Allianz Trade

From hard-to-abate to decarbonized: Strategies for transforming Europe's industrial sector

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Executive Summary

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- **Four hard-to-abate industries (aluminum, ammonia, steel and cement) will play a pivotal role in Europe's green transformation.** First, they are major energy consumers and carbon emitters. While the industrial sector as a whole accounted for 25% of the EU-27's final energy consumption in 2023 and 19% of its greenhouse gas (GHG) emissions, these four industries alone are responsible for 7.7% of energy consumption and 9.7% of emissions. Second, they are providers of indispensable inputs to green industries such as solar panels and wind turbines. Therefore, their decarbonization is not only critical for achieving the EU's climate targets but also in securing strategic independence. The EU cannot afford to lose this industrial basis. .

- **Decarbonization and global competitiveness are two sides of the same coin.** The EU can achieve both targets at the same time, even in hard-to-abate industries, if two conditions are met: a reliable and efficient energy system based on renewables and a functioning Carbon Border Adjustment Mechanism regime. The first is needed to meet the power demand of these industries with zero emissions, and the second to secure the billions of investments needed during the transition.

- **Aluminum: Quitting coal-fired production.** Aluminum is the most widely used non-ferrous metal and is crucial for sustainable industries like transport, construction and renewable energy. Its lightweight and recyclable properties make it essential for electric vehicles, solar panels and wind turbines. Demand is projected to rise significantly by 2030, with transport (+60%) and electrical equipment (+50%) seeing the highest growth. But aluminum production remains highly energy-intensive, accounting for 2% of global GHG emissions. The most critical step of decarbonization is transitioning to green electricity as 65% of aluminum's emissions stem from fossil-fuel-based power. Another major strategy is deploying near-zero-emission technologies, such as replacing carbon anodes with inert anodes, which eliminate process emissions and reduce operational costs by 10% over time. Combining these two strategies, Europe's aluminum industry can achieve a cost-effective decarbonization and maintain global competitiveness. Levelized costs of around USD2,500 per ton would be lower than many other markets such as Canada, South America and Russia, although not necessarily compared to the US and China.

- **Ammonia: From grey to green.** Ammonia production is crucial for global agriculture, with 70% of ammonia used in fertilizers. However, ammonia production is the second most carbon-intensive process among hard-to-abate industries, generating 1% of EU-27 GHG emissions. As hydrogen production is the most carbon-intensive stage, green hydrogen, powered by variable renewable energy sources (VRES), is critical for the production of green ammonia. It also is the most cost-efficient way, with a levelized cost of USD370 per ton (globally). However, Europe would remain at a cost disadvantage, with projected production costs of USD412 per ton compared to the US and China, which have lower costs at USD343 and USD403 per ton, while Brazil is the most competitive at USD292 per ton, benefiting from abundant renewables and offshore hydrogen storage.

- **Steel: Reuse, recycle.** Steel is also essential, with 52% used in construction and infrastructure, 16% in mechanical equipment and 12% in the automotive sector. However, steel production is one of the most carbon-intensive industrial processes, contributing to 7% of GHG emissions. By promoting circularity, i.e. scrap-based steel production and reducing overall steel consumption, reliance on resource-intensive inputs like iron ore and energy can be minimized. Technological advancements are also crucial for decarbonization. For example, Bio-based Pulverized Coal Injection (BIO-PCI) uses biochar to reduce carbon intensity in blast furnaces, while biomethane from organic waste can replace natural gas in Direct Reduced Iron (DRI) production. Green hydrogen presents the most transformative potential, enabling near-zero-carbon steel production by replacing coal as a reducing agent. For now, scrap-based steel production using electric arc furnace (EAF) technology is the most cost-effective solution, with a global levelized cost of USD440 per ton and USD439 per ton in Europe, making the region competitive. .

- **Cement and concrete: Cutting clinker emissions.** Cement and concrete production accounts for another 7% of global CO2 emissions, making decarbonization a critical challenge. Emissions in the sector stem primarily from the production of clinker, responsible for 88% of sector-wide emissions, with the largest share (53% of the total) attributed to the limestone calcination process. To decarbonize the cement sector, a combination of strategies is essential. Clinker substitution with supplementary cementitious materials (SCMs) can significantly reduce emissions while lowering operating costs by USD2.50–11 per ton of cement. Fuel switching to waste provides a cost-effective alternative energy source, while hydrogen and electrification of the heating process offer promising long-term emission reductions. However, even with these measures, a substantial share of emissions will remain, making carbon capture, utilization, and storage (CCUS) a critical technology to decarbonize 35% of the sectors emissions.

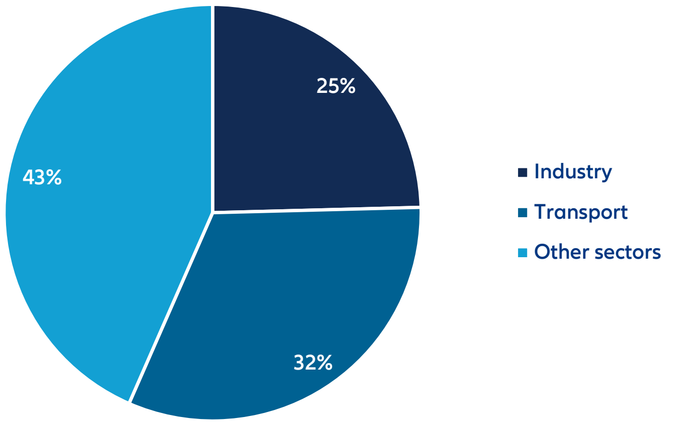
- **Of the four sectors, steel and ammonia have the largest green-financing gaps.** Over the past five years, capital expenditure has grown at an average annual rate of only +3% globally, which will not be enough to decarbonize three out of the four sectors. The steel and ammonia industries would need to invest an additional USD2,191bn and USD1,205bn, respectively, to achieve their green goals. For this, CAPEX must grow by +8% and +11% annually, respectively, until 2050. In contrast, the financing gap in the aluminium industry is smaller (USD317bn) and the cement sector's investments suggest that companies may be more on track to meet the decarbonization target independently – again, assuming that all capital is directed toward decarbonization efforts, which is not currently the case. This underscores why government action is so critical. Public-private collaboration is essential to expedite progress and help these industries meet the EU's 2050 target. Governments must provide grants, tax incentives and policy frameworks to reduce the financial burden on companies. Without increased investment now, the path to net zero will only become more challenging and costly in the future.

The heavyweights of emissions

The industrial sector is a cornerstone in the transition to renewable energy and a critical component in achieving broader climate goals, as stated by the newly published European Green Deal Industrial Plan[1]. Its substantial energy demands make a successful transition pivotal for the overall success of decarbonization efforts. Within the EU, the industrial sector remains a major driver of energy consumption, accounting for 25% of the EU-27's final energy use in 2023, as shown in Figure 1. This significant energy consumption is closely tied to high carbon emissions, particularly from 'hard-to-abate' processes that heavily rely on fossil fuels. For example, the manufacturing sector alone contributed 486.6mn tons of CO2 emissions, making it the fourth-largest source of EU-27 emissions (14%, see Figure 2). This follows transportation (31%), power generation (21%) and agriculture (15%). These numbers highlight the urgent need for targeted action within the industrial sector. Decarbonizing industry involves a multifaceted approach. Current efforts focus on improving energy efficiency, scaling up the adoption of renewable energy and advancing innovative solutions such as hydrogen-based processes and electrification. These technologies offer pathways to significantly reduce emissions from industrial operations. However, the challenge extends beyond emissions reduction. It also involves ensuring that European industries remain competitive in a global economy increasingly defined by low-carbon priorities.

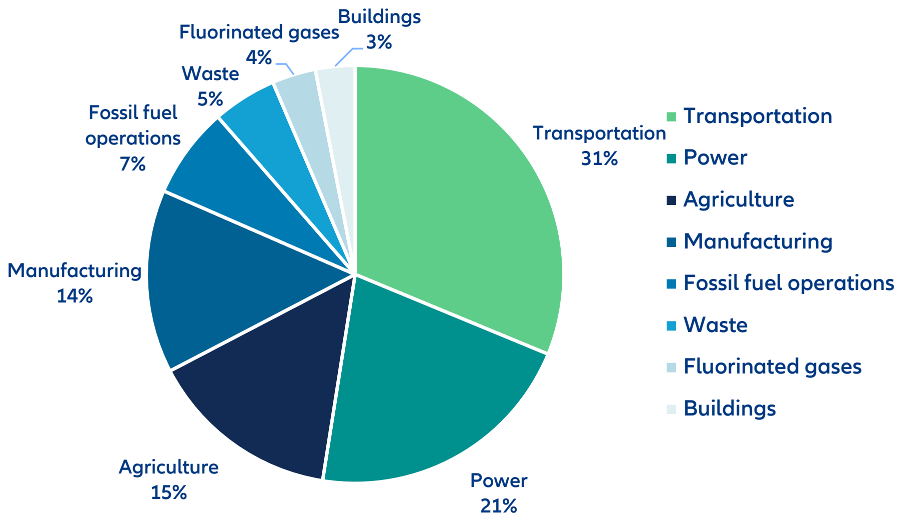
1. The Green Deal Industrial Plan - European Commission

Figure 1: Final energy consumption by sector in the EU-27, 2023



Sources: Eurostat, Allianz Research

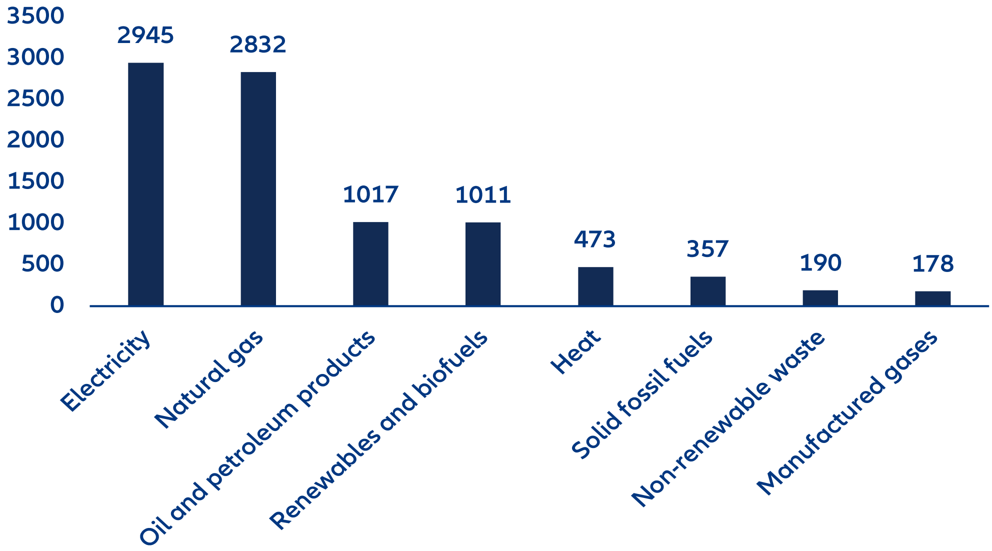
Figure 2: CO2 emissions by sector in EU-27, 2024



Sources: Climate Trace, Allianz Research

The substantial energy demands of the industrial sector in the EU-27 are intricately linked to the types of energy sources utilized, as illustrated in Figure 3. Electricity emerges as the dominant energy source, with a consumption of 2,945 PJ in 2023. This underscores its critical role in driving industrial machinery and processes, including operations in manufacturing, automation and advanced technologies. As industries adopt more electrified processes, electricity is expected to maintain its prominence, especially with the anticipated shift toward renewable energy generation. Natural gas closely follows, contributing 2,832 PJ, reflecting its entrenched position in industries reliant on high-temperature thermal processes, such as ammonia production. However, the heavy reliance on natural gas poses significant vulnerabilities, particularly due to price fluctuations, as observed following the Russia-Ukraine war. Moreover, despite its lower carbon intensity compared to coal and oil, natural gas remains a fossil fuel, making its substitution with cleaner alternatives a priority for achieving climate targets. At 1017 PJ, oil and petroleum products continue to play a significant role, particularly in industries requiring liquid fuels such as transportation (see box 1, page 19). However, the growing adoption of renewables and biofuels, which collectively reached 1011 PJ, signifies progress in reducing dependency on traditional fossil fuels. These renewable sources are increasingly being integrated into industrial energy systems, enabling a shift toward more sustainable operations. This energy source breakdown highlights the dual challenge facing the EU-27: reducing dependence on fossil fuels while ensuring a reliable and scalable supply of clean energy for industrial processes. Together with the consumption patterns seen in Figure 3, it becomes clear that decarbonization requires a multifaceted strategy. This includes accelerating the adoption of electrification, scaling up renewables and fostering innovation in energy storage and hydrogen technologies.

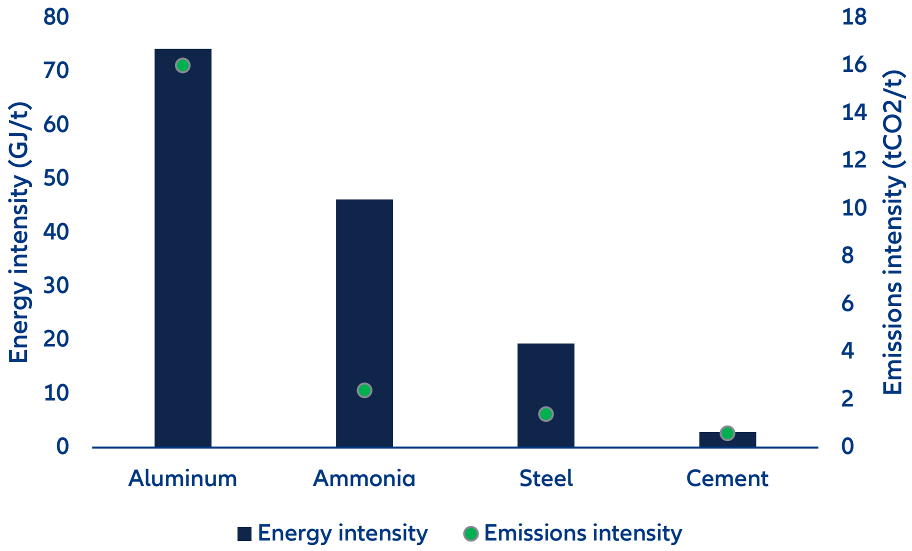
Figure 3: Final energy consumption of the EU-27 industry by source for the year 2023, PJ



Sources: Eurostat, Allianz Research

Figure 4 provides a closer look at energy and carbon intensities in four hard-to-abate industries: aluminum, ammonia, steel and cement. These industries are characterized by their high energy intensity, significant carbon emissions and deep integration into the global supply chain, making their decarbonization a critical component of achieving climate goals. The aluminum sector stands out with the highest energy intensity, exceeding 70 GJ per ton of output. This is largely due to the energy-intensive electrolysis process used in aluminum smelting, which relies heavily on electricity. In addition to its substantial energy requirements, aluminum production exhibits a high emissions intensity (16 tCO2 per ton of aluminum), reflecting the continued reliance on fossil fuel-based energy in many regions, i.e., the aluminum coal-based production in China[2]. Transitioning to renewable electricity and exploring innovative methods, such as inert anode technology, are essential for reducing the sector's carbon footprint. Ammonia production, critical for fertilizers (70% of ammonia), follows with an energy intensity above 40 GJ per ton. Its emissions intensity is also notable, largely driven by the use of natural gas as both a feedstock and an energy source in the Haber-Bosch process leading to 2.4 ton of CO2 per ton of output. The adoption of green hydrogen as a feedstock represents a promising pathway to decarbonize this sector. The steel industry, with an energy intensity of around 20 GJ per ton of crude steel, remains a significant emitter due to its reliance on coal-based blast furnaces. Transitioning to direct reduced iron (DRI) processes powered by hydrogen and secondary scrap-based steel is key to lowering both energy consumption and emissions intensity. The cement sector, while showing relatively low energy intensity compared to the other three (around 3 GJ per ton of output), still contributes substantial emissions due to the calcination process and fuel combustion. Innovative solutions, such as carbon capture and storage (CCS) and alternative clinker materials, will be crucial to its decarbonization.

Figure 4: Energy and carbon intensities of hard-to-abate sectors



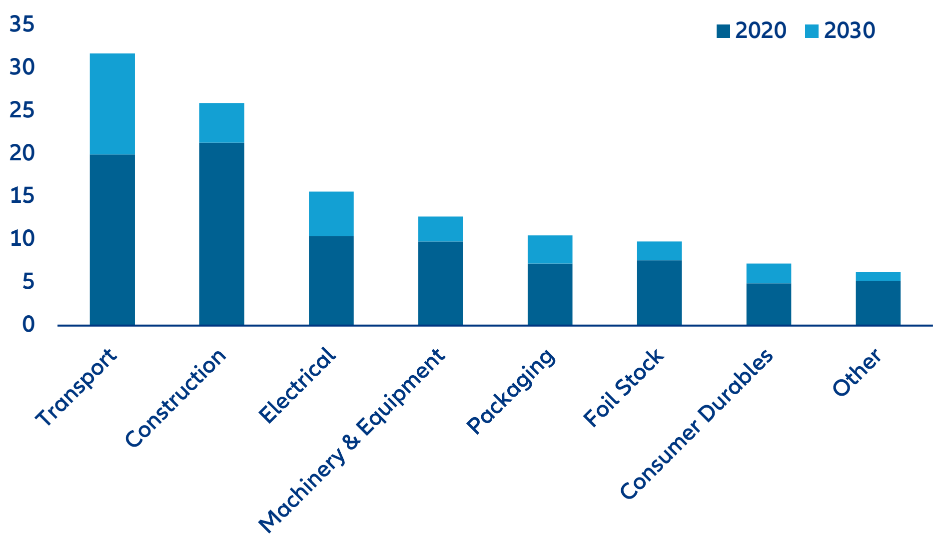
Sources: JATO, Allianz Research

2. Coal power plants: Aluminium's dirty little secret | Ember

Aluminum: Quitting coal-fired production

Aluminum, the most widely used non-ferrous metal globally, plays a critical role in advancing decarbonization across various industries, supporting the transition to a more sustainable future. Its lightweight, durable and recyclable properties make it a key material for sectors such as transport, construction and packaging. For instance, aluminum is essential in the production of electric vehicles, where it reduces weight and enhances energy efficiency. It is also integral to renewable energy technologies like solar panels and wind turbines and is increasingly favored for sustainable packaging solutions due to its recyclability. As illustrated in Figure 5, the demand for aluminum is projected to grow significantly across multiple sectors by 2030, with transport (+60%) and electrical equipment (+50%) driving the largest increases. This surge highlights aluminum's pivotal role in enabling sustainable development. However, rising demand poses a challenge for the aluminum industry itself, which must address its own carbon footprint.

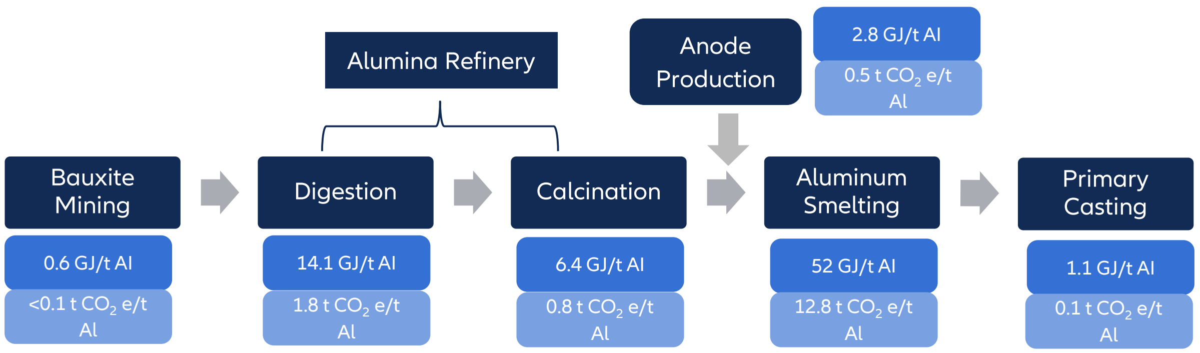
Figure 5: Consumption of aluminum semi-finished products by sector in 2020 and expected growth to 2030, Mt



Sources: International Aluminium Institute, Allianz Research

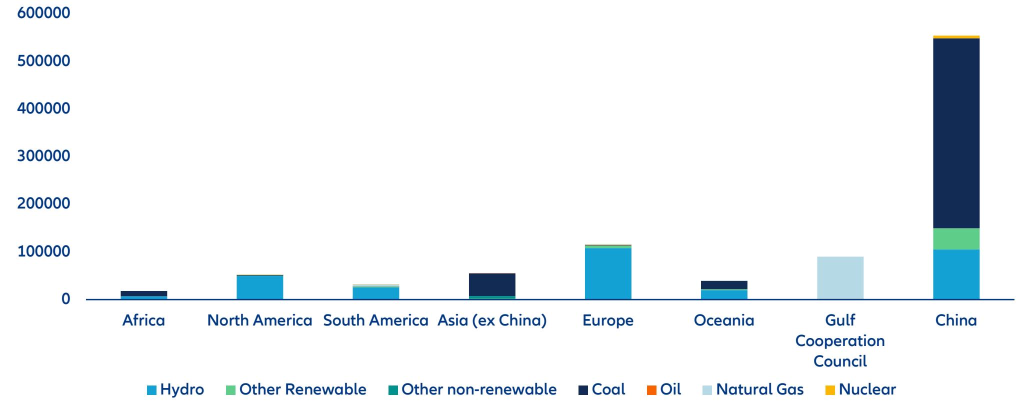
Aluminum production remains energy-intensive (Figure 6), responsible for approximately 2% of global GHG emissions because of its high reliance on fossil fuels to generate the substantial power required for the smelting process. Today, 66% of the energy consumed by aluminum smelters around the world comes from fossil fuels, primarily coal and natural gas, as illustrated in Figure 7. But there are significant regional disparities. In regions such as China, the world's largest producer of aluminum, coal dominates the energy mix, accounting for 399,024 GWh of power used in smelting plants. Similarly, in regions like the Gulf and Asia (excluding China), coal and natural gas play a prominent role, reflecting the widespread reliance on fossil fuels. In contrast, other regions, including Europe and North America, demonstrate a higher proportion of renewable energy sources, particularly hydroelectric power. Europe, for example, derives 108,357 GWh from hydro, while North America generates 49,626 GWh from this renewable source. The reliance on fossil fuels, particularly for main aluminum producers like China, underscores the need for a global and aligned transition in the aluminum production.

Figure 6: Primary aluminium production process and corresponding energy intensity (gigajoules per ton of aluminium) and carbon intensity (tons of CO2 emissions per ton of aluminium)



Sources: Mission Possible Partnership, Allianz Research

Figure 7: Energy mix in smelting plants across regions (Gigawatt hours)



Sources: Mission Possible Partnership, Allianz Research

Decarbonizing the aluminum industry is a complex challenge, but four key strategies can pave the way to achieving net-zero emissions. The first and most critical strategy is ensuring a reliable and steady supply of low-carbon power. Smelters, being the most energy-intensive component of the aluminum production process, present the greatest potential for decarbonization. This can be achieved through three primary approaches: connecting smelters to low-carbon electricity grids, producing low-carbon energy using Carbon Capture and Storage (CCS) or developing power purchase agreements (PPAs) with renewable energy providers. The suitability of each option depends on local electricity infrastructure, resource availability and costs. CCS, for example, can reduce smelter flue gas emissions by up to 90%, with additional reductions possible if emissions from fuel combustion and carbon anode production are integrated into the system. However, the low-carbon partial pressure in aluminum smelters results in high capture costs, ranging from USD180 to USD300 per ton of CO_2, significantly higher than in industries such as steel (USD50–USD170 per ton) or natural gas processing (USD20 per ton). Nuclear Small Modular Reactors (SMRs), though still in development, could offer a promising low-carbon power source for smelters, particularly in regions where intermittent renewable energy sources are less feasible.

The second strategy involves deploying near-zero-emission technologies across the production chain. A transformative example is the replacement of carbon anodes with chemically inert anodes in the smelting process. These inert anodes, made from materials that remain stable during electrolysis, eliminate all process emissions and have a lifespan of about one year – much longer than the one-month lifespan of carbon anodes. Despite high initial capital investment requirements to retrofit existing smelters, inert anodes could reduce operating expenses by approximately 10% over their lifetime, offering a competitive levelized cost of USD1,550 per ton of alumina compared to USD1,450 for carbon anodes.

The third strategy focuses on maximizing secondary aluminum production by improving recycling and collection rates for pre- and post-consumer scrap. While this does not directly address the energy intensity of smelting, it significantly reduces the demand for primary aluminum. Producing secondary aluminum emits just 0.5 tons of CO_2 per ton, compared to 16 tons for primary aluminum. Expanding recycling efforts could cut annual emissions by up to 25% by 2050. However, regional and sectoral disparities in recycling rates pose challenges. For instance, Brazil achieves a remarkable 95% recycling rate for aluminum cans, while North America lags at around 50%. Sectors using aluminum alloys also face added complexity in separating aluminum from other metals.

The final strategy is improving material and resource efficiency throughout the value chain. This involves designing lightweight products, extending product lifespans, facilitating end-of-life recycling and minimizing material loss in manufacturing. While not directly targeting the energy intensity of smelting, these measures can reduce overall demand for aluminum and contribute to decarbonizing the industry as a whole.

Table 1 provides a heatmap analysis highlighting the potential of various technology combinations based on three key dimensions: cost (high/low), carbon intensity (high/low) and technology availability. The business-as-usual (BAU) scenario assumes that the aluminum industry will focus on the most cost-effective solutions to meet an anticipated +80% increase in global demand by 2050. This approach involves limited adoption of low-carbon technologies, with the exception of inert anodes in newly built smelters. Under the BAU scenario, the most practical solution for balancing climate policy with economic competitiveness is the continued use of carbon anodes powered by fossil fuels, such as coal and natural gas, combined with Carbon Capture and Storage (CCS) technology to mitigate emissions. A coal-powered smelter with CCS could reduce emissions by 59% by 2050 at a levelized cost of USD2,980 per ton of aluminum output. Similarly, a natural gas-powered smelter with CCS could achieve a 65% reduction in emissions for the same cost. This approach relies on existing, mature technologies. The Technology Readiness Level (TRL) for coal with CCS is rated at 9 out of 10, indicating near-full readiness, while natural gas with CCS is rated at 8 out of 10, reflecting advanced maturity. By leveraging these technologies, the aluminum industry can pursue a pragmatic pathway that balances cost-efficiency with significant emissions reductions, ensuring scalability to meet growing demand in the short to medium term.

In the two alternative scenarios, fossil-fuel-based carbon anode smelters are projected to become economically unsustainable due to strict climate policies targeting the phase-out of coal. In the orderly scenario, levelized costs for aluminum production soar to USD6,409 per ton for coal-based smelters with CCS and USD5,263 per ton for natural gas-based smelters with CCS, making these technologies increasingly unfeasible. In the disorderly scenario, these fossil fuel-based solutions are excluded altogether. Under both the orderly and disorderly scenarios, the most economically viable options aligned with climate goals involve inert anode smelters paired with access to a decarbonized grid and/or power purchase agreements (PPAs) for low-carbon energy. This combination could enable the aluminum sector to achieve a 70% reduction in emissions by 2050, with a levelized cost of USD3,984 per ton of aluminum. However, significant challenges remain. First, while advancements in inert anode technology, particularly in North America[3] , show promise, it is not yet commercially available at scale. Second, access to low-carbon electricity grids remains limited, especially in China, where only 14% of smelters were powered by a low-carbon grid in 2020 (Figure 8). More critically, 53% of China's smelters, which predominantly rely on coal, are at risk of being unable to connect to low-carbon grids. This poses a significant challenge as China is the world's largest aluminum producer and CO2 emitter. Despite the potential benefits of inert anode technology combined with PPAs and low-carbon grids, these obstacles highlight the need for substantial infrastructure development and technological scaling to fully realize this pathway.

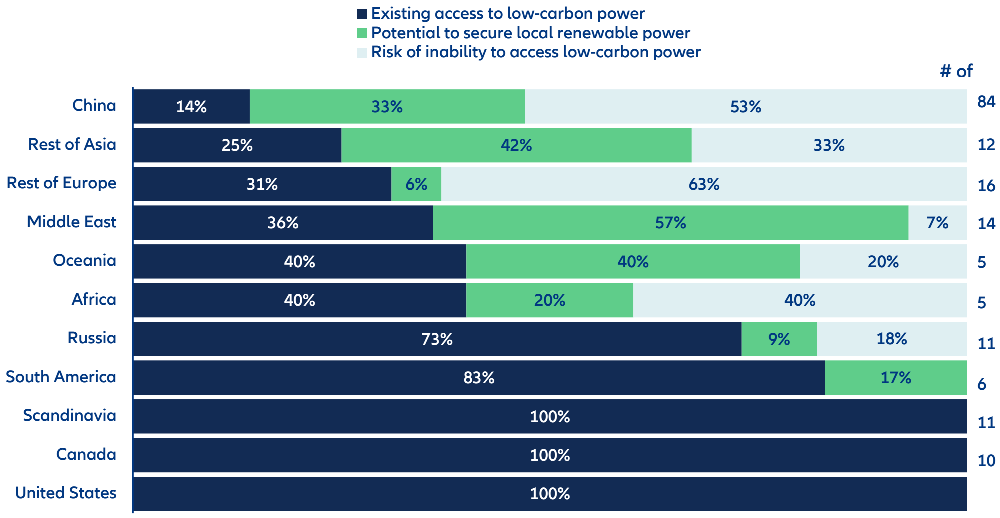
Table 1: Heatmap illustrating the aluminum sector transition

Product		Orderly	Disorderly	BAU	TRL
Carbon Anode	Coal				10
	Coal + CCS				9
	Grid				9
	Hydro				10
	Natural Gas				10
	Natural Gas + CCS				8
	PPA + Grid				9
Carbon Anode + CCS	Coal				3
	Coal + CCS				3
	Grid				3
	Hydro				3
	Natrual Gas				3
	Natural Gas + CCS				3
	PPA + Grid				3
	SMR				3
Inert Anode	Coal				7
	Coal + CCS				7
	Grid				7
	Natural Gas				7
	Natural Gas + CCS				7
	PPA + Grid				7
	Hydro				7
	SMR				4

Sources: Mission Possible Partnership, Allianz Research. Color codes: Red indicates high levelized cost and high carbon intensity, orange represents low levelized cost with high carbon intensity, yellow denotes high levelized cost with low carbon intensity, green signifies low levelized cost and low carbon intensity and gray indicates unavailable technology.

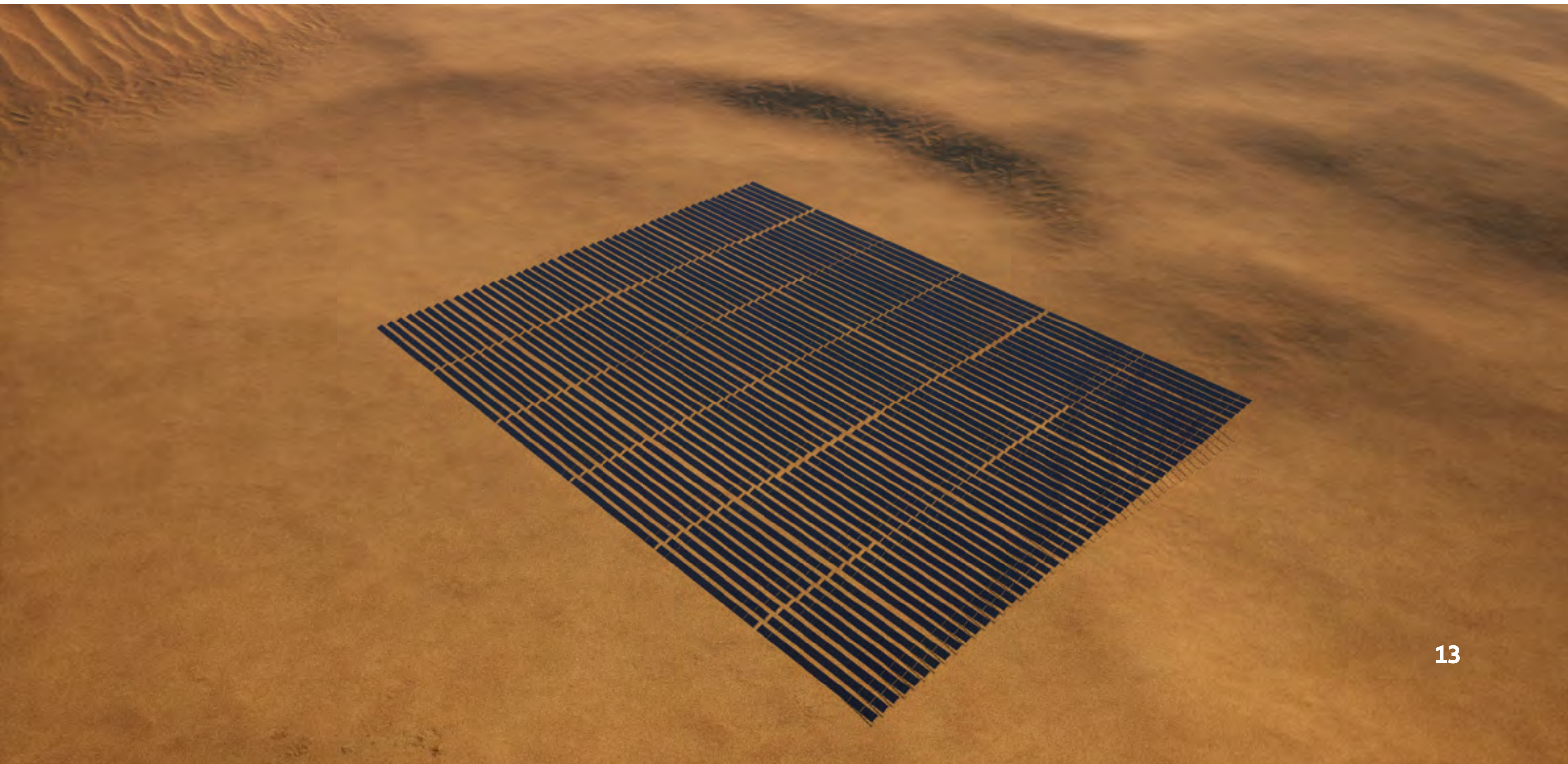
3. What is ELYSIS? | ELYSIS

Figure 8: Access to low-carbon power supply for smelters across regions in 2020 (% of regional smelters)



Sources: Mission Possible Partnership, Allianz Research

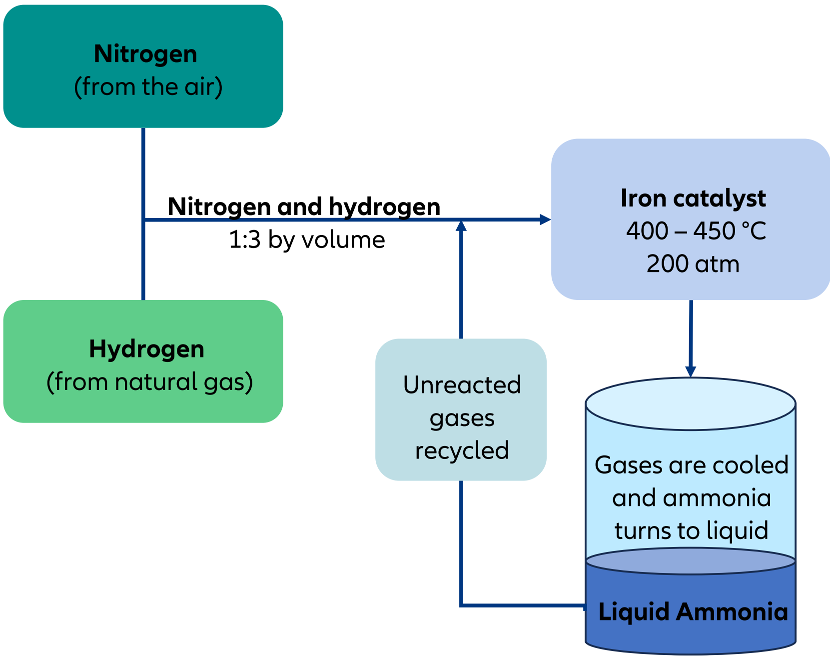
Europe's aluminum industry is well-positioned to align decarbonization with cost-effectiveness and global competitiveness by adopting advanced technologies. The most promising solution for Europe is the deployment of inert anode smelters powered by a combination of power purchase agreements (PPAs) and the electrical grid. With levelized costs slightly above USD2,500 per ton of aluminium, this approach would give Europe a significant competitive edge in producing green aluminium compared to regions such as Canada, South America and Russia. However, the US and China are poised to lead in this space, driven by early investments in innovative technologies such as the Elysis joint venture by Alcoa and Rio Tinto, which aims to scale up inert anode smelters. In comparison, carbon anodes combined with CCS are less attractive for Europe, with levelized costs around USD2,900 per ton, highlighting their higher expense and limited feasibility. Meanwhile, inert anodes powered solely by the grid offer another alternative but remain constrained by the availability of low-carbon electricity, underscoring the need for accelerated grid decarbonization efforts.



Ammonia: From grey to green

Ammonia production is currently the second most carbon-intensive process in the four identified hard-to-abate industrial sectors (Figure 4). Ammonia plays a vital role in supporting global agriculture, primarily through its application in fertilizer production: 70% of ammonia produced is dedicated to fertilizers[4]. Ammonia production involves two key stages: hydrogen production and its subsequent combination with nitrogen to synthesize ammonia (Figure 9). Nitrogen is generally extracted either from the atmosphere or through an air separation process powered by electricity. Currently, all hydrogen used in ammonia production is derived from fossil fuels, with natural gas responsible for 80% and coal supplying the remaining 20%. Fossil fuels also play a critical role in supplying the energy required to sustain the high temperatures and pressures necessary for the reactions. To produce one ton of ammonia, approximately 0.18 tons of hydrogen and 0.82 tons of nitrogen are consumed. This process generates significant direct CO_2 emissions (Scope 1), ranging from 1.6 to 4.0 tons of CO_2 per ton of ammonia, depending on the plant's operational efficiency and feedstock type. In 2020, global ammonia production was linked to approximately 430mn tons of Scope 1 CO_2 emissions. Furthermore, the electricity used in the production process contributed to an additional 40mn tons of Scope 2 CO_2 emissions, highlighting the substantial carbon footprint of the industry.

Figure 9: Simplified representation of production processes of ammonia (Haber-Bosch process)



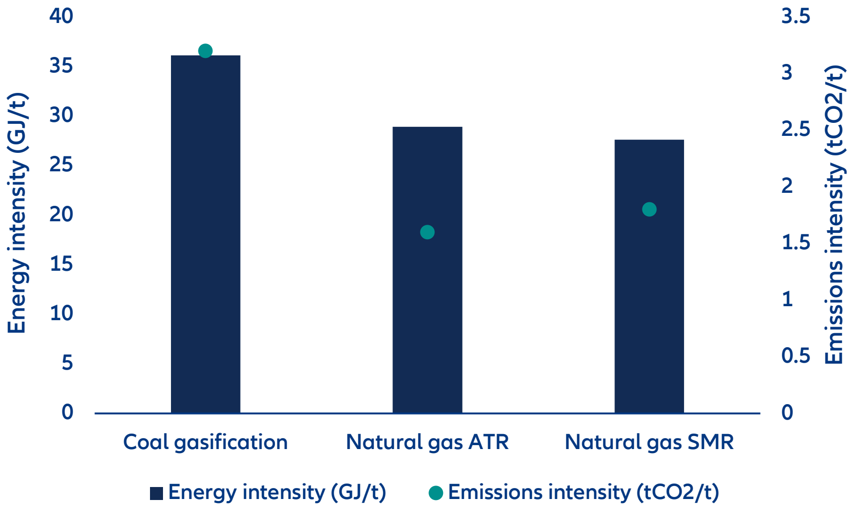
Sources: ACEA, Allianz Research

4. Executive Summary – Ammonia Technology Roadmap – Analysis - IEA

The production of hydrogen is the most energy-intensive and carbon-emitting process in ammonia manufacturing, significantly influencing the industry's overall environmental footprint. Hydrogen production is required as a precursor to synthesize ammonia by combining it with nitrogen, yet the methods to produce hydrogen vary widely in energy and emissions intensity. Among the common production routes, coal gasification is the most energy- and carbon-intensive, requiring 36.1 GJ of energy per ton of ammonia and emitting 3.2 tons of CO_2 per ton of ammonia produced (Figure 10). This method is typically used in regions with abundant coal resources but results in a high carbon footprint. Natural gas-based processes, including Steam Methane Reforming (SMR) and Autothermal Reforming (ATR), are less energy- and carbon-intensive compared to coal gasification. SMR, the most widely used method globally, requires 27.6 GJ per ton of ammonia and emits 1.8 tons of CO_2 per gayton of ammonia. ATR, a newer process gaining popularity, has a slightly higher energy requirement at 28.9 GJ per ton, but it is more carbon-efficient, emitting 1.6 tons of CO_2 per ton of ammonia. Unlike SMR, which relies on an external heat source, ATR combines partial oxidation and steam reforming in a single reactor, making it more thermodynamically efficient. Additionally, ATR operates at higher pressures, which aligns well with ammonia synthesis and simplifies CO_2 capture for carbon reduction. Despite these advancements, hydrogen production remains the dominant contributor to ammonia's energy use and GHG emissions, emphasizing the need for transitioning this production process to mitigate its carbon footprint.

Green hydrogen can be used to produce green ammonia, a promising pathway to decarbonize the ammonia industry by completely eliminating reliance on fossil feedstocks. This approach utilizes electrolysis, powered by renewable energy sources such as wind, solar and hydropower, to split water into hydrogen and oxygen. The hydrogen produced serves as the primary feedstock for ammonia synthesis, while renewable electricity also powers other critical processes, such as nitrogen extraction from the air via an air separation unit and the ammonia synthesis loop itself. By fully electrifying the production process and leveraging renewable energy, green ammonia eliminates Scope 1 and Scope 2 emissions and significantly reduces upstream Scope 3 emissions from fossil fuel extraction, a traditionally hard-to-abate source of emissions. Despite its potential, the adoption of green ammonia faces significant technical challenges, primarily due to the need to integrate large volumes of intermittent renewable electricity. The ammonia synthesis loop, which operates at very high capacity factors (around 95%) for efficiency, requires a constant and stable supply of hydrogen. This requirement is fundamentally misaligned with the variable nature of renewable energy sources, which typically operate at load factors of 20%–55%. Approximately 93% of the electricity used in green ammonia production is consumed by the electrolyzer for hydrogen generation, demanding a consistent and reliable power supply. This mismatch between renewable energy availability and the operational demands of ammonia synthesis poses a major obstacle to achieving efficient production.

Figure 10: Energy needs and carbon emissions to produce one ton of ammonia for three main production routes



Sources: IEA, Allianz Research

Blue ammonia provides a complementary pathway to green ammonia, leveraging carbon capture and innovative technologies to significantly reduce emissions while maintaining a feasible transition for the industry. To decarbonize traditional ammonia production, it is essential to address both the emissions generated during hydrogen extraction from fossil fuels and those resulting from fossil fuel combustion for energy. Blue ammonia offers a solution by capturing and either repurposing or permanently storing these emissions. In current ammonia production, process-related CO_2 emissions account for roughly two-thirds of total Scope 1 emissions and are already separated during hydrogen production. Established technologies, such as amine-based scrubbing, are widely used for this purpose. A portion of this captured CO_2 is utilized in industrial applications, such as the production of urea-based fertilizers or in the food and beverage sector. Additionally, an increasing share of captured CO_2 is being directed toward enhanced oil recovery or permanent storage in geological formations. The remaining one-third of Scope 1 emissions, arising from the combustion of fossil fuels, is more challenging to capture due to its dilution in flue gases. This post-combustion capture requires additional equipment and approximately 0.6 GJ of electricity per ton of ammonia. For blue ammonia to align with net-zero goals, an overall CO_2 capture rate of at least 90% is necessary, with emissions securely stored to prevent release into the atmosphere. Autothermal Reforming (ATR) offers significant advantages for blue ammonia production compared to Steam Methane Reforming (SMR). While ATR is not yet widely applied in ammonia plants, it is commonly used in large-scale methanol production and is gaining traction as a potential technology for new blue ammonia facilities. ATR combines hydrogen production and heating within a single reactor, reducing the reliance on external heating to just 10% of natural gas input. As a result, more than 90% of emissions generated during the ATR process are highly concentrated, making them easier and more cost-effective to capture with high rates of efficiency. Additionally, emerging ATR configurations, such as the ATR with a Gas Heated Reformer (ATR + GHR), are expected to be operational by 2030. These setups allow for waste heat recovery, boosting efficiency and reducing overall gas consumption. Furthermore, compared to SMR plants, which typically have production capacities of 2,000–3,000 tons of ammonia per day, ATR-based technologies are expected to enable much larger-scale facilities, potentially doubling production capacity and improving economic viability.

Despite promising commitments and investments in low-carbon ammonia production, the industry remains one of the hardest to decarbonize due to several key challenges. First, ammonia's critical role in global food production makes its decarbonization particularly complex. The high costs of low-emission alternatives, such as green ammonia (USD550–USD1,400 per ton, 2020) and blue ammonia (USD350–USD700 per ton, 2020), are far from competitive with conventional grey ammonia, which has historically cost USD250 per ton (2020). In the short run, these price disparities limit the widespread adoption of near-zero-emissions ammonia. Over the long term, the levelized costs of green ammonia are projected to decrease significantly, ranging from USD290 to USD770 per ton (2050). In contrast, grey ammonia will remain vulnerable to energy market volatility, as evidenced by the sharp increase in production costs to USD1,000–USD1,500 per ton following the natural gas price shock triggered by the Russia-Ukraine war. Second, several technologies needed to transition to cleaner ammonia production are still in their infancy (technology readiness level Table T). Scaling green ammonia is hindered by the variability of renewable energy, while technologies like carbon capture, utilization, and storage (CCUS) are economically viable only at large scales, requiring substantial upfront investments. These technical and economic hurdles slow the pace of innovation and adoption. Third, the long lifespan of existing ammonia plants, often exceeding 50 years, favors retrofitting over adopting entirely new technologies. The average age of plants varies from 12 years in China, where production is heavily coal-based, to 40 years in Europe. This creates resistance to change as retrofits with CCUS are seen as less disruptive than building new infrastructure, especially in regions with abundant cheap coal or natural gas. Additionally, optimal sites for green ammonia production, those with abundant renewable resources, often do not align with existing industrial hubs, posing further logistical and economic challenges.

Although the costs of green and blue ammonia present significant challenges, several strategies can help accelerate the sector's transition (Table 2). One promising approach for producing blue ammonia is Electrified Steam Methane Reforming (ESMR)[5] combined with Carbon Capture and Storage (CCS). This method uses electrically heated catalytic structures within SMR reactors to significantly lower CO_2 emissions while enabling compact reactor designs that are up to 100

5. Electrified methane reforming: A compact approach to greener industrial hydrogen production | Science

times smaller than traditional systems. This technology enhances catalyst efficiency, minimizes byproducts and could reduce global CO_2 emissions by nearly 1% and ammonia-related emissions by 97% by 2050. Another pathway to blue ammonia involves the use of Gas-Heated Reformers (GHRs). These systems operate as shell-and-tube heat exchangers with catalyst-filled tubes, where partially reformed gas is further processed in a secondary reformer. The hot gases from the secondary reformer supply the heat needed for the reforming reaction in the GHR. By 2050, GHR technology could achieve a 96% reduction in ammonia-related emissions compared to 2020 levels. However, both technologies are still in the early stages of development, with Technology Readiness Levels (TRLs) of 4 for ESMR and 6 for GHR. For green ammonia, the outlook is more optimistic. By combining electrolyzers powered by dedicated renewable energy with geological hydrogen storage, green ammonia production can achieve a 100% reduction in emissions at an estimated cost of USD468 per ton by 2050 (Figure 11, Table 4). Additionally, this technology is nearing full commercialization, with a TRL of 8 out of 9, making it a more mature and viable solution.

The ammonia industry presents significant opportunities for decarbonization, yet Europe faces unique challenges in adopting cost-effective technologies. Among the available pathways, producing green ammonia using electrolyzers powered by dedicated variable renewable energy sources (VRES) and supported by green hydrogen storage in geological formations is the most globally competitive solution (Figure 11). For Europe, however, this is less competitive due to higher levelized costs compared to other regions. Europe is expected to face the second-highest costs globally, at USD412 per ton of green ammonia, second only to Russia (USD483 per ton of green ammonia). In contrast, countries like the US and China are projected to have more competitive costs of USD343 and USD403 per ton, respectively. Brazil shows the most competitive advantage of green ammonia, with a remarkable levelized cost of USD292 per ton, nearly half the cost of production in Europe, driven by its abundant renewable energy resources and favorable geographic conditions for hydrogen storage, mainly in offshore natural gas fields[6].

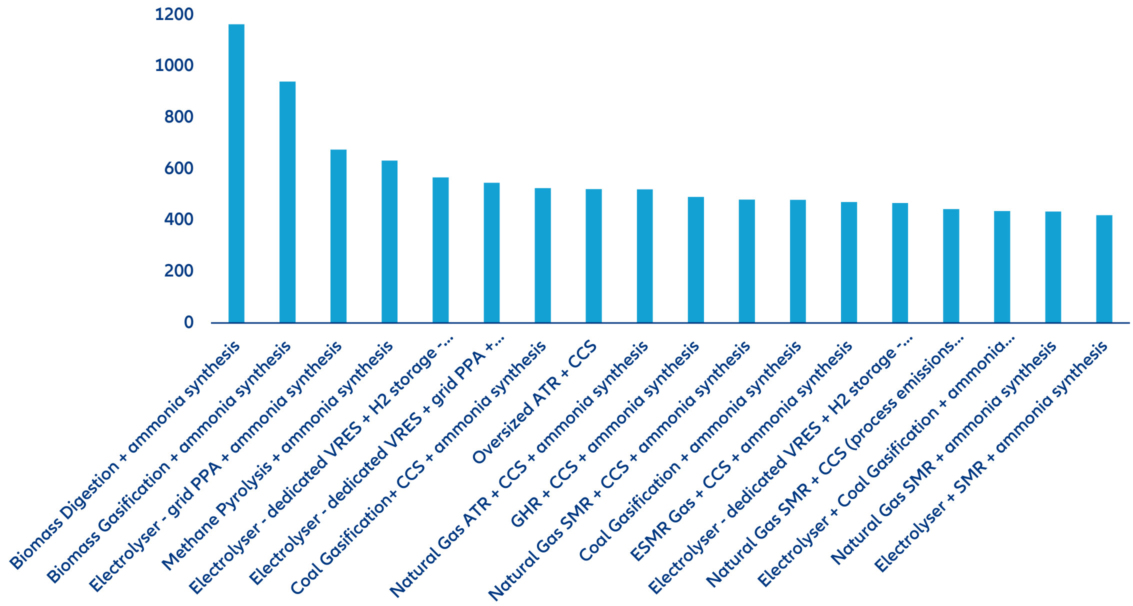
Table 2: Revenue from certain key manufacturers and suppliers are heavily dependent on China

Product	Technology	Orderly	CP	TRL
Biomass Ammonia	Biomass Digestion			3
	Biomass Gasification			3
Blue Ammonia	Coal Gasification			9
	Coal Gasification+ CCS			9
	Electrolyser + Coal Gasification			8
	Electrolyser + SMR			8
	ESMR Gas + CCS			4
	GHR + CCS			6
	Natural Gas ATR + CCS			9
	Natural Gas SMR			9
	Natural Gas SMR + CCS			8
	Oversized ATR + CCS			9
Green Ammonia	Electrolyser - dedicated VRES + grid PPA			8
	Electrolyser - dedicated VRES + H2 storage - geological			8
	Electrolyser - dedicated VRES + H2 storage - pipeline			8
	Electrolyser - grid PPA			8
Methane Pyrolysis	Methane Pyrolysis			7

Sources: MPP, Allianz Research. Colour codes: Red indicates high levelized cost and high carbon intensity, Orange represents low levelized cost with high carbon intensity, yellow denotes high levelized cost with low carbon intensity, Green signifies low levelized cost and low carbon intensity, and Gray indicates unavailable technology. The last column shows the technology readiness level (TRL) for decarbonization of the ammonia process (scale 1-10, 1=least ready, 10= readily available)

6. Hydrogen storage in depleted offshore gas fields in Brazil: Potential and implications for energy security - ScienceDirect

Figure 11: Levelized cost of ammonia processes in 2050

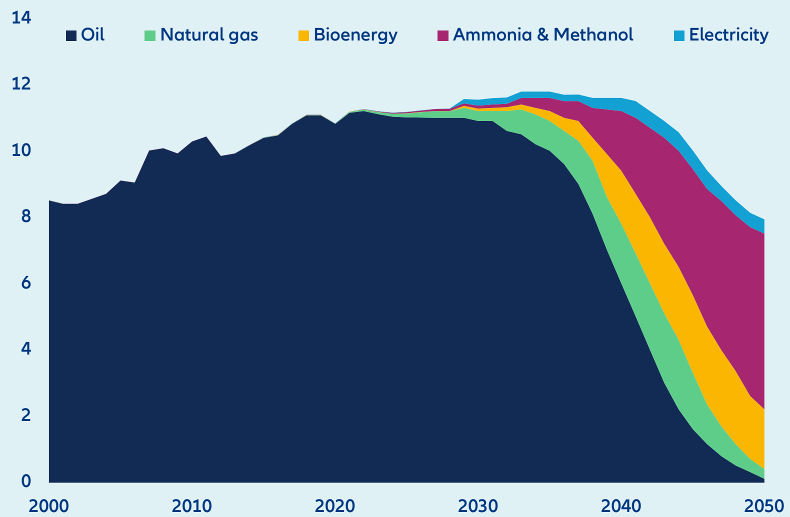


Sources: MPP, Allianz Research

Ammonia's role in decarbonizing the shipping industry.

Transportation is currently the most significant single contributor sector to CO2 emissions in Europe, accounting for almost a third of total regional emissions (31%, Figure 12). Although road transport accounts for by far the lion's share in terms of volume, shipping and aviation also represent a big part, while rail generates much less. Today, most of the global container fleet is powered by fossil fuels. Around 93% of the fuel oil used last year was either heavy fuel oil (HFO) or marine gas oil (MGO), which are low-grade and high-polluting fuels that not only exacerbate air quality issues, but are also responsible for other environmental concerns, such as sulfur emissions and water pollution from oil spills. Only around 6% of the fleet use liquified natural gas (LNG) while the remaining 1% use other fuels or alternative fuels, indicating the long road ahead to decarbonize the fuel mix.

Figure 12: Breakdown of final energy use of shipping sector, for a 2050 net-zero scenario, in petajoules (PJ)



Sources: BloombergNEF, Allianz Research

To accelerate the transition, ammonia and methanol can play a key role. Ammonia and methanol could account for nearly 70% of shipping's fuel demand in 2050 (Figure 12). Both are liquid at ambient temperatures, making them easier to store and handle compared to other low-carbon options, which also means that the existing infrastructure for liquid fuels can be adapted to handle them, reducing the cost and complexity of adoption.

Of the two, ammonia has a larger list of benefits, making it a particularly compelling choice for the sector's green future. Green ammonia (methanol to a lesser extent) also offers an energy density close to existing traditional fuels. In other words, it has a relatively high energy density compared to other alternatives like hydrogen, which makes it suitable for long-distance and deep-sea shipping, where large volumes of fuel are needed. Ammonia's volumetric energy density is much higher than liquid hydrogen, and although it is lower than that of traditional fuels like diesel, it remains competitive for certain shipping needs. Besides, green ammonia can be produced sustainably (through electrolysis powered by renewable energy), which positions it as the best long-term solution to reduce the shipping industry's carbon footprint. On top of this, it also offers scalability. Ammonia is already produced in large quantities for agricultural use so it can be scaled up relatively easily for use in shipping. Global production facilities could potentially transition to making green ammonia, leveraging existing infrastructure, unlike hydrogen, for example, which currently lacks the infrastructure for large-scale use in shipping.

Green ammonia's biggest advantage over other fuels (including methanol) is that it does not produce any CO2 when burned. This makes it one of the few true „zero-carbon" fuels for shipping, critical for achieving the maritime industry's ambitious goal of total decarbonization by 2050 (and eliminating sulfur emissions as well). As such, there is ongoing research to adapt ammonia for use in existing ship engines, and some companies are already building ammonia-powered vessels. This means that, with proper modifications, ammonia could be used with less disruption and lower initial costs than alternative fuels, which require completely new engine designs.

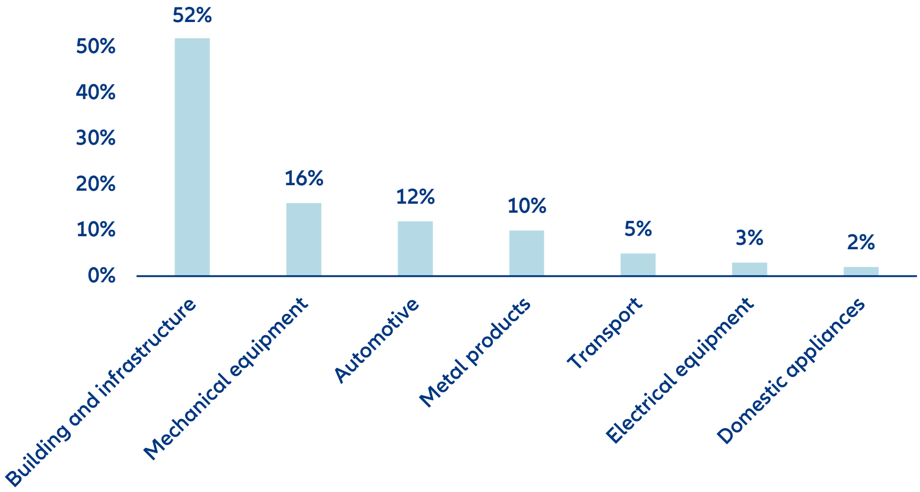
But the transition is still in its early stages and will require significant investment in new bunkering facilities and retrofitting ships. Moreover, the transition to ammonia faces two challenges. First, it is toxic so shipping companies must address safety concerns regarding its storage and handling. Stringent safety protocols will be essential to prevent accidents. In fact, the International Maritime Organization (IMO) is actively developing interim safety guidelines for ships already using alternative fuels like ammonia, recognizing the urgency of providing clear guidance to administrations, shipowners and the industry as a whole. The second challenge is that ammonia combustion produces nitrogen oxides (NOx), which are pollutants. Though technologies are being developed to capture or reduce these emissions, this remains an area that requires further attention.

Iron and steel: Reuse, recycle

Steel is an indispensable material for modern society and plays a pivotal role in enabling a low-carbon economy. As shown in Figure 13, its applications span across critical sectors, with 52% of steel being utilized in building and infrastructure, which includes constructing roads, bridges and wind turbines, essential for economic and environmental progress. Mechanical equipment accounts for 16% of steel use, supporting industries like agriculture and manufacturing, while the automotive sector represents 12%. Additionally, 10% of steel is directed toward metal products, 5% toward transportation and smaller portions are used in electrical equipment (3%) and domestic appliances (2%). This widespread reliance on steel underscores its importance in the global economy.

However, the production process remains one of the most emissions-intensive industrial activities, contributing approximately 7% of global greenhouse gas emissions. In 2020, steel manufacturing, spanning both primary and secondary production, emitted roughly 3.1 gigatons of carbon dioxide (Gt CO2).

Figure 13: Steel use by sector



Sources: World steel organization, Allianz Research

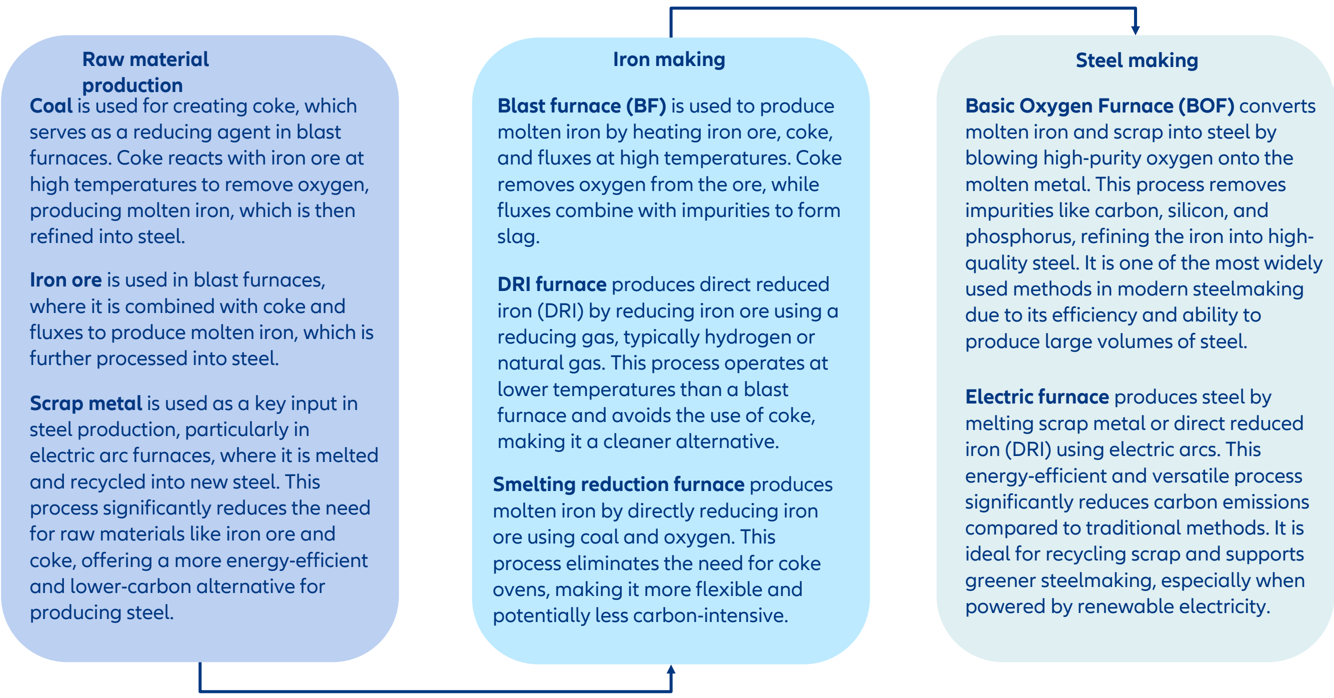
Producing one ton of crude steel generates, on average, 1.4 tons of direct CO_2 emissions (Scope 1) and 0.6 tons of indirect CO_2 emissions (Scope 2). Currently, steel production worldwide is dominated by three primary methods (Figure 14):

1. Blast Furnace–Basic Oxygen Furnace (BF-BOF): In this process, iron ore is reduced to molten iron in a blast furnace and then refined into crude steel in a basic oxygen furnace. The reduction and refining steps require extremely high temperatures (1,100°C to 1,600°C), which are achieved using fossil fuels. This route accounted for 70% of global steel production in 2020 and emits approximately 2.3 tons of CO_2 per ton of crude steel (t CO_2/t CS).

2. Electric Arc Furnace (EAF): EAFs use electricity to melt scrap steel, with the option to incorporate additional metallic feedstocks like direct reduced iron (DRI) or hot metal based on availability. This method contributed 25% of global production in 2020. Its emissions, averaging 0.6 t CO_2/t CS, vary significantly depending on the carbon intensity of the electricity supply.

3.Direct Reduced Iron–Electric Arc Furnace (DRI-EAF): This process reduces iron ore into a solid product (DRI) using a reducing gas, typically a mix of hydrogen and carbon monoxide derived from natural gas. The DRI is then fed into an EAF for steelmaking. Approximately 5% of global steel production in 2020 used this method, emitting an average of 1.4 t CO_2/t CS when powered by natural gas.

Figure 14: Processes of steel production

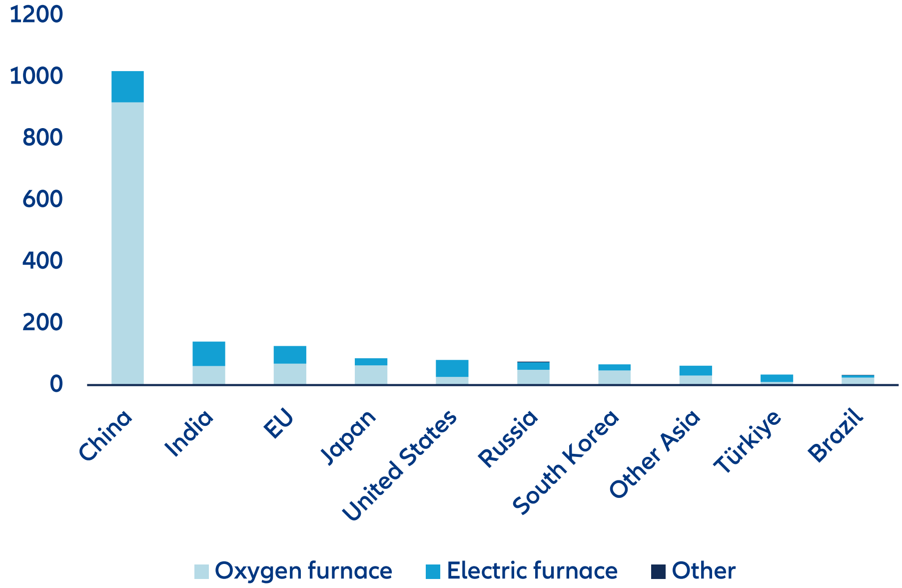


Sources: IEA, Allianz Research

As highlighted in Figure 15, countries such as China overwhelmingly rely on oxygen blast furnaces, producing 918mn tons of crude steel in 2023 using this method (90.1% of the total crude steel production). This reliance underscores the immense challenge of decarbonizing the steel industry in regions where such production processes dominate. Conversely, secondary steelmaking, which primarily uses electric arc furnaces (EAF) to recycle scrap metal, represents a more sustainable alternative with lower carbon emissions.

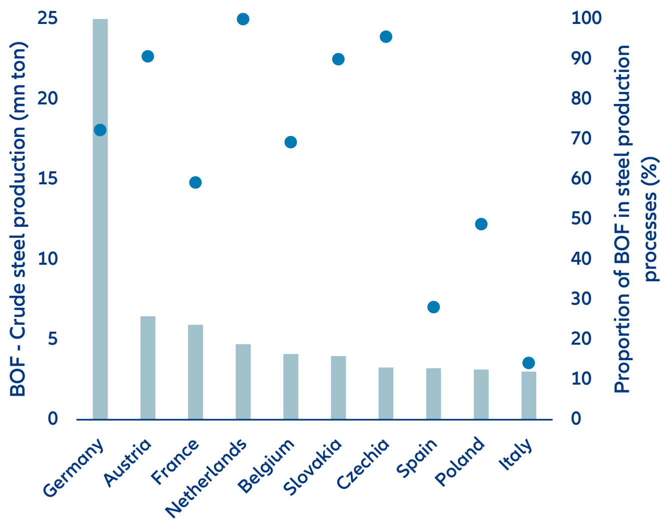
However, as the Figure illustrates, the contribution of EAF technology varies significantly across regions. For example, countries like the US and Turkey have a higher reliance on electric arc furnaces compared to China, India or the EU. This disparity is influenced by factors such as the availability of scrap metal, energy prices and the infrastructure needed to support EAF technology.

Figure 15: Production of crude steel in the world by process in 2023



Source: World steel organization, Allianz Research

Figure 16: Production of crude steel in Europe with the proportion of oxygen furnaces in the processes (2023)

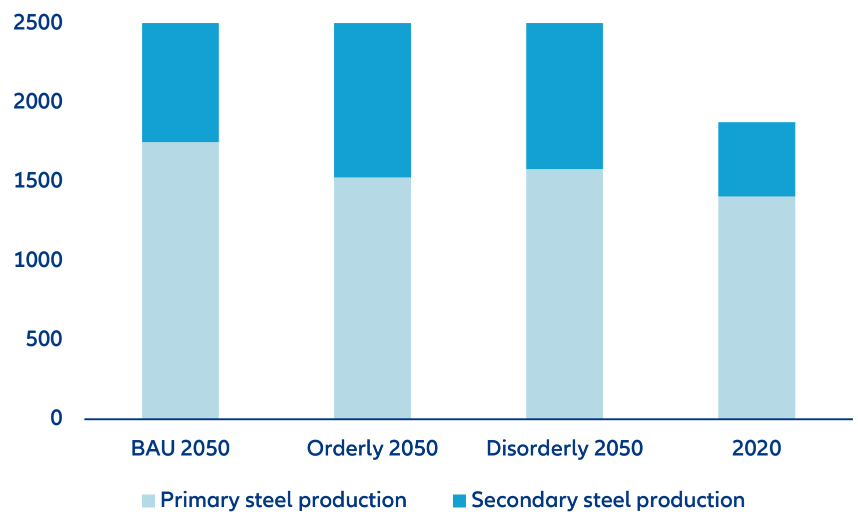


Sources: World steel organization, Allianz Research

Basic Oxygen Furnace (BOF) production remains a key method for crude steel manufacturing in many European countries, as shown in Figure 16. Germany leads the group, producing approximately 25mn tons of crude steel via BF-BOF in 2023, accounting for 72.3% of its total steel production. Austria, France and the Netherlands follow, with BOF production ranging between 4 and 6mn tons. Notably, the Netherlands relies entirely on BOF, with 100% of its steelmaking using this method. In contrast, countries like Italy and Spain have lower BOF production volumes, around 3mn tons, and rely more heavily on alternative technologies such as Electric Arc Furnaces (EAF). For example, EAFs account for 71.9% of Spain's steel production and 85.8% of Italy's, highlighting the growing importance of less carbon-intensive methods in the EU.

The first key strategy to accelerate the steel sector's transition involves both reducing the demand for primary steel and transforming how steel is produced relying more on scrap-based steel production. By decreasing overall steel consumption and enhancing steel circularity, the need for resource-intensive inputs, such as iron ore and energy, can be significantly lowered. This approach not only makes the transition more sustainable and cost-effective but also ensures it remains achievable within the necessary timeframe. Currently, the production of secondary steel, derived from recycled scrap, accounts for only 25% of global steel output. In 2020, this amounted to approximately 470mn tons of secondary steel compared to 1,406mn tons of primary steel (Figure 17). To achieve meaningful progress, a fundamental shift is required towards an economic model that prioritizes prosperity without depleting finite natural resources to better fit within the planetary boundaries[7]. This necessitates exploring ways to reduce total demand for primary steel while increasing reliance on secondary steel production, which is inherently less carbon-intensive. Figure 17 illustrates the projected evolution of crude steel production under three scenarios for 2050[8]. Across all scenarios, the share of secondary steel production grows, albeit to varying extents. In the most ambitious „Orderly" scenario, which prioritizes coordinated efforts for decarbonization, secondary steel constitutes 40% of total production. In contrast, the „Disorderly" scenario, characterized by delayed or fragmented action, achieves a slightly lower share of 38%. Meanwhile, the Business-as-Usual (BAU) scenario, reflecting minimal intervention, results in a modest increase to 31%.

Figure 17: Production of crude steel in Europe with the proportion of oxygen furnaces in the processes (2023)



Sources: MPP, Allianz Research

7. Planetary boundaries - Stockholm Resilience Centre
8. The scenarios, derived from MPP modelling, include BAU (baseline of inaction), Orderly (decarbonization via coordinated low-CO_2 steelmaking), and Disorderly (Technology Moratorium limiting investments to near-zero-emissions technologies from 2030 to achieve net zero).

In addition to increasing the share of secondary steel, achieving a significant technological shift is crucial to accelerating the steel sector's decarbonization. Various innovative and advanced technologies are poised to play pivotal roles in reducing emissions. One key strategy involves the adoption of Best Available Technologies (BAT), which represent the most effective methods currently available to optimize energy efficiency and minimize environmental impact. This approach exemplifies how existing infrastructure can be retrofitted with innovative solutions to lower emissions while maintaining productivity. Another promising technology is Bio-based Pulverized Coal Injection (BIO-PCI), which replaces traditional fossil-based coal with biochar or other biomass materials. This method reduces the carbon intensity of the blast furnace process by leveraging renewable bio-resources, offering a practical bridge toward decarbonization. Similarly, the use of biomethane, derived from organic waste such as agricultural residues or food waste, presents an opportunity to replace natural gas in processes like Direct Reduced Iron (DRI) production. Green hydrogen is emerging as a transformative solution for deep decarbonization. By replacing coal as a reducing agent, green hydrogen enables near-zero-carbon steel production.

These outlined technologies are envisioned to be integrated with existing steel production processes to improve energy efficiency and substantially reduce carbon emissions (Table 3). However, the effectiveness of these process-technology combinations varies significantly, both in terms of levelized costs and the speed at which they achieve emission reductions. To provide a comprehensive assessment of their transition potential, Table 3 presents a heatmap depicting a potential assessment based on three key dimensions: levelized cost (high/low), carbon intensity (high/low) and technology availability. The heatmap offers a clear and concise overview of the feasibility and effectiveness of each combination, serving as a critical tool for prioritizing decarbonization strategies. For example, integrating the BF-BOF (Blast Furnace-Basic Oxygen Furnace) process with technologies like BAT, Bio-PCI or green hydrogen fails to deliver the anticipated transition outcomes. These combinations fall short in both carbon reduction and economic viability due to their high levelized costs and limited emission abatement potential. As a result, they are deemed neither environmentally sustainable nor economically feasible. According to modeling results, BF-BOF processes can only achieve climate neutrality when paired with advanced carbon capture technologies, such as Bioenergy with Carbon Capture, Utilization, and Storage (BECCUS), Carbon Capture and Utilization (CCU) or Carbon Capture and Storage (CCS). However, these technologies significantly increase levelized costs, rendering the combination less attractive from an economic perspective. In contrast, the modeling identifies the most promising process-technology combinations under both orderly and disorderly transition scenarios. These include smelting reduction with CCUS and secondary steelmaking using scrap in Electric Arc Furnaces (EAF). Smelting reduction with CCUS offers substantial emissions reductions while maintaining a manageable cost structure. Similarly, secondary steelmaking with EAF, which relies on recycled steel, represents a highly efficient, low-carbon and economically viable option, particularly as circular economy practices continue to expand. These findings underscore the importance of focusing on scalable and economically feasible technologies to accelerate the decarbonization of the steel sector while achieving meaningful climate goals.

The timing of the transition to low-carbon steelmaking is a pivotal factor in achieving meaningful decarbonization. Regardless of the technological pathway chosen, key decision points present strategic opportunities to adopt lower-carbon technologies. While marginal emissions reductions can be implemented throughout the operational life of a steel plant, the most substantial and cost-effective decarbonization potential arises when furnaces approach the end of their functional lifespan. Refractory relining, a significant maintenance milestone, are typically required every 20 years, while major refurbishments or upgrades occur roughly every 40 years. Notably, nearly half of the world's steel plants are expected to reach their next major investment decision, such as refractory relining, before 2030. This timeline represents a critical window for transitioning to near-zero emissions technologies. However, if commercially viable low-carbon solutions are not available for deployment by these decision points, the industry faces a dual risk. On one hand, there is the danger of locking in high-emitting technologies for another two decades, perpetuating carbon-intensive operations. On the other hand, the sector could face the economic burden of prematurely retiring and replacing steelmaking assets to meet climate goals. To avoid such outcomes, the development, scaling and deployment of near-zero-emissions technologies must be prioritized to align with these crucial investment timelines, ensuring a sustainable transition for the steel sector.

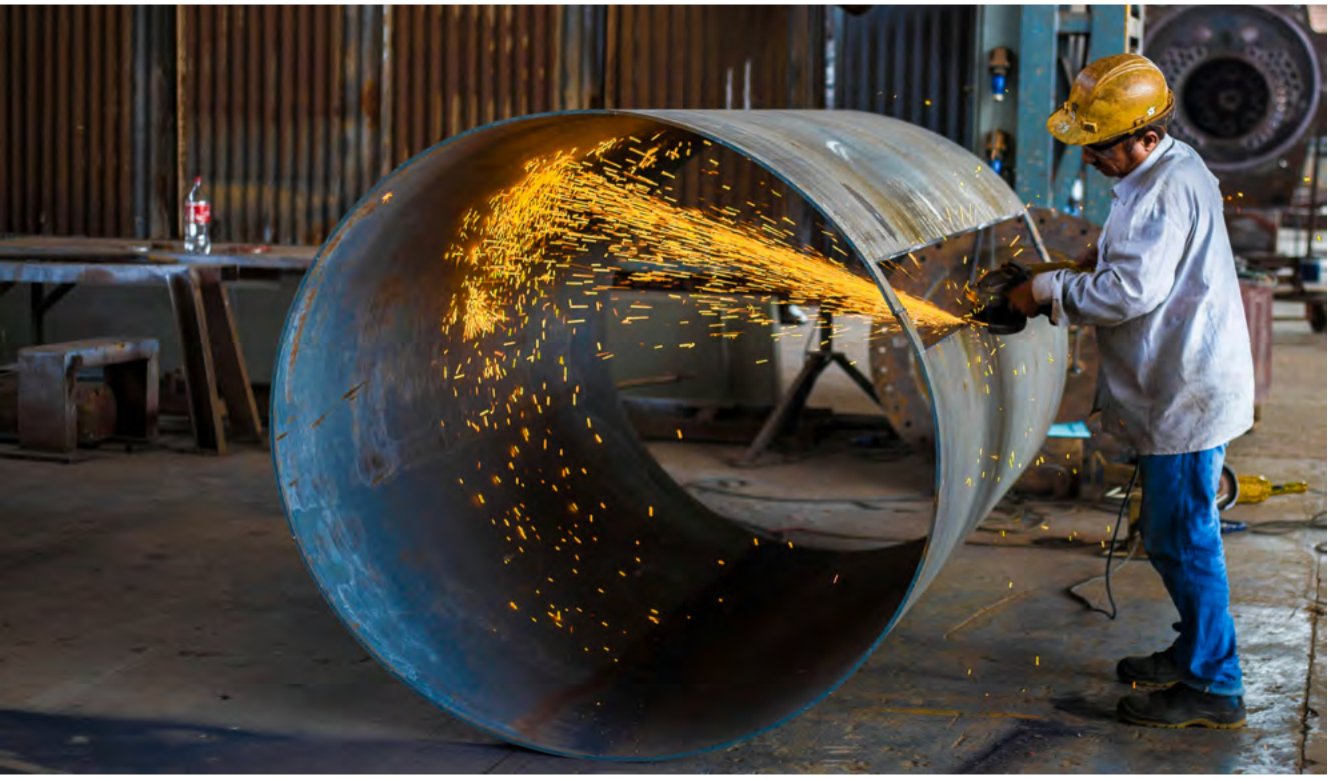
The steel industry offers immense potential for decarbonization through innovative technological advancements, as highlighted in the heatmap analysis. Among the available pathways, scrap-based steel production using electric arc furnace (EAF) technology stands out as the most cost-effective solution globally, with a levelized cost of USD440 per ton of secondary steel. In Europe, this approach is even more competitive, with costs slightly lower at USD439 per ton, positioning the region among the global leaders in cost efficiency for this technology. However, the scalability of scrap-based production depends heavily on the availability of high-quality scrap and access to low-carbon electricity, both of which present challenges in certain contexts.

A particularly promising low-carbon pathway for primary steel is DRI with BOF using green hydrogen, which achieves the lowest levelized cost for crude steel globally at USD538 per ton. However, Europe struggles with competitiveness in this area, as its costs are higher (USD569 per ton) than regions such as North America (USD509 per ton, NAFTA), where production is more economical. This disparity is largely attributed to Europe's higher costs of green hydrogen production (as for green ammonia), which impacts the feasibility of steel production reliant on hydrogen.

Table 3: Heatmap illustrating the steel sector transition.

Process	Technology	Orderly	Disorderly	Availability
Iron - Blast Furnace Steel Basic Oxygen Furnace (BF-BOF)	Basic	Red	Orange	2020
	BAT	Red	Orange	2020
	BAT and Bio PCI	Red	Red	2020
	BAT, Hydrogen and Bio PCI	Red	Red	2025
	BAT and BECCUS	Yellow	Gray	2028
	BAT and CCU	Yellow	Gray	2028
	BAT and CCUS	Yellow	Gray	2028
Iron - Direct reduce iron (DRI) Steel - Electric Arc Furnace (EAF)	Basic	Orange	Orange	2020
	100% green hydrogen	Yellow	Yellow	2026
	50% bio Methane	Orange	Yellow	2028
	50% green hydrogen	Orange	Orange	2026
	CCUS	Green	Yellow	2028
Iron - Direct reduce iron (DRI) Steel - Basic Oxygen Furnace (BOF)	Basic	Orange	Orange	2020
	100% green hydrogen	Green	Yellow	2026
	CCUS	Green	Yellow	2028
Smelting Reduction	CCUS	Green	Green	2030
Scrap	EAF	Green	Green	2020

Sources: MPP, Allianz Research. Color codes: Red indicates high levelized cost and high carbon intensity, orange represents low levelized cost with high carbon intensity, yellow denotes high levelized cost with low carbon intensity, green signifies low levelized cost and low carbon intensity, and gray indicates unavailable technology



Cement and concrete: Cutting clinker emissions

Cement and concrete are the foundational building blocks of modern society, quite literally paving the way for our success. As the second most consumed substance on Earth after water, concrete drives the global construction industry, which contributes over 13% to global GDP. Yet, with the sector responsible for 7% of global and 24% of industry CO2 emissions, it is one of the key industries to address for tackling climate change. Understanding where emissions in the sector originate and how to reduce them is therefore an important step toward a more sustainable future.

Emissions in the sector mainly originate from two sources: process emissions from producing clinker – the primary ingredient in cement – responsible for 53% of total emissions, and energy-related emissions, which account for 46%. Clinker emissions primarily result from the limestone calcination process, a chemical reaction in which limestone is heated to high temperatures in kilns, breaking down into lime (calcium oxide) while releasing CO2 as a byproduct. Energy emissions from fuel combustion are also mostly confined to clinker production (61%) where the energy is largely required for the heating process. Other emissions, originating from raw material extraction, cement grinding, concrete production and the construction process, are relatively minor, making up just 12% of the total value chain emissions. While cement and concrete production are highly emission-intensive, the structures they create gradually offset some of the initial emissions through a natural process called recarbonation. Within this process, concrete structures absorb CO2 from the atmosphere over their lifetime as calcium compounds in the material chemically react with carbon dioxide to form calcium carbonate, reducing overall emission of the sector by 6-10%.

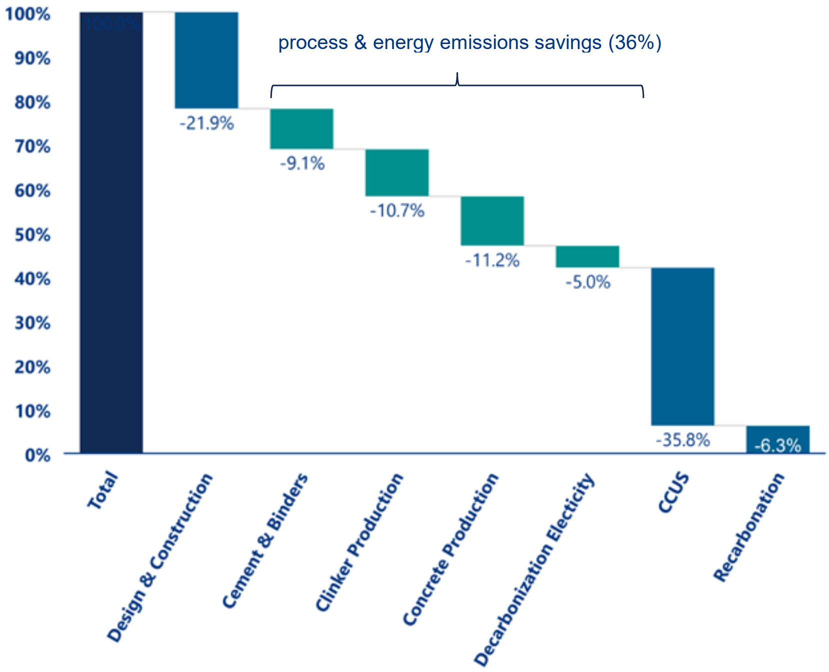
Decarbonizing cement and concrete requires a combination of options along the whole value chain. To reduce process emissions the challenge lies in reducing the emissions from clinker production. One option to reduce clinker emissions directly is to replace the limestone needed with decarbonated raw materials coming for instance from recycled concrete. Since those materials do not emit CO2 when heated they can reduce the emissions originating from the calcination process. While limited in its emission reduction potential this step can reduce total emissions by about 2% while promoting more circularity in the sector's value chain. A second option involves the replacement of clinker as a binder in cement and concrete by relying on supplementary cementitious materials (SCMs) such as fly ash from coal power generation or granulated ground blast-furnace slag (GGBS) from the production of steel. This alternative is one of the key levers to reduce the industries emissions but is limited by the technical reduction potential and the future availability of SCMs. On the technical side, replacing clinker in cement and concrete is feasible but it requires careful mix optimization and performance validation to maintain the required strength and durability. Currently, clinker constitutes 73% of the cement used in mixtures and accounts for 63% of the total binders in concrete. While a complete replacement of clinker is not feasible at present, estimates from the IEA and the Global Cement and Concrete Association (GCCA) suggest that clinker use could be reduced by 21–25%, lowering the clinker-to-cement ratio to 0.57 and the clinker-to-binder ratio in concrete to approximately 0.52 by 2050. In addition to technical feasibility, a major challenge is the availability of suitable replacement materials. Thus far clinker is most often substituted by industrial waste products such as fly ash or GGBS, but as the world continues to decarbonize these byproducts will become more scarce. To account for this, the industry will need to build up alternative value chains and switch to other alternatives over time, such as ground limestone pozzolans or calcinated clay.

Decarbonizing energy use constitutes the second key building block for the sector's decarbonization strategy. With more than 70% of energy used for heating the kilns in clinker production, the key energy-related decarbonization options involve improvements in heating efficiency and a switching from fossil-fuel-based heating technology to other low carbon alternatives. Efficiency gains can be achieved by using the most efficient kiln technology, which is currently a preheater kiln with precalcinator (PH-PC). A roll out of this technology today could lower the thermal energy use for clinker production in Europe by 11%[9]. Fuel switching depends on the cost and technology readiness of the alternative fuel. In the short run, heat generation emissions could be reduced by switching to industrial & municipal waste as well as biomass as feedstocks. These options require little to no additional cost and are gaining traction, with estimates suggesting that Europe's average fuel substitution rate could reach 60% by 2030. Beyond 2030, green hydrogen and kiln electrification emerge as key alternatives for decarbonizing the industry's energy supply. Their adoption, however, will depend on cost competitiveness and the carbon intensity of a country's electricity mix. According to the Mission Possible Partnership (MPP), these technologies could be cost-competitive with carbon capture at USD 2.5/kg for hydrogen and USD 32/MWh for electricity[10]. This provides options particularly for countries that can draw upon inexpensive electricity such as the US, India or China.

Even with reductions in process and energy emissions, along with improvements in cement and concrete use, 35-40% of emissions will likely remain. To abate these emissions, the sector will need to invest around USD380bn (or 27% of the total investments required for the sector) until 2050 to equip production facilities with the necessary carbon capture equipment (Figure 18). Currently, the most widely used carbon capture method is post-combustion absorption, where CO_2 is passed through an amine solvent, which binds it for further processing and storage. While this method can achieve a capture rate of up to 95%, it is comparatively expensive, with an operating costs of approximately USD50 per ton of cement. Emerging technologies like oxyfuel carbon capture and indirect calcination offer promising alternatives. These methods require only 15–20% of the energy used in absorption-based capture and could cut costs by 40–60% compared to more traditional methods. However, they come with other challenges with some requiring higher capital investments (e.g. calcium looping), while others, like indirect calcination, are limited to process emissions and do not address energy-related emissions[11]. The decision which technology to deploy will hinge on other decarbonization options available as well as the carbon transportation and storage infrastructure available on the specific location.

9. Cembureau
10. MPP considering a carbon price of USD 100/tCO2
11. ECRA

Figure 18: Net-zero consistent emission reduction pathway by category



Sources: GCCA, MPP

A full decarbonizing of cement and concrete will require considerable investment efforts, but only 35% can be considered additional investments[12]. Lower demand expectations for the sector, along with replacement investments that would have occurred regardless of the climate pathway, help reduce the investment gap between a net-zero and business-as-usual scenario. Additionally, several decarbonization measures – such as energy efficiency improvements, the use of SCMs and fuel switching to waste – come at little to no cost, or even generate cost savings. As a result, transitioning to a net-zero decarbonization pathway could even reduce within sector investment costs by 7% compared to maintaining a business-as-usual approach. However, the substantial costs of building the required hydrogen, electricity and CCUS infrastructure mean that the total – sector specific & infrastructure – investments needed to reach net-zero targets in the cement industry will likely still exceed BAU investments by approximately USD400bn (or 35%). Reducing the total investment required to decarbonize the sector therefore depends primarily on minimizing infrastructure needs. This can be achieved on one hand by utilizing process and energy efficiency improvements to their maximum potential while continuing to explore alternative chemistries that could enable lowering clinker consumption in the long run. Moreover, minimizing infrastructure needs can be achieved by moving from a largely on-site production process to a more scalable industrial production approach. Additionally, it would be beneficial for the sector to construct cement production facilities in geographical industry clusters together with other energy intensive industries. This would not only improve the supply chain for industrial byproducts such as SCMs but could also lower costs by leveraging a joint decarbonization infrastructure.

Besides infrastructure optimization, lowering CO2 emissions while minimizing costs requires deploying optimal technologies for a given production site (Table 4). This is highly country and site dependent, but there are cost advantages that make certain decarbonization technologies preferable on average. Process and energy emission reduction strategies often come at lower investment and variable cost compared with CCUS (Figure 19), which makes them economically preferable. However, as highlighted before, their emission reduction potential is more limited. Since decarbonization options are applied along the value chain and refer to different processes, they are only imperfect substitutes. Therefore, while the overall

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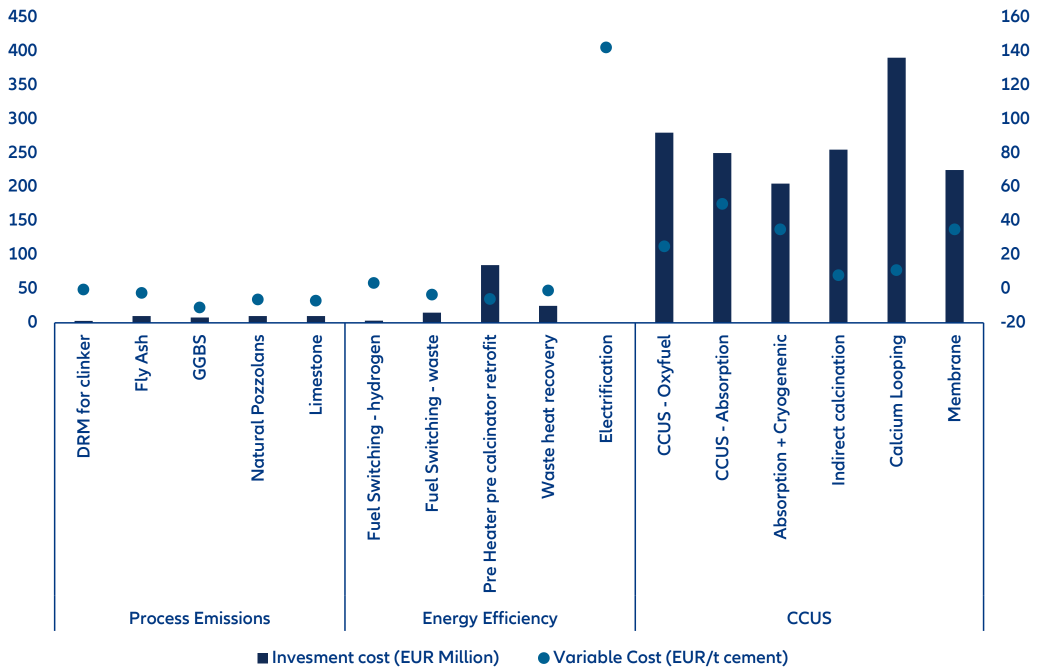
cost-benefit assessment provides a broad comparison across all decarbonization strategies, the within-category ranking allows for a more precise evaluation of the most effective options among similar approaches, such as SCMs or CCUS. For clinker substitution, SCMs based on industrial byproducts such as fly ash or GGBS are the most cost-efficient alternative today. While their supply is expected to decline over time, leveraging them as a transitional solution remains both necessary and economical. These materials reduce clinker demand and lower production costs by USD2.60–11 per ton of cement, providing an effective bridge until other process-related emission reduction technologies become viable. For energy substitution, only fuel switching to waste comes at a discount (USD -3.5 per ton of cement), but other technologies could also become viable if further cost reductions in electricity prices driven by an expansion of inexpensive renewable energy are realized. As carbon capture technology will be essential to achieving the sector's decarbonization targets, equipping production facilities with the best available technology will be crucial for minimizing emissions and ensuring a sustainable transition. Here, while limited to process emissions only, indirect calcination is a very promising option with variable cost at just USD6 per ton of cement. However, other technologies such as calcium looping or oxyfuel based CCS could also lower cost and are preferable over conventional absorption-based carbon capture methods.

Figure 19: Investment cost (in EUR mn – lhs) and variable cost (in EUR/ton cement – rhs) for different decarbonization options in Europe



Sources: ECRA, Allianz Research,
Note: investment only consider the sector specific costs and abstract from infrastructure investment expenses (eg electricity grid)

Tanle 4: Heatmap illustrating the cement & concrete sector transition.

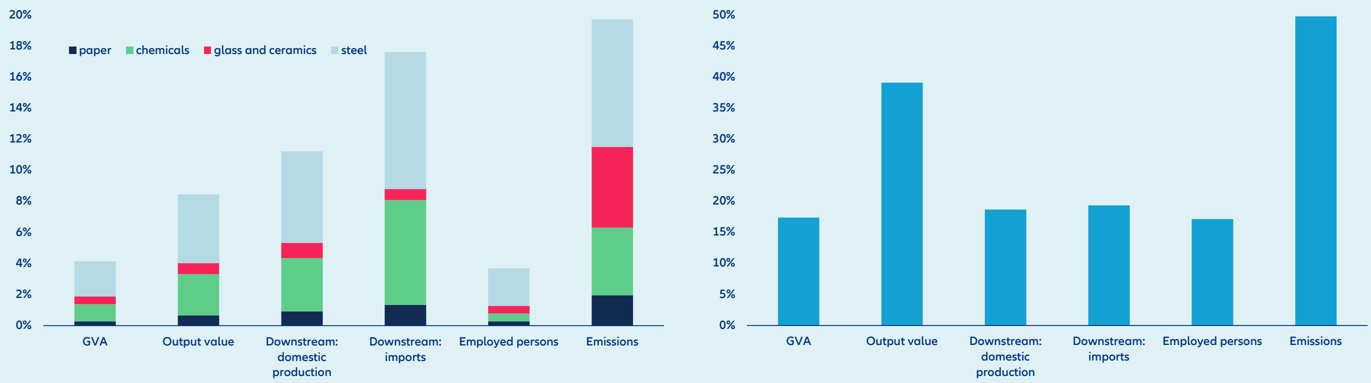
Topic	Measure	Assessment	Rank within category	TRL
Process Emissions	DRM for clinker		x	9
	clinker alternatives		x	3-8
	SCM - Fly Ash		2	9
	SCM - GGBS		1	9
	SCM - Natural Pozzolans		4	9
	SCM - Limestone		3	9
Energy Emissions	Fuel Switching - waste		1	9
	Fuel Switching - hydrogen		3	5
	Electrification & Decarbonization of Electricity Mix		2	4
	Efficiency - Pre Heater pre calcinator retrofit		x	9
	Efficiency - Waste heat recovery		x	9
CCUS	Oxyfuel		2	6
	Absorption		6	8-9
	Absorption + Cryogenenic		5	8
	Indirect calcination		1	7
	Calcium Looping		3	7
	Membrane		4	4

Sources: Datastream, European Commission, Allianz Research

Energy-intensive industries play a crucial role in Germany's economic strength but also in its path to net zero

One-fifth of German industrial value creation is at risk in the medium term – primarily due to high energy costs. In 2021, these sectors contributed 8.5% to the country's domestic output value and generated 4.1% of GVA, amounting to EUR13.6bn (Figure 20, left). Of downstream production, 11.2% was produced domestically while 17.6% was imported. Energy-intensive industries are also an important employer, accounting for 3.7% of total jobs in Germany, or approximately 1.6mn positions. However, the impact of these industries extends far beyond direct employment: they indirectly influence nearly a fifth of total GVA and jobs (around 10mn), and account for 39.1% of German output value in 2021 when considering the top six most affected industries across energy-intensive sectors (Figure 20, right). This indicates that nearly half of Germany's output value, along with more than a fifth GVA and of total employment, is at risk if energy-intensive industries face challenges, as seen with the energy-price shock since the invasion of the Ukraine. Energy-intensive industries are responsible for about 29% of total final energy consumption in Germany. Their emission intensity is notably high, with direct emissions constituting nearly one-fifth (19.7%) of emissions from the economic sector in 2022 and this share has increased from 18% in 2010, while indirect emissions from the top six downstream sectors account for almost half (49.8%) of overall German economic emissions. Consequently, the decarbonization of these industries is indispensable to reach climate neutrality in Germany but will not be achievable without an accelerated scale-up and roll-out of innovative climate-neutral technologies in energy-intensive industries.

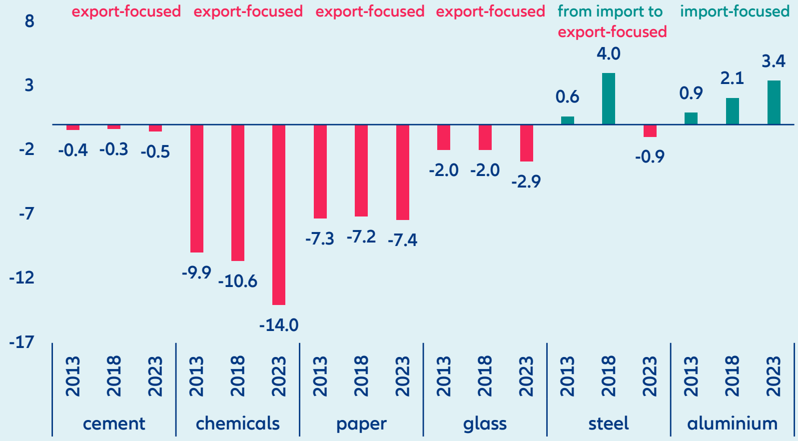
Figure 20: Economic importance of energy-intensive industries, direct (left) and top-6 indirect (right) in 2021 in % of total



Sources: Destatis, Allianz Research. Notes: Analysis of Input-Output-Tables 2021, Rev. 2019. Indirect industries evaluated as the top-6 sectors per energy-intensive industry along domestic production values EUR mn. Destatis 2024 Umweltökonomische Gesamtrechnung for TSH emissions are for 2022.

German core industries lose competitiveness but relocation can help make them climate neutral. Germany is grappling with higher production costs for green electricity, hydrogen and hydrogen-based industrial raw materials compared to countries with higher renewable energy potential. This situation is expected to keep energy prices in Germany high in the medium term, diminishing the competitiveness of its energy-intensive production sectors, already -15% below 2021 levels. Four main factors contribute to this loss of competitiveness: energy price differentials, limited access to affordable low-carbon energy, CO2 costs and high investment intensity. Consequently, there is a trend toward relocating energy-intensive production abroad, leading to increased imports of these goods (so-called "renewables pull"). To counteract cost disadvantages (production costs in Germany 20% to 80% higher than abroad), Germany should import energy-intensive primary products like pig iron, ammonia and methanol from emerging green markets. But many German industries are still export-focused (Figure 21) with net imports in energy-intensive intermediate goods decreasing by USD8.4bn between 2018 and 2023 alone, not yet indicating a shift away from local production. Such a strategy would not only reduce overall costs but also allow for the retention of downstream processing in Germany, preserving local value addition, while supporting the transition to net-zero emissions in the industry.

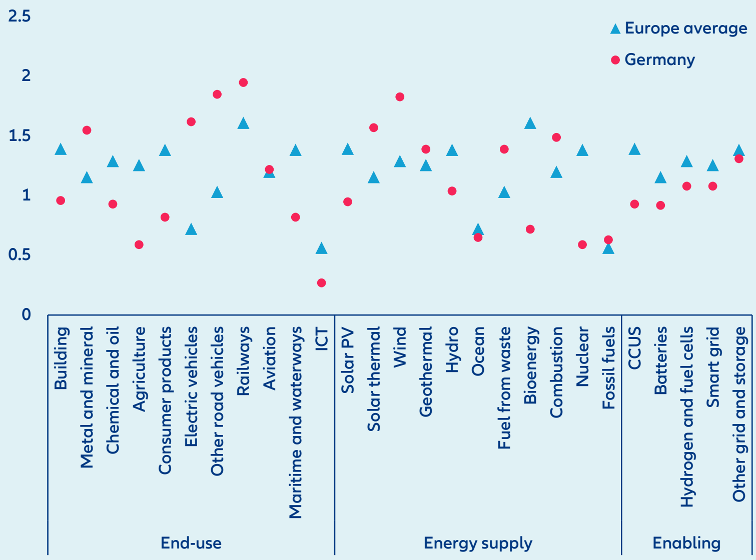
Figure 21: Net imports, in USDbn



Sources: UNComtrade, Allianz Research. Note: Net imports = total imported goods – total exported goods in USDbn.

Germany, despite its strong position in clean technologies, must respond strategically to competitiveness losses and the need for decarbonization in energy-intensive industries by rapidly scaling up again on innovative climate-neutral technologies. Historically, low-carbon energy (LCE) innovation has been strong, with LCE patents rising significantly after 2010, accounting for about 11.6% of all patenting activities between 2010 and 2019. However, there was a notable decline in LCE innovation post-2011, particularly after 2018. Germany's revealed technological advantage (RTA) in LCE technology was strongest in wind energy, solar thermal and combustion technologies for energy supply, as well as in road vehicles and railways (Figure 22). As industry dynamics shift and competitiveness wanes, it is crucial that national specializations align with the significance of end-use sectors. Currently, technologies still in prototype or demonstration phases could contribute to approximately 25% of the CO2 emissions reductions necessary for achieving net-zero emissions by 2070. However, transitioning from prototypes to mass market can take a decade or more. Given the urgency of climate change goals and the strong loss in competitiveness of core Germany industries, strategic decisions regarding outsourcing within the value chain but also focusing on innovation are critical. To regain a competitive edge, investments in new technology fields must be prioritized to accelerate the adoption of climate-neutral technologies beyond just the most prominent German end users. This requires determined interventions to establish favorable framework conditions across various sectors to foster innovation and facilitate a sustainable transition.

Figure 21: Specialization (RTA) by LCE technology fields, 2010-2019



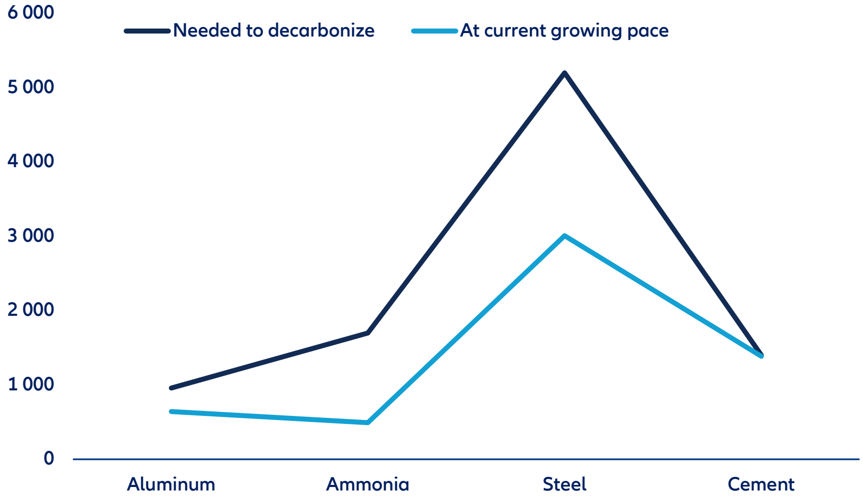
Sources: EPO, IAE, Allianz Research. Notes: Revealed technological advantage (RTA) index indicates a country's specialization in terms of LCE technology innovation relative to its overall innovation capacity.

Green financing gap: when the ideal is far from reality

It's a tough road ahead, but it's not impossible. While the goal of decarbonizing these sectors may seem like an enormous financial challenge, it is achievable, provided that companies in these industries are incentivized to significantly increase their investments. Consequently, government support is crucial. Over the past five years, capital expenditure (CAPEX) in these four sectors has grown at an average annual rate of +3% globally. Assuming this growth rate continues through 2050, and that all CAPEX is allocated towards greening their business models, we see that three of the four sectors are still far from the investment levels needed to fully decarbonize (Figure 23).

Steel and ammonia have the largest green-financing gaps, highlighting that many companies are not investing enough to meet the challenge, despite the urgency. Under our scenario, the steel and ammonia industries would need to invest an additional USD2,191bn and USD1,205bn, respectively, to achieve their green goals. To reach the target, CAPEX for these sectors must grow by +8% and +11% annually, respectively, until 2050. In contrast, the financing gap in the aluminum industry is smaller (USD317bn) and the cement sector's investments suggest that companies may be more on track to meet the decarbonization target independently – again, assuming that all capital is directed toward decarbonization efforts, which is not currently the case. This underscores why government action is so critical. Public-private collaboration is essential to expedite progress and help these industries meet the EU's 2050 target. Governments must provide grants, tax incentives and policy frameworks to reduce the financial burden on companies. Without increased investment now, the path to net zero will only become more challenging and costly in the future.

Figure 23: Accrued CAPEX between 2020 and 2050 by sector (globally, in USD billion), ideally needed for decarbonizing vs growing at current pace



Sources: LSEG Datastream, Allianz Research

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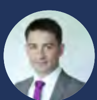

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