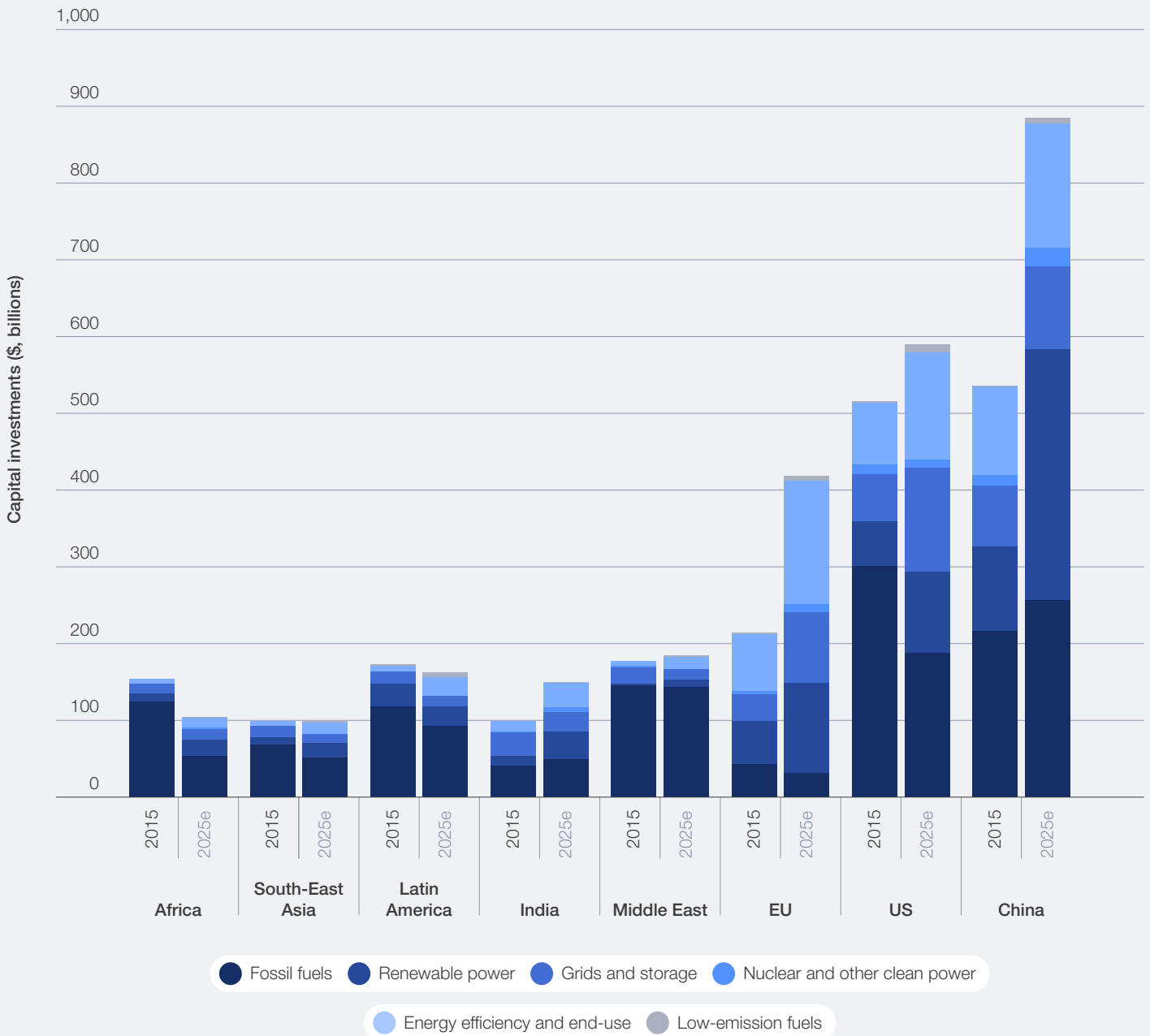
Note: e = estimate

Source: International Energy Agency (IEA).

Still, capital remains unevenly distributed. The Forum’s Energy Transition Index (ETI) 2025 shows that while 90% of clean investment since 2021 occurred in advanced economies and China, over 80% of future industrial demand lies in emerging markets, where financing costs are up to seven times higher (Figure 7).⁹⁵ Within sectors, funding clusters around lower-risk technologies and regions – hydrogen-steel and CCUS in Europe, SAF in OECD (Organisation

for Economic Co-operation and Development) markets – leaving others under-capitalized. First movers that align credible carbon performance with competitive economics already access lower-cost finance; others risk exclusion. The next phase of progress depends on broadening the investable base – through blended finance, transition bonds and carbon contracts for difference – to channel capital into projects that are both bankable and competitive.

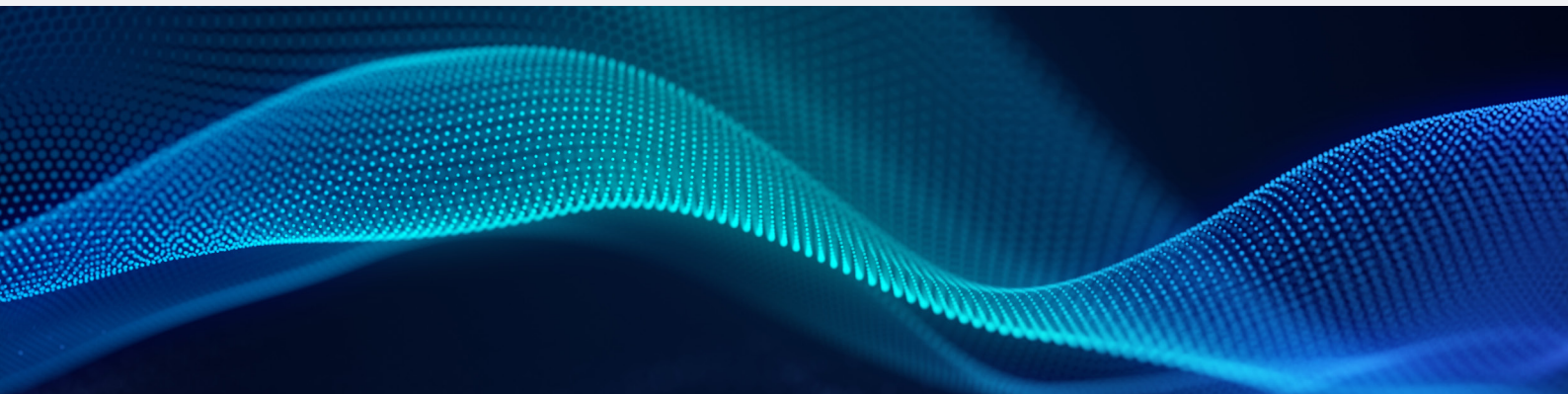
FIGURE 7 | Capital investments in energy by region (\$, billions), 2015–2025



Historically, clean energy investments have been concentrated in developed economies and China, while developing economies have trailed in attracting capital. Investments have seen a downward trend in many such regions (Africa, South-East Asia, Latin America) due to perceived risk.

Note: e = estimate

Source: International Energy Agency (IEA).



Strategic priorities

The transition is not just about cutting emissions, but about building competitive, productive and sustainable industries. Technologies are largely proven; the challenge now is delivery – aligning capital, infrastructure and policy to turn intent into investment and move from incremental progress to coordinated, system-wide execution. Five strategic priorities will define the transition going forward:

- 1 Create standards-based demand:** Lock in long-term offtakes through public procurement, standardized green-material contracts and buyers' clubs – and back them with credible product standards and carbon data transparency. Advance policy harmonization across key sectors – such as EU shipping alignment despite the delayed IMO decision – to provide consistent signals for investment and trade. The FMC demonstrates how coordinated buyer commitments can de-risk early markets and scale low-carbon solutions.
- 2 Build shared infrastructure:** Plan and finance integrated energy, hydrogen, CO₂ and port systems that serve multiple sectors, making shared grids, pipelines and storage hubs the core enablers of scale rather than secondary priorities.
- 3 Lower the cost of capital:** Use blended finance, carbon contracts for difference and carbon-finance mechanisms to hedge exchange-rate volatility, alongside sovereign

guarantees to de-risk early projects and crowd in private capital – particularly in emerging markets where financing costs remain prohibitive.

- 4 Prioritize market-ready solutions:** Fast-track electrification, efficiency and storage through grid access and corporate PPAs. Retire inefficient assets and secure critical mineral supply chains and fund technologies that meet market costs today – while supporting hydrogen and CCUS where infrastructure and offtakes enable near-term viability.
- 5 Balance top-down systems with bottom-up innovation:** In a period of policy uncertainty, top-down regulation can no longer be the sole driver. Scaling now depends on bottom-up innovations – from AI, digital tools and industrial start-ups – that advance independently of policy cycles. Align regulatory direction with technological ingenuity to turn local breakthroughs into scalable, system-wide solutions, ensuring flexibility and faster cost reduction.

Achieving industrial decarbonization at scale depends on execution, not just invention. Progress hinges on linking technology with the systems that enable it: demand signals, shared infrastructure, affordable finance and verified data. Aligning these levers will determine whether the transition remains a patchwork of pilots or becomes the foundation of a competitive, net-zero global economy.

Appendix







TABLE 6 Low-carbon technologies – policy developments, industry examples and momentum by sector

Efficiency and digital solutions		
Sector	Policy development	Industry example
 Aviation	ICAO targets 2% annual fuel-efficiency improvements until 2050 ⁹⁶	Mechanical (aerodynamics) and AI-based route and engine optimization by airlines and original equipment manufacturers ⁹⁷
 Cement	Digitalization encouraged through national energy-efficiency schemes ⁹⁸	45% of cement factories using predictive analytics for quality control ⁹⁹
 Steel	N/A	Automation of welding and cutting improves safety and productivity ¹⁰⁰
 Trucking	Fleet digitization incentives under the EU Smart Mobility Package ¹⁰¹	Cloud-based fleet management (Tow4Tech) for dispatch optimization ¹⁰²
 Aluminium	N/A	Vedanta Aluminium using AI and industrial internet of things (IIoT) for energy, inventory, and demand optimization ¹⁰³
 Shipping	IMO digitalization agenda supports data-driven voyage optimization ¹⁰⁴	Real-time internet of things (IIoT)-based fleet management and predictive maintenance ¹⁰⁵
 Oil and gas	N/A	Petrolink's PetroVue and PetroVault platforms for real-time drilling optimization ¹⁰⁶
 Chemicals	N/A	Evonik using generative AI for polymer R&D and process optimization ¹⁰⁷
Hydrogen		
Sector	Policy development	Industry example
 Aviation	EU Clean Aviation Joint Undertaking supports hydrogen propulsion R&D ¹⁰⁸	Airbus and MTU Aero Engines developing hydrogen fuel cell propulsion systems ¹⁰⁹
 Cement	Norway's hydrogen roadmap includes industrial integration ¹¹⁰	Heidelberg Materials building 30-megawatt electrolyser for green hydrogen ¹¹¹
 Trucking	India's National Green Hydrogen Mission supports heavy-duty hydrogen vehicles ¹¹²	Adani launched India's first hydrogen mining truck with a 200km range ¹¹³
 Aluminium	N/A	Novelis used hydrogen to power recycling furnace (United Kingdom, 2025) ¹¹⁴
 Chemicals	India incentivizes hydrogen for ammonia production, totalling over INR 1,500 billion (Indian rupees) (approximately \$170 million) under the National Green Hydrogen mission ¹¹⁵	Green hydrogen-based ammonia production pilots expanding ¹¹⁶

TABLE 6 | Low-carbon technologies – policy developments, industry examples and momentum by sector (continued)

Biofuels/SAF		
Sector	Policy development	Industry example
 Aviation	ReFuelEU mandates: 2% SAF blending in 2025, rising to 70% by 2050 ¹¹⁷	SAF production projected to reach 2MT in 2025
 Cement	National circular-economy frameworks support biomass co-firing ¹¹⁸	75% of Indian cement firms use biomass as alternative fuel ¹¹⁹
 Trucking	Low Carbon Fuel Standard and renewable diesel standards (California, EU) ¹²⁰	Renewable diesel gaining market share ¹²¹
 Shipping	IMO life cycle GHG regulation under discussion	FAME (fatty acid methyl ester) and HVO (hydrotreated vegetable oil) biofuels used in existing fleets ¹²²
 Chemicals	N/A	Bio-naphtha used for sustainable chemical feedstocks, green premiums declining ¹²³
Energy storage		
Sector	Policy development	Industry example
 Cement	Industrial electrification incentives in EU and Asia	Lithium-ion and hybrid storage for peak-load management
 Shipping	N/A	Offshore hybrid systems (lithium-ion, compressed air) emerging ¹²⁴
 Aluminium	China encourages aluminium producers to participate in power load regulation and energy storage to stabilize grids with high renewable penetration in its Integrated Energy System Solutions for Zero-Carbon Industrial Parks ¹²⁵	Lithium-ion and supercapacitors adopted for process flexibility
 Oil and gas	N/A	By-product hydrogen used for internal energy storage ¹²⁶
 Aviation	N/A	Integration of battery storage with hybrid propulsion systems, enabling short-range flight capabilities ¹²⁷
CCUS		
Sector	Policy development	Industry example
 Cement	EU Innovation Fund and national carbon capture and storage (CCS) strategies	Heidelberg Materials building world's first 1MT of CO ₂ per year capture project
 Shipping	At MEPC 83, the Marine Environment Protection Committee approved a dedicated work plan to develop a regulatory framework for onboard carbon capture and storage (OCCS) systems ¹²⁸	Onboard carbon capture trials ongoing, technology still nascent ¹²⁹
 Oil and gas	US 45Q, EU CBAM and national CCUS hubs	CCUS with steam methane reforming for blue hydrogen ¹³⁰

TABLE 6 | Low-carbon technologies – policy developments, industry examples and momentum by sector (continued)

Renewables		
Sector	Policy development	Industry example
 Cement	Renewable and waste heat recovery system (WHRS) expansion supported by energy-efficiency targets ¹³¹	1.8 GW new renewable and WHRS capacity added in 2025 ¹³²
 Steel	CBAM and regional carbon-pricing mechanisms ¹³³	Solar- and wind-powered electric arc furnace (EAF) operations expanding in Asia ¹³⁴
 Aluminium	National renewable obligations and RE100 commitments ¹³⁵	Indian aluminium sector adding 20 GW renewable capacity by 2030 ¹³⁶
 Shipping	IMO efficiency standards ¹³⁷	Wind-assisted propulsion cuts emissions by up to 90% ¹³⁸
 Chemicals	Corporate renewable PPAs	Chemical producers integrating PPAs into operations ¹³⁹
Nuclear		
Sector	Policy development	Industry example
 Aluminium	R&D frameworks for advanced modular reactors	High-temperature gas-cooled reactors (HTGRs) in R&D for electrolysis and process heat ¹⁴⁰

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